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1. Evaluate the state-of-the-art in remote sensing from aircraft and spacecraft and its application to resource management in Semi-arid lands.

2. Identify the best opportunities and constraints with respect to remote sensing applications in the Sahel.

3. Present the analysis and results of this contract activity in a format that is meaningful to resource planners and mangers.

In Part II, remote sensing applications to specific mesource management problems are detailed in a series of ten chapters:

- Cartography and Mapping
- Geology and Mineral Prospecting
- Monitoring Dune Sands and Dune Migration
- Meteorology and Water Balance Modeling
- Evaluating Surface and Subsurface Water
- Livestock Inventorying
- Assessing Agricultural Production and Development
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The views and conclusions expressed in this volume reflect the opinions of EarthSat's editors and contributing authors, and are not necessarily those of the Agency for International Development.

TABLE OF CONTENTS

Chapter 1 RESOURCE PROBLEMS AND OPPORTUNITIES FOR REMOTE SENSING IN THE SAHEL: INTRODUCTION AND CONCLUSIONS
Darryl R. Goehring, David S. Simonett and Jack B. Bale 1

PART 1

BACKGROUND INFORMATION ON REMOTE SENSING TECHNOLOGY AND ON THE SAHEL

Chapter 2 ROLES FOR REMOTE SENSING IN DEVELOPING COUNTRIES: RESOURCE MANAGEMENT AND REMOTE SENSING PRINCIPLES
Martin I.Stoller, David S. Simonett and John Everett 13

Chapter 3 SAHELIAN LANDSCAPES AND ECONOMIES IN RELATION TO REMOTE SENSING
Margaret T. Kolar and Jack B. Bale 33

Chapter 4 REMOTE SENSING SYSTEMS AND COSTS OF DATA ACQUISITION
John R. Everett and Earl S. Merritt 45

PART II

REMOTE SENSING APPLIED TO SPECIFIC SAHELIAN RESOURCE PROBLEMS

Chapter 5 CARTOGRAPHY AND MAPPING
Jack Palgen and Jan W. van Roessel 83

Chapter 6 GEOLOGY AND MINERAL PROSPECTING
Melville C. Erskine and S. Benedict Levin 101

Chapter 7 MONITORING DUNE SANDS AND DUNE MIGRATION
David S. Simonett 123

Chapter 8 METEOROLOGICAL AND CLIMATOLOGICAL ANALYSIS AND WATER BALANCE MODELING
Earl S. Merritt 135

Chapter 9 EVALUATING SURFACE AND SUB-SURFACE WATER RESOURCES
Richard S. Affleck and Richard J. Stanley 153

Chapter 10 SOIL SURVEYING AND MAPPING
David S. Simonett and Delanne Conte 175

Chapter 11 CLASSIFICATION OF NATURAL VEGETATION AND EVALUATION OF RANGE QUALITY
Charles E. Poulton and Wayne G. Rohde 191

Chapter 12 LIVESTOCK INVENTORYING
Charles E. Poulton and Bill J. Van Tries 207

Chapter 13 ASSESSING SAHELIAN AGRICULTURAL PRODUCTION AND DEVELOPMENT POTENTIAL
David S. Simonett and William H. Anderson 223

Chapter 14 LAND USE PLANNING AND DEMOGRAPHIC ANALYSIS
Jack B. Bale, Delanne Conte and Darryl R. Goehring 241

CHAPTER 1

RESOURCE PROBLEMS AND OPPORTUNITIES FOR REMOTE SENSING IN THE SAHEL: INTRODUCTION AND CONCLUSIONS

1.0 INTRODUCTION

During the course of the past several years major advances were made in the technology of remote sensing. The launch of an earth resources satellite (ERTS-1) in 1972 is an example of such a major, new technologic event. Complimentary advances have been made in techniques for interpretation of remotely sensed data and its application to problems of measurement and management of natural resources.

In this context of change the Agency for International Development (AID) contracted with Earth Satellite Corporation to undertake an evaluation of recent operational, research and experimental activity. Special emphasis was placed upon evaluation of applications of operational meteorological satellites and earth resource observation satellites like ERTS-1 and Skylab.

The stated objective of the AID - EarthSat contract was to accomplish the following:

1. Evaluate the state-of-the-art in remote sensing from aircraft and spacecraft and its application to resource management in semi-arid lands.
2. Identify the best opportunities and constraints with respect to remote sensing applications in the Sahel.
3. Present the analysis and results of this contract activity in a format that is meaningful to resource planners and managers.

The report is divided into two parts. Part I provides an economic and managerial setting for the use of remote sensing for resource management in the Sahelian environment. Included are descriptions of remote sensing systems and alternative costs. There are three chapters in this section:

- Roles for Remote Sensing in Developing Countries: Resource Management and Remote Sensing Principles
- Sahelian Landscapes and Economies in Relation to Remote Sensing
- Remote Sensing Systems and Costs of Data Acquisition

These introductory chapters deal with several sets of considerations which will impact any attempt to utilize remote sensing technology to gather management information. Chapter 2 brief-

ly discusses: 1) economics of information in the Sahelian contexts; 2) how remotely sensed data can be used in mangement processes; and 3) a series of commonly employed strategies which make remote sensing more cost-effective in gathering data. Chapter 3 presents a discussion of the natural and cultural environment of the Sahel and identifies those portions of the "target landscapes" which will impact the utility of the various remote sensing systems described in Chapter 4. When considered in total, the information contained in Part I will permit the non-technical policy maker to understand the key what, where, when and how issues involved in the efficient use of remote sensing systems to meet their information needs.

In Part II, remote sensing applications to specific resource management problems are detailed in a series of ten chapters:

- Cartography and Mapping
- Geology and Mineral Prospecting
- Monitoring Dune Sands and Dune Migration
- Meteorology and Water Balance Modeling
- Evaluating Surface and Subsurface Water
- Livestock Inventorying
- Assessing Agricultural Production and Development
- Land Use Planning and Demographic Analysis

Each of these chapters discusses applications in areas which have been identified by AID and detail problems, data sources and specific strategies within each area.

2.0 CONCLUSIONS AND CHAPTER SUMMARIES

The principal conclusions reached in this study relate to overall applications and issues common to resource management objectives. This discussion is followed by a synopsis of each chapter including major disciplinary conclusions.

2.1 PRINCIPAL CONCLUSIONS

There are seven principal conclusions that focus on the key issues affecting the use of remote sensing techniques and their role in the development of natural resource management systems in the Sahel.

1. Remote sensing applications should be organized to optimize information production and minimize acquisition costs.

   - An "information theory" approach may be taken in planning data acquisition programs. The key question is: "what is the planning or management benefit from acquiring these data?"

   - Multiple system approaches including multiple uses of imagery, multiple sensor acquisition programs, and multi-stage program design offer great potential for cost-effective information gathering. All acquisition programs should be designed to consider the largest variety of uses possible. All available and useful existing data sources should be identified and integrated. In the systems context, ERTS-1 imagery can provide information to delineate broad ecological provinces which serve to define the universe, and can serve as the small scale component of almost all multi-stage resource surveys. Resource conditions within these provinces can be established on the basis of samples provided through careful site selection employing sequentially: 1) low resolution image data from ERTS and Skylab; 2) high resolution remote sensing images from low, medium or high altitude aircraft, and 3) detailed ground based studies at selected locations in the Sahel, plus the historic data base.

2. The costs of a remote sensing survey include the costs of acquisition, processing, interpreting and verification of the data being collected. Additional costs will arise from data and information storage and handling. Costs can usually be minimized by adhering to the following general principles:

   - Larger areas are less costly per unit area to survey.
   - High resolution, sensing systems for single purpose applications which involve relatively high acquisition costs should be used in a multi-stage sampling strategy involving ERTS and Skylab.
   - Resource program coordination among user agencies can lead to economies of scale; and costs associated with remote sensing surveys can be lowered in a relative sense if they are shared in multi-purpose programs.

3. ERTS-1 imagery, now available for virtually all of the Sahel, provides a relatively low cost, unique data base suitable for reconnaissance scale evaluation of natural resources. Comprehensive coverage makes earth resources satellite imagery a useful component of integrated multi-stage sample surveys. The natural environment of Sub-Saharan West Africa is well suited to the following applications of ERTS-1 data:

- Construction of black and white and/or false color mosaics at scales of 1:1,000.000 to 1:200,000. to form a uniform base for all forms of area wide resource mapping and evaluation
- Updating the older 1:200.000 base maps for the Sahel
- Preparation of regional geologic and tectonic maps as a method for focusing mineral exploration
- Plotting the distribution of sand dunes by type and apparent rates of movement. This application does require some further research on the accuracy of determining movement estimation with ERTS
- Inventorying of natural features related to surface and sub-surface hydrologic resources including flood plains, bajadas, lakes, and phreatophytes, especially in color-combined images
- Reconnaissance surveying of soil associations, which will improve existing general soils maps
- Inventorying regional land resources which can serve as a first level data base for a carrying capacity model for human and animal populations

4. ERTS-1 is not an appropriate data source for detecting most small cultural features, such as dirt roads, villages, small fields and migratory agriculture. In order to develop needed data in these areas of interest, investment will be necessary in high altitude aircraft flights to acquire 1:120,000 - 1;150,000 - color and/or color infrared photography.

Applications appropriate to high altitude, medium scale aircraft photography are:

- Updating of cultural features on base maps
- Land use maps, including location of urban and village settlements, transportation routes and estimating population
- Detailed geologic and structural interpretations in areas shown to be of interest on ERTS-1 images
- Detection of watering points for stock management and control
- Improvement in soil association or soil series mapping in areas identified for more intensive development
- Identification of small field, shifting agricultural cropping areas as an input in production estimates

surveys (the costs are significantly higher per unit for small areas). Planning for data collection should be based on prior analysis of ERTS images and existing black and white air photo mosaics.

5. Meteorological satellite data and climatological records may be merged into a dynamic water balance modeling system which integrate earth resource satellite and aircraft data. The output from a single water balance modeling system can serve as management information for range management, agricultural planning, etc. These data have value for operational and planning activities such as:

   - Range/forecast potential assessment during the growing season
   - Agro-meteorological estimating of crop conditions and yield
   - Relief planning operations

6. Use of new generation, small but powerful computers for analysis of data and more effective data management should be considered. Computers can provide an important tool in developing countries for:

   - Easy storage, processing, and analyzing of a wide variety of data on different topics and different areas to best suit user and management needs.
   - Implementation of geo-coded information bases to retrieve and analyze resource data on specific geographic locations
   - Analysis of data to meet planning and management needs
   - Rapid updating of existing information

7. The effectiveness of a resource management program, using technologies like remote sensing, depends upon the interaction of planners, managers, analysts, and the indigenous population who would most be affected by resource projects. Key issues include:

   - Planning of skilled interpreters and analysts who are familar both with remote sensing techniques and the local environment; and
   - Utilizing remote sensing products to effectively integrate indigenous groups into the planning process.
   - Training local personnel for remote sensing analysis and incorporation of indigenous populations into the planning process assists development and implementation of effective resource management.

2.2 SUMMARY OF CHAPTERS

This section abstracts the principal applications of remote sensing for the Sahelian environment.

Key Applications

- Cartography and Mapping (Chapter 5)

  Base maps are fundamental for general development planning. Base map coverage currently exists for the Sahel. The French Institute Geographique National (IGN) compiled in late 1950 and early 1960 base maps for 98 percent of the area at a scale of 1:200,000. These maps have not been updated and copies are often difficult to obtain.

  Major mapping programs to revise or supplement the existing series require interdisciplinary planning to be cost-effective. Conventional photography versus use of ERTS-1 imagery and/or high altitude color and false color aircraft photography should be evaluated. Experience in the U.S. suggests significant cost savings can be effected by using ERTS and/or high altitude images for map updates. Geometric precision of photographic products from the ERTS multispectral scanner has been proven to equal U.S. National Map Accuracy Standards at 1:250,000 scale. It is therefore reasonable to assume that ERTS generated maps would be comparable to the standards of the existing IGN 1:200,000 maps.

  Thematic maps (i.e., vegetation, soils, geology, etc.) at scales appropriate for central or regional planning can be compiled using ERTS mosaics enlarged to IGN map series scale.

  Imagery acquired in 1973 and early in 1974 during Skylab missions 3 and 4 could be used in the same fashion. This material is only partially available at the time of this writing. It is now being catalogued and will be available from the EROS Data Center in Sioux Falls, in late 1974.

Geology and Mineral Prospecting (Chapter 6)

Remote sensing greatly facilitates the rapid and economical discrimination on a regional basis of geologic structures most favorable to certain types of minerals. Costs of exploration are related to information detail. It is important at the outset to delineate areas of prime interest, identify the level of detail required and choose the appropriate search methodology and sensor. This chapter specifies the most appropriate sensor systems for various exploration requirements. A most powerful and cost-effective aid for region-wide exploration is ERTS-1 combined with reconnaissance-type aeromagnetic surveys (1:250,000 scale). The costly search procedures using more expensive sensor devices for detailed airborne and ground surveys can be limited to areas which show high promise.

Remote sensing has an important role in the geologic engineering aspects of transportation planning, and the development of an infrastructure necessary for the economic exploitation of known mineral resources.

Monitoring Dune Sands and Dune Migration (Chapter 7)

Sand migration can be a consequence of overgrazing as well as a result of lower than normal rainfall. Migration of sand dunes southward from the Sahara into more humid areas of West Africa has been a reoccurring phenomena during the recent geologic past. Recent movements threaten important grazing resources, waterholes, settlements, farms, and transportation routes. Ability to correct this problem focuses on programs in range management and dune stabilization. Remote sensing contributes basic information when it is used to monitor the effect and success of these practices and modify the procedures. Capabilities have been demonstrated to do this on a regional as well as a local scale by the appropriate choice of sensor and level of detail. Particular emphasis is placed on the role of ERTS-1 satellite imagery for these purposes, because ERTS-1 imagery has been used in analogous situations to monitor dune migrations and to produce approximate calculations for rates of change.

- Meteorology and Water Balance Modeling (Chapter 8)

  A necessary element in any resource management program is an improved analysis of water budget factors (principally solar radiation, precipitation, and cloud cover) as they relate to potential evapotranspiration. Since the number of stations in the Sahel collecting weather data are insufficient to allow accurate extrapolation for the entire region, water balance analysis can be achieved by combining meteorological satellite data with available ground observations.

  Precipitation estimates (distribution and amount) can be prepared from satellite data for the entire Sahel on a daily basis. Evaluation of cloud cover to determine the degree of solar energy attenuation serves as an input to estimates of soil moisture levels. Meteorological satellites are best used for water budget studies in combination with data obtained from ground stations and higher resolution imagery. Although uniform water balance modeling programs are not being carried out in the Sahel, only modest reprogramming and calibration efforts would be necessary to initiate such a system.

- Evaluating Surface and SubSurface Water (Chapter 9)

  Improved hydrologic information can be obtained through remote sensing for six types of data. These include: 1) inventorying drainage basin morphology, (topographic mapping of drainage basins, evaluation of geologic structures and landforms which influence hydrologic events in a basin, and the calculation of water yield; 2) delineation of vegetation; 3) locating and identifying quality and timing of surface water and runoff; 4) timing and areal extent of floods through vegetation indicators and evidence of severe erosion and sediment deposition; 5) location, quantity, and quality of sub-surface water. (This must be accomplished indirectly, by first identifying surface lithologies, structural patterns and mapping fractures, second by vegetation type mapping); and 6) identification of sources, and the rate of travel of water pollution by means of tonal variations in multispectral signatures.

Capability to derive these data from ERTS imagery varies. The main contributions have been in the areas of inventorying and assimilating features into a regional overview, thereby narrowing the search and analysis of resources at specific sites. Many remote sensors (including color and color infrared photography, radar, and thermal infrared) have applicability in hydrologic analysis. Choice of any sensor or precise data collection strategy will depend on the specific nature of water management problems and policies. Special emphasis should be given to integrated use of meteorological and ERTS satellite remote sensors because of their unique capabilities for broad area and point source data.

Soil Surveying and Mapping (Chapter 10)

Planning agricultural development and range improvement programs requires reconnaissance information on soils. The fact that soils associations and individual soils tend to conform to landform units in an orderly and understandable relationship makes them mappable even on small scale imagery. Such relationships enable experienced soil scientists to map soils associations at scales of 1:200,000. ERTS or other small scale imagery should be used for this task because it is relatively inexpensive, it offers broad regional coverage, and can be readily mosaicked. Use of more detailed techniques depends largely on the purpose of soil mapping programs. Remote areas with complex landscapes and little ancillary data may require more detailed ground and air surveys to verify data provided through remote sensing. Soils engineering and irrigation project planning require detailed types of information that can only be accommodated through ground investigations.

Evaluation of Vegetation and Range Quality (Chapter 11)

Forage production estimates in the Sahel must be accomplished in the face of unique difficulties related to the extended drought and year to year rainfall variability. Periods of heavy grazing have so degraded the range resources that optimal ecological conditions cannot easily be determined.

An inventory of the present situation by any method would only reflect the current stressed conditions and contribute little to a solution.

A more viable approach is to identify areas for future range improvement. A program aimed at growing more feed, rather than maintaining animal populations at a reduced level would seem a reasonable goal. An inventory of current natural vegetation conditions would contribute to an estimate of range potential, since animal carrying capacity is determined from knowledge of physiological and ecological tolerances of various plant species to grazing and what management procedures have been utilized. Information on past conditions can be obtained from earlier aerial photography and used in combination with new imagery to identify trends in the condition of the range resource.

An inventory of range resources can be carried out systematically and cost-effectively with remote sensing. The first phase would consist of reconnaissance mapping using mosaics of 1:1,000,000 ERTS images to delineate ecological provinces. Enlargements to 1:200,000 scale would allow identification of broad physiognomic-structural vegetation units. To accurately calibrate any regional model of range resources in the Sahel, further detail would be necessary within these boundaries. A multi-stage sampling strategy using high resolution color or color infrared aerial photography in selected areas plus ground observations could provide such calibration.

Livestock Inventorying (Chapter 12)

Actual counts of animals using remote sensing have only been achieved by low flying aircraft. Arid and semi-arid regions pose special problems: animals are highly migratory. Techniques are available with small scale ERTS imagery to stratify the procedure of locating animals by monitoring the greening and browning of the landscape and, by selectively increasing the scales of imagery, to focus on habitats occupied by animals. The procedure requires contact scales as large as 1:3,600 to 1:600 for the final stage when animals are to be counted. For this reason, the emphasis

in remotely sensing animals falls on identifying habitats correctly in the early stages of multi-stage sampling programs.

Assessing Agricultural Production and Development (Chapter 13)

Remote sensing of agriculture presents problems that are similar to those encountered with natural vegetation. as well as problems which are unique to the particular cultural setting and land tenure system. While areas of crop farming can be identified along river courses and around villages using ERTS, useful information on crop vigor and yield are difficult to obtain. First of all, Sahelian landholding systems create small, impermanent parcels which are hard to detect with ERTS imagery. Small parcels are operated under a horticultural system (gardening) when crops tend to be mixed. Widely scattered hand sown fields of staple grains (mostly millet) blend with the natural background and are hard to identify except on very large scale imagery. Present drought conditions which leads to poor and varying yields makes it difficult to employ crop calendars, spectral signatures or other techniques that are helpful in identifying crops in areas with "dependable" meteorological conditions. Reliance must be placed on high altitude photography to establish a sample frame for agricultural census rather than to use ERTS imagery. Best estimates of regional yield potential will come from agro-meteorological modeling utilizing meteorological satellite data.

Monitoring Land Use and Demographic Analysis (Chapter 14)

Remote sensing can be effectively employed in a land use planning program to: 1) provide an initial source of information; 2) to identify the factors responsible for change in the resource base; 3) to help define management policy; and 4) to monitor the effect of these policies. By assuming an ecological perspective, (i.e., by understanding how populations perceive and utilize their environment), environmental conditions can serve as a surrogate for land use data in areas where human activity can not be directly

monitored with remote sensors. Implementation of such a methodology requires extensive calibration but detailed information provided by multiple resource surveys (including multi-stage sampling) and heavy reliance on collateral data sources can provide invaluable information for land planning.

Population estimates have been accomplished (with remote sensors) by developing estimates based on housing occupancy ratios and counts of houses, as well as by sampling population densities per unit area of land use classes and then using the total area of a given land use as the multiplier to calculate total population of a given area. These methods enable inter-censal population estimates to be obtained and fill in where primary data are lacking. Population counts in the Sahel are difficult due to the wide distribution of people and the large nomadic population. Tendencies for population to be distributed according to resource abundance, however, simplifies the locational problem provided that the distribution of resources is known. In this case, population distributions and actual estimates can be prepared by using first level information from ERTS imagery to stratify the search procedure by narrowing the search to habitats likely to support people. The identification and counting procedures which would follow can be conducted by progressively larger scale imagery, to scales as large as 1:20,000 to 1:5,000. Sample population censuses may then be extrapolated over the land use classes as shown in aircraft photo images. Programs to provide land use information and population can only be accomplished effectively if they are developed within the framework of well-conceived, comprehensive regional or national planning policies.

PART 1

BACKGROUND INFORMATION ON REMOTE SENSING TECHNOLOGY AND ON THE SAHEL

CHAPTER 2

ROLES FOR REMOTE SENSING IN DEVELOPING COUNTRIES: RESOURCE MANAGEMENT AND REMOTE SENSING PRINCIPLES

1.0 INTRODUCTION

One of the conclusions that can be drawn from recent events in the Sahel is that integrated and comprehensive central planning for the development and protection of the natural resource base is a prerequisite for sustaining the productivity of arid and semi-arid lands.

The peoples of the fragile and difficult Sahelian environment have historically existed in a delicate balance between sheer survival and marginal productivity due to the vagaries of nature. Traditionally the environmental/survival balance was characterized by high mortality rates among the tribesmen and the very lowest per capita productivity and income. Recently, however, pressures on the land and resource base from growing human and animal populations coupled with the current drought situation have drastically tipped this fragile balance. Survival itself will require an increase in the capability to plan for the reconstruction and future development of the region. To accomplish the necessary planning for improved agricultural, rangeland and other resource management, better and more complete data on the extent, character, value and use of existing resources is required.

Remote sensing can play a cost-effective role in acquiring key data for future development planning in the Sahel. The cloudless atmosphere during most of the year permits the use of a wide variety of sensors and the very scarcity of cloud cover and moisture permits the use of both earth resources and meteorological satellites for purposes not readily accomplishable in other environments of the world. Remote sensing is <u>not</u> a panacea for resource development and management problems. However, it <u>can</u> provide the data which are the basic tools for sound resource inventorying, monitoring and management.

The technical chapters in this report discuss in considerable detail how remote sensing technology may be used to gather natural resource information in arid and semi-arid environments. Those chapters are written with a full recognition that significant portions of available remote sensing technology may not be used by the countries in the sub-Saharan zone of Africa in the near term for two basic reasons: 1) there is a shortage of technical skills and trained professionals and thus the amount of remote sensing data which can be acquired and integrated into the planning

and development processes is limited; and 2) there are insufficient funds available to finance substantial remote sensing programs, or to analyze and apply imagery and data even if obtained at a low cost in bulk quantity, unless there is relatively rapid payoff. In that context, economy in data collection, interpretation, and application is of major importance.

2.0 EFFICIENCY IN REMOTE SENSING PROGRAMS

Planners and managers who are ultimate consumers of remote sensing and other data have the responsibility for defining the requisite development objectives. They themselves must understand and specify the data parameters required to achieve these objectives. Data collection for the sake of data collection and map production, with no direct link to management decision making, is by no means uncommon. Indeed a common occurrence in most developed countries and many less developed countries is to collect data on the basis of some mandate whose precise purpose is long out-dated and forgotten.

Chapter 4 describes the relationship between various remote sensing systems and the costs of data collection and processing, a key input into management decisions. It is apparent from the cost chapter and technical chapters (5-13) that if central planners and resource developers are prepared to use information derived from small scale imagery, they may be able to accomplish a wide variety of data collection, resource planning and management objectives in a highly efficient way and at relatively low cost. One of the most important conclusions of this report to the resource manager is that the availability of ERTS-1 data at low cost makes it possible for less developed countries to afford to address a wider range of operational questions that would be possible through any other means.

2.1 BASIC PRINCIPLES FOR PROGRAM MANAGERS

There are some basic, common sense principles which may be used to guide remote sensing activity. They call for the use of objectivity, prudence and technical accuracy in the selection and design of remote sensing programs. Among the key guidelines are:

1. Demonstrate that the data collected can be assimilated and integrated into current or near-term operations. Continuously ask the question, "What discussions or actions can be taken with these data?"

Given the human and financial limitations of the technical and central planning functions in the less developed countries, the operational rule that remote sensing data collection be

useful for specific planning or management action is central. For, even using this stringent economic benefits criterion, the information collection requirements in the Sahel will substantially exceed the rate at which data are now collected and assimilated into the planning and development process.

2. Search for the most cost-effective means for data collection.

Assuming that available imagery combined with small amounts of additional data can answer key resource management questions, stress is placed on the use of sampling procedures to reduce the volume of information well below that which is gathered using traditional, non-selective remote sensing techniques. Moreover, emphasis is placed upon the use of the more generalized, broad area data (small scale imagery, such as ERTS-1) consistent with the operational or planning purposes to reduce both the quantity of information gathered and the costs of data acquisition and interpretation.

3. Plan remote sensing data acquisition in light of both management as well as conventional inventory applications.

Plan for multi-purpose use, if possible. Carefully planned selection and use of remote sensor systems can provide data for a variety of decision making purposes. Generally, the dynamic inputs will arise from the use of earth resource satellite or meteorological satellite data.

4. Develop a data management system capable of efficient storage, retrieval, and manipulation of data.

Data management systems establish a rational plan for data storage and manipulation. The purpose of a data management system is to provide a basis for production of information for a wide variety of management and decision making purposes in a timely fashion.

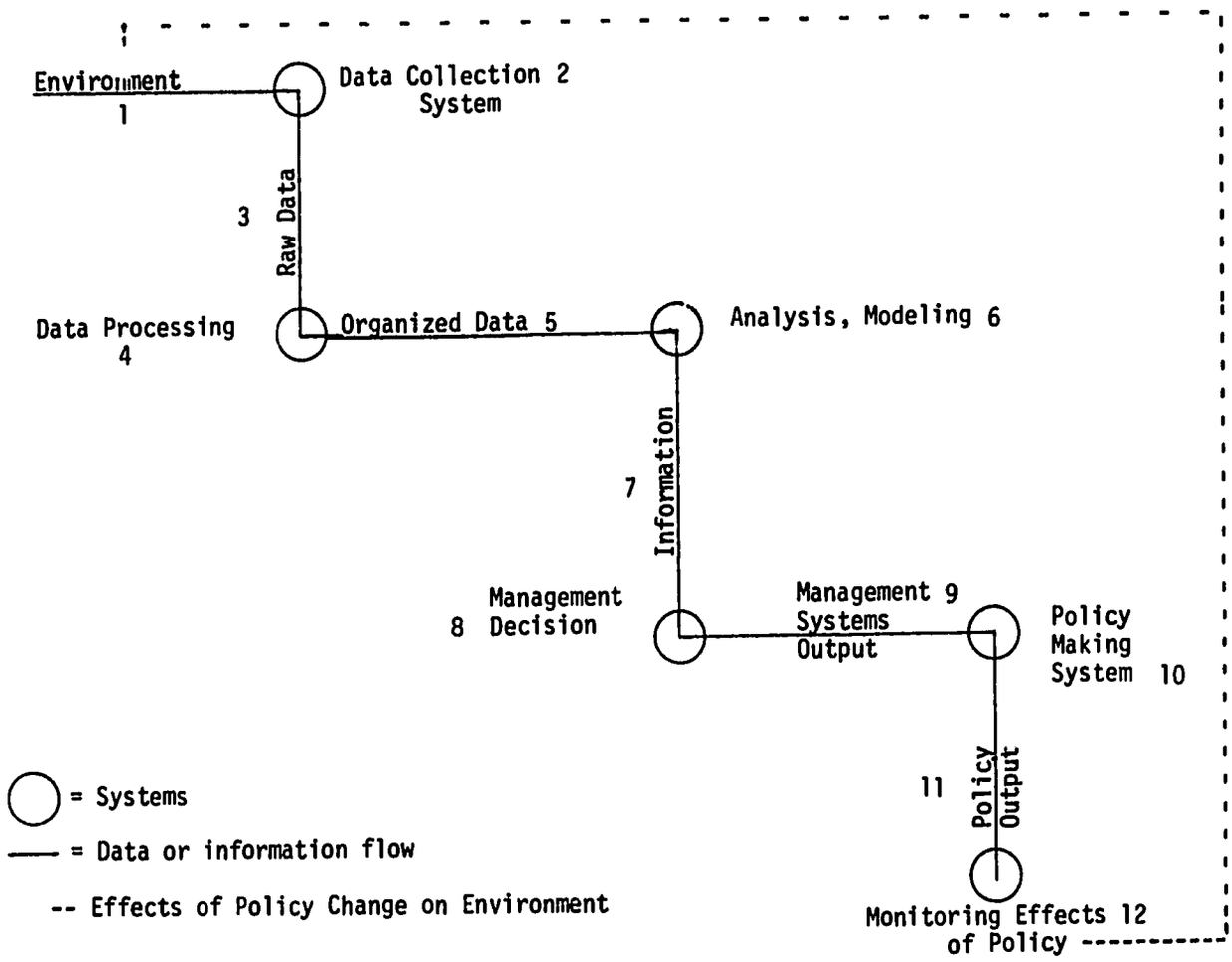
3.0 RESOURCE MANAGEMENT PROCEDURES

Resource management procedures include the policies, programs, and decisions necessary to develop, use and preserve natural resources. The process begins by establishing goals for resource development and preservation, moves to the formulation and execution of project plans, and continues with the monitoring of the results and adjusting the original plans as needed through a feedback mechanism. Remote sensing can play a role in many of the procedural steps of resource management and is particularly important in the initial planning, data collection, inventory operations, analysis, and monitoring phases of resource management programs.

3.1 REMOTE SENSING AS PART OF A MANAGEMENT SYSTEM

Remote sensing techniques for data collection and resource observation are meant to be part of a management system. Figure 2-1 shows schematically the way policy decisions and environmental realities are linked in an effective system.

FIGURE 2-1: RESOURCE MANAGEMENT SYSTEM LINKING POLICY DECISIONS AND ENVIRONMENTAL REALITY



This diagram is presented to emphasize that remote sensing is part of a resource management system, and for the system to function properly each link in the chain must function properly. Remote sensing is important principally in steps 2, 3, 4, 5 and 12 of the chart and it may also be valuable in Step 6 as well. In each of these steps, remote sensing may prove to be (depending on the problem) very useful, useful, or of limited use. It may also form a large, moderate, or only a

small portion of the material collected or processed at a given step. It is helpful to systematically review each of the steps at the beginning of a project where remote sensing is involved. It is particularly important to start from Step 12 and work backwards through the system identifying problems and potential uses enroute.

A country or regional group which proposes to include remote sensing in its development efforts must face not only the issue of how to use sensors most appropriately, but also the issue of how to incorporate the data into a usable management system. The purpose and design of an information system will provide context to the remote sensing technician; that context will determine the kinds of data he acquires, and also the scales and methods in which the data are interpreted.

A particularly difficult and critical issue is where to establish the institutional base for a data management system and what form is the system to take? Obviously, each government or regional group can best determine for itself the most effective system to accomplish its objectives.

4.0 DATA MANAGEMENT SYSTEMS

A country or regional institution that proposes to use remote sensing in its development efforts is confronted with the dual issues of a) How to use sensor techniques appropriately?; and b) How to incorporate the data acquired into a resource management system?

An obvious limitation to the establishment of a resource management system is the lack of trained technical staffs to handle both the imagery interpretation and data storage and retrieval. A basic problem, therefore, confronting the less developed country is not merely one of acquiring and applying the necessary technology, but of creating the institutional and human capabilities to analyze, store and retrieve the data collected by the technology, and to integrate them into management programs.

The countries of the Sahel are in a unique position to use earth resource satellite and meteorological satellite systems in conjunction with conventional data sources to establish flexible resource monitoring and management systems. Less than 24 months ago, it would have been impossible for any but the most sophisticated and technologically advanced countries to contemplate the establishment of a dynamic resource data management system. Within the past two years there have been major advances in the development of small, powerful and relatively inexpensive computers and associated programs designed for geopoint (data stored in a series

of cells identified by their geographic positions) data storage and retrieval systems. These systems are now commercially available, stimulated in some measure by the existence of dynamic data from ERTS, and by a broadened interest in land use planning.

Such systems are perfectly scaled to the requirements of central planners and resource managers in less developed areas of the world, since these smaller computers can deal with the smaller scale data applicable to national resource planning. A base scale appropriate to the use of a system as defined above might be 1:1,000,000 or 1:250,000. Data stored and presented in that scale are sufficiently refined for order-of-magnitude estimates in area resource forecasting and for planning purposes.

The data at this scale is sufficiently compressed so that the planner deals at the appropriate level of aggregation. Information from ERTS and other smaller scale information sources on soils and vegetation type, hydrology and geology, crop acreage and land use patterns, etc. would be inserted into the cells and updated as new dynamic information to become available. Output data for preliminary planning for land use, road building, irrigation projects, range management, crop acreage forecasting, etc. could be provided by appropriate geographic locations in the form of maps or reports.

It is not the intent of this volume to present a detailed statement on data management systems. It is important to point out and illustrate the fact that new forms of inexpensive small computers combined with new software packages make real time resource planning or forecasting a possibility for the less developed areas of the world.

5.0 BASIC CONCEPTS OF REMOTE SENSING

There are a number of concepts that influence both the selection of sensors and the extent to which remote sensing technology can contribute to resource management. The discussion presented below is intended to outline some of the principles and philosophic underpinnings for remote sensing. Several authors have dealt with some of these concepts and reference to their works may be helpful (National Academy of Sciences, 1970; Tomlinson, 1972, Colwell, 1971).

While there are numerous remote sensing principles and concepts, the most important for the purposes of this study involve: 1) the roles of remote sensing as part of a management

system which was discussed in the previous section; and, 2) the subject of image "resolution" and its effect on data acquisition.

5.1 RESOLUTION AND DATA ACQUISITION

In the classic algebra of remote sensing, "resolution" is considered to have three interdependent dimensions: spatial, spectral and intensity. Since they are interdependent, trade-offs must occur when one attempts to design a remote sensing system for a specific application. The resolution of any one of the three dimensions can be increased or decreased only with some concomitant alteration of resolution in one or both of the other dimensions.

The indivisibility of resolution and the trade-offs among the spatial, spectral and intensity dimensions are expressed by the equation:

$IR = (R_S') \times (R_S'') \times (R_I)$: where IR is indivisible or system resolution, R is the Resolution and the subscripts S', S" and I, refer to spatial, spectral and intensity components of resolution.

Spatial Resolution is the minimum distance between two objects at which the sensor can record them as two distinct entities. In photographic systems, this is expressed as: line pairs per millimeter that can be resolved on the film. In scanner systems this is expressed as: instantaneous field of view (IFOV) which is an angular measure expressed in radians. With radar systems, range resolution (the direction away from the aircraft) is expressed in meters and is dependent upon the length of the transmitted pulse, and azimuthal resolution (the direction along the path of the aircraft) which in turn is expressed in radians and depends upon effective beam width.

Spectral Resolution may be viewed in simple terms as the broadness or narrowness of the portion of the electromagnetic spectrum that is sensed. It is dependent upon the band pass or width of spectrum admitted to the filter and detector system and the amount (number of photons) of energy present in that particular portion of the spectrum. Instruments designed with narrow bands have the characteristics of high spectral resolution (i.e. accurate color measurements). The trade-off is, however, between intensity resolution and spatial resolution. It is difficult in the data produced by narrow band instruments to separate the signal from the noise in the system (poor intensity resolution) unless in the imaging process relatively long dwell times

(length of time a particular area is examined by a sensor). The usefulness of very narrow band instruments is therefore quite limited. Conversely broadband remote sensing instruments produce relatively lower spectral resolutions but have good spatial and intensity resolutions.

Intensity Resolution can be simply defined as the sensitivity of a sensor to differences in signal strength. The signal may appear in the form of reflected light in the visible portion of the spectrum in photographic systems, or emitted energy in the thermal infrared and passive microwave portions of the spectrum. In keeping with our trade-off equation, as intensity resolution improves, either spatial or spectral resolution or both must suffer.

Depending on what is to be sensed, instruments are selected with particular types of resolutions. To study the conditions of the roofs of houses, high spatial resolution is necessary. Thus, one could use a camera with panchromatic film (poor spectral resolution). However, for any reasonable flying height it is not possible to distinguish cereal crops on the basis of morphology alone (high spatial resolution). In the latter case, one could use a multispectral scanner (good spectral and intensity resolution but relatively poor spatial resolution) to rapidly classify crops over a wide area.

In addition to the three traditional dimensions, there is a fourth or temporal dimension. There are very few aspects of nature that do not change relative to others and with respect to themselves throughout the course of the year. There are very few which do not have a better time of day or year in which to be observed relative to other aspects of nature. There are also very few man-made or cultural features for which there is not an ideal viewing time or viewing duration. Thus, in sensing a substantial number of dynamic events -- crop identification and growth, rangeland development, hydrologic processes, drought evaluation processes, earthquake damage, cultural change, marine processes, to name only the most obvious -- time is often used as a key discriminant.

The use of time for discrimination permits one to alter the specifications in the other three dimensions of resolution in such a fashion as to permit more economic remote sensing procedures. With a reasonably accurate local crop calendar which details traditional times of planting, growth and harvest, remote sensing observations can be planned so that a limited number of observations at unique and critical time periods can provide the discriminating information needed to separate one crop type from others. The net effect of using the time dimension and local a priori data is that crops may be identified over larger areas with sensors

possessing spatial and spectral resolutions too poor to identify the same crops on the basis of spectral and morphological characteristics. The introduction and the use of the time dimension in a resource program may have the net effect of sharply reducing cost of data acquisition and processing.

All passive remote sensing systems (those operating in the visible or infrared portions of the spectrum), are dependent upon the sun for their energy. The power spectrum of sunlight is shown in Figure 2-2. This figure shows that the thermal infrared (heat portion of the spectrum requires a much larger band width to allow the same amount of energy to reach a detector than the red portion of the visible spectrum. This demonstrates the principle that for a given spectral and intensity resolution, greater spatial resolution is possible in the visible than in any other portion of the electromagnetic spectrum.

5.2 THREE LEVELS OF PERCEPTION

The three levels of image perception important in resource assessment evaluation are: a) detection, b) identification, c) analysis.

Detection means simply that an examination of the data reveals that something is present, e.g., in an image of a river the presence of an object which is not water is noted. Identification means that enough information is present in the remote sensing data to identify the object or feature perceived, e.g., there is a boat in the river. At the analysis level of resolution, it is possible to perceive information beyond mere identification of the object, e.g., the boat in the river is a dug-out canoe carrying three people.

Detection is adequate for simple dichotomies, e.g., something is or is not present. It is used in the first stage of a multi-stage sampling strategy to define the extent of the universe. Identification is usually sufficient for regional studies e.g., this is a thorn tree savanna; and is sufficient for some probabalistic measures based on more detailed work. Image perception at the analysis level is necessary for highly detailed and operational work, e.g., there are 12 *Acacia* trees per hectare; and forms the third level in a multi-stage sampling strategy.

In practice it requires three times the spatial resolution to progress to identification. A one to two order of magnitude (100 X to 10,000 X) increase in spatial resolution is necessary to pass from identification to analysis. These are average ratios, and the exact spatial

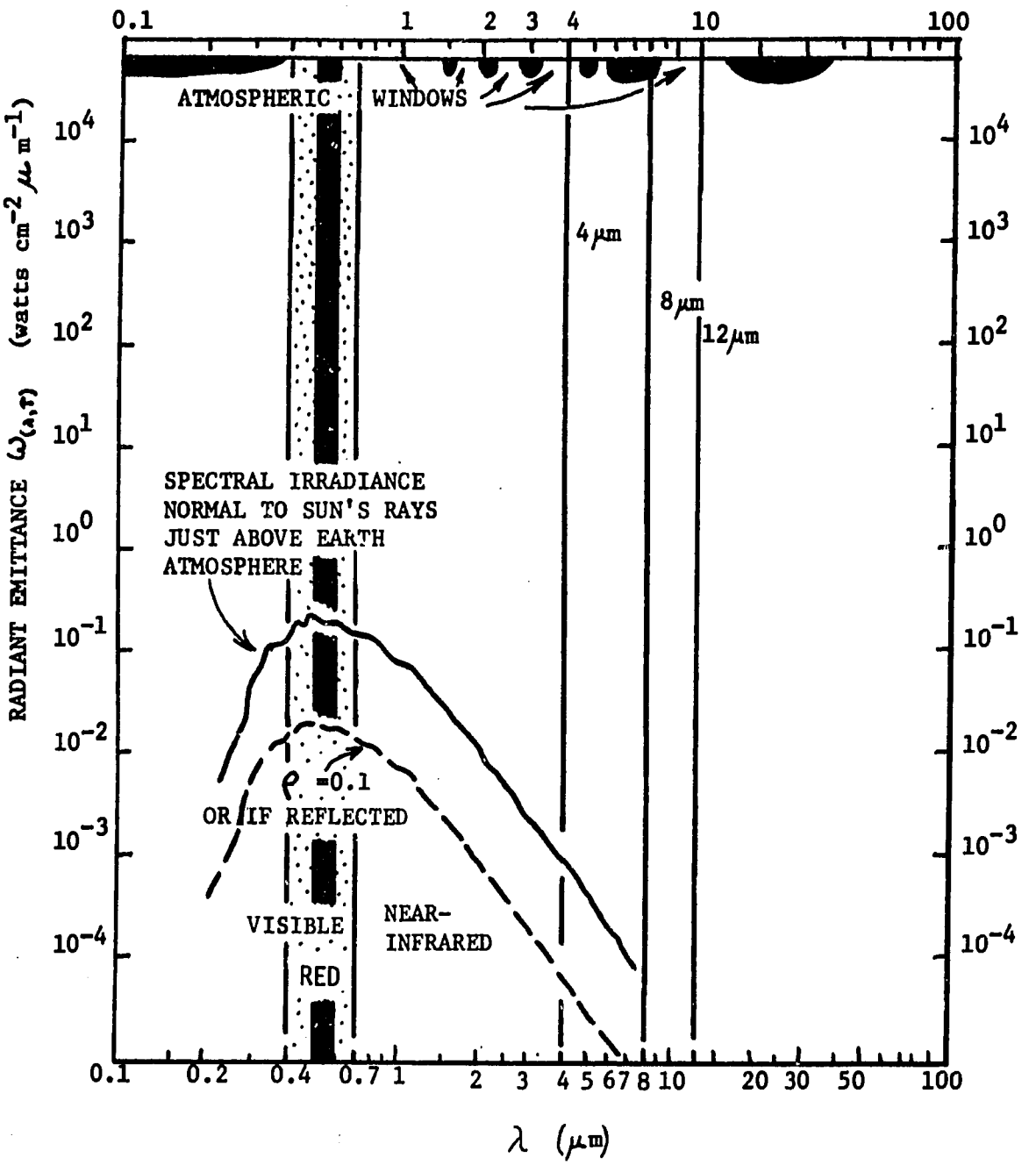


FIGURE 2-2 Spectrum of radiation emitted, reflected or absorbed in the ultra violet through infrared portion of the spectrum.

resolution increase will be primarily dependent upon the character of the target and the amount of information (type of analysis) desired. As a general working rule there is a scale of acquisition of remote sensing data that is better for each one of the three levels of perception. There is no single scale which can serve all of the three purposes.

As a general rule central planners require information at the first two levels of detection and identification, and implementation activities are conducted at the second and third levels. There is a trade-off function in almost every remote sensing program between the levels of resolution since the image perception or information content is a resolution-dependent phenomenon. Very high resolution and very low resolution carry their own sets of problems. The higher the resolution the greater the cost of acquisition, processing, interpretation and data management. The higher the resolution the more difficult it is to generalize based upon point observations. Data of low resolution combine on average a great deal of information into each resolution cell or picture element. This constitutes both a loss of information and implies an averaging response that can produce spurious results. However, small scale lower resolution imagery provides regional perspective and a basis for generalization and allows large areas to be interpreted, analzyed and understood quickly. Small scale data provides a framework for identifying needs for specific point source information.

To describe a more complex situation: At the analysis level of resolution it is possible to perceive information beyond the theoretical limits of resolution of a particular remote sensing system. As an example, items from ERTS imagery as small as eight meters in one dimension have been detected (road systems where the contrast between the object and the background was favorable). In the case of linear features, the human eye and mind help to piece together the concept of road which for any single information cell along the system may be ambiguous. The key point is that there tends to be spatial, spectral and intensity resolution values appropriate to the particular purposes to be served by the remote sensing survey. In order to choose the most satisfactory compromise scales, the whole range of uses for which the remote sensing images will be employed must be known at the earliest time in planning the survey.

6.0 STRATEGIES ASSOCIATED WITH REMOTE SENSING

Within the past 10 years a number of new techniques for design and application of remote sensing systems have evolved. These include:

1. Multiple uses of imagery
2. Multispectral discrimination
3. Multi-sensor combinations
4. Multiple-stage approaches

When used either separately or in combination in an optimum fashion they can make remote sensing more cost-effective as an information gathering technology.

6.1 MULTIPLE USES OF REMOTE SENSING IMAGERY

Multiple uses of remote sensing imagery can improve the cost-effectiveness of remote sensing techniques. This is particularly true now that high altitude aircraft and spacecraft are capable of producing vast quantities of data for substantial areas of the world. These data are applicable to many disciplines and should be used as frequently as possible as base information source data. They are particularly useful for general reconnaissance purposes and for monitoring events and phenomena over large areas. Low altitude imagery tends to have fewer multiple use applications because the specificity of the sensor system increases for more detailed survey work.

An example of multiple use of remote sensing imagery is the Government of Brazil's Project RADAM (Moura, 1971). In this survey the Government of Brazil acquired side-looking airborne radar imagery of 4.5 million square kilometers of the northern part of the country. The output of the survey included maps of geology, hydrology, vegetation cover, soils, and land use potential. Interpretations were supported by a limited amount of aerial photography and helicopter-supported field work at selected points within the area. Because of the variety of interpretations for which this imagery was used, the cost of acquisition for anyone discipline was very small. By virtue of the multi-disciplinary nature of this project, there were many benefits derived from the interchange of information among the different scientists working on the project. For instance, it was found that in areas underlain by Precambrian rocks, the distribution of vegetation types was a very good indicator of the underlying geology.

6.2 MULTISPECTRAL DISCRIMINATION

Many applications of remote sensing techniques are based upon the concept of multispectral discrimination. Theoretically, every substance reflects or emits a unique spectrum of

electromagnetic energy; with observations in enough narrow spectral bands, most substances can be uniquely identified. Such techniques work well in the laboratory or in astronomy for identifying mixed gases, but are only moderately successful when working at the earth-atmosphere environmental interface. However, in the real world, almost every sensor records or "sees" a variety of substances present within each resolution element. It is technically difficult to utilize sensing devices with band widths that are narrow enough to allow accurate and unique sensing of spectra.

However, even with the broad band approach it is still possible to divide the spectrum into meaningful bands. The spectral interval is too broad to be descriptive of a particular material but is sufficiently narrow for that material to be predominant in that band. For an ideal multispectral sensor all materials of interest would predominate in one band. In the real world however, there is too much variability within materials let alone between materials.

What is required then is to collapse variance. This can be done in several ways, such as by choosing a particular time of day or year, or by developing constant environmental associations or surrogates, (e.g., mapping plant communities which indicate underlying geology instead of attempting to map geology directly). This is accomplished without relinquishing the search for specific spectra associated with specific materials. It is encouraging to note that with only four bands, several ERTS investigators have reported considerable success at identifying spectral signatures for geologic substances (Vincent, 1973 and Geotz et al., 1973), and applying multispectral classification schemes to identification of crop and land use types (Draeger et al., 1973; Morain and Williams, 1973).

6.3 MULTI-SENSOR REMOTE SENSING

It is often advantageous to acquire information using a number of sensors simultaneously. Such an approach permits maximum correlation between different types of remotely sensed data and minimizes system costs attributable to the platform. This provides for mutual support

among the sensors used.* Data from non-imaging sensors** can be compared to imagery from the visible portion of the electromagnetic spectrum and compared to information acquired beyond the visible wavelengths. Such an approach can also reduce the amount of ground support needed and if the various sensors can be mounted on the same aircraft or spacecraft, a great cost-saving in data collection can be achieved.

6.4 MULTIPLE-STAGE APPROACHES

The combined use of spacecraft, aircraft and ground-derived information may be needed to provide cost-effective data gathering or resource management programs.

One of the simplest approaches is called "targeting." This process is simply locating areas where change has occurred or are otherwise of particular significance. Smaller scale imagery with gross resolution may be used to accomplish these tasks in a cost-effective manner. Once change is detected, planning for more detailed surveys can proceed. The more expensive large scale image acquisition missions therefore are concentrated only in the change areas. Bale and Bowden (1972) demonstrated how this detection capability can be utilized to pinpoint small areas (minimum 10 to 12 acres) of urban change in California desert communities. Subsequent detailed identification and analysis was accomplished by ground survey techniques.

Multi-Stage Surveys

These types of surveys use multi-stage techniques to map the spatial extent and distribution of phenomena that are detectable on small scale and identifiable on larger scale images. At the heart of the technique is a process of extrapolation from one defined "landscape unit" ("Photomorphic Regions" of McPhail 1969) to similar or homogeneous units. This technique is

* Thermal infrared scanners record emitted radiation (thermal) within certain wavelength bands generally from about 3.5 to 13.5 microns. Gray tones on imagery, derived from this system, are a function of the emitted temperature of the terrain feature being sensed. It is often quite useful to have other forms of imagery, such as photography, to relate data concerning one environmental parameter to others.

** Non imaging sensors include those which sense force fields (e.g., magnetometers, airborne gravimeters, electromagnetic systems, etc.) and those which acquire data at specific points (e.g., spectroradiometer) along a line or limited number of lines parallel to the flight path of the aircraft such as spectrometers, thermal and microwave radiometers, or radar or laser altimeters.

highly dependent upon having capable interpreters and resource scientists to carry out the extrapolation.

The general category of multi-stage surveys subsumes a large variety of surveys where multiple image acquisition missions may involve different platforms at different altitudes. The prime characteristic of these surveys which serves to combine them into a single class is that base imagery for the entire area is first acquired at the smallest available scale (satellite coverage). Larger scale imagery is then obtained for predetermined homogeneous landscape units and used to provide calibrated or detailed sample information. Selection of landscape units are made on the basis of prior information or after an initial period of study of the area. Well conceived multi-stage surveys provide a maximum amount of flexibility. Acquisition techniques for the large scale imagery used for calibration can range from relatively high cost, controlled aerial photography ($9.00 or more/square kilometer in the United States to uncontrolled 35 mm obliques ($.40/square kilometer) imaged from a high-winged, single engine light aircraft (e.g., Cessna 170). Such variation allows collection of a maximum amount of information within the constraints of a resource manager's budget.

The latter scheme, using light aircraft and 35 mm transparencies, has been used as an aid in the identification of very localized phenomena depicted on the ERTS-1 frames included as illustrations in this report. Because these transparencies are relatively inexpensive to obtain, the above-mentioned system is an attractive method for acquiring seasonal information or monitoring dynamic change (i.e., adding a temporal dimension to the management information base).

Multi-Stage Sampling

The multi-stage sampling approach to remote sensing surveys is similar to the multi-stage survey in that remotely sensed data are obtained at various scales and level of detail. The key difference is that multi-stage sampling techniques are designed to provide quantified measureable data, rather than extrapolating by the qualitative transfer of generic recognition (homogeneous landscapes) from area to area and from large to small scale imagery. The multi-stage sampling approach utilizes statistical methods and probability theory to determine where to acquire data. This technique provides very reliable quantitative estimates of resource character, type, quantity and value. It has been applied commercially to establish timber values, land carrying capacity for cattle, etc.

Sampling in the simplest terms is the selection of a portion of a universe as representatives of the whole. This technique is familiar to social and physical scientists who deal with mass data.

The primary applications of sample surveys in natural resource fields have been the assessment of the quantity, quality, and distribution of resources such as agricultural crops, range grasses, forest trees and water resources. Population censuses are now frequently conducted on a sample basis.

Remote sensing can provide the means to obtain reliable estimates concerning the resources of vast areas from relatively small samples. In forest and agricultural surveys, aerial photography has long been used to improve sampling efficiency. Among the sampling techniques used are:

1. Stratified sampling (where strata are defined by delineating relatively homogeneous areas on photographs).
2. Double sampling with stratification at the first phase.
3. Double sampling with regression.

These sampling techniques are usually geared to incorporate medium scale resource photography of a type generally available from government agencies for the U.S. and fully available for the Sahel. Combining information from traditional sources with available ERTS data significantly reduces survey costs.

Even a cursory inspection of space imagery strongly suggests that its use in a management-oriented resource inventory requires some form of multi-stage sample design. With ERTS, one can survey vast land areas rapidly, but it is difficult to identify species of natural vegetation or even general classes except in gross physiographic terms. Furthermore, the location of subjects of relatively small size cannot always be accurately and easily pinpointed on the ground directly from the space imagery, particularly in wildland areas. While it is not generally feasible to accurately locate small ground plots directly from space imagery, it is feasible to build a bridge of successively larger and larger scale aerial imagery so that the ground plot may be linked to the space imagery. It is around this linkage process, from the ground plot sample to space, that the sample design is built.

After the space images are selected, they are prepared for sub-sampling. Sub-units may be laid out in the form of a grid as was done in a forest inventory using Apollo 9 Infrared Ektachrome photographs covering five million acres in Louisiana, Mississippi, and Arkansas in the United States (Langley et al., 1969). In that survey, the space photographs were partitioned into 4 X 4 mile squares. Regardless of how the space images are partitioned, the sub-units should be identifiable from an aircraft during the sub-sampling phase. More important, they should be of a size that variation between units would be either small or controllable by means of photo interpretation. The variation within units is controlled by appropriate sub-sampling and photo interpretation. Stratification also should be considered if population characteristics differ among areas that exhibit the same image characteristics from one area to another.

In summary, the recent development of sampling procedures which incorporate available ERTS and aerial photography has proven highly cost-effective and promises to make certain phases of resource management and development activity possible on a dynamic basis. As for the use of sampling procedures, there are no standard sampling procedures applicable to all resource inventories using space or aerial imagery. The design used in a particular situation must take into account such variables as: a) the kinds of parameters being estimated; b) the distribution of the variables used to estimate the parameters; c) the existing information relating to these variables; and d) trade-offs between needs for statistical survey reliability and additional costs of each level of greater reliability (What error can you live with?).

7.0 SUMMARY AND CONCLUSIONS

It is obvious that there exists a wide range of trade-offs between information costs and information quality. Usually a system is designed as a compromise between the perceived information needs of resource managers and the size of their budgets. Reductions in information quality is usually manifest in a switch to smaller scales, decreases in image resolution, or reductions in coverage. More important to the Sahel situation are the potential balance between man and machine.

A number of alternatives exist in how the interpretation, ground work and other tasks in remote sensing are accomplished. The approach used to extract information depends upon availability of machines and technical manpower, the goals of the interpretation effort, and the cost

constraints levied upon the organization engaged in the interpretation effort. Just as it is possible to reduce labor requirements by using machines, one can reduce the requirement for sophisticated support facilities by increasing training and using more labor inputs. The exact mix appropriate for any developing country is not known, though economic arguments can be made for labor intensive activity in the short and medium term. In addition to all the economic arguments, the involvement of local labor will help stimulate the transfer of information concerning the technology and resource development potential, hastening its acceptance in local management processes. Finally, people learn to use image formats quickly and become useful communicators of the new ideas. In several documented instances, people with very little formal education have quickly bridged the perceptual gaps between ground and satellite views of the regions in which they live. Moreover, sophisticated identifications and interpretations have resulted from such tests which have put remotely sensed data directly into the hands of users (Fisher and Robinove, 1974). Obviously, some uses of much data, such as water balance modeling, can only be accomplished with relatively heavy dependence upon automated data handling and processing technology. In this case too, reliance can be placed on the simpler rather than the more difficult-to-teach technologies.

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CHAPTER 3

SAHELIAN LANDSCAPES AND ECONOMIES IN RELATION TO REMOTE SENSING

1.0 INTRODUCTION

The Sahelian-Savannah area includes major portions of six countries of Francophone Africa. These countries -- Senegal, Mauritania, Mali, Upper Volta, Niger and Chad -- extend from the Atlantic coast to the interior of the continent at the eastern end of the Chad Basin. They have many resource development and management problems in common which stem principally from the general aridity of the region. Annual rainfalls range from 1000 mm in the south to 250 mm or less in the north, and set the area apart from the rest of West Africa, leading to a concentration on nomadic livestock raising and semi-sedentary agriculture.

Three great surface water systems drain the area's vast plateaux and plains some 300 to 600 meters above sea level. The Senegal, the Niger, and the Chad basin are focal points for both the sedentary and nomadic populations and the floodplains of these rivers provide some potential further irrigable land.

Many of the great West African empires and civilizations were centered in the Sahel with capitals established near the water courses. Perhaps the Sahel bred empires because it is the meeting ground of many peoples: the nomadic Moors and Tuaregs; the hamitic, semi-nomadic Fulani; and the many sedentary cultivators of the region. Cultivation was recorded nearly 2500 years ago by Hanno, and was well advanced during the empires. This legacy can still be seen within the traditions of the Hausa and Mossi states.

The Sahel pastoralist follows ancient nomadic patterns in response to the climate and annual vegetation growth that normally accompanies the summer rains. His seasonal movements avoid the more humid areas and consequently, the destructive tse-tse fly. The farmer and the pastoralist may co-exist, seasonally rotating the use of the land, though in recent years competition for land has been heightened by the northward expansion of agriculture.

Even under conditions of average precipitation, the agricultural and nomadic peoples of the Sahel and northern Savannah face a marginal existence. The recent years of drought have brought

widespread distress and starvation, and have highlighted the region's serious resource management problems. The combination of drought, population pressure, lack of mobility (considering general land transportation systems and the nomad's dependence on reliable water resources), overgrazing and absence of resource management have seriously endangered the environmental resource base: The ecological balance is precarious at best. The problem which remote sensing must address results from the complex interaction between the events of nature and human actions. The region is capable of withstanding the whims of nature but is vulnerable to the acts of man.

2.0 PHYSICAL CHARACTERISTICS OF THE REGION

2.1 CLIMATE

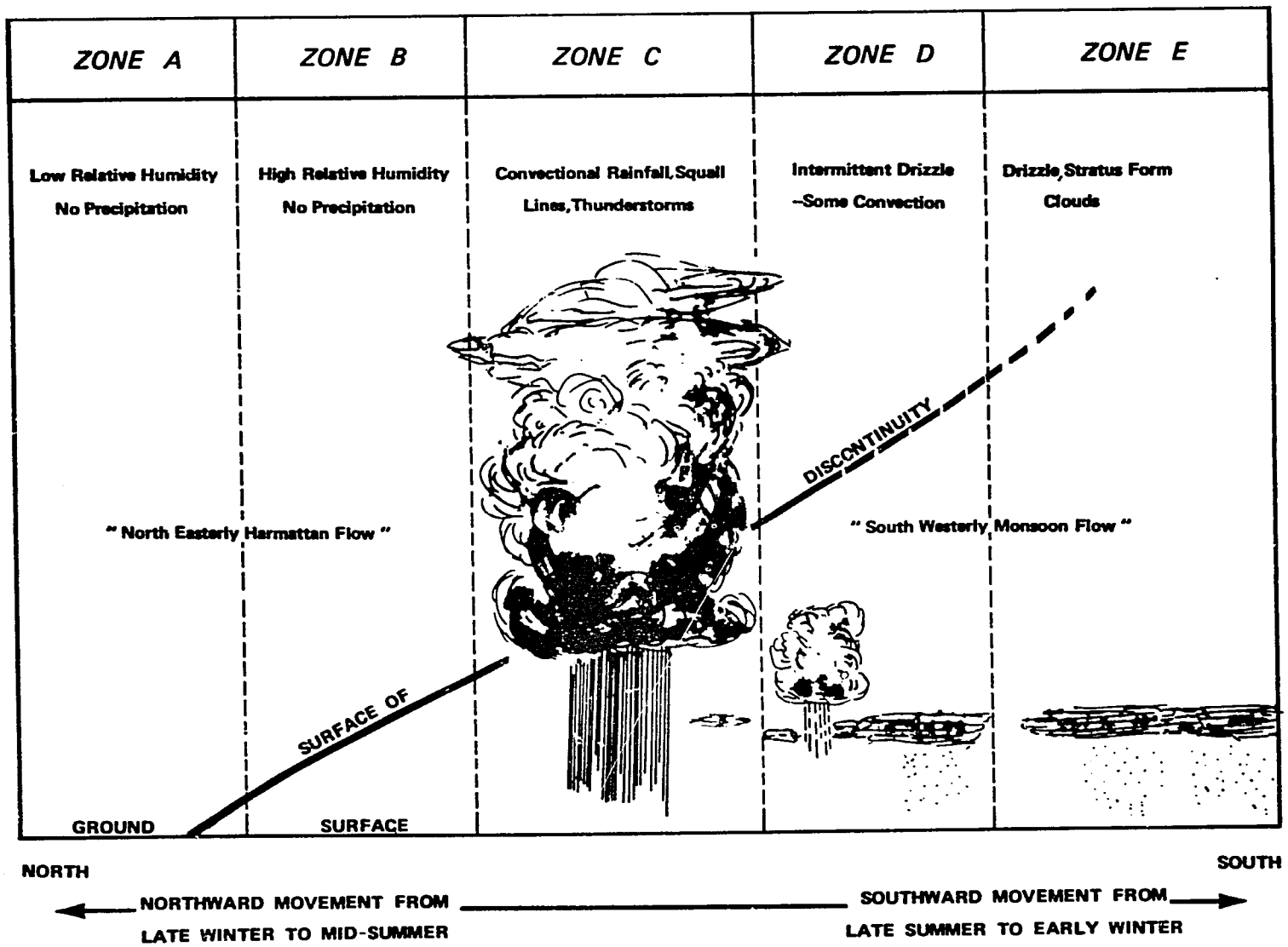
Precipitation over the Sahel is usually confined to the northern hemisphere summer season. The northward migration of moist unstable air associated with the Inter-Tropical Convergence (ITC) is the factor responsible for the rainy season. During the winter season West Africa is dominated by a generally easterly flow (Trade Winds) of the subtropical high pressure system centered over the Sahara. Mitchell (1973) has identified five rainfall zones which are associated with the discontinuity that separates these pressure systems. The leading edge of the discontinuity fluctuates seasonally, like the pressure systems, and moves northward to 21 to 25°N, from a winter position over the southern coastal areas of West Africa at 5 to 9°N. Figure 3-1 is a schematic representation of the discontinuity between the air masses. Only seldom will the moist tropical air penetrate farther inland than a position where zone C (Figure 3-1) covers the narrow Sahelian belt, and most of the rainfall which the Sahel receives comes from this zone of activity.

The most noteworthy characteristic of the rainfall is its variability. Resource management must be based on acceptance of the potential variation in seasonal precipitation totals rather than any average figure. Mitchell (1973) identified the following factors as principal contributors to this variability:

1. The extent of northward movement of the zone of discontinuity each year (zone C may not reach the Sahel during some years);
2. Variable amounts of moisture are actually precipitated in zone C because the rain producing disturbances are convective in nature and are partially dependent on a strong easterly flow at higher altitudes for their formation; and
3. Early or late rains, including the occasional winter mid-latitude cyclonic disturbance referred to as Heugs, may penetrate to the northern part of West Africa. These are often counter-productive since they can stimulate a growth response in some plant communities at the wrong time of year.

Figure 3-1

ZONES ASSOCIATED WITH THE PRINCIPAL RAIN PRODUCING MECHANISM IN SUBSAHARAN WEST AFRICA



(Modified from Mitchell, 1973)

Temperatures for the area range from warm to very hot, with no frost. The lower temperatures are found in winter and are also associated with the seasonal passage of the discontinuity (Figure 3-1) which accompanies the northward movement of the ITC in summer. Thus, most reporting stations exhibit a bimodal temperature regime with low monthly averages recorded in mid-winter and during the summer months.

Moisture laden winds of a generally southerly vector are associated with the seasonal summer intrusion of the ITC. Locally these are referred to as monsoons. Their impact is greatest in the areas of West Africa south of the Sahel. Dry, northeasterly winds flowing from the well developed subtropical high pressure system dominate the dry season. Locally these winds are referred to as the Harmattan. When well developed, they are associated with large diurnal temperature variations and sand or dust storms.

In this semi-arid area, atmospheric moisture is low throughout much of the year and cloud development over the Sahel is intermittent even during the summer. Long periods of good weather for imaging is common and sensors which record in the visible portion of the electromagnetic spectrum may be used with confidence. The periodic dust storms of the Harmattan and seasonal burning of bushfallow in the more humid areas can obscure portions of the area but the duration of such disturbance is not usually lengthy (Deshler, 1974). Occasionally the Harmattan keeps clouds of fine dust in the air for weeks.

2.2 PHYSICAL LANDSCAPE

The Sahel, like most of West Africa, has a lithologic basement referred to as the African Shield. This complex is largely composed of Precambrian granites and Paleozoic metamorphic rocks. Extensive strips of Ordovician and Silurian sandstone and shale occur along the Niger trough. Within the northern boundaries of the Sahel countries one finds such mountain ranges as the sandstone Mauritanian Adrar and the crystalline massifs of Adrar Iforas, Air and Tibesti. Cretaceous and Tertiary rocks are found in both East and West. All these rocks, subjected to long weathering, have given rise to extensive deposits of Pleistocene and Recent alluvials, colluvials, and sand dunes.

Along the tenth parallel, the central plateaux of the Sahel begin their descent towards a series of drainage basins. A low trough trends east-west with low gradients and the anastomosing drainage channels, marshes, lakes and extensive tributary networks of the Senegal, Niger and Lake Chad systems. Though the Senegal and Niger drain into the Atlantic, abrupt changes in flow

direction and gradient as well as belts of alluvial deposits attest to a complex morphogenetic history. The rivers, tributaries and lakes offer transportation routes, rich alluvial soils for farming and irrigation potential. Away from the drainage basins the Sahel is semi-desert, where rivers and shallow lakes not only fluctuate greatly in size and flow, but often dry up completely during the dry season.

The soils of the region range from the grey, steppe soils of the desert fringes to the ferruginous soils of the southern savannah region. The steppe soils may be fertile, but they can often be highly saline and impermeable. Hard laterite is often found in the savannahs, bared by erosion from the beating rainfalls on cleared and heavily cropped land.

The diversity of soil types, the semi-arid to sub-humid climate and the sensitive relations between soil and vegetation communities in such areas ensures that remote sensing with visible and near infrared region sensors -- including the ERTS-1 MSS -- will be of considerable value for natural resource inventory. In essence the natural environment predisposes the area to orderly and distinctive relations between soils, vegetation, lithology, and drainage dissection, which are very amenable to remote sensing.

2.3 VEGETATION

Though the original vegetation climax was probably forest and woodlands even to the fifteenth parallel, man has so denuded the area that low sparse thorn tree communities are common. The southern more densely populated savannah zone is extensively burned for cultivation. The repeated annual burnings have led to sparse stands of fire-resistant trees. The dum palm, baobab, shea-butter, kapok, and acacia are common. Shrubs of the Combretum spp. are often found on rocky hills or lateritic outcrops. The trees are deciduous, usually with small leaves to prevent excessive transpiration. Grasses are shorter and more tender than further south, excellent for livestock raising.

Further north, crown cover decreases. Thorn tree, Acacia spp., are most common. Occasional baobabs can be found marking the site of a present or former village. The tender annual grasses make the area well-suited for livestock grazing during the rainy season, especially since it is beyond the domain of the tse-tse fly.

The degradation of the natural woodland by man began long ago. Hanno noted bush burning in this region before 600 B.C., though the practice was intensified during the Ghana, Mali and Songhai Empires. In the sparsely vegetated north, fire probably had less effect on the environment than grazing livestock. The cost of this change in ecological balance has been severe erosion and extensive laterization of soils.

Except in the southern fringes of the region the plant communities are sparse, sufficiently so during much of the year that detection of vegetation is difficult and may require either special film-filter combinations or special processing in the photo laboratory. Experience in Central Australia and the deserts of southwest U.S. has indicated that careful mission planning with aircraft and appropriate film-filter combinations are needed to obtain information on plant communities.

Similarly, use of multi-date and special processed ERTS imagery is necessary to emphasize vegetation patterns. Even with such special processing there are areas with such low plant density that mapping must be by surrogate -- using the natural landscape units as the basis for designating plant communities.

3.0 CULTURAL CHARACTERISTICS

3.1 THE PEOPLE OF THE SAHEL

The Sahelian region has one of the most complex population and cultural distributions in Africa. Sub-Saharan West Africa has long been a zone of tension between the nomadic caravan travellers, the hamitic pastoralists and the negroid cultivator. Various cultural processes including intermarriage among these groups have produced a large variety of tribes, languages and ways of life within the region.

The Moors and the Tuaregs are the true camel-riding nomads of the desert. Crossing the Sahara from North Africa long ago, they spread the unifying influence of Islam in their wake, laying the cornerstone for the foundation of the Sahelian trade empires. In the northern Sahel, they continue a nomadic existence: a mobile population, seasonally moving to better grazing grounds or better markets for their sheep, goats and camels. To the south, more are settled, with huts instead of tents, driving their herds north only in the rainy season. The present drought has taken its toll on the lives of the nomads, as regular pastures disappear and water holes dry up. Women and children have been forced to give up their free existence to settle

near towns and refugee camps, while the men drive what is left of their herds south to the more humid coastal boundaries.

The people of the savannah regions have been cultivating the land for thousands of years, though the practice was greatly advanced during the great trade empires beginning around 400 A.D. Depending on proximity to river courses, they cultivate floodland and upland. Most fields are quite small. Very small garden plots are maintained close to home with the larger fields away from the main community. Settlements may be as small as several huts enclosed by mud walls for one extended family in the Malinke region, or as large as the great walled Hausa cities which often exceed ten thousand, or even the urban capitals of the Sahelian countries. Away from the cities, the architecture of the houses and their placement within a village may reflect the distinctive cultural pattern of an individual tribe, so that it may be possible to identify the inhabitants on remote sensing images by settlement patterns alone.

The sedentary population of the Sahel is not evenly distributed throughout the region, though the locational variation of natural resources, i.e., water supply and fertile soil, does not provide an adequate explanation. Historical tribal boundaries, developed through years of intertribal warfare, are found to include extensive buffer zones between neighboring populations. These buffer zones account for part of the vast expanses of uninhabited areas. The densely populated, soil-poor, Mossi region of Upper Volta is one such anomaly. Generally, the southern savannah zone is more densely populated than the northern arid zone, which provides the grazing land for the herds of the pastoral peoples.

The pastoralist Fulani people, the most widely distributed people of the Sahel region, are hamitic in their linguistic affinity. While maintaining some close ties with their kinsmen throughout the Sahel, they have widely diversified their customs from solely nomadic pastoralism which is traditional for this group. In many instances, they rely in part on cultivation, but always retain some livestock. In the Futa Jallon, they have settled into highly structured villages; but this is the exception. More often, they are scattered throughout the grazing lands, living in low round huts with distinctive high conical roofs. They move their herds of cattle north during the rainy season to avoid the tse-tse fly and to find the tender annual grasses that germinate after the rains. During the dry season, they return south, grazing their herds on the stubble or harvested fields or on the annual grasses sprouting near the floodlands of the receding rivers. In many areas the interdependence between pastoralists and agriculturalists is very subtle.

The widely dispersed habitations of the people and their livestock, their mobility, and the relatively low contrast of their permanent settlements to the surrounding land -- earth roads, mud and thatch huts, and irregular patterns of cultivation -- all make the detection of settlements and the works of man more difficult with high altitude or spacecraft remote sensors, than is the case with the patterns of the natural environment. Many of the relations between land use, agriculture, and settlements therefore must rely on surrogate measures with remote sensing to a higher degree than will be the case in inventories of soils, vegetation and geological mapping.

3.2 THE ECONOMIES

The economy of the Sahelian countries is generally one of subsistence, with little overseas export of foodstuffs or minerals. Millet and sorghum are the chief subsistence crops of the area, with groundnuts and cotton the main cash crops. Livestock, chiefly humped cattle, hairy sheep and goats, is one of the most important resources of the region, with cattle-on-the-hoof, meat products and hides being exported to the humid, livestock-poor coastal areas of West Africa. Cultivation, at the end of the dry season, is accomplished by burning the bush grown during the fallow period, which may be as long as 20 years in areas with few inhabitants, much less in the more densely populated regions near large cities. Annual or seasonal crop rotation may be practiced as well as inter-cropping, e.g., groundnuts interspersed with millet, guinea corn or cotton. Along the floodlands of the Niger, cultivation is correlated to the cresting and receding waters of the river, with later planting seasons as the crest moves downriver. Along the fringes of Lake Chad a similar regime is followed of planting following floods with a harvest being obtained hopefully before the next lake rise. Several mechanized schemes for cash crops have been attempted with varying degrees of success, most notably groundnut cultivation in Senegal and both irrigated and non-irrigated cotton schemes in Mali. Stock raising adds more to the economies of the Sahelian countries than does agriculture. The climatic conditions make the area more suitable to raising the large hump-backed cattle, sheep and goats than further south. Though the Fulani pastoralist is quite possessive of his herds, great quantities of meat, hides and skins are annually exported to the coastal West African states. The present drought conditions in the region are causing the herds to dwindle both through mortality and out-migration. It is this effect that is perhaps the most disastrous for the Sahel.

Industries play a minor role in the Sahelian economy. Most industry has developed since 1960, and most are dependent upon agriculture or food processing. Extractive industries offer an important potential. The largest present operations involve phosphates which are being mined in Senegal, and a large mining industry of copper and iron ores in Mauritania. The location of uranium deposits in Niger indicates potential for a mining industry there.

The spatial distribution and size components of the agricultural practices listed above are not such that a great deal of information can be directly gathered using high altitude imaging systems. Low altitude missions are costly and under optimum conditions are useful for site specific information. Much useful information can be gathered by using a balanced data gathering strategy that includes corollary sources and field work along with remote sensing. Use of such an approach to develop interpretation surrogates can provide detailed regional information about area-extensive agricultural activities. Since industrial development is limited to a few point sites, information concerning all but mining activities can be gathered by census and not via remote sensing.

3.3 POLITICAL AND SOCIAL PATTERNS

Before the European colonizers arrived in the Sahel, the tribal spheres of influence and the nomadic routes and trading routes were oriented toward North Africa rather than to the densely forested coastal regions. The Sahara proved more forbidding than the sea for Europeans, who penetrated the interior by the available navigable rivers.

The French founded commercial establishments in Senegal in the 17th century and gained access to the Sahelian hinterland by travelling up the Senegal and then the Niger rivers. French West Africa included all the Sahelian region with the exception of Chad, which became part of French Equatorial Africa in 1903. The Sahelian countries achieved independence in the early 1960's but have retained close ties with the French community.

Political boundaries do not necessarily coincide with natural resource problems in the Sahel, as is true throughout the world. Several regional commissions have been established to deal with these shared problems, including the Lake Chad Basin Commission, the Niger River Basin Commission and the Organization for the Development of the Senegal River Basin. Traditional nomadic, pastoral movements and seasonal migrations of harvest labor also ignore political boundaries. The movements of goods and people can create problems for an exact economic analysis of a country's resources.

Four of the Sahelian countries, Mali, Upper Volta, Niger and Chad are totally land-locked, and must rely on good trade route relationships with neighboring coastal countries to move their goods to the sea.

A centralized political or social structure is necessary for any resource management program, whether or not the information used as a basis for decision making and planning is gathered by remote sensing. Positive control superimposed upon traditional social institutions and multinational resource problems can ensure some compliance with a given management policy. Local use of data and local design of specific management actions to parallel the national or centrally issued policy directives can hasten the acceptance of both the data use and the management programs. To this end, cooperative regional commissions such as mentioned above and dependence upon family or "tribe" territories as planning areas might be ways to provide the necessary infrastructure to maximize the utility of remotely sensed data.

4.0 SUMMARY AND CONCLUSIONS

Every environment has its own mix of cultural and physical features, which condition the way remote sensing may be used. The mix in the Sahel is such that inventories and monitoring of the natural resource base will be generally more satisfactory than those of cultural features. Very significant values can be anticipated from remote sensing programs in the following areas: meteorology and water balance modeling; water resource analysis; vegetation classification and mapping and range condition monitoring; soil association mapping; geological and geophysical prospecting, and general cartography. More mixed results are likely in land use and population studies, livestock enumeration, and agricultural resources.

Remote sensing technology can be useful as an information gathering strategy only if certain conditions can be met. These include:

- that remote sensing is cost-effective within the constraints of the existing Sahelian economy,
- that the remote sensing system proposed is compatible with the environment and the particular problem,
- that the information derived meets management needs,
- and finally that a political or social infrastructure is available to support management decisions based on the remote sensing returns.

Many information gathering techinques can be used but solutions to problems facing the Sahel countries will depend on the quality of the management strategy and how it is implemented.

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CHAPTER 4

REMOTE SENSING SYSTEMS AND COSTS OF DATA ACQUISITION

1.0 INTRODUCTION

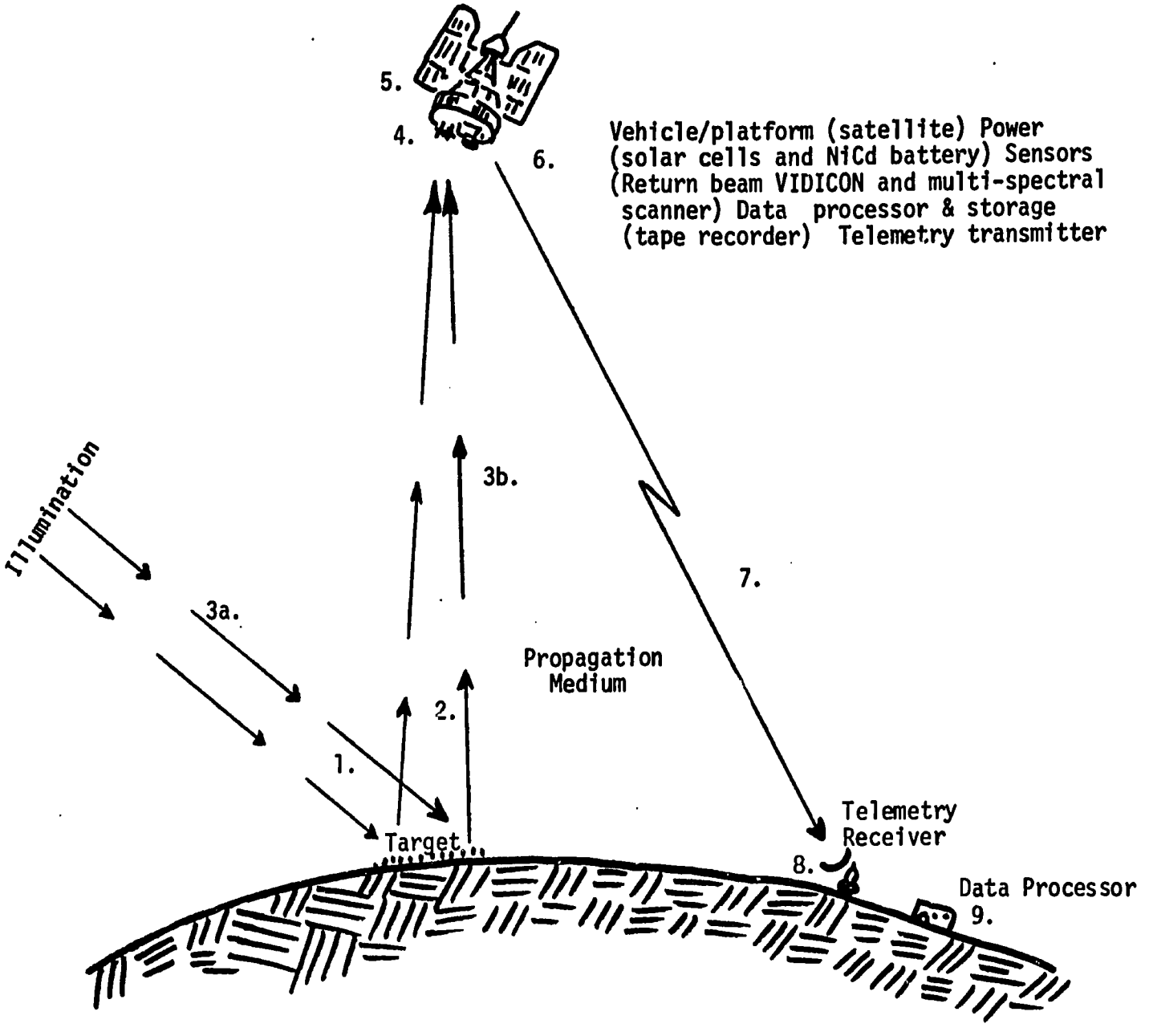
Of the wide variety of remote sensing systems and services available, some have only one or a limited number of applications (e.g., mercury sniffers), whereas other systems, such as metric cameras, provide data useful to a wide variety of resource applications. In choosing a remote sensing system for a particular program or for incorporation into a resource management data system, it is critical to understand how the system functions, what platforms it uses, what it senses, what form the data are in and how they can be applied to resource problems, and the relative costs of using one system or another. This chapter will address the characteristics of available remote sensing systems and comparative costs of application. Discussions of specific resource applications are in the chapters that follow.

2.0 BACKGROUND

Remote sensing systems are integrated assemblages of components functioning together to acquire information about the environment in a useful and understandable format. A remote sensing system consists of: (a) sensor subsystem, (b) data (image) recording, processing and display subsystem, (c) a vehicle or platform, (d) power subsystem, (e) navigation subsystem, and (f) a subsystem to recover or deliver the data. In some remote sensing systems, one or more of these components may be absent, but generally they are all represented in one form or another.

Figure 4-1 schematically depicts a remote sensing system with its various components and the signal flow through the system. The target is illuminated either by electromagnetic energy sent by the remote sensing system, or by the sun or by self emission and radiates a signal that is detected or imaged by the sensor aboard the platform. After the signal is detected, processed and stored on the platform, it may be transmitted by telemetry to a ground station or returned as film where it is processed and relayed to the user.

The sensor subsystem is the device (camera, scanner, magnetometer, etc.) that detects electromagnetic energy emitted or reflected by the scene, or by the force or chemical fields produced by objects in the scene. In order to be detected remotely, an object must be in contrast



Legend
1. Radiative illumination (active or passive)
2. Signal insertion (by reflection or emission)
3. Propagation in medium (characteristic)
4. Signal extraction (sensing, imaging)
5. Signal processing (e.g., conversion to video signal, digitizing, tape recording)
6. Signal insertion (telemetry transmission)
7. Propagation in medium (telemetry)
8. Signal extraction (by ground receiving station)
9. Signal processing (including transmission to user)

Figure 4.1 Diagram of a Remote Sensing System

with its surroundings; radiate, transmit or absorb energy in a characteristic manner; or generate a characteristic energy or chemical field whose magnitude variations are measurable. The sensor subsystem is what "sees" the environment.

The platform or vehicle transports the sensor system and its supporting equipment. The choice of platform depends upon the speed and altitude at which the sensor must be flown and upon the size of the sensor. Aircraft, helicopters, rockets, balloons, ships, and spacecraft are all commonly used platforms for remote sensing.

After the image or data are sensed, if they are to be useful, they must be retransmitted to the ground directly to a receiving station or they must be recorded, processed, displayed or otherwise preserved until they can be operated on or interpreted. The subsystem for recording or display may be as simple as a piece of photographic film or as complicated as the wide band tape recorder used to store ERTS data on board the satellite. The critical aspect of these subsystems is that they faithfully record, preserve and display what is sensed. No matter how good a camera is, if the film is of poor quality, the picture will have poor contrast, definition and resolution.

Many sensors require energy to function, transmit data, point the instruments, maintain the on-board environment, or for some sensors, to provide scene illumination energy. It is important that the energy be supplied by a system that is reliable for the period required. There are many forms of power subsystems, most of which use a generator, solar cells, or batteries as the source of electrical power. Some space vehicles already use nuclear power packs as a source of power.

The navigation subsystem provides information on geographic location, altitude, velocity, and attitude of the vehicle, all of which is necessary to interpret the information sensed. The information produced by the navigation subsystem may be used to guide the vehicle, point the sensors, or relate the information sensed to a specific area and determine the scale. These systems are usually composed of several elements that may range in complexity from a magnetic compass to an inertial navigator.

Once the sensing system has acquired information, the data recovery or delivery system relays or retransmits the information or otherwise processes it into a form to be delivered to the user. For satellite systems such as the Earth Resource Technology Satellite, this includes a telemetry transmitter on board the satellite, a ground receiving system and an electron beam

recording system which produces imagery. For photographic systems, the data recovery or delivery system may be simple photo processing and printing equipment which develops the exposed film and produces copies that can be used by resource analysts.

From the standpoint of those involved in resource management and development decisions, the subsystems of greatest interest are the sensor systems, vehicles or platforms, and the systems that record or display the data or imagery. These subsystems will be discussed in greater detail in the following sections and in Table 4-1.

3.0 SENSOR SYSTEMS

Remote sensing systems which rely upon the electromagnetic radiation emitted by the objects which comprise the scene, or upon reflection of the natural illumination from the sun, stars, moon, or sky are termed "passive" systems (e.g., aerial photography). Those which depend upon reflection of illuminating radiation supplied by the system are termed active. An active system (e.g., radar) is not restricted to daylight operation.

Several acquisition modes, each with distinct advantages and disadvantages, are in current use: 1) Photographic cameras record imagery photochemically on films sensitive to various parts of the spectrum; 2) Optical - Mechanical scanning radiometers transform received radiation to electronic signals which are stored on magnetic tape, telemetered to a receiving station in real time, or transferred to a film record through the inter-medium of a cathode ray tube; 3) TV cameras (image orthicons and vidicons) -- are snap shot devices like a photographic camera but they convert the optical image, which is recorded on a photo-emissive surface, to electronic signals which may be either magnetically stored or relayed in real time; 4) Radar electronically scans the reflected energy with the same antenna that transmitted the energy pattern to the scene. This energy is modified in amplitude and phase by features in the scene and is converted by means of cathode ray tube to a film image.

The heavy curve on Figure 4-2 shows the power spectrum of the sun's energy at the top of the atmosphere. The broken heavy curve shows the power distribution of that energy reflected through the atmosphere. The atmospheric "windows" indicated at the top of the graph indicate the ranges of wavelengths of electromagnetic energy between 0.1 and 100 micrometers that can be transmitted through air, thus indicating the spectral regions in which it is possible to perform remote sensing from space.

TABLE 4-1 SENSOR MATRIX, WHICH RELATES REMOTE SENSING SYSTEMS TO WAVELENGTH SENSED, PLATFORMS, SOURCES OF DATA AND SERVICES OF APPLICATION

WAVELENGTH									PLATFORMS						SENSOR SYSTEMS	AGRICULTURE							GEOGRAPHY						GEOLOGY							HYDROLOGY					
Gamma Ray	Ultraviolet	Visible	Near Infrared	Thermal Infrared	Microwave	Radio Frequency	Magnetic Field	Gravity	Air Chemistry	Spacecraft	High Altitude Aircraft 10km	Medium Altitude Aircraft	Low Altitude Aircraft 10km	Helicopters	Balloons		Vegetation Classification	Crop Identification	Acreage & Yield Estimate	Rangeland Mapping	Range Productivity Est.	Livestock Inventory	Soil Mapping	Land Inventory & Monitoring	Cartographic Information	Topographic Mapping	Planimetric Mapping	Transportation Routes	Population Movement	Geological Mapping	Mineral Exploration	Petroleum Exploration	Geothermal Exploration	Geologic Hazards	Wind and Water Erosion	Dune Migration	Meteorology Climatology	Water Balance Modeling	Surface Water	Subsurface Water	Groundwater Discharge	Soil Moisture
X												1	1	1		Gamma Ray Spectrometry	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	M	S	-	-	-	-	-	-	-	-	-	-
																Photographic Systems																										
		X	X							2	1,2	1,2	1	1	0	Metric Camera																										
		X									1,2	1,2	1	1	0	Black and White Pan Photography	S	S	S	M	S	M	M	M	M	M	M	M	M	M	M	M	S	M	M	M	S	-	S	S	S	S
	X											1,2	1,2	1	0	Ultra violet Photography	-	-	-	-	-	-	S	-	-	-	-	-	-	S	S	-	-	-	-	-	-	-	-	-	-	-
		X	X							2	1	1		1	0	Low Sun Angle Photography	-	-	-	-	-	-	-	-	-	-	-	-	-	M	M	M	S	M	-	M	-	-	-	S	S	-	-
		X								2	1,2	1,2	1	1	0	Color Film	M	M	M	M	M	M	S	M	S	S	M	M	S	M	M	M	S	M	M	M	-	-	M	-	S	M
		X	X							2	1,2	1,2	1	1	0	Black and White Infrared Film	S	S	S	S	S	S	S	S	S	S	S	S	S	M	S	M	S	S	S	S	-	-	M	S	M	S
		X	X							2	1,2	1,2	1	1	0	Color Infrared Film	M	M	M	M	M	M	S	M	S	-	M	M	S	M	M	M	M	M	S	M	-	-	M	S	M	M
	X	X	X													Multiband Photography	M	M	M	M	M	S	S	M	S	-	S	S	S	M	M	S	S	M	M	M	-	S	M	S	S	M
																T.V. CAMERAS																										
		X	X							2,3	2	1,2	1	1		Vidicons	S	S	S	M	S	M	M	M	S	-	-	M	S	S	-	-	S	S	S	S	-	-	S	S	-	-
		X	X	X						2,3	2	1,2	1	1		Orthicons	S	S	S	M	S	M	M	M	S	-	-	M	S	S	-	-	S	S	S	S	-	-	S	S	-	-
																Scanners																										
	X										1,2	1,2	1,2			Ultra Violet	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	-	-	-	-	-	-	-	-	-	-
		X	X							2,3	1,2	1,2	1,2			Visible and Near Infrared	M	M	M	M	M	M	S	M	S	-	S	S	S	M	M	S	S	M	M	M	-	S	M	S	S	M
				X						2,3	1,2	1,2	1,2			Thermal Infrared	S	S	S	S	S	S	M	M	-	-	S	S	-	M	M	M	M	M	S	M	S	S	M	M	M
			X	X						2,3	1,2	1,2	1,2			Multispectral	M	M	M	M	M	M	M	M	S	-	S	S	S	M	M	M	M	M	M	M	S	S	M	S	M	M
	X	X	X	X						2,3	2	1,2	1,2	1	0	Spectroradiometer		S	-	-	-	-	M	-	-	-	-	-	-	M	M	S	S	S	-	M	M	S	-	-	-	-
	X	X	X	X						2,3	2	1,2	1,2	1	0	Spectrometer	-	S	-	-	-	-	S	-	-	-	-	-	-	S	S	S	-	-	-	-	M	S	-	-	-	-
					X					2,3	2	2				Microwave Radiometer	-	-	-	-	-	-	S	-	-	-	-	-	-	S	S	-	-	-	-	-	S	S	S	-	S	M
					X						1,2	1,2				Sidelooking Airborne Radar (SLAR)	M	M	S	M	S	-	S	M	S	-	M	S	-	M	M	M	S	M	S	S	-	-	M	S	-	-
																Geophysical Systems																										
						X							1	1		Airborne Magnetometer	-	-	-	-	-	-	-	-	-	-	-	-	-	M	M	M	M	S	-	-	-	-	-	S	-	-
						X							1	1		Active Airborne Electromagnetic	-	-	-	-	-	-	-	-	-	-	-	-	-	S	M	S	M	M	-	-	-	-	-	S	S	-
						X							1	1		Passive Airborne Electromagnetic	-	-	-	-	-	-	-	-	-	-	-	-	-	S	M	S	M	M	-	-	-	-	-	M	M	-
														1		Airborne Gravitymeter	-	-	-	-	-	-	-	-	-	-	-	-	-	M	S	S	S	-	-	-	-	-	-	-	-	-
									X					1		Airborne Geophysical Systems	-	-	-	-	-	-	-	-	-	-	-	-	-	S	M	S	S	-	-	-	-	-	-	-	-	-

Numbers indicate sources of data:
1)Private contractor; 2)NASA/USGS;
3)NOAA; 4)Military; 0) No clearly identified source

Letters indicate degree of contribution
M - Major Contribution
S - Supportive Contribution
- - Little to no contribution

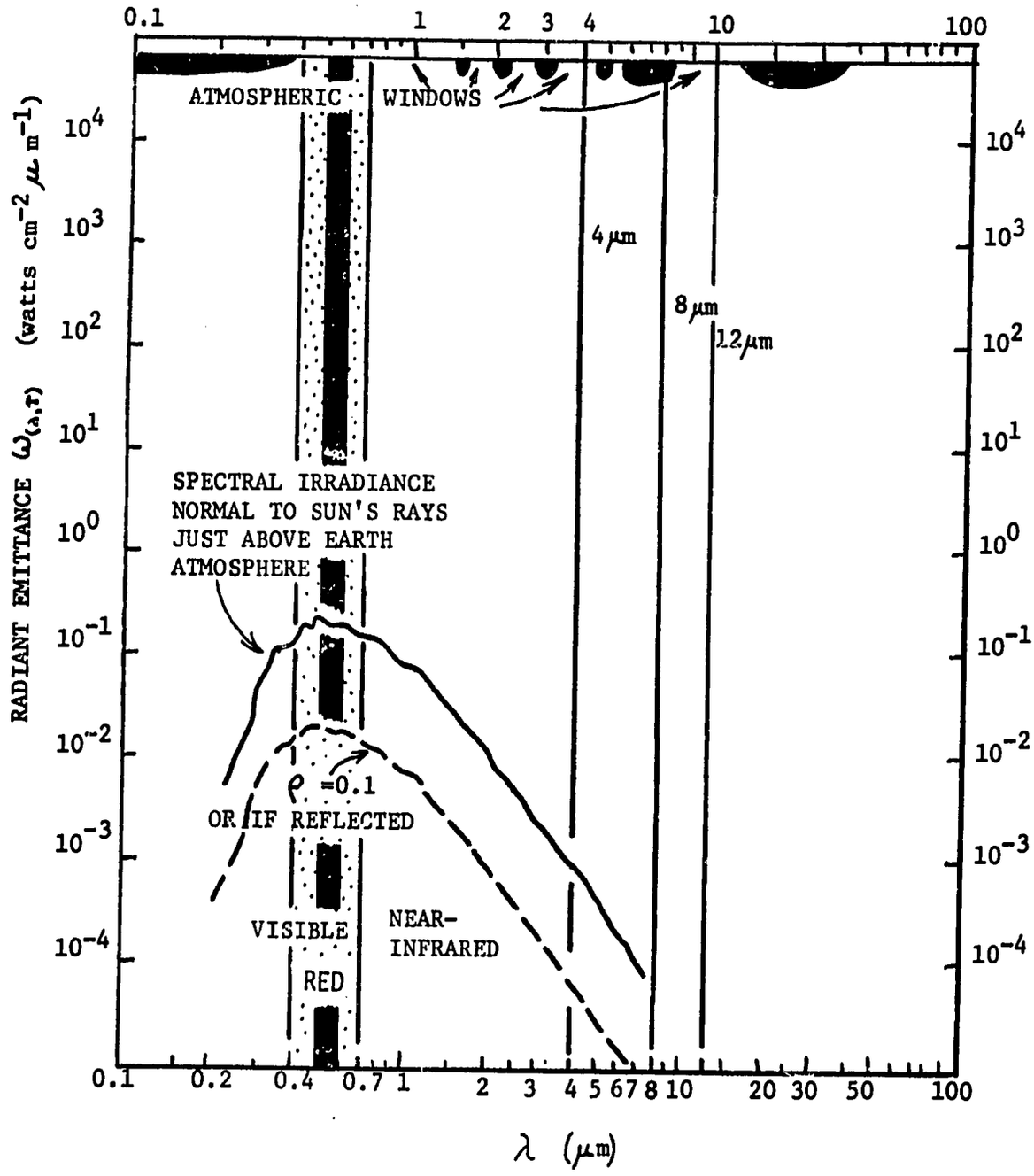


FIGURE 4-2 Spectrum of radiation emitted, reflected or absorbed in the ultra violet through infrared portion of the spectrum.

The discussion of remote sensing systems that follows will adhere to the general format of classifying systems by the wavelengths in which they operate. This format cannot be adhered to completely because several sensors operate over rather wide bands of the electromagnetic spectrum. Each brief discussion will describe the system, how it operates, the wavelengths or parameters it senses, the type of data it produces, and will point out in particular the ground support, data processing requirements, or special equipment needed to interpret the data. Table 4-1 relates sensor systems applications, wavelengths or parameters sensed, sources of the data or services, and platforms upon which the sensor can be mounted.

3.1 GAMMA RAY SPECTROMETRY

Radioactive decay of uranium and its daughter products has been measured from the air since the post-war uranium boom. Current techniques utilize the spectral composition of gamma radiation to differentiate between the radiation from the radioactive decay of uranium, thorium and potassium. Airborne measurement of the uranium daughter product, Bi^{214}, the thorium daughter product, Th^{208}, and K^{40} provides data for direct uranium exploration and for geologic mapping.

At present most airborne surveys make use of 4-channel gamma ray spectrometers which record, in addition to the above three decay products, the total gamma ray count. The data is automatically compensated for Compton Scatter and recorded on magnetic tape.

One company manufactures and leases a 400-channel gamma ray spectrometer of very large crystal volume. The cost-effectiveness of this system over 4-channel systems has yet to be demonstrated.

3.2 PHOTOGRAPHIC SYSTEMS

These are the oldest of the commonly used remote sensors. All photographic systems are similar whether they are designed to sense ultraviolet (UV), visible, or near infrared (IR) radiation. A lens focuses the incoming energy on film coated with a photosensitive chemical producing a latent image. The film is later developed to produce the image. Photography of high resolution and geometric fidelity can be acquired from very low to spacecraft altitudes. It provides an instantaneous view of the scene from a single point.

The lower limit of spectral sensitivity for photographic systems is about 260 nm* (ultraviolet) because of ozone absorption in the atmosphere. The upper limit is about 980 nm (near infrared) which is defined by the sensitivity of available emulsions.

Various film, filter and lens combinations can restrict the range of wavelengths sensed so that the visible and near visible portion of the spectrum can be subdivided into many bands. Imagery of the same scene acquired in two or more of these bands at the same time is called multiband photography. This type of photograph is used in multispectral differentiation.

Ultraviolet Imagery

Selecting the short wavelengths beyond the visible spectrum, ultraviolet (UV) imagery offers promise of identifying some rock and soil types. Preliminary work indicates that carbonate and phosphate rock types show characteristics spectral features in the ultraviolet, which make them easier to identify in the UV than in the visible range. A camera having a quartz lens and interference filters centered in the UV is used to acquire aerial photography in this spectral region. Precise image motion compensation is required in order to get sharp pictures because the imagery must be acquired at low altitudes due to atmospheric absorption, and because long exposure times are necessary to acquire adequate amounts of UV energy.

Metric Camera

Metric cameras are used to acquire photography with the high geometric fidelity necessary to construct topographic maps. Aerial surveys for civil engineering applications, until very recently, have relied on black and white metric frame photography. This is because photogrammetrical uses of the data require geometric image fidelity, and because better resolution is achieved with panchromatic film. Also, black and white film is easily and cheaply processed. Color and color infrared films, however, are becoming more widely used in these cameras. Although these films lack the resolution of black and white films, the addition of color greatly increases the interpretability of these images. Black and white and color infrared films are particularly useful for interpreting vegetation, but normal color film is probably the best all around film for the widest variety of interpretations.

* The abbreviation for nometer is nm. One nm is one billionth of a meter. One micrometer of micron (μ) equals 1,000 nm.

Infrared films, both color and black and white, are used with filters that eliminate all light of wavelengths shorter than green (500 nm). This greatly reduces the amount of atmospheric scattering recorded by the films, thus giving these films the ability to penetrate haze.

Low Sun Angle Photography

Low sun angle photography (LSAP) combines the advantages of high resolution and geometric qualities of metric camera photography and the ability of side-looking airborne radar (SLAR) to highlight topographic features. Virtually any aerial camera can acquire LSAP by using panchromatic film with a deep yellow filter (wratten 15) or black and white infrared film with a deep red filter (wratten 89B). To duplicate the low angle of illumination characteristic of SLAR, imagery is acquired in the early morning, late afternoon, or in mid-winter so that the sun elevation is between about 20° and 35°. This produces a high contrast image with strong shadow effects that emphasize geomorphic features, which may be related to bedrock geology. Texture characteristics of particular rock types and linear topographic features associated with fractures are particularly emphasized (Lyon et al., 1970). One great advantage of this technique is that for small areas where cloud cover is not a critical problem, LSAP is much less expensive to acquire and process than SLAR imagery.

Multiband Cameras

Multiband or multispectral aerial cameras use several film-filter combinations to obtain a spatially correlated set of photographs in different bands of the spectrum. This technique can sense wavelengths from the near ultraviolet to the near infrared portion of the electromagnetic spectrum or approximately 260 nm to 900 nm.

A difference in the spectral reflectance of objects in the various bands can be detected as images of different density on a set of multispectral photographs. These differences can form the basis for multispectral identification. Images from different bands can be combined in numerous ways using any one of several color combining instruments in order to enhance specific features. Photography in certain spectral intervals in the visible and near infrared, when acquired with suitable film-filter combinations, is a useful tool in the classification of vegetation and soil types, discrimination of superficial geology and delineation of water courses.

3.3 MULTISPECTRAL SCANNER

Multi-channel scanner systems are designed to simultaneously sense several discrete spectral bands over a broad range of the spectrum, extending from the ultraviolet through the visible and near infrared into the thermal infrared. The spectral range of scanner systems is much greater than for photographic systems.

Spinning or oscillating mirrors sweep the scene below the scanners. Diffraction gratings, prisms, spectrometers or filters are used to separate the incoming energy into several bands of relatively narrow wavelength. These are converted into electrical signals which are recorded on magnetic tape or on film by means of a glow tube or cathode ray tube. These systems have several advantages over film recording devices. The spectral range and signal dynamic range are much greater than for film. Low signal levels, which adversely affect photographic film recording at both the upper and lower spectral limits of sensitivity, are less serious with scanning systems because the detected energy can be electronically amplified. This amplification permits filtering to much narrower spectral bands than is possible with camera systems. The tape recorded data from multispectral scanner systems are readily adaptable to computer processing. Because only single optical path is used in the collecting optics, each band of energy is precisely registered with the other bands. Thus, point by point correlations between spectral bands can be made for each terrain feature in performing signature analysis, pattern recognition, image enhancement, etc. Analysis of two or more channels of multispectral data can yield diagnostic information for identification of a variety of target materials.

For operational convenience, multispectral scanners can be grouped into two classes: those that detect natural reflected energy and must operate during daylight hours, and those that sense emitted energy and can operate day or night. The near or reflected infrared spectral zone, i.e., 700 to 3000 nm contains several spectral absorption bands resulting from H_2O and CO_2 in the atmosphere. For water discrimination, a single channel of data positioned adjacent to a water absorption band (i.e., at about 1200 to 1300 nm) provides good results.

Single band and multiband sensing of thermal infrared energy (3500 to 14000 nm) can significantly complement visual photography and visible light sensors, enabling delineation of vegetation boundaries, water courses, soil moisture, rock discontinuities, gross lithologies and many other features.

Of particular interest is the thermal radiation emitted from the terrain in the 8 to 14μ atmospheric window. By ratioing different discrete spectral bands in the 8000 to 14,000 nm (8200 to 10,900 nm and 9400 to 12,100 nm), the emissivity deviations due to absorption of silicon-oxygen restrahlen bands are detectable. The more acidic the rock, the greater the variation. Thus, a measure of the silica content of a rock can be obtained and used in mapping lithologic boundaries and making judgements concerning gross rock type.

3.4 SPECTRORADIOMETRY

A spectroradiometer measures both the radiometric composition of light or electromagnetic energy and the strength or intensity of the energy in very small bands of the spectrum. This is done by passing the incoming energy sequentially through a series of filters that divide the spectral range of interest into many small units, and focusing this beam on a sensitive detector. The response of the detector is recorded on magnetic tape for computer processing.

Infrared spectroradiometry in the 8 - 14μ region can yield mineralogical and chemical composition data on dry surface rocks free of vegetation. The bulk composition of the rock and other surface materials are identified by matching the incoming spectrum with standard curves in the memory of a computer.

3.5 SPECTROMETRY

Spectrometry is similar to spectroradiometry except that the resolution of the instrument in the spectral domain is at least one wavelength and in some field instruments can exceed 1/10 wavelength.

Laboratory instruments have existed for years particularly in the infrared area for the identification of materials at the molecular level. Field instruments sensitive from the UV through the thermal IR are a product of the last decade of research in remote sensing. They too are used for the identification of material but at a higher level of aggregation, i.e. wheat from oats, from barley etc. The principal use as an airborne devise is that of characterizing the atmosphere and calibrating a multispectral scanning radiometer.

3.6 MICROWAVE (PASSIVE) RADIOMETERS AND SCANNERS

A radiometer consists of a highly sensitive receiver and antenna operating in the microwave spectrum between 1 and 100 GHz*, designed to detect apparent microwave surface temperatures. If the antenna pattern is integrated and read out continuously, it is known as a radiometer; if it scans the terrain either by moving the antenna or electronically scanning the antenna pattern it is a scanner. Microwave brightness depends on the physical, chemical and electrical properties of the terrain observed by the radiometer. It is thus difficult to associate terrain composition and structure with isolated measurements of the passive emission. However, multispectral radiometric data, properly corrected for atmospheric and surface roughness effects, can provide lithological data and information on soil moisture. Poor resolution, low signal levels and emission differences produced by variations in surface roughness and soil moisture make data from these instruments difficult to interpret for most purposes. However, research indicates that these instruments will provide valuable information for water balance studies.

The small amount of passive microwave energy available and the relatively long wavelengths involved, require relatively large antennas for a given spatial resolution. This has impeded the development of practical microwave scanners. Most existing scanners are experimental instruments.

3.7 ACTIVE MICROWAVE IMAGING SYSTEMS

The most commonly used active microwave system for resource evaluation and management activities is the side-looking airborne radar (SLAR). The SLAR instrument transmits and detects the reflected radar signal. The time between transmission and echo determines distance or position, and the strength of the returned signal determines the intensity of an element in the image. Existing SLAR systems operate with wavelengths from about 0.5 cm to 200 cm. Commercially available systems use wavelengths of less than 5 cm.

There are two types of side-looking airborne imaging radars: brute force or real aperture systems use a large antenna to obtain good azimuth resolution, whereas coherent or synthetic aperture systems employ a relatively small antenna in conjunction with a sophisticated signal processor for the same purpose. Range resolution in both systems is determined by effective pulse length.

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* Gigahertz is abbreviated GHz. One GHz is one billion cycles per second.

SLAR systems scan the terrain by virtue of aircraft motion. The terrain is illuminated at an appropriate sampling frequency by either a narrow pulse or a pulse compression waveform, depending on the resolution and range requirements. Synthetic aperture systems store the return signal on data film. Real aperture systems record directly onto an image film. The synthetic aperture data film is converted into an image in an optical correlator using coherent light.

Because of its small scale, rapidity of acquisition, sensitivity to aspect angle and surface roughness, a radar image provides an excellent synoptic picture for regional resource evaluation, particularly if the area possesses moderate to low relief. The imagery is small scale, and even with enlargement, must be considered a reconnaissance tool. The coarse resolution can be an asset because distracting detail which might obscure useful geologic structural information is lost. SLAR surveys require sophisticated aircraft and instrumentation, and consequently are expensive ($2 to $6 per square kilometer depending on location and size of area to be flown).

The great advantage of SLAR is that because it is an active sensor and the wavelengths used penetrate all but the heaviest of clouds and rain, it can be used day or night and in virtually any weather. SLAR, combined with a small amount of geodetic control or ERTS imagery, can be used to produce very accurate, detailed planimetric maps for a wide variety of resource inventory purposes including geology, vegetation mapping, hydrology and land use. One SLAR system has been approved for topographic mapping at a scale of 1:250,000 in the United States.

3.8 GEOPHYSICAL SYSTEMS

These systems differ from the previously discussed systems in that (1) the surveys are flown as close to the ground as possible, (2) the response is from a significant volume of rock (they have a finite depth of penetration of the earth's surface), and (3) the detailed location of the aircraft flying the survey is of great importance. Hence, these systems are of greatest value for geological interpretation and mineral and groundwater exploration. Geophysical survey data are generally interpreted and presented at scales of 1:100,000 to 1:20,000. For instance, in flying aeromagnetic data in complex igneous-metamorphic terrain, often an attempt is made to distinguish individual rock bodies down to dikes with thicknesses of a few meters. At these detailed scales, most airborne geophysical surveys are designed to detect individual ore bodies or fault zones.

Airborne Magnetometer

Designed during World War II to detect submarines, the airborne magnetometer measures either changes (Gulf Research and Development fluxgate) in the earth's magnetic field or the total magnetic field (GeoMetrics and Barringer proton procession) with great precision. Data are recorded on magnetic tape. The changes in the earth's magnetic field are due primarily to changes in the concentration of two minerals: 1) magnetite, a very common mineral whose concentration varies systematically and predictably with rock type, and 2) pyrrhotite, a rather uncommon mineral often associated with massive copper-zinc sulfide ore bodies and sulfide iron-information.

Magnetic surveys are used in petroleum exploration as a guide in the reconnaissance interpretation of depth-to-basement and basement structure. In metallic mineral exploration, aeromagnetic surveys are used for rock type determination and for rock boundary determinations. There are a great many contractors for aeromagnetic surveys worldwide. The survey specifications depend on the geology and purpose for which the data is flown. Unit costs of reconnaissance aeromagnetics can often be greatly reduced when the surveys are used in conjunction with small-scale imaging devices such as ERTS and SLAR. Aeromagnetic surveys of large areas are generally flown by contractors, but since the equipment is relatively inexpensive and easy to install in any aircraft, many organizations have their own magnetometer for use in special surveys.

Aeromagnetic surveys are generally included when other airborne geophysical surveys are flown because the additional cost is small and the data are a very powerful aid in interpreting other sensor data.

Active Airborne Electromagnetic Systems

Airborne electromagnetic (AEM) and helicopterborne electromagnetic (HEM) systems have been designed to measure changes in the conductivity of the ground beneath the aircraft. Most primary ore bodies of the metals (copper, lead, zinc, silver, nickel, cobalt) consist of sulfide minerals that are many times more conductive than the rocks that contain them. AEM and HEM systems operate at frequencies from about 300 Hz to 8,000 Hz* and explore depths up to as much as 200 meters beneath the earth's surface. The systems basically consist of two coils, a transmitter, and a receiver coil. A generator loads the transmitting coil to the frequency desired and the secondary fields are measured at the receiver, referenced according to phase. In some systems,

* Hertz is abbreviated Hz. One Hz is one cycle per second.

more than one receiving coil is used and in some, more than one frequency is used. The lower the frequency, in general, the greater the depth of exploration, but the less discrimination of conductivity and resolution of anomalies in space. Lower frequencies also require heavier power generators and larger aircraft.

There are a great many airborne EM systems available from many contractors (Hood, 1974 and see Table 4-2), and almost all surveys are flown by contractors since most systems are very difficult to install and operate. For a discussion of the effects of frequency, coil configuration, and orientations, see Ward (1967).

The quantity actually measured by EM systems is the conductivity times some significant dimension of the conductor (for veins or tabular bodies, it is the conductivity times the thickness) and the frequency range is chosen for good conductivity discrimination among the better conductors.

There are two other minerals, both of more common occurrence than sulfide ore bodies, which cause spurious anomalies:

1. Graphite, very common as a layer within meta sedimentary rocks, and
2. Pyrite/pyrrhotite, common as the sulfide facies of sedimentary iron formation.

Conductivity anomalies due to these minerals must be rejected on other than electrical bases (geologic, geochemical). Most contractors of AEM and HEM surveys are Canadian. Data are generally presented on contoured aeromagnetic maps as anomalies by point symbols.

Passive Airborne Electromagnetic Systems

The limit of exploration in the active electromagnetic systems described above is generally the ambient electromagnetic noise level of the system. This noise is primarily from two sources:

1. Naturally occuring electromagnetic fields due to, among other things, distant thunderstorm activity, and
2. Instrumental noise due in large part to relative movement between the transmitting coil and the receiving coil.

Noise levels in existing systems (AEM and HEM) have been reduced by experience and good engineering to one or two parts per million of the transmitted signal. Thus, improvement in the depth of exploration to be expected from further development of these systems is small.

EM SYSTEM Tx Rx Flight Dirn	MANUFACTURER/ CONTRACTOR - Survey Platform	NORMAL SURVEY HEIGHT IN METRES Tx	Rx	COIL SEPARATION	FREQ. (Hz)	MEASURE I/P-In Phase O/P-Out of Phase	NOISE LEVEL in parts per million	RESPONSE FROM OVERBURDEN (in Canada)	POWER REQUIREMENTS
Vertical Coaxial Rigid Coupled	Barringer - Helicopter	30 m	30 m	9.1 or 4.9m	900	I/P and O/P	2 ppm	Small	28V DC 340 W
	Kenting - Canso	45 m	45 m	25 m	390	I/P and O/P	15 ppm	Small	
	Northway LHEM 200	30 m	30 m	9.1 m	4000	I/P and O/P	5 ppm	Moderate	28V DC 25 W
	LHEM 250	30 m	30 m	9.1 m	1000	I/P and O/P	5 ppm	Small	28V DC 60 W
	Sander - helicopter	40 m	40 m	7 m	500	I/P and O/P	±1 ppm I/P ±.5 ppm O/P	Small	28V DC 250 W
	Scintrex Helicopter HEM 701	30 m	30 m	9.1 m	1600	I/P and O/P	3 ppm	Small	28V DC 15 W
Multicoil Room Rigid Coupled	Barringer - Helicopter Aerodat Dighem	30 m	30 m	9.1 m	914	I/P and O/P	2-4 ppm	Whale Tail - large Fish Tail & Coaxial- Small	28V DC 370 W
Min. Coupled Towed Bird	Northway LHEM 210	137 m	70 m	130 m	400 & 2300	O/P	840 ppm	Large	28V DC 560 W
	McPhar F-400	130 m	40 m	120m; 60m behind & 90m below	340 and 1070 Hz -time shared	O/P	500 ppm	Medium	28V DC
	McPhar F-500	130 m	40 m	120m; 60m behind & 90m below	340, 1070 & 3450	O/P	500 ppm	Medium	28V DC
Time Domain Towed Bird	Barringer INPUT Geoterrex-Canso Questor-Canso & Skyvan	120 m	50 m	75m behind and 75m below	286 pulsed ½ sine waves per sec.	Transient at 6 intervals		Large on Channel 1 decreasing to zero on other channels	
Wing Mounted Max. Coupled	Geoterrex Otter Kenting Otter	45 m	45 m	19 m	320	I/P and O/P	20 ppm	Small	28V DC 500 W
	SOQUEM Cessna 305	40 m	40 m	11 m	694	I/P and O/P	30 ppm	Small	28V DC 80 W
	Scintrex- Tridem	60 m	60 m	17.7 m	500 2000 8000	I/P and O/P 3 freq. simultaneously	20-40 ppm " "	Small Moderate Large	28V DC 200 W
Rotary Field	ABEM (Sweden) - two plane	80 m	80 m	300 m	880	Relative I/P and O/P	1%	Fairly Large	
Ground Loop	Scintrex- Turair II	Ground Loop	60 m	Several kilometres	200 & 400	Field Strength Ratio and Phase Gradient	0.1%	Variable	MG on ground
Very Low Frequency (VLF)	Barringer Radiophase and E-Phase	30 - 300 m	30 - 300 m	∞	15 KHz to 25 KHz	I/P and O/P		Large	
	Geonics EM-18	60 - 90 m	60 - 90 m	∞	15 KHz to 25 KHz	I/P and O/P	0.5%	Large	28V DC 50 W
	McPhar KEM	30 - 300 m	30 - 300 m	∞	15 KHz to 25 KHz	Dip Angle and Amplitude	0.5 V at sensor coils	Large	28V DC 10 W
AFMAG	McPhar AF-4	30 - 300 m	30 - 300 m	∞	140 & 500 Hz	Tilt Angle essentially I/P	1° - 2°	Small	28V DC

TABLE 4-2 Airborne electromagnetic survey systems available for purchase or as a contract service (Hood, 1974).

There are two types of systems available which attempt to work with or around these noise limits. Both are passive systems (i.e., they measure ambient fields and, therefore, consist only of a receiving coil) and they both respond primarily to changes in the conductivity of the ground.

The first development, AFMAG (Audio Frequency Magnetics), measures the dip of the magnetic field vector in the direction of flight at two frequencies, 140 Hz and 510 Hz. The electromagnetic energy at these frequencies is due to thunderstorm activity all over the earth. In simple terms, the AFMAG fields may be described as a series of rapidly occurring pulses that contain all the frequencies in the audio spectrum. In the absence of any conductors, the propagation direction of individual pulses is random and the magnetic field is horizontally polarized. As a conductor is approached, the propagation direction of the pulses becomes less random and, more and more of the magnetic field is oriented perpendicular to the conductor. At the same time, the plane of polarization of the magnetic field is tilted out of the horizontal. In exploration, this tilt of the plane of polarization of the magnetic field is used to locate subsurface conductors.

At the low frequencies of AFMAG, the depth of exploration is much greater than any of the active AEM or HEM systems, but both spatial resolution and the ability to discriminate between kinds of geologic conductors are reduced. The system is a good detector of major regional fault zones and is thus useful in groundwater exploration. It is very inexpensive to add to reconnaissance and aeromagnetic surveys. It is seldom used, at present, as a direct massive sulfide exploration tool.

The second type of system developed to avoid AEM noise limits are the VLF systems which operate off the signals from U.S. Navy transmitters for time synchronization in communication and navigational systems (15 to 30 kHz*). These systems (McPhar's KEM and Barringer's Radiophase and E-phase) operate on the same principle as the AFMAG system, except that the source stations put out essentially constant signal strength, and therefore amplitude anomalies as well as vector directions have significance. The Barringer systems are, in addition, phase referenced to the

* Kilohertz is abbreviated KHz. One KHz is one thousand hertz or one thousand cycles per second.

vertical electrical field and are displayed as in phase and quadrature measurements. The depth of exploration with these systems is small but the spatial resolution is very high; they are used in the same aircraft with standard AEM and HEM systems as geologic mapping tools. In areas of thin, non-conductive cover, these systems can be a major aid in geologic mapping.

3.9 AIRBORNE GEOCHEMICAL SYSTEMS

Existing airborne geochemical techniques all depend upon obtaining gaseous concentrations of the element sought. The type of metal and its quantity are determined by correlation spectrometry of the gaseous air stream. Two manufacturers produce airborne mercury sniffers (Scintrex and Barringer). The Barringer Airtrace system is a new airborne biogeochemical technique developed as a complementary tool to other airborne geophysical methods. It depends upon the little known biogeochemical phenomenon that organometallic compounds are dispersed into the overlying atmosphere by vegetation and soil humus. The system can detect biologically complexed and absorbed metals, such as mercury, copper, lead, zinc, nickel and silver (Hood, 1974).

The systems for airborne geochemistry are potentially powerful exploration aids, particularly for sorting AEM and HEM anomalies, but they presently suffer from two problems which only further surveys can help correct: 1) there is a lack of background level data which would relate anomalies to ore concentrations of metals, and 2) calibrations have not been made for the dispersive effects of wind and other atmopsheric phenomenon.

3.10 OTHER REMOTE SENSING SYSTEMS

There are several remote sensing instruments, particularly those that operate in the radio frequency range, which show some potential for providing useful data for resource management. However, they are either unavailable commercially or are in the developmental state. These include multifrequency microwave radiometers, long wavelength monocycle radar and multi-frequency SLAR systems.

4.0 PLATFORMS

Remote sensing can be conducted with a variety of platforms, including surface vehicles, aircraft and spacecraft. Each platform and sensor combination has unique advantages and disadvantages. Hence the appropriate combination must be carefully selected to satisfy the objectives of the particular remote sensing survey. If the unique characteristics of the target are known

a sensor can be selected or designed for the detection and observation of that target. Indeed, a combination of sensors may be used to provide more definitive information about a target, though not without increasing the volume of data.

The methods of remote sensing described in the previous sections can be divided into three broad categories by basic physical principles. These categories include:

- Force field sensing which is concerned with the earth's natural and spontaneous fields of gravity and magnetism, and described in Section 3.8;
- Airborne geochemical sensors, described in Section 3.9;
- Electromagnetic sensing, which is concerned with the whole spectrum of electromagnetic energy, radiated, transmitted and absorbed by all material.

The electromagnetic methods may be further subdivided into three classes. These classes are suggested by the major interactions of electromagnetic radiation with materials comprising the earth. The three types of electromagnetic sensing techniques are:

1. Electromagnetic sounding or sensing in depths below the surface of the earth (low frequency detection);
2. Surficial electromagnetic sensing of the surface of the earth limited by atmospheric transmission or distance (ultraviolet and gamma ray surveys).
3. Proximal electromagnetic sensing of the earth's surface limited by atmospheric transmission or distance (ultraviolet and gamma ray surveys).

Of course, there are many different techniques for making observations within each of these classes. With the force field methods, there is no atmospheric transmission, but field strength and resolution decrease rapidly with increasing distance between target and sensor. Thus, resolution of gravity and magnetic survey techniques is restricted to relatively low altitude aircraft, either helicopters or fixed wing aircraft.

In the case of electromagnetic sensing, transmission and resolution are inversely related to wavelength. Generally, high transmission is achieved only with the longer wavelengths (and for earth materials, very long wavelengths) but these are incapable of revealing any detail. On the other hand, fine resolution and detail may be achieved with shorter wavelengths. However, such radiation is not easily transmitted through the atmosphere nor will it penetrate very far into the denser and more conductive materials that comprise the earth. Of the five classes of remote sensing, only the surficial electromagnetic sensing methods have the optimum characteristics

of atmospheric penetration and good resolution for sensing detail at a distance. Surficial electromagnetic sensing techniques may be flown on satellites; low, medium, high or very high altitude aircraft; helicopters; rockets; ballons; or kites.

The three major categories of platforms commonly used in remote sensing are helicopters, aircraft and satellites. Helicopters are used for systems that must be flown close to the ground or flown very slowly. Sensors in this category include EM systems, airborne gravimeters, and geochemical sensing devices. When flying EM systems, it is common to include airborne magnetometers. Helicopters are also an excellent mode of transportation for ground truth teams.

4.1 AIRCRAFT

Aircraft for the purposes of this discussion are arbitrarily divided into low (below 1km), medium (between 1 and 10 km) and high altitude (above 10 km). Low altitude aircraft generally fly slower than the medium or high altitude aircraft. They are used for ultraviolet sensing systems and infrared spectroradiometers, which require relatively long exposure or dwell time; geophysical systems, such as gamma ray spectrometers, magnetometers and active EM systems; and high resolution photography and scanner imagery. Medium altitude aircraft are used to acquire moderate resolution data and high altitude aircraft are used to acquire synoptic imagery. Table 4-1 indicates appropriate sensor-platform combinations. The table clearly shows that in most instances, it is possible to mount several sensors on the same platform. A high percentage of the cost of most aircraft remote sensing surveys is aircraft mobilization and flying costs. Thus, even though a particular sensor may only provide supporting data for a particular application, it may cost little more to acquire that data if the sensor can be mounted on the airplane with other sensors.

4.2 SPACECRAFT

Spacecraft have several distinct advantages over other platforms. Their high altitude provides an ideal vantage point for acquiring synoptic imagery. The accurately known position and stability of their orbits permit acquisition of scanner imagery with extremely good geometric characteristics. Imagery acquired from satellite altitudes is essentially free of terrain relief distortion. Orbiting vehicles offer the possibility of repeated coverage for the cost of a single launch.

5.0 PLATFORM SENSOR COMBINATIONS

In a broad sense, there is a unique relationship between the type of platform and the sensors that can be carried on that platform. The broad relationship lies in the classes of sensors discussed in the previous section. For example, while aerial photography can be accomplished from all altitudes and all platforms, aerogeophysics or gamma ray remote sensing can only be accomplished from very low flying aircraft. New sensors now being developed for airborne use (side-looking radar, remote pollution (gas contraction) detection and infrared scanners) can all be flown at either aircraft altitude or satellite altitude. The resolution available from various platforms with a similar sensor is a function of optics, electronics, and the state-of-the-art in each of these areas.

Table 4-1 indicates possible (commonly used) sensor and platform combinations. Aircraft and helicopters can carry an almost infinite variety of sensor complements. Indeed several private contractors and NASA have aircraft equipped with multiple systems and sets of systems that can be interchanged to tailor the sensor package to the job at hand.

5.1 SATELLITE SYSTEMS THROUGH 1980

Unlike aircraft, it is not possible to change sensors once a spacecraft is launched. Thus, this section will discuss not only platforms but the integrated satellite remote sensing systems of interest to resource management that will be available through about 1980.

The Earth Resource Satellite systems and sensors planned for the period through 1980 include earth observing satellites devoted to meteorology, land resources and ocean resources. There are obvious overlaps between the sensor characteristics that are used for each of these applications. For example, thermal infrared remote sensing techniques applied to the oceans are also applicable to land and meteorological problems. Tables 4-3 and 4-4 present a listing of existing, approved and planning stage satellite systems through 1980.

Meteorological Satellites

The meteorological satellite program will continue uninterrupted with TIROS operational systems now termed NOAA satellites. At present there are six operating satellite systems that are primarily devoted to providing meteorological information. These are NOAA 2, NOAA 3, SMS/GOES, Nimbus 5, DAPP, and ATS-F. All of these systems are projected to operate through 1976.

TABLE 4-3 CURRENT SATELLITES

Satellite	Agency	Orbit	Altitude	Period	Applicable Sensors	Observation Type
NOAA-2 •Direct Read •Tape	Commerce	Sun Synch Polar 0930L 2130L	1430 Km	115 min	Scanning Radiometer (SR) Visible .5-.7 μm - 3.6 Km Thermal 10-12 μm - 7.2 Km Very High Resolution Radiometer (VHRR) Visible -.5-.7μm - .9 Km Thermal 10-12 - .9 Km	Cloud Cover - Day/Night Surface (IR) Temp Day/Night Surface Albedo - Day - same -
Nimbus •Tape	NASA	Polar Sun Synch 1200M 2400	1085 Km	110 min	Temperature/Humidity Radiometer (THIR) Visible - Nine Thermal 10-11.5μm - 7.2 Km 1/Electrically Scanned Microwave Radiometer ESMR Microwave - 19.35 GH_Z - 23.4 Km 1.55 cm	Cloud Cover - Day/Night Surface (IR) Temp - Day/Night Surface (Microwave) Temperature Day/Night Cloud Cover where the clouds are precipitating or very moist
DAPP 1-2 •Direct Read •Tape •Digital	Air Force	Polar Sun Synch 0600L 1200L 1800L 2400L	1085 Km	110 min	Visible Sensor .4-1.0μm - 5.6/3.6 Km Thermal Sensor 8-13μm - 5.6/3.6 Km	Cloud Cover - Day/Night Cloud Cover - Day/Night Surface (IR) Temp Day/Night
ERTS-1	NASA	Polar Sun Synch 0930L 18 day Repeat	905 Km	103 min	Multispectral Scanner - MSS Visible .5-16, .6-7μm Near IR .7-.8 1.1μm .09 Km	Surface Spectral Albedo in 4 Bands day time 18 day repeat cycle

1/ESMR is currently not calibrated.

TABLE 4-4

FUTURE SATELLITES

Future 1974-1976+

Satellite	Agency	Orbit	Altitude	Period	Applicable Sensors	Observation Type
NOAA-3 Launch 1974	Commerce	Sun Synch Polar	1450 Km	115 min.	Same as NOAA-2	Same as NOAA-2
SMS/GOES 1973	Commerce	Earth Synch at 100 W	35,000 Km	24 hrs.	Visible/Infrared Spin Scanner Radiometer (VISSR) Visible .5-.7 μm .9 Km Thermal 10-12 μm 3.6 Km	Cloud Cover - Continuous Surface Albedo - Day Surface (IR) Temp - Continuous
Nimbus F 1974 (Nimbus G) 1976	NASA	Sun Synch Polar	1085 Km	110 min.	1/ Surface Composition Mapping Radiometer Visible .8-1.1 μm .6 Km Thermal 2 Bands 8.4 -9.5 μm) .6 Km 10.2-11.4 μm) Electrically Scanned Microwave Radiometer (ESMR) Microwave - 37 GH_Z - 16.3 Km Earth Radiation Budget (ERB) Total .2-40 μm - 63 Km	Cloud Cover - Day (Restricted Coverage) Surface Albedo - Surface (IR) Temperature Day-Night Restricted Cover Surface (microwave) Temperature Net Radiation for Selected Spots
TIROS N 1976+	NASA	Sun Synch Polar	1630 Km	120 min.	Advance Very High Resolution Radiometer (AVHRR)	

1/ The surface composition mapping radiometer ceased to function shortly after launch.

The sensors carried by these systems have relatively poor spatial resolution but rather good spectral and radiometric resolution. In addition to meteorological applications, the data can be applied to a wide variety of earth resource problems. Imbedding a strip or frame of imagery or data from a higher resolution system such as ERTS-1 in the relatively low resolution meteorological data can partially overcome problems of resolution. NOAA-2 and NOAA-3, which are currently operating, carry scanners that provide two channels of data in the visible and infrared with low resolution coverage (3.6 km) over the entire world and 0.6 kilometer resolution over selected areas of the world. These satellites can potentially cover the entire earth every 12 hours. The data are telemetered to a number of earth receiving stations and are available through the meteorological services of several countries.

The Geostationary Operational Environmental Satellite (GOES) orbits the earth at an altitude of about 36,000 km. At this altitude the orbital speed is synchronous with the rotation of the earth at the equator. Thus a geosynchronous satellite can provide continuous coverage of any point on earth within the field of view of the sensor. The planned GOES system will provide for two satellites. One satellite will be positioned near 100° W on the equator while the other will be positioned at about 60% W. A continuous day and night surveillance of the United States is planned utilizing sensors in the visible and infrared portions of the electromagnetic spectrum. The sensor resolution is one half mile in the visible band and four miles in the infrared.

No GOES coverage is expected for the Sahelian region. The Applications Technology Satellite (ATS-6) presently positioned to cover the United States will be positioned over Nairobi in mid 1975 to conduct an experiment with India. The ATS-6 has a visible and infrared scanner which may be operated over Africa. The decision for such operation may be assisted by requests for various Sahelian countries and support from AID.

Nimbus 5 carries an electronically scanning microwave radiometer (ESMR) with approximately 25 kilometer resolution. The satellite also carries a scanning temperature humidity infrared radiometer (THIR) with approximately 22 kilometer resolution. In addition to these imaging systems the Nimbus 5 carries an infrared profiling radiometer and a microwave spectrometer. These instruments are optimized to provide meteorological data, much of which can be applied to such problems as water balance studies and construction of hydrological models. The satellite has a sun synchronous orbit at about 1100 kilometers that allows the satellite to cover the entire earth's surface every 12 hours.

The DAPP meteorological satellite operated by the Air Force also potentially covers the earth every 12 hours. It acquires imagery in the visible portion of the spectrum with 0.9 kilometer resolution and in the thermal infrared with 3.6 kilometer resolution. These data complement those produced by the NOAA program.

Applications Technology Satellite-F (ATS-F) like the rest of the ATS series is an experimental vehicle for testing various instruments. ATS-F is a geostationary satellite equipped with two very high resolution solid state cameras, one for sensing in the visible and the other for sensing in the thermal infrared portion of the spectrum. These cameras can acquire imagery every twenty minutes day and night from which time lapse movies of cloud movements may be constructed. For the whole earth disc the resolution is about 22 kilometers in the visible range and 17 kilometers in the infrared. The cameras can focus in on selected areas and acquire imagery with about 3 kilometer resolution. At present the major applications of these data are in the field of meteorology.

Future developments in the meteorological satellite program include a launch of Nimbus 6 in late-1974 and possibly Nimbus 7 in 1977. The Nimbus 6 launch will continue to provide temperature humidity infrared radiometer (THIR) data which can provide some useful infrared data in the Sahel region, and will fly new vertical temperature sounders and microwave radiometers. The TIROS N series is a new series of TIROS satellites to be initiated in 1976. TIROS N will carry high resolution sensors covering more spectral bands.

The existing TIROS operational satellite program will provide significant information for evaluation of relative water budget information over the Sahel region and will provide a basis for continued accumulation of meteorological satellite data that can be used in climatological studies. The continuation of the program will also permit the development of long range plans for utilization of data acquired from the meteorological satellite. No extended periods are anticipated when a major part of the world will not be covered by meteorological satellites.

Earth Resources Technology Satellites (ERTS Series)

In the class of earth observation satellite that have a primary emphasis of land resource remote sensing, the currently operating ERTS-1 has been in orbit for nearly two years. It is scheduled to be replaced by ERTS-B in early 1975. The sensor packages carried on these earth observation satellites will be the same, i.e., a three camera return beam vidicon (RBV) system

and the four-channel multispectral scanner (MSS) system. Each frame covers about 34,000 square kilometers and the imagery has a spatial resolution of about 80 meters. ERTS-B will be launched with a Thor-Delta launch vehicle into a circular near-polar (99% inclination) at an altitude of 900 kilometers. The next planned earth observation satellite which is directed toward land resources is the EOS A, now planned for launch in 1978 or 1979. EOS will carry multispectral scanners operating in 7 spectral bands and may carry a side-look radar system.

The manned satellite, Skylab, which completed its mission in early 1974, carried a variety of sensors of interest in resource management including a six band multiband camera, a high resolution camera, and a 13-channel scanner which acquired data in the visible, near infrared and thermal infrared portions of the spectrum. The quantity of data, though significant, acquired by Skylab was severely constrained by the amount of film and magnetic tape that could be carried back and forth by the astronauts and by limitations imposed by the vehicle itself and the other experiments on board. Under optimum conditions Skylab could have acquired imagery of only about 50 percent of the earth's surface between 50° north and 50° south. The actual percentage covered was much smaller than the maximum and confined almost entirely to areas specified by principal investigators. Several passes are available for the Sahel but the coverage is far from complete. Skylab is of interest in the context of this study largely because it indicates what may be possible with future satellite systems. The resolution of the photography ranges from about 10 meters to 25 meters and the scanner imagery has a resolution of about 80 meters.

The Synchronous Earth Observing Satellite (SEOS) when launched in 1978 will have a 23,300 kilometer earth synchronous orbit and will be able to observe an entire hemisphere at the same time. The precise complement of instruments to be carried by the satellite has not been decided, but it will probably include multispectral scanners, solid state cameras and spectrometers. These will provide the flexibility to address a wide variety of natural resources and environmental problems.

The Space Shuttle scheduled for launch in approximately 1980 will be capable of carrying an extraordinarily diverse range of instrument packages. The flexibility of this vehicle is increased by it being a manned vehicle. Further, Shuttle can be launched on call with almost any orbit and reused after its return. This allows for man and machine interaction for the acquisition and on board processing of data. The presence of man and the large size of the

vehicle make it possible to mount sensors too large, heavy or complicated to be used on other spacecraft. It will be possible to carry imaging passive microwave scanner, side-looking radars and complicated scanners and computers into space. The variety of tasks that can be performed and types of data that can be acquired is limited only by man's ability to conceive them.

SEA SAT, scheduled to be launched in 1978, is designed primarily to examine the surface of the ocean. However, it will probably carry an imaging radar and a radar altimeter for measuring the geoid, both of which have applications to earth resource problems. SEA SAT may well provide the first space-acquired SLAR imagery of the earth. The measurements of the geoid can identify major gravity anomalies, which may indicate otherwise undetected aspects of the geological regime.

6.0 ROLE OF AUTOMATIC DATA PROCESSING

For many remote sensing systems the rapidity of acquisition and the volume of data acquired far exceeds the ability of interpreters to manually reduce the data. Every year ERTS alone acquires many thousands of images in four spectral bands each covering 34,000 square kilometers of the earth surface. There are several multispectral scanner systems that acquire as many as twelve channels of data in a single overpass, and one that acquires 24 channels. A single commercially available SLAR aircraft can easily acquire 120,000 square kilometers of SLAR data and 80,000 square kilometers of photographic imagery in a single day. The immense capacity for data acquisition of these few systems indicates the magnitude of the task of data reduction.

Sophisticated computer techniques are one possible solution to this problem. Computers can preprocess the data or enhance particular features, extract certain types of features, and perform various types of automatic classification operations.

Preprocessing or enhancement involves processing data so as to emphasize one or more types of features. The goal of enhancement is to improve the ease or accuracy of interpretation in order to reduce the time spent manually, and thus, reduce the cost and time required for data reduction. Several categories of enhancement techniques commonly used include:

- Noise removal and radiometric, spectrometric and geometric corrections. This involves various filtering techniques, spectrometric and radiometric adjustments, and spatial adjustments necessary to bring the image into conformance with some standard, such as an existing map.

- Edge sharpening. These procedures emphasize boundaries between landscape elements and linear feature within elements.
- Density slicing divides the image into sub-images based on intensity considerations.
- Multispectral combination. These techniques include addition, subtraction, multiplication or ratioing of two or more spectral bands of data. Many of these techniques emphasize differences in surficial composition of landscape elements.

Feature extraction involves determination or identification of specific features based on their context within an image or on statistical manipulation of the data, to give specific features new unique digital characteristics. Water can be separated rapidly and relatively confidently on new infrared imagery based on its very low reflectivity. After performing certain types of ratioing operations on multispectral thermal infrared scanner data or infrared spectroradiometry, it is possible to identify or extract some specific rock types.

In classification operations, landscape elements (or data elements) are grouped on a statistical basis and classified according to some probabilistic or deterministic scheme. The classification is based on characteristics present in the data. Under appropriate circumstances, the boundaries can be made to correspond with the traditional classification of landscape units. This approach has met with some successes in the field of crop classification with the large fields in the U.S.A. Classifications can be based on characteristics such as, multispectral character, textural characteristics, density or intensity factors, and size or spatial distribution. To utilize these approaches, it must be possible to relate the categories created based on the data to categories present in the landscape. For more extensive discussions of the problems and possibilities inherent in automatic data processing of remote sensing data refer to Simonett (1974), Shahrokhi (1972), Proceedings of the Seventh International Symposium on Remote Sensing of the Environment (1971) and Steiner (1972).

7.0 IMPORTANCE OF GROUND INFORMATION

Knowledge of what exists on the ground is critical to the effective use of remote sensing because it provides the link between the objective or real world and the elements perceived in remotely acquired data. Without this critical link, remote sensing would have little to contribute to resource management. A certain amount of ground information is necessary to determine the appropriate type of remote sensing survey or the contribution of remote sensing to a particular resource management problem. Existing information (reports and maps), the

experience of the interpreters, low level aircraft flights and traditional ground survey techniques can all supply necessary ground information.

Existing information in the form of reports and maps is an excellent source of readily available ground information. Excellent detailed surveys and maps exist for selected areas of the Sahel. These provide data not only for the specific areas covered, but data that can be extrapolated by analogy to other similar areas in the region through the use of small scale imagery.

The training or experience of the interpreter of remotely sensed data can supply large amounts of the required ground information. Thus, field experience is extremely important in training interpreters. Having seen a particular natural feature on the ground, an interpreter may then identify similar features in low altitude color aerial photography. Having identified the feature on this type of imagery, it is then feasible for an interpreter to recognize the same feature in a wide variety of other types of imagery. An interpreter familiar with a particular area is an exceedingly valuable source of information on areas with similiar types of environments.

Low level aircraft flights over the area of interest by those involved in the interpretation of remotely sensed data can provide a first hand appreciation of the area and answer many questions that would otherwise require ground investigations. This method is rapid and provides interpreters with a perspective of the ground akin to that of the remotely sensed data. Overflights are an excellent method of carrying out a preinterpretation reconnaissance of the area and of checking the results of interpretation. Initial flights should be planned on the basis of existing maps. Subsequent flights should be based on the results of interpretation, so that they can efficiently cover the points or areas that were difficult or impossible to interpret on the basis of the remotely sensed or existing data. A methodology known as "air check" involves carefully planned low altitude flights during which a well-trained resource specialist records his observations keyed to time and position, and acquires hand held photography of specific features for later study (Brewer, 1971). Low level flights are also an excellent method for planning ground operations.

Traditional ground survey techniques must be used in areas for which no data are available from other sources. Although these data have very high confidence limits associated with them (what is seen or perceived is actually there), the methods in most instances are slower and more

costly than other data acquisition methods. Thus, they should be used only where other methods of acquiring ground information are not feasible.

The acquisition of ground information is the most costly per unit area phase in a program of acquiring information for monitoring the results of a resource management project. The effective use of remote sensing and data extraction techniques is directed toward reducing this phase of a project to a minimum. However, in the final analysis it is on the ground that the validity of efficacy of any remote sensing technique is finally tested.

8.0 COSTS

The cost of a remote sensing survey includes the costs of data acquisition, processing, interpretation, and verification. These costs in turn depend on the sensor or sensors used. Sensor selection must depend on the purpose and location of the survey, the areal size, the required level of detail, existing information on the area, the available facilities and equipment for processing and interpretation, labor availability and costs, platform availability and costs, shipping costs and for some surveys the time of year. Each of these factors can vary, which makes it impossible to discuss costs in anything but general terms.

A few general principles to guide consideration may be helpful:

- The larger the area, the less the cost per unit area for data acquisition and interpretation. This is true because the cost of mobilization is usually prorated on a per kilometer basis over the actual cost of acquisition and, as in most other fields of endeavor, there are economies of size.
- In general, the higher the resolution, the larger the scale or the more specific the sensor, the higher the cost of acquisition, processing and interpretation. This suggests a multi-level approach beginning with large area, low resolution generalized coverage and proceeding to studies of selected smaller areas with more specific higher resolution techniques. At each level the available data should be exploited to the maximum degree possible before proceeding to the next step.
- Multi-purpose or multi-resource programs reduce the cost accorded to each end use. This is obvious because the costs of data acquisition, processing and capital investment for interpretation can be shared among users.
- The cost of adding a sensor to a platform is usually relatively small. Most of the cost of data acquisition is the cost of flying.
- Computer and computer assisted interpretation becomes economical when large areas are covered, a large number of comparisons among several data types are required and the decisions to be made are relatively simple. The same is generally true of other machine assisted techniques.

From the above, it is clear that costs of a remote sensing program will depend on the details of the specific situation. However, it will be useful to examine costs associated with a specific application at several levels of detail using two sets of assumptions about the sources and types of data available. The application chosen is land use mapping. The data used are taken from a number of works including Sizer (1973), Simonett (1973) and Thorley et al. (1973). The costs given are in 1973 U.S. dollars for areas mapped in the United States. Costs for equivalent work in the Sahel region can be expected to be somewhat higher, primarily due to location which will entail higher mobilization and processing costs. For instance, mobilization costs for most of the U.S. are negligible for high altitude aircraft; just to mobilize and demobilize such an aircraft from Europe to the Sahel would cost about $40,000.

The cost ratios presented in Table 4-5 are on a square kilometer basis and include the costs of data acquisition, processing, interpretation, and map preparation. The cost base (100) is Level II using satellite imagery only, that is the cost of extracting the maximum amount of information from ERTS imagery is taken as the basis for comparison. At 1974 prices in the United States this cost ranges between $0.25 and $0.45 per square kilometer depending upon the area and land uses represented. Because of location and logistical problems costs are expected to be somewhat higher in the Sahel.

The table clearly shows the savings available from relying on small scale (space) imagery for initial interpretation and the increase in cost with increase in level of detail and increase in scale. The efficiency of a multi-scale or multi-stage sampling approach is obvious from a comparison of the two approaches yielding complete Level II land use information.

The costs reflected in this table can be compared to those for geologic applications contained in Chapter 6. A comparison of this type points out the differences in costs for different applications (uniform mapping versus a search for point targets) and the difference in approach for different applications.

A comparison of costs for the acquisition of data using two aircraft sensor systems, color infrared photography and a 12-channel multispectral scanner, points out the importance of selecting the proper system for a particular task and emphasizes the importance of using general purpose sensor data to select the areas over which more specific data are to be acquired. To acquire color infrared photography over a 100,000 square kilometer area in the Sahel would cost approximately $240,000. To acquire multispectral scanner (12 channels) imagery over one fifth of

TABLE 4-5

COSTS OF LAND USE MAPPING

Products in each instance are line overlays with title and legend. Cost ratios presented include data acquisition, interpretation and drafting costs. Costs are approximate. The Level II "Satellite Imagery Only" level of effort is taken as the basis of comparison and arbitrarity given the value 100.

Level of Detail	Scale of Final Product	Method or Basis	Data Sources	Cost/Square Kilometer	Comments
LEVEL I	1:250,000 to 1:500,000	Satellite Imagery	1:250,000 ERTS Imagery	60	
		High Altitude Aircraft Imagery	1:50,000 Aerial Photographs	800	
LEVEL II	1:250,000 to 1:63,360	Satellite Imagery Only	ERTS Imagery	100	Incomplete Level II information but include most of Anderson's (1972) and Poulton's (1972) Level II classes.
		High Altitude Aircraft Imagery	1:90,000 aerial photographs	900	All level II Information
	1:63,360	Multiscaled Approach	ERTS Imagery, High altitude Aircraft photography and Ground Truth	300	
LEVEL III	1:24,00 to 1:63,360	Commercial	Relys on 1:90,000 high Altitude photography	1100	Detail equivalent to Poulton's (1972) tertiary classes.
	1:12,000 to 1:40,000	Commercial	1:24,000 aerial Photography	2300	

that area (20,000 square kilometers) would cost about $240,000. A mobilization cost of about $40,000 would be associated with both surveys. The color infrared photography would be acquired from an altitude of about 8,000 meters at a scale of 1:80,000 on 22.9 cm film; the multispectral scanner imagery would be acquired from 3,300 meters on 70 millimeter film at a scale of 1:50,000. These differences in cost, though great, do not begin to reflect the even greater differences in cost associated with the interpretation of the data. The multispectral scanner produces a minimum of twelve times as much data per unit area as does the color infrared survey. Table 4-6 compress the costs of several forms of remotely sensed imagery. These figures do not include mobilization.

Thus, costs of remote sensing surveys for resource management programs must be approached on a case by case basis, considering the purpose and location of the survey, the required level of detail, the existing information and required ground verification, amount and type of equipment available, labor costs, and timing of the survey.

9.0 SOURCES OF DATA

Table 4-1 and the chapters on specific applications contain information on sources of remote sensing data and services. The EROS Data Center in Sioux Falls, South Dakota is the repository of all ERTS, Apollo and Gemini imagery and of the NASA aircraft imagery acquired in support of these programs. The National Oceanic and Atmospheric Administration (NOAA) can supply the unclassified data from the meteorological satellites. There are numerous aerial survey companies equipped to supply a wide variety of photography and aeromagnetic data.

A variety of ERTS-1 film products are available to the public from the EROS Data Center. These include both single band black and white as well as color products. A partial list of data center products plus their cost as of January 1974 are presented in Table 4-7. Typical costs for photographically enhanced commercially available products are also included. Commercial costs as presented do not include the initial costs of obtaining 70 mm NASA transparencies.

Countries with limited experience in remote sensing, but contemplating extensive resource surveys should pay close attention to the following: 1) Project design, 2) Remote sensing program and data acquisition, 3) Contract specifications verification, 4) Evaluation of competitive bids by aircraft survey and equipment companies, 5) Monitoring of performance of contractors, 6) Training of indigenous personnel in interpretation, data processing and resource management, 7)

TABLE 4-6

COST OF ACQUIRING SELECTED TYPES
OF REMOTELY SENSED IMAGERY

Type of Data	Altitude	Scale	Cost/km^2 ($)
ERTS Imagery	900 km	1:1,000,000	0.003
Photography (color infrared)	8 km	1:80,000	2.40
(black and white)	1.5 km	1:10,000	25.00
Multispectral Scanner (12 Ch)	3.3 km	1:50,000	11.50
Side-Looking Airborne Radar	10 km	1:400,000	2.0 to 6.0

TABLE 4-7

ERTS FILM PRODUCTS PRICE LIST

	Black & White		Color	
Product	EROS	Commercial	EROS	Commercial
70 mm (Transparencies)	$2.50	--	$ 4.00	--
9" X 9" (Paper Prints)	1.75	$ 7.00	7.00	$ 7.95
18" X 18" (Paper Prints)	3.50	13.50	15.00	20.00
36" X 36" (Paper Prints)	9.00	25.00	25.00	50.00

Setting of quality standards, 9) Formulation of future updating procedures, 9) Designing appropriate geobase information systems to merge conventional and remote sensing acquired data, and 10) Establishing procedures for all operational and remote sensing acquired with the cultural environment and institutions of the particular country. Such services are comparable to those provided by major supervisory engineering firms in the construction of major public works, irrigation projects, pipelines and so on. There are a small number of firms with the requisite skills for major resource surveys.

10.0 CONCLUSION

In planning the acquisition of resource management data using remote sensing techniques one must select among the wide variety of sensors, platforms and services available. Selection should be guided by the problem and desired results and by the precepts of working from the general to the specific and the possibility of multiple end uses of the data. Subsequent chapters will treat different applications areas in more detail and provide insight into specific approaches that have been successful under conditions similar to those present in the Sahel. The rapidity with which detailed information can be acquired over large areas makes remote sensing a potentially valuable tool for resource management in the Sahel.

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PART II

REMOTE SENSING APPLIED TO SPECIFIC SAHELIAN RESOURCE PROBLEMS

CHAPTER 5

CARTOGRAPHY AND MAPPING

1.0 INTRODUCTION

Management information can be collected and stored in many different ways. For over a thousand years, the map has been one of the most effective ways to store and present vast amounts of spatial information. The effective use of maps in displaying resource data is dependent upon the use of a map base designed to most effectively correlate the information to be mapped. A base map is an outline map which serves as the presentation format for various types of information. It may consist of administrative divisions, coastlines, contours, river or road patterns, but in every case general characteristics of the area in question are displayed. For example, the topographic map is the most common base map and can serve as a tool for planning new roads through difficult terrain. Alternatively, an administrative and city base map can be used for displaying regional population density or location of industry in relation to cities and political units.

The scale of the base map and the recorded details of the resource determine how well other information can be tied to locational points on the base map. The smaller the scale of the map the more general the information and data displayed as a rule. The accuracy of the base map determines how well information can be applied to a designated physical point on the ground.

When using remote sensors to collect data for resource management, the scale and accuracy with which a specific type of information can be related to physical points on the ground must be carefully considered. On one hand, information not tied to a certain location may be of little value; on the other hand, pin-point accuracy may not be essential. The optimal accuracy should be determined in relation to disciplinary or operational information needs. Base maps can be obtained through four methods:

1. on-site ground surveys historical maps were usually derived from this method;
2. abstracting base information from existing maps;
3. abstracting base information from aerial photography or imagery;
4. direct transfer of photography or imagery (orthophoto maps).

The French Institut Geographique National (I.G.N.) has completed topographic base maps at a scale of 1:200,000 for approximately 98 percent of the Sahel region. Coupled with this existing map information, a substantial amount of aerial photography and satellite imagery (ERTS, Skylab) covering most of the Sahel is available. A complete accounting and examination of available map and photography/imagery is necessary before implementing substantial research or development activities. The following section presents not only general principles of cartographic applications of remote sensing, but also a synopsis of the location and condition of existing imagery and maps.

2.0 MAPPING ASPECTS OF IMAGE PRODUCING REMOTE SENSING SYSTEMS

Using imagery or photography to produce base maps presents a relatively inexpensive, accurate and timely method for obtaining map information. Three major types of transformations can be distinguished:

- Image to base map
- Base map to image
- Image to Image

The essential criteria for undertaking these types of transformations is to improve the accuracy and legibility of the data. Transferring an image to a base map can take two forms: 1) a photograph or image can be considered a base map, and all information contained can be directly transferred to a map (orthophoto maps); and 2) selected features on an image, i.e., roads, settlements, water bodies, etc. can be transferred to a base map to eliminate non-essential information.

Comparing a base map to an image can correct previous mapping distortions and improve and update the base map information. Image to image transformations present a method for accounting for periodic changes and update of information.

Conventional aerial photography has been the standard mapping transformation medium for most parts of the world, but other remote sensing systems may be considered for the Sahel region:

- Airborne multispectral scanners (MSS) and cameras
- Airborne side-looking radar (SLAR)
- Satellite photography, imagery, and scanning (sensing)

The following sections examine current and future applications of remote sensor systems for mapping applications in the Sahel.

2.1 EARTH RESOURCES TECHNOLOGY SATELLITE IMAGERY: IMAGE TO BASE MAP TRANSFORMATION

ERTS images can be used as a base map, and a series of map products can be generated:

ERTS digital multispectral scanner (MSS) images. ERTS data is received in digital format on a computer tape and can be processed into photographic form. The original ERTS tape has not been corrected for geometric distortions and therefore has low geometric accuracy, but has been corrected for attenuations in the scanning system thereby increasing radiometric accuracy. The MSS image derived from the tape represents the original acquisition form and has not undergone continuous processing which reduces information content.

ERTS/MSS photographic output product. This product incorporates several systematic geometric distortion corrections. Its geometric accuracy has been improving steadily. Initial ERTS-1 images had a positional RMSE (Root Mean Square Error) of 1,000 meters or more.* Current ERTS/MSS photographic products have RMSE's of 200 meters or better. However, in some instances, it is necessary to rotate and translate the image to provide the desired correspondence with the local map grid. The best map projection for use with MSS images is the Universal Transverse Mercator (UTM) projection. Radiometric accuracy remains very high.

MSS precision processed images. These images are spatially rectified in which image points are matched with identifiable ground control points with known coordinates. The RMSE of such images is probably of the order of 100 meters or better.

Insights from these spatially rectified images have been fed back into the standard bulk processing procedure, with the result that the geometric quality of bulk processed images is now nearly as good as the quality of precision processed images. Radiometric accuracy in precision processed images tends to be degraded.

Lithographic map products derived from ERTS/MSS images. Lithographic maps are maps produced by printing from a plane surface on which the image to be printed is ink-receptive and the blank areas ink-repellent. Colvocoresses (1973) indicated that the maximum printing scale for this type of map product should be 1:250,000. At this scale, to comply with U.S. National Map Accuracy Standards, the RMSE should be no more than 75 meters (i.e. 80 meters RMSE has been achieved).

* The location error between any two widely spaced points on the image had a positional error of 1,000 meters or more.

An ERTS photo map obviously does not meet this standard, but is not very far from it. The same general standards should be acceptable for the 1:200,000 base map series currently available for the Sahel region.

ERTS Mosaics. ERTS images can be assembled in the form of mosaics to produce a full coverage view of the region of interest. In a mosaic, the interrelationships of the physical and cultural environment can be analyzed in a comprehensive planning context, rather than with the limitations placed on using a single ERTS frame or portion of a frame. for example a mosaic of the country of Iran was produced using 138 ERTS images. Mosaics can be either uncontrolled (no ground control is used) or semi-controlled (the images are adjusted to correspond with a set of control points plotted in a certain map projection).

ERTS used for Map Series. ERTS images from bulk processing*, can sometimes serve as the basis for a map series, because the image centers are maintained within ± 15 kilometers by NASA. So, any ERTS images can be related to a specific point on the ground that is less than this distance from its image center. This idea was presented by Schoonmaker (1973), but it has limited interest for the Sahel due to the existence of a fair to excellent, nearly complete map series at 1:200,000 scale.

2.2 ERTS, SKYLAB: BASE MAP TO IMAGE TRANSFORMATION

Information from existing base maps can be transformed (overlayed) on an image. This technique called "image annotation" can update only selected information needs and is a less costly method than to transform the entire image to fit the base map. In the case of the Sahel, precision image annotation from the existing 1:200,000 maps can be an important aspect of a multistage statistical inventory in which one begins with a space image, and then "zooms in" on a small area where ground observations exist which can subsequently be correlated with the whole space image. Should positional shifts occur in the transfer of information from stage to stage, the plot of land examined from ground surveys may indeed by entirely unrelated to the point on the space image thought to be its representation. Spatial rectification techniques applicable to ERTS and Skylab imagery can be used for precision image annotation (van Roessel and Langley, 1973). This technique has yielded RMSE's of 200 meters or better for ERTS imagery, and 100 meters better for Skylab S-190A photography.

* Bulk processed images contains radiometric and initial spatial corrections introduced during the process of videotape to film conversion. Precision processing refers to imagery that has received radiometric and spatial corrections, including transformation into UTM coordinates.

2.3 SKYLAB S-190A IMAGE TO BASE MAP TRANSFORMATION

After a rectification of space imagery has been performed, selected information can be mapped to any desired ground coordinate system. One application of such a mapping is the transformation of a linear feature as observed on a SKYLAB image to base map coordinates. These coordinates can then be used to project the precise location of the specific feature. Knowing its precise location may be useful in settling boundary disputes between countries or between mineral right concessions.

2.4 SLAR: IMAGE TO BASE MAP TRANSFORMATION

Side-looking airborne radar can be used to produce base maps. The method is very suitable for extremely large areas with persistent cloud cover that need to be mapped in very short periods of time. Moderate terrain relief is a significant prerequisite for this mapping method.

With the SLAR mapping method, radar image strips are joined into mosaics which may be either uncontrolled (for general reconnaissance mapping) or semi-controlled.

For the manufacturing of semi-controlled SLAR mosaics, a variety of control methods may be used. Two such methods have been successfully used for Project RADAM in Brazil: 1) the position of the aircraft can be recorded through the use of ground-based distance measuring equipment; and 2) across-track controlled tie lines may be obtained which can serve as a rigid frame in the compilation of the mosaics. In both cases, major ground control can be established by using geodetic satellite locating equipment. These methods are described by van Roessel and de Godoy (1971).

Generally the positional accuracy of the semi-controlled radar mosaics appears to be of the same order of magnitude as the accuracy obtained for ERTS-derived base maps.

3.0 AVAILABLE IMAGERY AND MAP COVERAGE OF THE SAHEL

3.1 ERTS COVERAGE FOR THE SAHEL REGION

Since launch (July 1972), ERTS imagery has been acquired repetitively over sub-Saharan West Africa, due to the special priority allocated by NASA in response to the Sahel emergency situation. Because of the minimal cloud cover over the Sahel, a large number of acquisitions have been possible, and many locations are covered on a seasonal basis. To evaluate that coverage, an ERTS coverage map has been prepared (Figure 5-1), using the various data available in the ERTS coverage Cumulative Non-U.S. Standard Catalog.

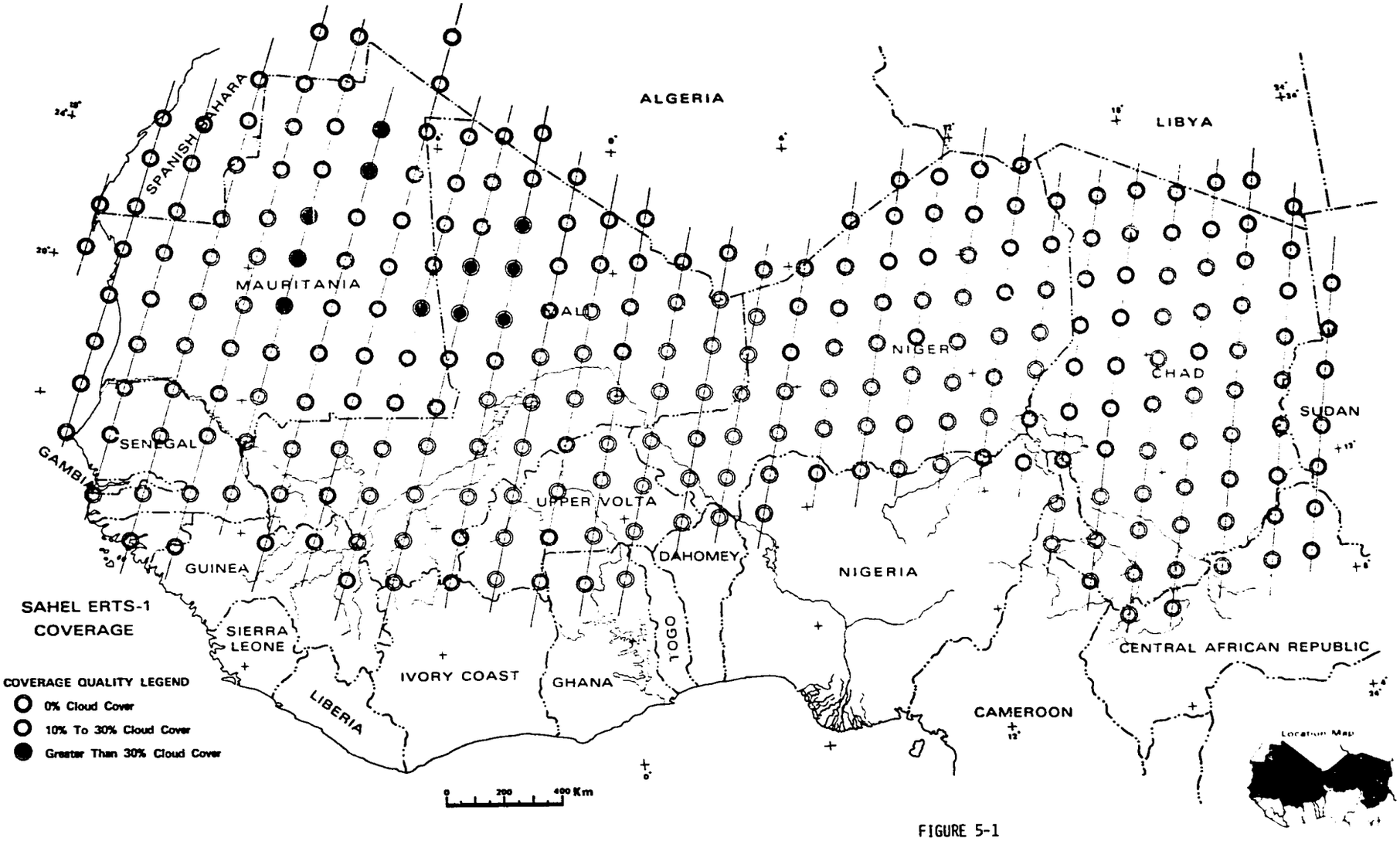
SAHEL ERTS-1
COVERAGE
COVERAGE QUALITY LEGEND
0% Cloud Cover
10% To 30% Cloud Cover
Greater Than 30% Cloud Cover
ALGERIA
LIBYA
SPANISH SAHARA
MAURITANIA
MALI
NIGER
CHAD
SUDAN
SENEGAL
GAMBIA
GUINEA
UPPER VOLTA
DAHOMEY
NIGERIA
SIERRA LEONE
LIBERIA
IVORY COAST
GHANA
TOGO
CAMEROON
CENTRAL AFRICAN REPUBLIC
0 200 400 Km
Location Map

FIGURE 5-1

Acquisitions of ERTS imagery for a specific location can be obtained from the EROS Data Center by specifying the geographic coordinates of the image centers. Image selection is facilitated by the following criteria provided by the Center in its general cataloging process. General image qualities have been ranked by NASA using values from 8 (best quality) to 0 (worst quality). Owing to the large number of acquisitions over the Sahel, only the images ranked 8 have been catalogued in Figure 5-1. Cloud cover evaluations done by NASA personnel indicate cloud covers ranging from zero to 90 percent and designated 0 to 9. In preparing the list of ERTS imagery of the Sahel, it was soon determined that a number of ERTS images were mistakenly reported by NASA to have an abnormally high cloud cover percentage. The mistakes have been traced to the lack of familiarity with sub-desert and desert environments, dunal systems, extensive playas and sand seas that exhibit high reflectivity and wave-like or concentric patterns. All of these could easily be mistaken for specific types of cloud formations. Furthermore, the standard NASA procedure is to use Band 4 for cloudiness evaluation. This is detrimental in the case of the Sahel because winter imagery is typically hazy, and dust clouds result in greater atmospheric attenuation in Band 4 than in the infrared bands 6 and 7. It is recommended for the future that Band 7 be used exclusively to evaluate cloudiness over this semi-arid region.

Matching of continuous ERTS imagery strips each consisting of cloudless images acquired at one day intervals seems experimentally to deliver the best data base for the regional studies necessary to understand the complex environment of the Sahel. Once orbits are matched, the construction of regional ERTS mosaics can proceed. Regional seasonal comparisons can then be made.

The three logical operations described above are easily programmable and future best coverage indices could be accomplished through computerized operations using the basic information now supplied by NASA. Since the design of the appropriate software could not be addressed during this effort, the accompanying ERTS-1 coverage map was generated manually. For the future, however, and especially to accommodate ERTS-B data, the appropriate computer-compatible system should be developed.

The Sahel region as shown on the ERTS-1 coverage map has a very high percentage of cloudless images. Approximately 80 percent of the entire area has been imaged without interference from clouds. The remaining 20 percent is covered by images with cloud covers ranging from 10 to 30 percent. Therefore it can be safely said that only a small portion of the entire Sahel region can not be directly analyzed from space-acquired data. Indeed, the regions in Mauritania and Mali where cloud coverage of imagery is estimated to be in excess of 30 percent, are highly suspicious. A few images in those areas estimated by NASA to have up to 90 percent cloud cover appear to be regions where the highly reflective appearance of the terrain affected the photographic representation of the scene (i.e., the grey scale variation was very narrow). Acceptable false color composites (color images where each band is given a specific color and then all bands are combined to produce a false color imagery) prepared from these images indicate the importance of submitting such images to careful pre-processing, i.e., improving the image quality through photographic, noise, and radiometric correction techniques. Users in need of data over such areas should be encouraged to consult with specialists in pre-processing prior to leaving any blind spots in the data base for their investigations. In a number of cases, visual inspection should convince them that the information is readily available from the imagery, and that the images show highly reflective terrestrial features and not clouds.

3.2 PHOTOGRAPHIC COVERAGE FOR THE SAHEL

Standardized aerial photography exists for more than 95 percent of the entire Sahel region (Figure 5-2). It was flown at a constant scale by specialized teams of the French Institut Geographique National (I.G.N.) for periods from 1955 to 1970. French technical assistance has done much to keep active the extensive photographic plant developed by the French in the post-World War II days. Flight lines are organized to provide 60 percent sidelap and 15 percent strip overlap for stereo coverage and location indicators. Strips were oriented in an east-to-west direction. Navigation was very accurate, and the scale is constant at 1:50,000. However, a few early missions provided photography at a scale of 1:40,000 and more recently, scales of 1:80,000 to 1:100,000 have been tested. From a resource management viewpoint these standardized aerial photographs provided by the I.G.N. are important but they are less than optimally useful, in that they have been executed on black and white panchromatic film, using a minus blue filter. Such a film record is adequate for standard photogrammetric mapping practices but is less than optimal for some discipline-oriented applications. Resolution on the ground is very high, approximately two to three meters. Very little experimental color or color

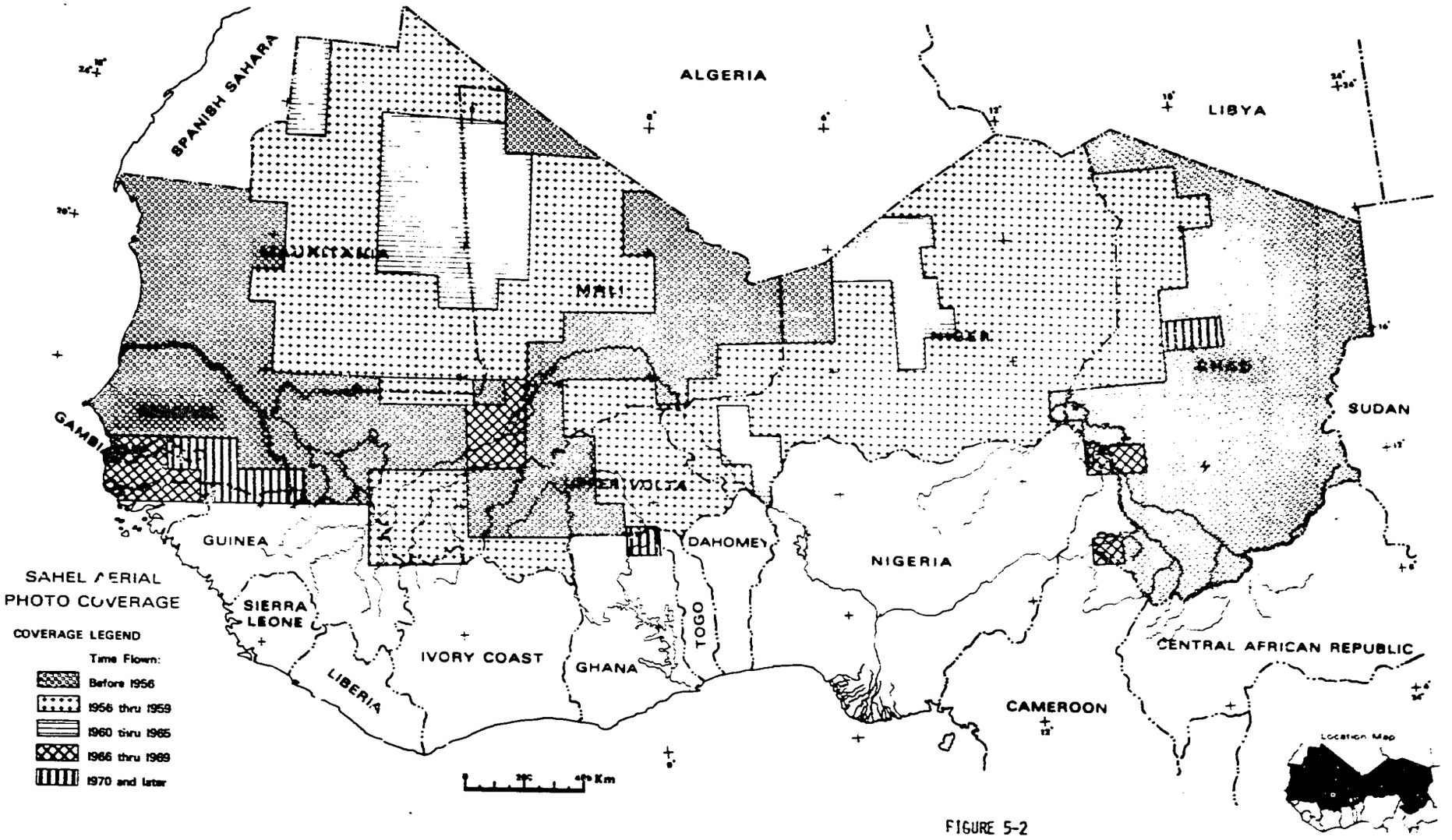
SPANISH SAHARA
ALGERIA
LIBYA
MALI
NIGER
CHAD
SUDAN
GAMBIA
GUINEA
SIERRA LEONE
LIBERIA
IVORY COAST
GHANA
TOGO
DAHOMEY
NIGERIA
CAMEROON
CENTRAL AFRICAN REPUBLIC
SAHEL AERIAL PHOTO COVERAGE
COVERAGE LEGEND
Time Flown:
Before 1956
1956 thru 1959
1960 thru 1965
1966 thru 1969
1970 and later
Km
Location Map

FIGURE 5-2

infrared film has been utilized. Use of black and white infrared material was attempted in a few cases, but it was limited to areas south of the Sahel region.

A very limited number of special projects have been flown. These are related to local sectors where precision altimetric or topical mapping was required for areas such as cities and irrigation projects. Because the number of aerial photographs covering a given area increase substantially as the rate of scale increases, larger scale photographs of those areas would be increasingly difficult to mosaic and very costly to process. Such mosaics seldom offer more visual information than the standard 1:50,000 scale photos unless special instruments are utilized. For this reason they are not cost-effective and their use should be avoided.

The photo crews of I.G.N. have developed and are using accurate standards for determining correct film exposures in the multivariable conditions of Saharan and sub-Saharan Africa. Film processing in the laboratory is excellent, as illustrated by the quality of the prints. Spectral quality is also high which enables enlargements well in excess of most usual analysis requirements. These enlargements would be especially useful for detailed local studies and sub-sampling from ERTS data. There is, however, little possibility of obtaining special types of prints owing to the lack of flexibility in the standard products delivered by I.G.N.

Photo indices of the Sahel coverage are available (at least in theory) from any local I.G.N. sales office established in all of the Sahel countries. Index collections should be available in most of the ministerial departments of those countries, but storage conditions and maintenance of the photo index collections varies greatly. Sometimes storage of index sheets is inadequate due to sheer lack of physical facilities. Frequent changes in personnel who are responsible for index keeping and updating usually leads to partial loss of the complete index collection at any one location. Indices are available in many formats and the most recommended format consists of red overprints showing localized picture centers, flight lines and image numbers on the verso of a special edition of the 1:200,000 base map series. Ordering indices directly from I.G.N. is recommended because most local sales offices do not offer photo index copies for sale.

Prints of aerial photographs are stored in standardized collections of the 1° x 1° square format. Often these photos can be found in technical departments or in the National Topographic Service offices, but climatic conditions, prevailing dust and repeated use have generally degraded a fair percentage of that photo material. Many print sets date back to the late 1950's, and, since they have been poorly stored, it is not unusual to discover that the most important images

are either unusable or have disappeared. Building a coherent image analysis scheme around the systematic use of photo collections available within the Sahel countries is therefore not possible.

Costs for ordering and producing extra prints from the existing aerial photoarchives is reasonable by international standards. I.G.N. charges less than $1.00 per image, but insists on reproducing full sets for each square degree being ordered. Because images were acquired with 60 percent lateral overlap, splitting the set into even and uneven photo numbers allows one to keep archival coverage and to use one-half of the photo coverage in the field. Nevertheless, the very large number of images required, at a scale of 1:50,000 to cover any reasonable area within the Sahel is, by itself, an obstacle to the systematic utilization of this data base. No Sahel country can afford to use its own resources or the cost of maintaining such an archive unless copies are provided as a subcomponent of specific bilateral technical assistance projects. The I.G.N. itself is statutorially obligated to operate overseas on a strict commercial basis, and therefore cannot provide free services to any Sahel country. Delivery time is usually reasonable but takes months for certain photos which may date back to the early 1950's. These must be retrieved from remote storage areas in France before being processed. Production of prints for overseas use must also be scheduled without interfering with the regular I.G.N. production for French official and civilian users.

An alternate and perhaps better source of photographic information for the Sahel exists in the U.S., though it has never been utilized. Its use for classical mapping is technically difficult but it has great value for resource analysis. This source, the trimetrogon photography flown by the United States Air Force during World War II, covers a major portion of the northern Sahara and parts of Sahelian Africa as well. Trimetrogon photography consists of a combination of one vertical photo, generally at a scale of 1:40,000, with a pair of oblique views taken on both sides. Access to the trimetrogon archives of the U.S. Air Force is subject to requests issued by the recipient country. These 1942-44 views may provide exceptionally useful historical records concerning vegetation coverage, drainage patterns and aeolian deposition at that time. They should definitely be utilized as a historical information source in any assistance program for the region.

Satellite imagery was acquired over areas of the Sahel before and after the launch of ERTS-1. High quality enlargements of this material are available directly from the NASA installation in Houston and from the EROS Data Center in Sioux Falls, South Dakota. Gemini, Apollo and Skylab imagery should be utilized as they provide exceptional records of the environment in that area during the 1962-67 and 1973 periods.

We can conclude that adequate historical photographic information does exist for the entire Sahel region. Although this material is not current, it can be used in conjunction with more recent satellite data as part of a multi-stage sampling system.

3.3 MAP COVERAGE OF THE SAHEL

Standardized maps at a scale of 1:200,000 exist for 98 percent of the entire Sahel (Figure 5-3.) Maps of the remaining area are already in production. This exceptionally high percentage of cartographic coverage is due to the well-planned effort of the Photogrammetric Division of the I.G.N. prior to 1960. During the period after 1960 map production was generated under I.G.N. technical direction at various annexes in West Africa. The most important of these was located at Dakar, Senegal. The major production effort occurred during the period from 1953 to 1965. Earlier maps produced between World War I and World War II were at larger scales, but these have little direct information value now, and copies are difficult to obtain. The level of obsolescence of these earlier maps is much higher than the 1:200,000 scale products.

The 1:200,000 series was planned as a base map for the entire Sahel region and has been an acknowledged technical success as a development map. Production is of high quality, usually a three to five color offset process, and has been carried out in accordance with the most exacting international quality standards. Symbols differ from those utilized in similar United States map series, and require careful study by new users. Approximately 25 to 30 percent of the Sahel was mapped in recent years, including half of both Senegal and Niger, and part of central Mauritania. During the 1960's, about 35 percent of the Sahel was mapped. Using accepted international standards, these maps should provide reasonably current information and their revision should not be necessary for at least ten years. The remaining maps of the Sahel, produced during the 1950's, are already becoming obsolete. Their updating should be considered.

In settled areas of the Sahel, either full geodetic triangulation or aerotriangulation has been utilized to assure accurate geometric control in the planimetry of this base map series. In Saharan and sub-Saharan sections a widespread net of Laplace points and standard astronomical determinations of numerous geographic positions provide a ground control network of adequate density. With the exception of a few remote regions, overall map precision of the Sahelian base map series corresponds well to the accepted international standards for that scale. Although based on the special French translation system which is necessary to accommodate the linguistic diversity of the region, place name designations of this series is generally excellent.

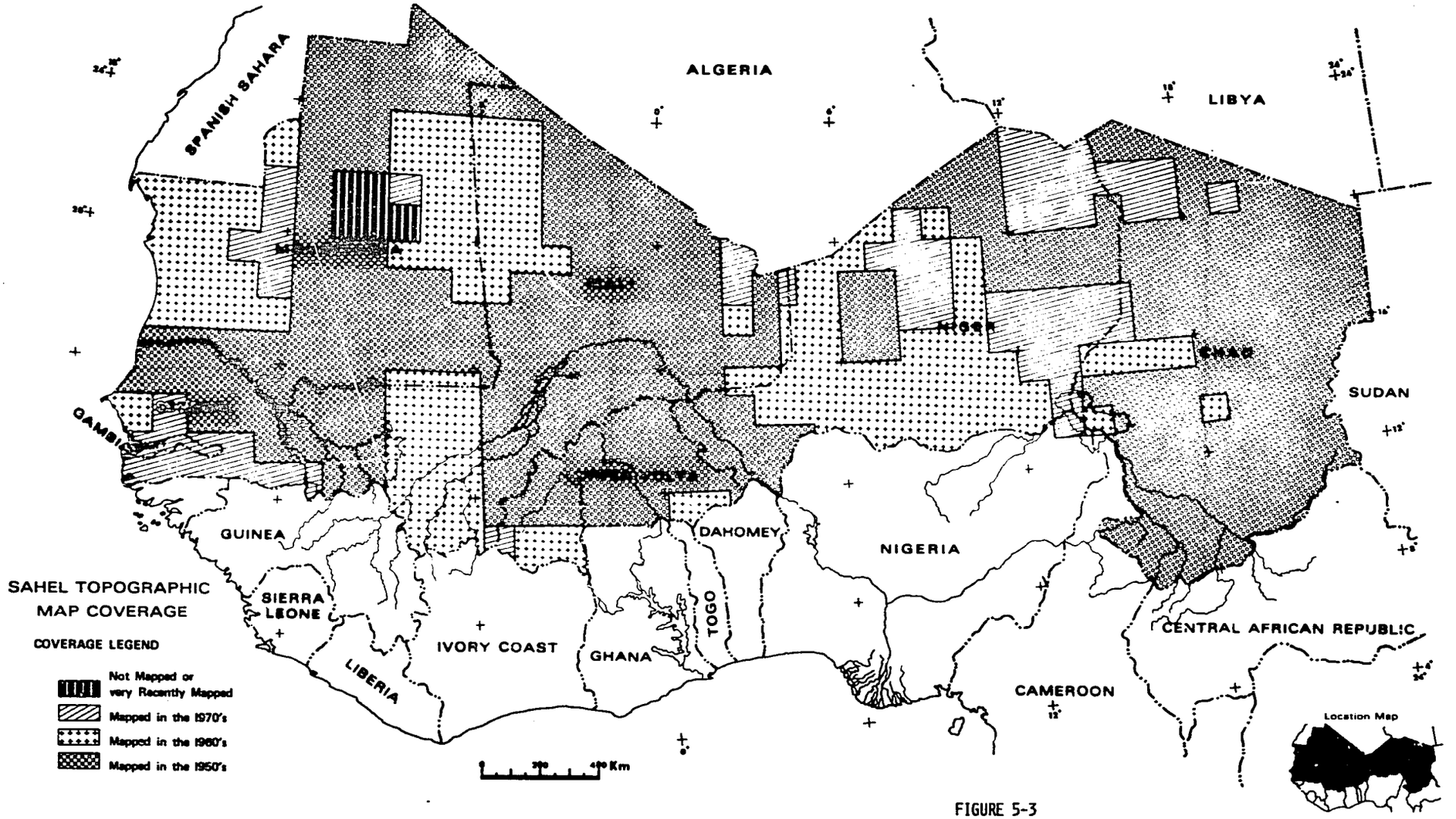
SAHEL TOPOGRAPHIC
MAP COVERAGE
COVERAGE LEGEND
Not Mapped or
very Recently Mapped
Mapped in the 1970's
Mapped in the 1960's
Mapped in the 1950's
SPANISH SAHARA
ALGERIA
LIBYA
SUDAN
GAMBIA
GUINEA
SIERRA
LEONE
LIBERIA
IVORY COAST
GHANA
TOGO
DAHOMEY
NIGERIA
CAMEROON
CENTRAL AFRICAN REPUBLIC
CHAD
NIGER
Km
Location Map

FIGURE 5-3

Inaccuracies may appear in the representation of permanent and transient water bodies, rivers and vegetation cover, but these are acceptable because they are inherent to the limitations of traditional cartographic mapping at the 1:200,000 scale. Users not familiar with the Sahel may be amazed to find how often mapped human settlement patterns are unreliable, but they should remember that the trend of African populations responds quickly to minute ecological changes.

Finally, base maps at 1:200,000 offer only relative representations of altitude. The general presentation of relief fulfills most basic needs in development planning. Precision leveling nets running along the major river, highway and road systems are accurate and sufficient for general studies with regard to hydrology and geology.

Production of special maps at larger scales around the major Sahelian cities or for specific development programs have never been encouraged by the I.G.N. Those needs have been addressed by the national topographic services of the Sahel countries. The few large scale topographic maps prepared by the I.G.N. for specific local needs make no claim to present all the data required for detailed engineering planning. Many of these maps were the experimental products of exploratory large scale photogrammetric methods. Failure to understand these limitations has led to costly misunderstandings and major development problems in such well-publicized cases as the "Office du Niger" project. The lack of appreciation of the limitations of the special base maps contributed to partial failure of that project. Closer scrutiny of the technical parameters accepted in the generation of any map of that type should be required prior to their use in a development program.

Map update activity in the Sahel has not been undertaken nor systematically planned after 1960. In addition, the national governments have not obtained from the colonial power, nor developed their own, technical capacity, personnel resources, or financial resources necessary for the costly map maintenance task. Nor has the I.G.N. been successful in getting those expenses inserted into the bilateral technical assistance budget. As a result, the Sahel map series is progressively becoming more and more obsolete and is losing a fair part of its current utility. Most printing plates or masters from which any update activity should be focused were transferred to I.G.N. installations in France. The limited quantity of printing plates left at the annex in Dakar are either copies or were already obsolete in 1960. No printing plant for polycolor offset maps nor adequate presses seem to be available in the Sahelian region at present. Cartographic and printing personnel trained by the I.G.N. have been redirected to other technical tasks supported by the various national topographic services. Their knowledge and experience is often under-

utilized. Efforts made by UNDP in the second half of the 1960's to develop and support a regional map printing activity in Bamako, Mali remain an isolated attempt. The excellent cartographic camera delivered under that scheme and the personnel trained for its use remain inactive because of a lack of consumables. This camera and camera crew, however, could provide excellent services within the region that could be utilized for enlarging ERTS imagery to high quality standards.

Map directories for the Sahel are easily obtained from the I.G.N. sales offices in the major cities of the region as well as from the I.G.N. offices in France. Indices are frequently updated, but the actual map supply in these offices is usually very limited. Only a few sets are kept in stock, and in most cases, sheets in high demand are no longer available. Stocks of Sahel maps are dwindling at the I.G.N. central store near Paris and sales to the many support agencies interested in the region have made the supply situation worse. Cost for reprint operations for any map sheet is relatively high because large quantities need to be produced at a single time to keep the unit cost acceptable. Furthermore, production schedules for the current metropolitan map production at I.G.N. are rather tight due to an increase in user demand from French user agencies and civilians. Therefore, the supply of existing maps should be considered as a serious problem, because a number of the base map sheets may simply not be available in the near future. A systematic stock-taking activity by the I.G.N. is necessary to ascertain the dimensions of the problem. It should be remembered that a reprint process, even without update, would take a full year to budget, organize and accomplish. In the meantime, organization of an operational archiving system in the U.S. for high resolution projectable color diapositive material should considered. Such a system would cover the more urgent needs of U.S. technical assistance in the Sahel. Technology and special equipment exist at USGS to provide support compatible to that given the 1:250,000 map series of the United States. Should specific sheets of the standard 1:200,000 map series become unavailable, access to the equivalent map material might be obtained from the U.S. Defense Mapping Agency. Declassification problems should be expected to occur, but there is for the moment no other hard copy substitute map readily available for this region.

Unit cost of the 1:200,000 map sheets of the Sahel region produced by I.G.N. is slightly higher than the price of the standard 1:250,000 U.S. map sheet. The price is $4.00 per sheet, and includes handling, tax and airmail postage. Delivery is rapid if the order is specific and utilizes the I.G.N. rush reference system. Considering the importance of the Sahel program to various international agencies, easy access to at least one set of the 1:200,000 maps for the whole

region should be arranged as part of the initial planning for further assistance efforts. Copyright arrangements could be discussed with local governments and eventually with the I.G.N., taking into consideration the potential supply problems that have been discussed.

In conclusion, adequate map coverage for general development planning does exist for the entire Sahelian region. Access to these maps is easy, but supplies are dangerously limited. At the present time no reprinting action is being considered. Costs for the product are reasonable considering the relatively high information content of the maps. Production limitations are those inherent to all classical line map products. Best use could be made of these map products in correlation with ERTS images that have been enlarged to the same scale.

4.0 PROBLEMS AND LIMITATIONS

Selection of appropriate mapping techniques for the Sahelian area will have to depend on the following: First, one will have to consider the combined disciplinary and operational needs for mapping products. Second, a decision will have to be made as to whether the requirements are long term or short term. Third, budgetary considerations will have to play a prime role in selecting various mapping options. In view of these considerations and the great variety of possible mapping and imagery techniques, it is obvious that recommendations for optimum cartographic techniques to be employed in the Sahel cannot be made at this early stage.

As was stated in the introduction, thorough management of the gathering and dissemination of information is essential for any kind of resource management. Base maps serve the purpose of tying remotely sensed information to physical points on the ground, and vice versa.

An obvious beginning toward such a modern information management system for the Sahel region could be accomplished by the establishment of an image-overlay-base map data bank. Anyone interested in a certain physical location in the Sahel area could then enter the coordinates of a given point into a computerized system and would be provided with the list of all maps, overlays, etc., that would cover the desired position. That facility would complement the effort presently underway at Niamey by UNESCO with regard to other types of information available over the Niger Basin.

A secondary extension of such a data bank would be to develop a system that would facilitate the creation of multidisciplinary combinations of overlays and images through some of the image transformation processes described earlier.

The updating of base maps produced during the 1950's should also be considered, perhaps by using simple manual labor intensive methods that could take advantage of the availability of ERTS imagery enlargements as a data source. Should updating be delayed until the late 1970's, a major revision would be required.

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CHAPTER 6

GEOLOGY AND MINERAL PROSPECTING

ROLES OF REMOTE SENSING

The general geologic map of Africa indicates for the sub-Sahara or Sahelian region a diversity of geologic environments encompassing a range from very old basement rock formations to the most recent unconsolidated sediments. It is significant that the range and variety of geologic settings do not rule out the possible occurrence of several types of mineral deposits. Indeed, the results of the rather limited exploration and exploitation to date provide some basis for anticipating further discoveries.

Significant acceleration of mineral resource inventory and development are of major importance especially in arid regions, like the Sahel, where the agricultural potential is limited. In such regions, the earliest discovery and delineation of an economically exploitable mineral deposit may be a critical step toward the initiation of revenue-generating productive activity so crucially needed for economic viability.

In view of the relative difficulty of surface access to much of the Sahelian arid region, and the paucity of resource development funds in most of the countries involved, several clear-cut roles for remote sensing in the mineral resource sector exist:

1. To facilitate the rapid and economical discrimination, on a regional basis, of terrain geologically most favorable to certain types of mineral resources, and, correspondingly, the deferring of less favorable terrain to save time and cost in the exploration phases.

Various types of mineral deposits are commonly found in particular types of geologic environments. The latter are relatively distinctive geologic settings which can be characterized in terms of type of host rocks, their age and tectonic history, their lithologic and compositional character, their structural attitude, their relevant physical and chemical properties (e.g., porosity, solubility), and their proximity in space and time to certain genetically related features or processes. One does not seek petroleum, for example, in the gneisses and schists of the ancient shield platforms; nor does one prospect for diamonds in limestone or dolomite formations.

This predictable relationship between mineral deposit types and geologic settings makes it possible and profitable for early discrimination of geologic environments conducive to mineral resource exploration. The first steps in the fulfillment of this role of remote sensing

are the preparation of regional geologic and tectonic maps, or the correction and extension of existing preliminary or reconnaissance maps.

2. To facilitate the discovery and delineation, on a localized basis, of geologic settings (tectonic, structural, lithologic) favorable to the occurrence of individual mineral deposits of potential economic value.

In principle, each distinct type of mineral deposit can be characterized to a greater or lesser extent, in terms of its regional and local geologic setting and certain physical and chemical properties. Iron deposits, for example, generally have a magnetic susceptibility measurably higher than that of the surrounding host rocks, which thus provides a basis for detection and discrimination. Stratified copper sulfide deposits are measurably higher in electrical conductivity than are their host rocks. Certain types of copper-nickel deposits exhibit anomalously high electrical conductivity in combination with relatively high magnetic susceptibility, and both are detectable by airborne sensors. The thermal emittance of geothermal energy sources is anomalously high, and detectable by appropriate thermal infrared radiation sensors carried by aircraft or by satellite. Radioactive ores emit detectable gamma rays. Beryllium-bearing pegmatites in some regions are distinguishable by their high albedo. The domes, folds, and fault structures favorable to the accumulation of petroleum are very commonly discernible and distinguishable in aerial photographs, in satellite imagery, and in radar imagery. Elsewhere, geo-botanical anomalies attributable to the peculiar chemical make-up of certain types of mineralization are detectable by airborne and by satellite-borne multispectral scanners. These examples illustrate the point: the local geologic settings and distinctive properties of many types of deposits are distinguishable by remote sensing. A summary of the applicability of various active and passive remote sensing techniques to both regional and more localized exploration, and to geologic mapping, is provided in Table 6-1. The application of rationally selected combinations of remote sensing techniques could well accelerate the discovery of mineral deposits of significant size and grade.

3. To provide cartographic and terrain data and analysis for the planning and development of infrastructure elements essential to the economic exploitation of mineral deposits.

It is elementary that, with few exceptions, a large tonnage and a high grade (high unit value) are necessary but not sufficient attributes of an economically exploitable mineral deposit. Especially in more remote locations, careful and timely consideration must be given to access roads, water for processing the raw product, generating sites and transmission lines for power,

railway or pipeline or conveyor system for transporting the product, harbors and channels for ships, and other essential support elements. The feasibility of providing these may determine whether a mineral deposit, no matter how large or rich, is profitably workable or not. The cartographic products and terrain analysis which can be generated by the sophisticated processing and interpretation of remotely sensed imagery and data can be of great help in the planning of infrastructure projects relevant to mineral resource development, in justifying the funding proposals, in accelerating the implementation of such projects, and in minimizing costly mistakes. An example of such application is the interpretation of satellite and aerial photography for terrain analysis of the high voltage power line from the great hydroelectric site on the Congo to the copper mining district of Shaba (Katanga). Another is the proposed use of SLAR (radar) imagery for optimum alignment of a railroad from the immense Serra dos Carajas iron deposit in the Amazon region through the equatorial rain forest and across rivers to the coast, and the selection of an optimum deep water harbor for ore-loading.

In summary, then, remote sensing techniques can serve at least three roles critical to and supportive of programs for the rapid inventorying of the mineral potential of arid and semi-arid regions and the acceleration of programs for the early, orderly, and economical exploitation of resources which are discovered. In the application of these techniques the judicious selection of particular sensor systems and their carefully optimized use, in recognition of their different capabilities, are of great importance. The following section of this chapter addresses the uses of various relevant techniques.

REMOTE SENSING SYSTEMS AND THEIR USE

Over the past twenty years the types of remote sensing surveys available to the geologist have increased enormously. The manufacturers of equipment and survey contractors increasingly are making many claims for the superiority of their particular kinds of survey data. It has thus become necessary to develop specialists in geologic remote sensing capable not only of interpreting the specialized data, but of selecting from among the many available systems those most appropriate to the objectives and to the geologic and geographic context.

For any but the most general interpretation, the design of a remote sensing research program for a particular kind of resource involves the selection and specification of a sequence of remote sensing methods. Each method is more specifically directed toward the target sought than the one preceding it but each one costs more per unit area than the one before so that it must be applied in a more restricted, more favorable area.

TABLE 6-1

REMOTE SENSING TECHNIQUES APPLICABLE TO GEOLOGIC MAPPING AND MINERAL EXPLORATION

TECHNIQUES	MEASUREMENT MADE	SCALES	Costs ($per KM^2) Data Acquisition	Interpretation
I. SATELLITE SYSTEMS				
A - ERTS-A	AMBIENT REFLECTANCE IN 4 SPECTRAL BANDS, 2 VISIBLE LIGHT AND 2 PHOTOGRAPHIC INFRARED	1:1,000,000 to 1:200,000	0.0008	0.09 0.50
B - METEOROLOGICAL SATELLITES	AMBIENT REFLECTANCE AND EMISSION IN THE THERMAL INFRARED PORTION OF THE SPECTRUM	1:5,000,000 to 1:200,000	0.0005 0.06	0.10 0.60
II. AIRCRAFT SYSTEMS				
A. IMAGE SYSTEMS 1. SIDE-LOOKING AIRBORNE RADAR (SLAR)	ACTIVE REFLECTANCE IN THE MICROWAVE PORTION OF THE SPECTRUM	1:1,000,000 to 1:50,000	2.00	0.10 to 2.00
2. PHOTOGRAPHY	PASSIVE REFLECTANCE IN RELATIVELY WIDE BANDS IN THE VISIBLE AND NEAR INFRARED, DISPLAYED IN COLOR OR BLACK-AND-WHITE	1:100,000 to 1:5,000	0.06 24.00	1.25 250.00
3. VIDEO(RBV & WISP)	PASSIVE REFLECTANCE IN RELATIVELY WIDE BANDS IN THE VISIBLE AND NEAR INFRARED DISPLAYED IN COLOR OR BLACK-AND-WHITE, OR EMITTANCE	1:100,000 to 1:10,000	0.05 20.00	1.00 100.00
4. SCANNERS	REFLECTANCE IN ENERGY BANDS FROM ULTRA-VIOLET THROUGH THE THERMAL INFRARED	1:100,000 1:10,000	4.00 10.00	0.50 100.00
B. NON-IMAGING SYSTEMS 1. AEROMAGNETIC	THE INDUCED NON-VARYING MAGNETIC FIELD	1:250,000 to 1:25,000	0.90 20.00	0.50 8.00
2. AEROELECTRO-MAGNETIC ACTIVE SYSTEMS	INDUCED SECONDARY ELECTRO-MAGNETIC FIELDS IN THE FREQUENCY RANGE FROM 50 Hz to 10,000 Hz	1:25,000 to 1:10,000	48.00 100.00	9.00
3. AEROELECTRO-MAGNETIC PASSIVE SYSTEMS a. VLF SYSTEMS	PERTURBATIONS IN THE ELECTRO-MAGNETIC FIELDS GENERATED BY THE NAVAL VLF (VERY LOW FREQUENCY NAVIGATION TRANSMITTERS 10KHz to 40KHz	1:50,000 to 1:25,000	20.00	4.00
b. AFMAG (AUDIO FREQUENCY NATURAL ELECTROMAGNETIC FIELDS)	PERTURBATIONS IN THE NATURAL (AMBIENT) EM FIELD VECTOR AT 90Hz TO 500Hz (NARROW BAND)	1:50,000 to 1:25,000	20.00	4.00
4. GAMMA RAY TOTAL COUNT OF SPECTROMETRY	RADIOACTIVE DECAY (PASSIVE RADIO-ACTIVE GAMMA RAY EMISSION OF THE GROUND BENEATH THE AIRCRAFT)	1:50,000 to 1:25,000	10.00 25.00	1.00 5.00
5. VAPOR DETECTION SYSTEM a. MERCURY	MERCURY VAPOR IN AIR	1:25,000	30.00	2.00
b. SO_2 GAS BY SPECTRAL CORRELATION	SO_2 GAS IN AIR	1:25,000	30.00	2.00
c. ORGANOMETALLIC VAPORS BY SPECTRAL CORRELATION	METALS OR ORGANOMETALLIC VAPORS GIVEN OFF BY VEGETATION UNDER THE SUN'S HEATING	1:25,000	50.00	5.00

TABLE 6-1 (Cont'd)

GEOLOGIC PARAMETER IDENTIFIED	COMMENT
REGIONAL STRUCTURE - TECTONIC UNIT BOUNDARIES, SECONDARY BASINS SEPARATE FOLIATED FROM PASSIVE ROCKS IN THE PRECAMBRAIN SEQUENCE, MAP AND INTERPRET FOLDS AND FAULTS AND GROSS ROCK TYPES FAULT ZONES WITH ABUNDANT GROUND WATER- HOT SPRINGS, THERMAL ANOMALIES	THE DIRECT SEARCH FOR NEW (UNMAPPED) SEDIMENTARY BASINS HAS GREAT DIRECT SIGNIFICANCE IN PETROLEUM EXPLORATION. RECOGNITION OF GROUND WATER TARGETS AND GEOTHERMAL POTENTIAL ARE IMPORTANT - IN CONJUNCTION WITH ERTS MAY RECOGNIZE POTENTIAL DIAMOND PIPE SETTINGS.
FAULTS, TECTONIC UNITS, GROSS ROCK TYPES; ESPECIALLY GOOD IN TERRAIN OF LOW RELIEF SUCH AS THE SAHEL	THIS IS THE TECHNIQUE OF CHOICE FOR MANY INTERPRETERS IN PRECAMBRAIN SHIELD AREAS
RECOGNITION OF MINERALIZED DISTRICTS AND MINERALIZATION CONTROLS RECOGNITION OF MINERALIZATION AND INDIVIDUAL OUTCROPPING VEINS	COMPARED TO THE ABOVE METHODS, A VERY LARGE NUMBER OF INDIVIDUAL PHOTO FRAMES MUST BE HANDLED FOR REGIONAL INTERPRETATION.
AS FOR PHOTOGRAPHY ABOVE, BUT THE CAMERA CAN BE HAND-HELD IN THE AIRCRAFT BY THE INTERPRETER	THE COMPLETE VIDICON SYSTEM HAS SOME ADVANTAGES OVER PHOTOGRAPHY FOR AIRCHECK FOLLOW-UP OF OTHER SENSORS' INTERPRETATION.
MAJOR ROCK TYPE (% SiO_2) IDENTIFICATION, GEOTHERMAL PROSPECTING, HYDROPROSPECTING	THERMAL AND WATER PROSPECTING ARE OPERATIONAL AND ROUTINE, ROCK IDENTIFICATIONS ARE STILL EXPERIMENTAL AND OF LOW DISCRIMINATION.
THE INDUCED FIELD MAY BE RELATED TO PERCENT MAGNETITE IN THE IN THE ROCKS BENEATH THE AIRCRAFT AND TO THE DEPTH TO THE MAGNETITE. THIS IS THE ONLY RECONNAISSANCE SYSTEM WHICH GIVEN RELIABLE ROCK TYPE INFORMATION IN THE COMPOSITION RANGE OF INTEREST IN MINERAL EXPLORATION	AEROMAGNETIC DATA MAY BE USED TO DETERMINE: 1) THE DEPTH OF A SEDIMENTARY BASIN (E.G. IS THERE ROOM FOR OIL?); 2) IGNEOUS ROCK TYPE IN OUTCROP OR NEAR OUTCROP; 3) FOR DIRECT IRON ORE EXPLORATION
THE SECONDARY FIELDS ARE DUE TO CONDUCTIVITY IN THE ROCK AND THE SYSTEMS AVAILABLE ARE DESIGNED TO DETECT SMALL PLANAR HIGH CONDUCTIVITY MASSIVE SULFIDE ORE BODIES (TO A DEPTH OF BURIAL OF UP TO 400 FEET IN THE MORE EXPENSIVE SYSTEMS.)	THE SYSTEMS ARE GENERALLY USED IN PRECAMBRAIN SHIELD AREAS FOR THE DETECTION OF COPPER AND ZINC ORES OF THE VOLCANOGENIC MASSIVE SULFIDE TYPE.
PERTURBATIONS ARE DUE TO CONDUCTIVITY VARIATIONS IN THE ROCKS BUT THE SYSTEMS HAVE DIFFICULTY IN SEPARATING CONDUCTIVITY DUE TO WATER IN A FAULT ZONE FROM CONDUCTIVITY DUE TO MASSIVE SULFIDES (I.E., A GOOD FAULT DETECTOR).	THE COST OF ADDING VLF RECEIVER TO A RECONNAISSANCE AEROMAGNETIC SURVEY IS SMALL AND IT BECOMES A GOOD REGIONAL MAPPING TOOL FOR FAULTS. (+\$0.25/km^2 DATA + \$0.10 INTERPRETATION.
AS FOR VLF SYSTEMS ABOVE BUT HAS GREATER DEPTH OF EXPLORATION (PERHAPS DOWN TO 600 OR 700 FEET).	THE COST OF ADDING A VLF RECEIVER TO A RECONNAISSANCE AEROMAGNETIC SURVEY IS VERY SMALL AND IT BECOMES A GOOD REGIONAL MAPPING TOOL FOR FAULTS. (+\$0.25/km^2 DATA + \$0.10 INTERPRETATION).
DIRECT DETECTION OF OUTCROPPING ORES OF URANIUM, THORIUM, OR CARBONATITIES. INDIRECT MAPPING OF SOME IGNEOUS ROCK TYPES AT HIGHEST EXPENSE INDICATES.	GOOD DIRECT EXPLORATION TOOL IN ARID AND SEMI-ARID TERRAIN.
DIRECT DETECTION OF MERCURY ORES; INDIRECT DETECTION OF OTHER SULFIDE ORES BY MERCURY HALO PATHFINDER. INDIRECT DETECTION OF SULFIED ORES BY DETECTION OF SO_2 OXIDATION PRODUCT OF THOSE ORES. INDIRECT DETECTION OF METALLIC ORES BY MEASUREMENT OF THE ANOMALOUS CONCENTRATIONS OF ORGANOMETALLIC VAPORS IN THE AIR OVER VEGETATION WHICH HAS ANOMALOUS CONCENTRATION BECAUSE IT IS GROWING ON ORES OF THE METALS.	DIFFICULT TO USE IN AREAS WITH MUCH WIND. DIFFICULT TO USE IN AREAS WITH MUCH WIND. AS FOR MERCURY ABOVE BUT STILL EXPERIEMENTAL - BACKGROUND VARIATIONS HAVE NOT BEEN REPORTED.

As a very simple example, consider exploration for sedimentary iron formation as iron ore. Sedimentary iron formation, in general, contains abundant magnetite, the most magnetic mineral. An aeromagnetometer can directly detect magnetite but, depending upon how it is used, one may incur costs up to $28 per square kilometer to obtain and interpret the aeromagnetic data. To fly all of Upper Volta's approximately 272,000 square kilometers would cost more than $7.5 million but it would undoubtedly find most of Upper Volta's sedimentary iron formation. However, we know a good deal more about sedimentary iron formation than that it is in part magnetic. We know that it occurs as a metamorphosed sedimentary rock in Precambrian terrain and that therefore it has relatively long magnetic strike length. Suppose, therefore, we use ERTS imagery to locate the Precambrian metasedimentary rocks at a cost of $60,000 (1:250,000 scale interpretation for foliated and massive rocks only). According to the general geologic map of Africa, about 90 percent of Upper Volta is Precambrian and generally more than half of the outcrop area of Precambrian terrain are granites and gneisses (Douglas, 1970) of no present economic interest. These are generally readily separable on ERTS imagery. Assume therefore, on this basis, that we could eliminate half of the country as uninteresting for iron ore exploration. We could then fly the other half with a reconnaissance aeromagnetic survey, widely spaced lines at right angles to the strike of primary foliation, at a cost of $1.40 per square kilometer just to detect, not map, sedimentary iron formation. The cost of this aeromagnetic survey would be $190,000. This would highlight perhaps 10 percent of the area (10% of 136,000 square kilometers) as most prospective for sedimentary iron formation, and this selectively reduced area could then be mapped in detail by aeromagnetics at a cost of $28 per square kilometer, or $380,000 total. The total cost of this designed remote sensing program is $630,000 or less than one-tenth of the cost of proceeding directly to airborne magnetometry for use over the entire area.

The preceding discussion of sedimentary iron formation exploration indicates among other things the need for and value of good geologic models to guide the choice of exploration tools. A geologic model is a geological-geophysical concept of a particular type of mineral deposit, characterized (quantitatively where possible) in terms of its genetic history, its structural and lithologic setting, its composition mineralogically and chemically, its size, its distinctive physical and chemical properties, and the lower limit of grade or unit value of interest. The model may rule out certain types of sensor systems and survey designs at the outset; or it may suggest that some other combination of remote sensors and survey design would permit rapid and economical discrimination of the targets of interest. Figures 6-1 and 6-2 illustrate the

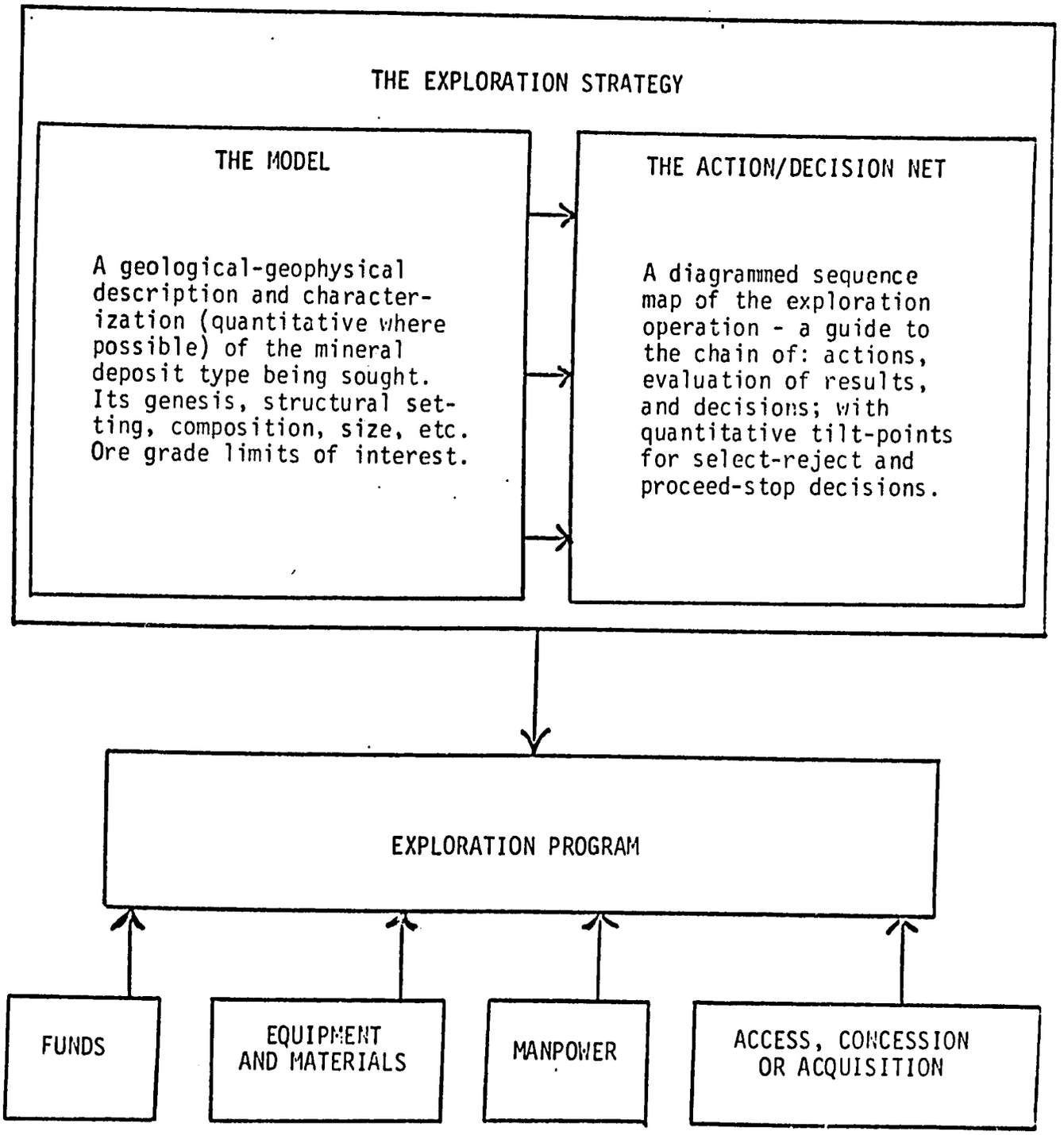


Figure 6.1 Relationship of Geologic Model to Exploration Strategy

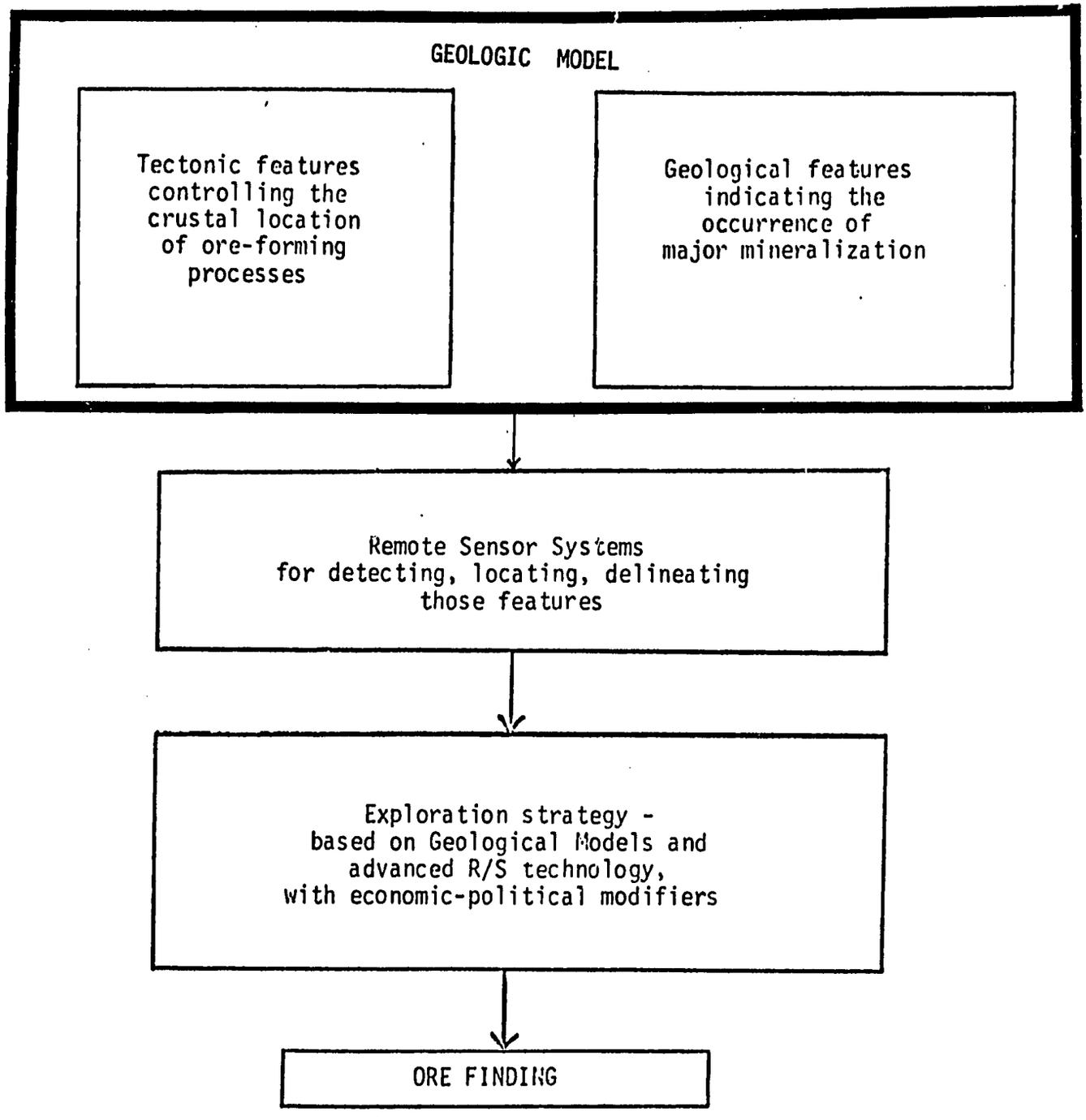


Figure 6.2 Geologic Model, Remote Sensing Systems, and Exploration Strategy

relationship of the geologic model and the sensor system to the design of mineral exploration strategy applicable to regions such as the Sahel.

Table 6-2 is a summary of the more important mineral targets of the Sahel region by geologic environment, with comments on the remote sensing tools that might best lead to discovery of each type of target. This table is based upon the International Geologic and Tectonic Maps of Africa at 1:5,000,000 scale and the Bulletin of the American Association of Petroleum Geologists, October 1973, the annual AAPG Bulletin which summarizes all 1972 petroleum exploration and development outside of the U. S. and Canada.

The most powerful and cost-effective reconnaissance scale (1:250,000) which provides an exploration framework and encourages exploration of any region is the combination of regional imagery (ERTS or SLAR at 1:250,000) and reconnaissance-type aeromagnetic surveys (Figure 6-3). The aero-magnetic surveys should be specified differently for the Precambrian basement and the younger sedimentary rocks. The specification details would depend upon the image interpretation but, ideally, reliable guides to exploration could be provided at a scale of 1:250,000 for less than $2.00 per square kilometer for the entire Sahel region (ERTS at 1:250,000 and reconnaissance aeromagnetics interpreted together). Morley's (1969) statement concerning mineral exploration strategies in Canada are pertinent here:

> "Current practices by many budget control agencies require that a low cost/benefit ratio be forecast for a program before approval for it is given. Geological and geophysical mapping seems to be an activity that, up to the present, defies such analysis. It is difficult enough to estimate in retrospect; to project into the future seems to be a well-nigh impossible task.
>
> "Government geological survey organization get caught in a squeeze. On the one hand, they are forbidden to undertake projects which could be expected to have a good short-term and more easily predicted 'pay-off', because this would be to close to prospecting and therefore should be left to private industry. On the other hand, the long-term programs, which are of immense importance to the future economic well-being of a nation such as sound, systematic topographical, geological and geophysical mapping are most difficult to prove a direct benefit for. If one manages to find an example in which a dollar benefit was derived from a certain project, by definition, that project must be classified as 'prospecting'. On the other hand, if the relationship between the benefit and the project is rather vague and indirect, as it mostly is for mapping, the argument for a low cost/benefit ratio is not convincing. One university geological department (probably with tongue-in-cheek) calculated the value of all the mines, the discovery of which its graduates were associated with. The total came to $40 billion -- a cost/benefit ratio of 1 to 4,000 over a 20-year period. The validity of this statistic is questioned.
>
> "For geological and geophysical mapping, one pragmatic method of judging the effectiveness might be to determine the total amount spent by private companies prospecting in the area since the time of the mapping. The ratio of government to

FIGURE 6-3: CHAD SUDAN BORDER, SAHARA TO SAHEL

PHYSICAL FEATURES

A. ERDI PLATEAU

B. LIBYAN DESERT

C. SAND STREAMERS AND DOMINANT WIND DIRECTION

D. DEPRESSION DE MOUREDI

E. ENNEDI MASSIF

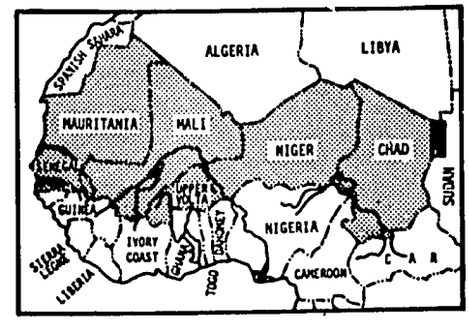


Figure 6-3: Chad-Sudan Border, Sahara to Sahel

Figure 6-3 is a split mosaic at a scale of 1:830,000 made from four ERTZ-1 frames that were imaged in a single orbit. These images of MSS band 7 were acquired on the morning of November 14, 1972. The northernmost two frames are on the left, and the southern two are printed on the right-hand page. As can be seen by referring to the longitude and latitude ticks on the edge of the imagery, or by looking closely at the location map, this series provides a view of the eastern edge of the Chad depression that extends southward along the Chad-Sudan border on the east flank of the Ennedi Massif from 19° North, 23° 30' East to 13° 30' North, 21° East.

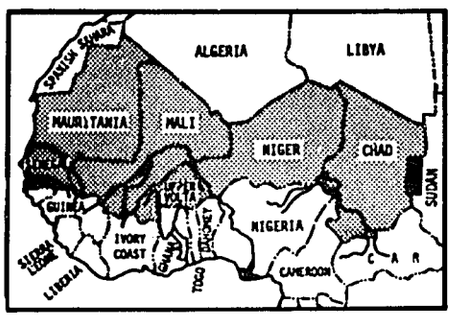
These four ERTS images cover a strip of land approximately 180 kilometers wide stretching from the desert environment of the Sahara into the more highly vegetated Sahel region of Chad. Sand streamers and elongated dunes (white to light grey), lying parallel to the direction of the wind, are indicative of the desert environment. The dark grey areas in the northern frame are outcrops of rock on the southern edge of the Erdi Plateau. From the middle of the second frame a thin veneer of Devonian sedimentary rocks overlies Precambian greenstones of the Ennedi which are characterized by complex folding and fracturing.

In the southern two frames, east-northeast trending greenstones give way to more highly metamorphosed and granitized Precambian rocks. In this area there are several local patches of flat lying sedimentary rocks overlying the Precambian rocks. The loop of Wadi Howa in the east central part of the third frame marks a broad structural warp.

The overall darker tone of the southern two frames indicate the presence of more vegetation and thicker soils. Most of the larger streams in this area are marked by heavier vegetation along their banks (galeria forest) and consequently stand out as dark anastromosing features. There are some sand streamers and isolated active sand dunes in this region (lighter tones), but many of these sand features in this area are stabilized by vegetation and represent earlier aeolian episodes during Pleistocene and Early Recent periods. The active as well as inactive dunes are aligned principally in a NE-SW direction paralleling the NE trades (Harmattan).

A color-combined image of the southern two frames would show striking variations in tones arising from the differences in rock types, plant communities, and dissection patterns.

FIGURE 6-3: CHAD SUDAN BORDER, SAHARA TO SAHEL



PHYSICAL FEATURES

A. WADI HOWA

B. STREAM WITH GALERIA FOREST

C. LONGITUDINAL DUNES (NOTE SHIFT IN WIND DIRECTION TO THE SOUTH)

D. SAND DEPOSITED IN WATER ERODED FEATURES AT THE ESCARPMENT THAT FORMS THE EASTERN EDGE OF THE CHAD DEPRESSION

private company spending could then be taken as a cost/effectiveness figure. The assumption is that the company would not have gone into the area if basic mapping had not been provided. This is not always a valid assumption but it is perhaps more valid than assuming that all the discoveries in the area were as of a consequence of the basic topographical, geological and geophysical mapping, as many cost/benefit studies on the subject do.

"Such a study has not been done for the Canadian aeromagnetic program, but it has been observed, over the years, that prospecting activity invariably increased considerably whenever aeromagnetic maps were published for an area. If a government is seeking a low cost/benefit ratio only, the best thing to do would be to spend nothing. Any discovery made would therefore yield a ratio of zero.

"The Geological Survey of Canada, in combination with the provinces, has already spent 12M dollars on airborne magnetometer surveys and published over 5,000 maps. The complete cost of this program has been more than paid for by the government revenue derived from a single mine discovered, as a direct consequence of an aeromagnetic survey, in the second year of the program in 1949. This was the iron mine at Marmora, Ontario. How many mines were discovered indirectly by these maps would be very difficult to find out since every mining company uses them along with government geological maps. How the companies use them and what exploration tactics are employed are closely-guarded company secrets.

"In the final analysis, one of the best ways to judge the worth of a product, such as a map, is to see how often and for how many years it is used and referred to. Many of the 5,000 aeromagnetic maps of Canada have been reprinted a second time after an initial printing of over 1,000 20 years ago. It is fully expected that these same maps will find use 30 years from now."

Discussions of geologic mapping and mineral exploration applications of remote sensing in the Sahel must focus also on the exploration for specific economic targets as outlined in Table 6-2. It should be noted that, for regions as difficult of access at present as most of the Sahel, there are relatively few mineral commodities of high enough unit value, and which on the average occur in large enough deposits to justify exploration of the basis of rational economic considerations alone. For example, economic exploitation of an iron deposit requires major transportation systems, but because of its low unit value, there is an economic limit on how far any iron ore may be shipped on any given transportation system. Direct shipping Bessemer iron ores (high grade) are worth only about $12.30 per ton in the ground. Table 6-3 gives some very simple economic models to illustrate this.

The metals for which one can afford to explore on this basis and which may reasonably be supposed to exist in the Sahel in deposits of economic size are:

1. <u>Copper</u> in

    a. Proterozoic stratiform deposits of the Zambian-Zaire copper belt model

    b. Archean volcanogenic massive sulfides of the Abitibi greenstone belt model associated with zinc and silver

    c. Association with nickel in mafic and ultra-mafic intrusive rocks as at Sudbury, Ontario

TABLE 6-2 GEOLOGIC ENVIRONMENTS
OF POSSIBLE ECONOMIC SIGNIFICANCE IN THE SAHEL REGION

GEOLOGIC ENVIRONMENT	POSSIBLE ECONOMIC TARGETS	COMMENTS ON REMOTE SENSING AND EXPLORATION
I. RECENT ALLUVIAL DEPOSITS	PLACER GOLD, TIN, DIAMONDS, RUTILE	IMAGERY AT 1:250,000 SCALE AND 25 TO 75 METER RESOLUTION HELPFUL FOR GEOMORPHOLOGICAL CORRELATION OF FLUVIATILE, LACUSTRINE, DELTAIC, AND BEACH ALLUVIUM, TERRACES, ETC.
II. YOUNG SEDIMENTARY BASINS (MESOZOIC TO RECENT)		
A. CONTINENTAL MARGINS AND DELTAIC DEPOSITS (SENEGAL)	HYDROCARBONS (OIL AND GAS) SALINES	RECONNAISSANCE REMOTE SENSING METHODS (1:250,000) CAN PROVIDE BASIN OUTLINE AND INTERNAL STRUCTURAL CONTROL (ERTS, SLAR, AEROMAGNETICS) AND DEPTH AND BOTTOM SHAPE (AEROMAGNETICS). GEOTHERMAL RESOURCES ARE BEST DETECTED BY THERMAL INFRARED SURVEYS OF STRUCTURALLY FAVORABLE AREAS (ERTS, SLAR). URANIUM DEPOSITS CAN BE DETECTED OR AT LEAST INDICATED DIRECTLY (GAMMA RAY SPECTROMETRY) BY SURVEYS AROUND PROSPECTIVE BASIN EDGES AS DETERMINED BY REMOTE SENSING SURVEYS (ERTS, SLAR).
B. GRABENS, RIFT ZONES (LAC TCHAD, FOSSE DE LA BENOUE)	HYDROCARBONS (OIL AND GAS) SALINES GEOTHERMAL	
C. SHALLOW CLASTIC SEQUENCES RESTING DIRECTLY ON PRECAMBRIAN (NIGER BASIN)	HYDROCARBONS (OIL AND GAS) URANIUM	
III. OLDER (PRECAMBRIAN) PLATFORM COVER (PROTEROZOIC TO LATE PALEOZOIC)		
A. LIMESTONES	MISSISSIPPI VALLEY TYPE LEAD-ZINC DEPOSITS	RECONNAISSANCE REMOTE SENSING METHODS (1:250,000 SLAR, ERTS, AND AEROMAGNETICS) AGAIN CAN PROVIDE FUNDAMENTAL BASIN STRUCTURAL CONTROL. THE LEAD-ZINC DEPOSITS IN THIS ENVIRONMENT HAVE SEVERAL REMOTE SENSING SIGNATURES (ERTS, ELECTROMAGNETIC AND MERCURY HALO) OF USE IN EXPLORATION. URANIUM EXPLORATION WOULD BENEFIT FROM BASIN STUDIES AS ABOVE AS WELL AS RADIOACTIVE (GAMMA RAY SPECTROMETRY) SURVEYS OF BASIN EDGES.
B. SHALES	HYDROCARBONS (COAL, ETC.)	
C. CLASTIC	URANIUM	
IV. PRECAMBRIAN ROCKS		
A. INFOLDED, DOMINANTLY SEDIMENTARY ROCKS	IRON DEPOSITS (SEDIMENTARY IRON FORMATION) MANGANESE DEPOSITS (SEDIMENTARY IRON FORMATION) URANIUM COPPER DEPOSITS (COPPER BELT TYPE ORES)	WITHIN PRECAMBRIAN SHIELD TERRAIN 95% OR MORE OF THE VALUE OF ORES PRODUCED COMES FROM THE INFOLDED SEDIMENTARY AND VOLCANIC ROCKS--THE MASSIVE GNEISSIC-GRANITIC TERRAINS WHICH MAKE UP OVER 50% OF ARCHEAN ROCKS PRODUCE LESS THAN 5% OF THE VALUE OF THE PRECAMBRIAN ORES. THUS THE COMBINATION OF REMOTE SENSING SURVEYS (SLAR OR ERTS AND LOW-FLOWN RECONNAISSANCE AEROMAGNETICS) WHICH DEFINES THE LOCATION AND GENERAL COMPOSITION OF THE INFOLDED ROCKS IS A MOST POWERFUL EXPLORATION GUIDE. AEROMAGNETICS IS A DIRECT SEARCH TOOL FOR MAGNETIC IRON FORMATION AND ALSO HELPS DEFINE INTRUSIVE ENVIRONMENTS WITHIN THE VOLCANIC BELTS. MASSIVE SULFIDE ORES MAY BE DETECTED DIRECTLY BY ANY OF THE ELECTROMAGNETIC METHODS LISTED, BUT SOME METHODS HAVE BETTER DISCRIMINATION ON SPURIOUS ANOMALIES. GAS DETECTION METHODS SHOW PROMISE BUT NEED MUCH MORE WORK.
B. INFOLDED DOMINANTLY VOLCANIC ROCKS	COPPER-ZINC-SILVER DEPOSITS (VOLCANOGENIC MASSIVE SULFIDES) GOLD DEPOSITS IRON DEPOSITS (SEDIMENTARY IRON FORMATION)	
C. GNEISSIC-GRANITIC TERRAINS	MINOR PEGMATITE MINERALS	
V. AREALLY SMALL INTRUSIVES OF ALL AGES		
A. MAFIC INTRUSIVES (INCLUDING ULTRAMAFIC) WITH REGIONAL STRUCTURAL CONTROL	DIAMONDS (KIMBERLITE PIPES)	DIAMOND PIPES ARE DETECTABLE WITH A COMBINATION OF IMAGE INTERPRETATION AND AEROMAGNETICS (SLAR AT 1:100,000 AND AEROMAGNETICS FLOWN ALONG REGIONAL FAULT ZONES). ELECTROMAGNETICS AT FAIRLY DETAILED SCALES FOLLOWING REGIONAL IMAGE INTERPRETATIONS AND RECON AEROMAGNETICS IS A POWERFUL ASSIST IN ALL THE OTHER TYPES OF DEPOSITS.
B. MAFIC INTRUSIVES WITHIN THE VOLCANIC SECTION IN PRECAMBRIAN ROCKS	COPPER-NICKEL DEPOSITS	
C. ALKALIC INTRUSIVES, CARBOTATITES (REGIONAL STRUCTURAL CONTROL)	COPPER-LEAD-ZINC DEPOSITS (PALABORA MODEL) RARE-EARTH DEPOSITS PHOSPHATE (AS APATITE) DEPOSITS	
D. SILICEOUS INTRUSIVES (PLUGS AND RING STRUCTURES)	TIN DEPOSITS GOLD DEPOSITS (PRIMARILY ASSOCIATED WITH RHYOLICTIC ROCKS IN INFOLDED VOLCANIC ROCKS)	

TABLE 6-3. SIMPLE ECONOMIC MODELS TO GUIDE EXPLORATION THINKING

I. IRON ORE (High Grade)		
Value at Liverpool, England		$ 12.30/ton
Cost of mining and milling	$ 5.00/ton	
Cost of shipping by boat from Africa to European market @ $0.001/ton-mile x 4,600 miles	4.60	9.60/ton
Money available for rail shipment at zero profit		2.70
Possible rail shipment distance @ $0.02/ton-mile		140 miles
II. IRON ORE PELLETS		
Value at Liverpool, England		30.00
Cost of mining and milling	10.00	
Cost of shipping by boat from Africa to European market @ $0.001/ton-mile x 4,600 miles	4.60	14.60
Money available for rail shipment at zero profit		15.40
Possible rail shipment distance @ $0.02/ton-mile		720 miles
III. COPPER CONCENTRATES (60% Cu)		
Value at Liverpool, England Shipping Costs are the same as above		$1,200.00/ton

2. Zinc in

   a. Archean volcanogenic massive sulfides of the Abitibi greenstone model in association with copper

   b. Mississippi Valley type deposits in association with lead

3. Lead in Mississippi Valley type deposits in association with zinc

4. Nickel in mafic and ultra-mafic intrusive rocks, sometimes associated with copper and platinum group minerals

5. Gold in

   a. Siliceous volcanogenic intrusive rocks

   b. Placer concentrations

6. Tin in

   a. Small siliceous intrusives with associated ring structure

   b. Placer concentration associated with gold and very occasionally diamonds

7. Uranium in sandstone roll type deposits.

In addition to the metals listed, the geologic environments of the Sahel region do not rule out the possibility of discovering others of value -- for example, chrome ore and high grade manganese of the type mined in Ghana. Further, there are indications of various non-metallic mineral resources and substantial amounts of indigenous construction materials. Both of these, however, are of low unit value and not amenable to other than near-local use.

Of the hydrocarbons probably only oil is of sufficient economic value to be worth exploration in the Sahel, although natural gas and possibly high grade coal would be of value if found near the Atlantic coast. According to the American Association of Petroleum Geologists' Bulletin (October 1973), all known sedimentary basins have received or are receiving at least some attention by the major international oil companies. Concession agreements between the Sahel countries and any exploring company should contain provisions for data presentation to the country as a minimal condition for keeping concessions in good order. These data -- air photos, aeromagnetics, and geologic reports -- should be compiled by the country and made available to interested parties to encourage further exploration.

Philosophy of Exploration Strategy Design

The exploration problem applies a rational sequence of method that progressively lead to definition of an ore body. The methods should define:

1. Favorable region - geological provinces, political units, etc. (thousands of square kilometers).
2. Favorable districts within region - structural and stratigraphic conditions suitable for ore occurrences (hundreds of square kilometers).
3. Location of anomalous features within favorable districts - geophysical, geochemical, structural and stratigraphic (tens of square kilometers).
4. Evaluation of anomalies - detailed field studies (few square kilometers).
5. Exploration of anomalies - detailed field studies (few square kilometers).
6. Development drilling - defines ore body (location, shape, depth, size, grade).

Methods used in a multi-stage exploration program should be increasingly discriminating and normally investigate areas decreasing in size toward the eventual selection of a drill site. In general, each successive exploration method costs more per unit area investigated; the highest cost/unit area is for drilling. Figure 6-4 shows relationships between cost/unit area, definitiveness and exploration tools. On this figure the definitiveness scale is:

0 - Little or no value in copper search

1 - Definition of provinces in which copper deposits may occur

2 - Definition of favorable areas within province

3 - Locates anomalous features

4 - Evaluates anomalous features in general fashion

5 - Evaluates anomalous features in detail

6 - Defines copper prospect well enough for land acquisition

7 - Defines areas for detailed field study

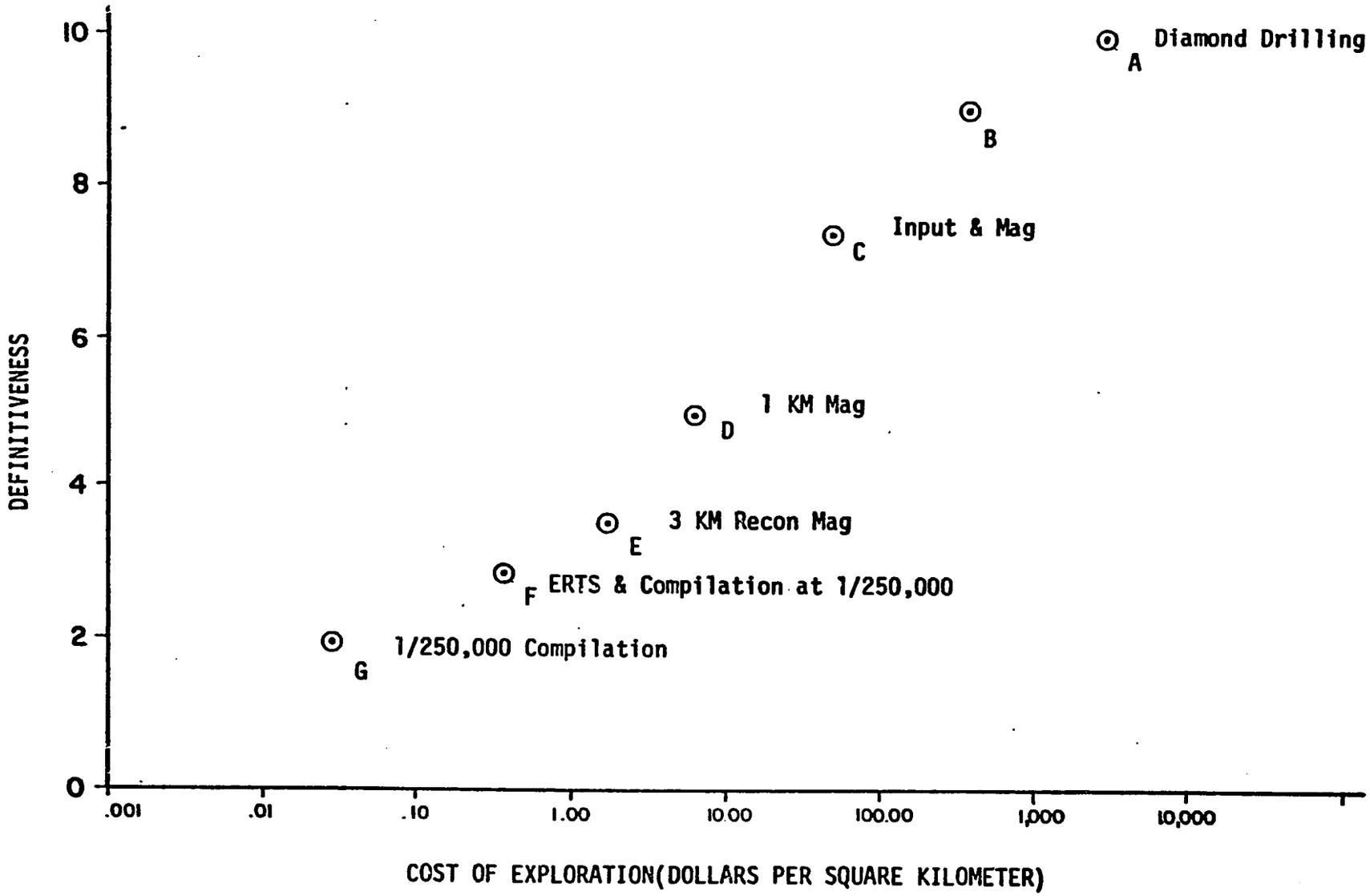
8 - Indicates valuable sulfide mineralization in place but assays not particularly meaningful

9 - Defines targets for diamond drilling

10 - Produces assayable samples of ore-grade mineralization suitable for feasibility study

Also on Figure 6-4, the cost of covering a large area with an exploration method is:

A. Cost of churn drilling for copper deposits at the rate of one 1,000-foot hole per square kilometer.



"Input" is an active airborne electromagnetic system, "Mag" is airborne magnetometry.

Figure 6-4

B. Cost of reconnaissance-induced polarization surveys at a spacing of one kilometer.

C. Cost of a combined input-aeromagnetic survey at 1/3 kilometer line spacing with interpretation.

D. Cost of aeromagnetics of large areas at one kilometer line spacing with interpretation.

E. Cost of reconnaissance aeromagnetics (three kilometer line spacing) and interpretation.

F. Cost of compilation of all published data and a simple integrated ERTS interpretation at 1:250,000.

G. Cost of a compilation of all published data on the area at 1:250,000.

All of the above listed economically viable exploration targets require a certain minimum of regional geologic data for the rational design of more detailed remote sensing exploration surveys. These data can be produced on a cost-effective basis at the optimum scale of 1:250,000 by a careful combination of image interpretation (ERTS or SLAR), compilation of existing geologic data, and wide-spread aeromagnetics of varying flying height and line spacing. These data would provide the structural (image interpretation) and lithologic (aeromagnetic interpretation) control necessary to determine where to apply the more expensive surveys.

Deposits of the first five metals all consist of sulfide mineralization which is much more conductive than the rocks in which they are contained and the next step in remote sensing exploration would be flying AEM (aerial electromagnetic) or HEM (helicopter electromagnetic) and detailed aeromagnetics in the appropriate geologic environment, carefully chosen from the reconnaissance surveys. The electromagnetic survey will reveal many conductive anomalies that must then be sorted by other means. In the past few years this has been done by ground methods but if airborne geochemistry can be perfected, it will greatly reduce the proportion of electrical conductivity anomalies that must be further investigated on the ground.

The geologic environment of primary tin occurrence (ringlike complexes) can often be recognized directly on the reconnaissance surveys suggested above. The occurrence of potassic granites can be further confirmed by the use of an airborne gamma ray spectrometer, although this is not necessarily cost-effective. Placer tin deposits cannot be recognized as such by remote sensing methods, but in this region the best placer tin concentration will probably be both alluvial and eluvial and the remote sensing target is generally the primary mineralization. In addition, remote sensing can aid in extrapolating from known occurrences by facilitating geomorphic correlation of terrace features.

Uranium is generally prospected with a gamma ray spectrometer flown over basin edges in regions where the basement consists of the supposed granite source rocks. The Bi^{214} anomalies so obtained are used as pathfinders to indicate the portion of the basin edge most prospective for ground follow-up work. Outcrops of high grade basement deposits of uranium can be detected directly by remote sensing. However, they make up such a small part of the world uranium ore reserve that they do not make a good target for cost-effective exploration.

Since "ore" has an economic definition (in contrast to the mineralogical definition of "mineral deposit"), it is not possible to detect "ore" by remote sensing methods. Remote sensing methods aid in detecting favorable geological environments, and in some instances mineral deposits, but these may or may not have a high probability of containing ore. To follow-up these indications, additional substantial expenditures are required for local mapping, sampling, drilling, and feasibility studies to prove an ore deposit.

To summarize, the Sahel may well have significant as yet unknown mineral potential in the ferrous metal group, in base metals, in precious metals and non-metallics, and in hydrocarbons. To detect, discriminate, inventory, evaluate and develop any such resources will require a sequence of systematic exploration and development steps, the earlier phases of which may be significantly accelerated and executed more economically through the judicious use of remote sensing.

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CHAPTER 7

MONITORING DUNE SANDS AND DUNE MIGRATION

1.0 INTRODUCTION

Dune stabilization by vegetative regrowth is an historical goal of resource management. Murphy (1945) attributed the decline of population in North Africa following the Classical Period to a changed cultural attitude toward vegetation, the removal of trees, and overgrazing. In semi-arid regions of the United States, Australia and Kazakhstan, similar dire consequences resulted from severe changes in the type or rate of resource use. The need to rehabilitate and regenerate the productivity of these climatically transitional regions which Meinig (1962) once called "the margins of the good earth", is of utmost necessity in areas where a population is already settled and must be supported.

Dune sands and sand seas are among the most fragile resources in the Sahel. The governments of the region, confronted with the knowledge that drought coupled with severe overgrazing by nomadic pastoralists has led to widespread loss of sand stability, first must determine the basic distribution of dunes by type and vegetation cover, the extent and location of present damage, and the amount of sand in movement; second, assess what remedial measures, if any, may be applied within the cultural milieu of the nomads; and, third, plan and implement actions, initially where settlements or transportation routes are threatened by moving sand. The second and third of these concerns are beyond the scope of this analysis, except as the efficacy of remedial actions may be monitored with remote sensing, and except as remote sensing may be used to quantitatively estimate amounts and rates of sand movement. The balance of this presentation therefore focuses on the application of remote sensing to questions of dune fragility, dune types and associated micro-environments, plant cover, aeolian damage, and sand movement.

2.0 DUNE FRAGILITY

Dunes are naturally fragile because the sand is unconsolidated. Natural vegetation which might provide stabilization is sparse because of the scarce water availability. Even a modest natural decrease in plant cover during drought greatly increases dune sensitivity to blow-outs. Once bared of vegetation, sand is free to move in response to moderate to strong winds.

This intrinsic sensitivity is exacerbated by man's activities and by stock trampling and overgrazing. Overgrazing in unfenced range is most pronounced close to water holes, especially where dunes are interspersed with heavy textured soils. Sands respond more rapidly to light rain than clays, and fresh new growth -- mainly on the lower, somewhat moister sites -- becomes the focus of concentrated grazing and trampling.

In the better water areas, older weathered dunes -- relicts of earlier arid periods -- may be used for agriculture. These, too, are sensitive to wind erosion. Many farmers have confronted the same scenario: in North Africa, the mallee country of Australia, the Kalahari fringes of South Africa, and the Valentine and associated sands in southwestern Kansas and and Oklahoma. Lured by a period of above normal precipitation, the agricultural frontier moves into these precarious soil/environmental associations only to be thrown back when rainfall reverses itself. Crops having failed, the soil lies bare to the onset of erosion by wind and water.

Just as these patterns are well-known, so too - in broad outline - are the methods of control, at least in a technical sense: control of stock by fencing, rotational grazing, provision of grassland and seed regeneration refugia, and retirement from cultivation of the worst wind eroded sites. However, there are almost insuperable problems involved in gaining acceptance for stock control in areas of traditional, pastoral nomadism. Increasing human and animal populations cause the grazing ranges of each nomadic group to overlap and, hence, their traditional short-run optimizing behavior to conflict. Recognizing that land left ungrazed for a time will regenerate, they nevertheless graze hard, because land left for tomorrow will benefit another. Attempts to establish grazing associations (cooperatives) with circumscribed boundaries, and new methods of intra- and inter-regional marketing organizations involving successive stock sales from the more arid to the humid areas, must be initiated if sand areas are to be freed from the present hazardous over-use.

2.1 DUNE TYPES AND ASSOCIATED MICRO-ENVIRONMENTS

Dunes within the Sahel range strikingly in type, density, height, and spacing. While the principal dune fields are of the sief or longitudinal type, the Sahel contains an extraordinary diversity of dune types including sand seas comparable to the Gozes of Kordofan, complex imbricate transverse and herring-bone dunes, including the Dune de Rateau and, in the more humid regions, the upsiloidal or U-shaped dune. The tallest are several hundreds of feet high, but most are from 50 to 80 feet above intervening troughs.

As is abundantly evident on ERTS images of the Sahel and the Sahara desert, the dunes are aligned with the prevailing circulation around the subtropical high pressure cell found over the central Sahara. The principal driver, the Harmattan, each year freshly reworks the dunes and creates dust clouds which sweep from the Sahara to the sea.

The dunes are a striking feature of the whole Sahelian landscape. In some areas they cling close to their source. In others, they have grown ab initio in sandy terrain. In other areas, successive reworkings have driven great swaths of longitudinal and transverse dunes long distances across heavier textured and hardpan soils, across relict laterite and iron stone into the paths of major ephemeral and neo-perennial streams, diverting their courses and producing a complex interdigitation of stream direction and counterposing dune direction which tends to break both the dune and the river systems into an intricate rectilinear pattern.

Some dunes are currently fixed in their lower slopes by vegetation, and some are fully vegetated; some are relatively free moving and have been for a considerable time. Others have renewed their movement recently, in response to excessive overgrazing and the depletion of perennial plant species.

In many areas, the fluvial transport of fines produces a heavier textured soil in the dune troughs. These small internal drainage basins tend to become saline and develop a ring of halophytic plants around the edge of playas (seasonal, short-lived water bodies). The halophytes give way to xerophytic shrubs and occasional trees on the lower dune slopes. The tops of dunes are frequently subject to recurrent blowing, and bare patches are common even in locations where extensive grazing has not seriously damaged the natural plant communities.

The complex of dune types, their diversity and age, weathering status, fragility and inter-fingering with non-dune environments, make for a great variety of dune and dune-associated environmental situations which lend themselves well to remote sensing both for basic enumeration and for detecting change.

Another advantage for studying dunes in semi-arid and arid zones by remote sensing (in particular ERTS and Skylab imagery) is the combination of the sensitive relationship between plant community and position on a dune, and their orderliness of height, spacing and density, which make them the most structured features of the landscape.

Clues to potential dune migration, amounts and rates of movement, can also be observed. The detection of dune changes that lead to loss of soil stability and, in turn, to inundation of settled areas, may be foreshadowed by observing bare sand in previously vegetated areas, and by changes in soil color toward lighter shades as darker, fine materials and organic materials are winnowed out of the surface soils.

3.0 REMOTE SENSING APPLICATIONS TO DUNE ENVIRONMENTS

The principal remote sensing papers which bear on these matters are: Simonett, Morain, Cochrane, and Egbert (1969) using Gemini photography for the Alice Springs area of Central Australia; McKee and Breed (1973 using ERTS-MSS imagery to study desert dune areas throughout the world, emphasizing Africa; MacLeod (1973) in Mali, using both ERTS and Skylab imagery; Seevers and Drew (1973, 1974) studies with ERTS in the Sand Hills of Nebraska; Bowden et al. (1974) in the Los Angeles coastal lowland; unpublished studies by Simonett using Skylab imagery in the Alice Springs area of Australia; and, earlier work by H.T.U. Smith (1966) using aerial photography of world desert and semi-desert areas.

The most ambitious of these studies is that by McKee and Breed (1973 abstract, paper not yet published), which examines some of the extensive sand dunes in the Sahel region. These investigators have concluded that: "ERTS imagery has the advantage of permitting (1) direct comparison of areas because the same scale prevails on all images, (2) ready observations of relationships to surrounding features, (3) recognition of major trends and lineations where minor details are obscured, (4) mosaics from false color prints which show sand patterns over large areas and prove useful as base maps and, (5) color images which are a much better guide to the presence of sand either bare, lightly vegetated, or in dune form, than any of the single black and white bands of ERTS-1." As part of the study they are analyzing the relationships between dune characteristics and presumed principal controlling factors including wind direction and strength, topography, vegetation, moisture, available sediment, and distance from source.

Paul M. Seevers and James V. Drew (1974) evaluated ERTS imagery for mapping and managing soil and range resources in the Sand Hills of Nebraska, a region similar to the areas in the more humid portions of the Sahel. Ground truth was collected from selected range sites for comparison with MSS Band 5 imagery to determine the relationship between optical density and vegetation biomass. Color composite images were used to construct soil association maps for areas where modern soil association data were currently unavailable. Four resource maps were also prepared, as follows:

1) the location of sub-irrigated range sites and lakes (sub-irrigated refers to lower sites where the sub-surface water table naturally occurs close to the surface); 2) the frequency of wind-erosion affected areas per township (a 36-square mile area); 3) areas of less than 10 percent vegetation coverage in the fall and spring, which represent seasons of potential wind erosion hazard; and 4) the distribution of center pivot irrigation systems (identified by the presence of perennial or annual crop production). All of these items are of direct interest to the Sahel, and it is reasonable to pursue a comparably detailed investigation of sand dune sites in that area.

The topographic features, soil associations and range sites within the Sand Hills region of Nebraska are shown in Table 7-1. Seevers and Drew used imagery of several dates to delineate soil associations which are extensions of those given in recently published soil association maps for Sand Hills counties. The Valentine-Elsemere-Gannet soil association, consisting of dunes and sub-irrigated valleys, were identified on color composites of MSS Bands 4, 5, and 6 on May 14, 1973 imagery, prior to the summer haying operations. Within this association, the Elsemere and Gannet soils of the sub-irrigated range sites showed vegetation to be relatively dense and physiologically active, providing strong reflectance in MSS Band 6, in comparison with the Valentine soils of the sand range site, that commonly occur upslope from the other soils, which had less reflectance.

Spectral similarities exist between the mown sub-irrigated sites in Nebraska, and the heavily grazed sub-irrigated sites in the Sahel. A standard management practice in advanced livestock economies is to mow or graze sub-irrigated sites to prevent annual accumulation of dead vegetation. The practice makes near-infrared reflectance from vegetative growth during the spring strikingly evident. A comparable situation exists in the Sahel where heavy grazing takes place in sub-irrigated sites such as in lowland sites on the lower slopes of dunes and on borders of inter-dune troughs in the more arid areas.

In contrast, the relatively low density patterns of vegetation on the choppy, steeply sloping uplands permitted tentative identification of the Valentine hilly soil association. This upper-lower slope soil relationship pattern is typical in many sand dune areas and can be reasonably extrapolated to the Sahel.

TABLE 7-1

Relationships of Topographic Features, Soil Associations and Range Sites Within the Sand Hills Region of Nebraska

TOPOGRAPHIC FEATURES	SOIL ASSOCIATIONS	RANGE SITES
1. Rolling and steeply sloping (choppy) uplands with dry valleys	Valentine-Dunday	Sands, Choppy Sands and Sandy
2. Rolling uplands with dry valleys	Valentine-Anselmo	Sands and Sandy
3. Steeply sloping (choppy) uplands	Valentine, hilly	Choppy Sands
4. Rolling uplands, with sub-irrigated valleys	Valentine-Elsmere-Gannett	Sands and Sub-irrigated
5. Rolling uplands, dry valleys sub-irrigated valleys	Valentine-Dunday-Loup	Sands, Sandy, Sub-irrigated
6. Rollings uplands	Valentine, rolling	Sands
7. Rolling uplands with dry valleys of sand hills - loess border	Anselmo-Valentine-Dunday	Sands, Sandy

Shadow differences in addition to reflectance differences were used to separate sub-irrigated and other vegetation. Color composites generated from ERTS-MSS Bands 5, 6, and 7, summer imagery (when plant growth generally was active over the entire range), permitted the identification of patterns of cultivated cropland and the delineation of the Anselmo-Valentine-Dunday soil association in the Sand Hills-loess border. Also noted by Seevers and Drew were

> "relationships established through comparison of ERTS-1 imagery, with published soil association maps for Cherry County, Nebraska, and adjacent Sand Hill counties, for which no comparable soil association map was available. Comparisons of the soil association map constructed for Cherry county with data obtained from field observations and from high altitude color infrared aerial photography indicate a high degree of accuracy for the soil association map interpreted directly from ERTS imagery (MSS Bands 4, 5, and 6, and MSS Band 6 of another image)." They continue . . . "Because of unique combinations of vegetation and land surface configuration within the Sand Hills region, ERTS-1 imagery is suitable for interpreting soil units and range sites at a level of generalization intermediate between county soil association maps and standard soil surveys made by observations of soil profiles and landscapes on the ground." (emphasis provided)

A modest field sampling program in the Sahel -- presuming the same general situation prevails -- might enable soil associations to be extrapolated and mapped over large areas at a scale equivalent to that commonly used in Australia soil surveys (1:50,000 or 1:63,360).

It was noted earlier that there is a very sensitive relationsip in semi-arid and arid regions between vegetation biomass, plant community, and position in a dune landscape. This observation is also confirmed in the Nebraska Sand Hills by Seevers and Drew who point out that "because of the total spectral response of the sandy soils, differences in image densities in relation to vegetative biomass are more distinct in the Sand Hills region than in other range land areas in Nebraska." They also noted that "overgrazing in the Sand Hills region is particularly critical in view of the fragile nature of the sandy rangeland and its potential for destruction by wind erosion. Continued overgrazing results in a sharp decrease in range condition class and increases wind erosion hazard." This observation typical of all semi-arid and arid sand dune areas throughout the world, was also noted repeatedly by MacLeod (1973) in his study on applications of remote sensing (ERTS) to resource management and development in Sahelian Africa (Republic of Mali).

Seevers and Drew (1974) also used ERTS-1 images from MSS Band 5 on August 17th and 18th, 1972, and May 14th and 15th, 1973, to map areas with less than 10 percent vegetative cover within a resource district in the Sand Hills. Areas that did not recover to more than 10 percent vegetative cover by mid-May 1973, were viewed as being potentially hazardous in terms of wind erosion. Following areas of critical lowered biomass in the more humid Sahelian

regions with multi-date ERTS imagery would be an important potential monitoring procedure. Seevers and Drew also reported that within the vegetated Sand Hills regions, areas from 2 to 50 hectares or more in size stripped of vegetative cover by wind erosion that were actively eroding, were "readily interpreted on ERTS-1 imagery obtained during the growing season." Using ERTS-MSS Band 5 on May 14 and 15, 1973, they prepared a map showing the number of blowouts per township (36 square miles) within a single resource district. Experimentation with the technique should be continued because it may well prove satisfactory in the more humid sand dune areas of the Sahel.

Sand dunes in Central Australia, an area receiving from 8 to 10 inches of precipitation per annum, have been examined by Simonett, Morain, Cochrane, and Egbert (1969), using Gemini space photography. Later unpublished studies by Simonett in 1971 involved further field work, the use of black and white aerial photographs of multiple dates, low altitude color and false color aerial photography and, more recently, inspection of ERTS images and Skylab S-190A and S-190B color photography. These studies have shown that very subtle vegetation-soil relationships may be identified within sand dune systems near Lake Napperby, north and west of Alice Springs, even on ERTS imagery which has the coarsest resolution of the materials studied. Differences between low trees of Acacia communities, various types of shrublands (Melaleuca spp.) and desert grasslands (Triodia spp.) have all been detected on these images. Variations in burn patterns and stand density are apparent, particularly on Skylab imagery. Significant variations in grazing density were also observed in Mali by MacLeod (1973) in a large ranch fenced off from excessive grazing.

Patterns similar to those noted in the Sand Hills of Nebraska were noted in the central Australian area where light-toned and bare soil areas were found on the dune crests and dark-toned, dense vegetation in the lower areas. Features more comparable to the Sahel were also observed, including saline ponds between the dunes where the wind has scoured down to the water table. Clumps of acacia tended to cluster in the sub-irrigated drainage area at the lower foot slopes of the dunes. This same feature -- sub-irrigation -- is common in all undulating sand areas, particularly where dunes are close to the water table and where they lie above a major hard pan.

Although high altitude aerial photography can be used to map sand dune location, detect damage from sand movement, and assess the amounts and rates of sand movement, its limited areal coverage and increased cost prohibit its use except in a supporting role for more

sharply defining critical areas of concern in the Sahel. Aircraft-based thermal infrared imagery also presents the same limitations, but satellite thermal infrared imagery can be effectively used for moisture detection and monitoring the effects of weather and climate on dunes vegetation, thus providing a substantial input to range control programs for assessing potential damage to forage areas.

Establishing the feasibility of dune monitoring requires quantitative studies employing manual ERTS interpretation, use of digital tapes, and utlimately high altitude aircraft coverage and field work. The general expectation is that ERTS imagery will have a useful role in dune monitoring. Bowden et al. (1974), in a study of the effects of specific foehn type wind conditions (Santa Ana) on dust plumes in the Los Angeles coastal lowland, substantiate this role for dune environments such as the Sahel, in their conclusion that:

> "The actual extent and magnitude of the dust plumes have rarely been recorded because of the extensive area involved. The ERTS-1 image presents the first compact view of the entire dynamics in progress at one point in time. Neither aircraft imagery nor ground data presents such a complete overview of the affected area. Monitoring of such environmental conditions for long periods of time with sequential imagery may be very useful to those engaged in making sensible resource management decisions."

4.0 AEOLIAN DAMAGE AND SAND MOVEMENT: MEASURMENT WITH REMOTE SENSING

The location of areas threatened by damage from sand movement and the amounts and rates of sand movement are matters of concern in the Sahel. Consideration needs to be given to the contributions which remote sensing may make on both topics.

Active sand movement occurs throughout the Sahel in several different types of area. The first type comprises areas of moving sand that have long been vegetation-free (based on early maps, explorer's reports and other historical evidence). The evidence of movement of these dunes is mixed; in many cases the borders of the dune field seem relatively fixed even though some internal shifting of sand takes place. The borders of the dune field have, in effect, stabilized much in the same way as natural dune fields in the western United States. In rare instances, these dunes continue to advance at rates varying from a few hundred feet per annum to several miles. Separating fixed from moving dunes and quantifying mass movement could, in some cases, be achieved through using multiple ERTS images over a span of several years.

Detecting movement depends on the amount of movement and the contrast between sand and background terrain reflectance. A detection procedure using an overlay of multiple ERTS

images would be sufficient to give a first approximation of movement rates. Refined quantitative measures could be made with high altitude aircraft imagery in areas where these comparisons showed appreciable change. The work of McKee and Breed on dune types and movement will be of value in assessing these possibilities.

The second type of area of moving sand comprises those areas where dune vegetation was under stress and was stripped naturally or by man's activity. A whole suite of situations occur, ranging from mere intensification of crest mobility in seif dunes to complete transverse dune motion. Slight changes may be undetectable with ERTS, or may be lost in natural background motions. Substantial change should, however, be visible in the burying of troughs, covering of small saline basins, and engulfing of lowland trees and drainage depressions. The study by McKee and Breed using ERTS imagery overlay techniques, image enhancement and substantial image enlargement, again bears on these issues.

The establishment of rates of movement by dune type and geographic area, if feasible with ERTS, would provide a basis for regional damage anticipation, planning to avoid sensitive areas and, when used with agro-meteorological satellite modeling, forming the basis for assessing the interaction dynamics of the processes involved. These topics, while not yet fully demonstrated as to feasibility with ERTS imagery, should be considered in long-term studies on environmental dynamics in the Sahel. Assessing the reality of postulated effects of long drought periods requires long-term analysis and earlier aerial photography, such as that employed by H.T.U. Smith (1963) in his studies in North Africa.

5.0 SUMMARY AND CONCLUSIONS

These studies suggest that the mapping of unvegetated, lightly vegetated, and moderately vegetated sand dunes and the continued monitoring of their condition and motion are reasonable possibilities with ERTS images. A well planned and managed monitoring program might be initiated in an appropriate context employing ERTS to examine questions relating to soil deterioration and range overgrazing and sand motion throughout the Sahelian sand dune areas. The special and subtle interrelationships between sand/soil sites and their plant communities will enable a scale of detailed mapping with ERTS imagery of very great value in programs of range sand site analysis; the scale and quality of ERTS information is especially appropriate to the problems of mapping and monitoring very large sand dune areas. Proper calibration requires detailed low altitude photographic studies and ground observations to support ERTS analysis.

While Nebraska, Central Australia and California are not the Sahel, the results obtained in these locations are such that ERTS imagery could obtain a perspective of the Sahel. Based on sample studies within the Sahelian region and on broad areas analysis, several governments and international agencies might develop a region-wide assessment of accelerated sand dune erosion and of basic soil associations in the dunes. The case for substantial studies in this area is not obvious, for further pilot research is needed. The outlook is sufficiently encouraging, however, to warrant close scrutiny by the Sahelian governments and international agencies.

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CHAPTER 8

METEOROLOGICAL AND CLIMATOLOGICAL ANALYSIS AND WATER BALANCE MODELING

1.0 INTRODUCTION

Chapter 8 "Meterological and Climatological Analysis and Water Balance Modeling" and Chapter 9 "Evaluating Surface and Subsurface Water Resources" are presented in sequence because they represent two components of the hydrologic cycle. The division between the two is traditional in a disciplinary sense and is maintained here for convenience. Since these chapters present the atmospheric and terrestrial portions of the hydrologic cycle much material will be common to both. Because the one natural system (the flow of water through the earth's environment) transcends traditional disciplines, much information and the applications areas considered will differ. In this chapter the point of view of the atmospheric scientist is presented, here the concern is with the amount of water delivered to the Earth's surface. Chapter 9 focuses on the distribution, location, and management of water resources.

The importance of water to the sustenance of every living thing has been profoundly appreciated since the beginning of man's time on earth. So, too, the vital role of the hydrological cycle, the process by which the terrestrial supply of water is constantly replenished, has been acknowledged. The problem facing the Sahelian region of Africa, the loss of an adequate water replenishment, has been complicated by major changes in human settlements in both the ancient and modern world. In the ancient world, the disappearance of the original high civilizations in the formerly fertile areas of the Tigris and Euphrates River valleys was undoubtedly related to changes in the hydrologic cycle. The situation facing the countries of the Sahel is not different, in kind, from that of the Tigris/Euphrates region.

During the past few decades, water balance (water availability) at the earth's surface has been the subject of extensive research. In the period prior to the mid-1930's, much of the research dealt only with the terrestrial branch of the hydrologic cycle, examining the changing balance between precipitation, evaporation, transpiration, runoff, underground flow and changes in ground water storage (water budget analysis). This conventional approach to water budget studies often yielded results that were not widely accepted by hydrologists. The basic problem in many of these analyses was that evaporation from the surface of the earth was assumed to be uniform.

The fact is that water is continuously and differentially removed by turbulent diffusion near the surface, by convective currents due to temperature differences in the air, and by the wind. All of these factors affect the amount of evaporation that can take place. Neither the direct measurement of precipitation nor the direct assessment of evaporation are readily possible in any area where the spatial distribution of percipitation patterns tends to be quite spotty. The following sections will examine the role of remote sensing from meteorological and earth resource satellites, as well as by aircraft borne sensors, in assessment of short and long term variations in the water balance of the Sahelian region.

2.0 THE WATER CYCLE

The earth is constantly releasing water vapor into the atmosphere, through surface evaporation and through transpiration by living matter. The transfer of water from the earth's surface to the atmosphere is an integral part of the hydrologic cycle. The principle of conservation of water in its three phases on earth essentially describes this cycle as a closed sequence by which water enters the atmosphere from the earth's surface in a gaseous state and returns to the surface in a liquid or solid state. There, some water is retained and some evaporates again into the atmosphere. This exchange of water proceeds in a continuous cycle.

Except for a negligible outflow from the interior of the earth, all the energy that drives the water cycle comes from the sun. Solar radiation reaching the earth's orbit amounts to about 2 calories per square centimeter per minute, a quantity termed the solar constant. The amount of solar energy actually received by the earth in one minute is equal to the product of the solar constant and the cross sectional area of the earth. The solar energy reaching the earth is subjected to absorption in the ultraviolet region (by ozone in the upper atmosphere), scattering or absorption by air and water molecules, and reflection back into space by clouds. Approximately 81 percent of the incoming radiation reaches the earth surface. This is depleted by about 33 percent through direct reflection from the surface of the earth back into space. The actual amount that is reflected back into space is determined by the color or the albedo of the earth's surface. The remaining radiation is absorbed by the earth's surface. Approximately 75 percent of this absorbed energy is re-radiated back into the atmosphere as long wave radiation, leaving only 25 percent available for the evaporation process. Thus the most important factor to the atmospheric demand part of the hydrologic cycle is sunlight and its temporal and spatial distribution.

Air temperature, humidity, and wind, which are highly correlated with solar input, modify the evaporation process. Clouds modify the amount of incoming solar radiation.

Precipitation shows large variations in time and space. The seasonal progression of precipitation in the Sahel is closely linked to the seasonal variation of the sun's position with respect to the equator. During the northern hemisphere summer, the probability of precipitation occurring over the Sahelian region is at a maximum. During the winter period it is minimal. The onset of the period of highly probable precipitation is extremely irregular, however, in both time and space. Many regions of the Sahel may receive no rain even at the height of the rainy season. Variations in precipitation during the day are governed largely by the diurnal heating cycle which causes maximum convection and therefore maximum precipitation probability during the afternoon. Variations in precipitation on a time scale of 2 to 5 days can generally be explained by the passage of disturbance or squall lines which move from east to west over the southern portion of the Sahelian zone. Variations in precipitation on a longer time scale appear to be correlated with the changes of circulation patterns over the entire globe. This latter variation has been dominant in the Sahelian zone drought for the past 5 to 7 years.

The spatial variation in precipitation over the Sahelian zone for a given day is only partly understood. The weather regimes that cause most of the precipitation occurrences are isolated thunderstorms which form in the moist air masses moving north with the intertropical convergence zone. These occurrences are limited in their time and space dimensions but often produce significant amounts of rainfall within limited areas. The formation of the isolated thunderstorms may be related to spatial variations in ground albedo and vegetation cover but these interrelations are not understood. Extensive rain patterns over the Sahel are often associated with the disturbances which move east to west along the intertropical convergence zone. Precipitation within these disturbances arises from cumulus and cumulonimbus clouds and thus the spatial variability in precipitation is great in such cases as well.

It follows from the foregoing discussion of evaporation and precipitation that the amount of water available for the growth of vegetation is highly variable in space and time. A basic obstacle to the accurate description of the local water budget and its application to estimation of agricultural and range forage production is the general lack of data relating to evaporation and precipitation over the Sahel region. The following sections discuss the application of remote sensing techniques to offset the current lack of data on the day to day water budget of the Sahel.

3.0 THE ROLE OF REMOTE SENSING

3.1 INTRODUCTION

One of the principal tasks facing those concerned with the long term problems in the Sahelian region is the development of predictions and estimates of agricultural production and range capacities of the region and the estimation of the potential for development of new agricultural programs to offset the trend toward long term losses in range carrying capability. The estimation of range carrying capacity requires knowledge of the availability of natural seed, the distribution of soil textures, and the moisture available for plant growth. The ground observing stations in the Sahel cannot adequately provide the information necessary to evaluate these elements.

Meteorological satellites are the most effective collection systems for meteorological and climatic data, but other remote sensing techniques can supplement meteorological satellite information. The Earth Resource Technology Satellite (ERTS-1) can provide only indirect information on the water balance. For example, comparison of several observations over the same area may yield information on moisture stress. This kind of information can be a very useful supplement to a diagnosis developed for the meteorological satellite analyses. A secondary but useful type of supplementary data which can be provided by ERTS and relates directly to water balance is the spectral reflectance which may approximate albedo if the energy in the four MSS bands is integrated.

The long term record of ERTS type data that may be developed over the next few years will provide an indirect climatological data base. The current ERTS data record is insufficient for such uses.

Aircraft systems and future spacecraft which carry thermal infrared sensors may provide a direct assessment of evaporation and transpiration. Experimental programs have shown that the infrared emission is related to the amount of evaporation and transpiration that is occurring in the vegetated areas. Techniques using thermal infrared approaches are now experimental. They may, however, be used in a supplementary qualitative manner to confirm other types of investigations. Future testing and development is however necessary.

The ability to apply meteorological satellite information to obtain an improved knowledge of the time and space variation in precipitation and evaporative demand will form the emphasis for the remainder of this chapter, since ERTS and other remote sensing systems provide only limited

meteorological and climatological data. The application of remote sensing to the water balance/range forage problem provides an expanding capability to improve this situation in the following three areas:

- Improved description of the distribution of soils, in particular the distribution and movement of the wind-driven sands,
- Improved knowledge of the distribution and vigor of the existing natural seed stock. (This evaluation uses data from the previous year to assess the distribution of grasses and assumes that the seed developed by those grasses will be deposited in the same area).
- Improved diagnoses of the water factors, i.e., precipitation or solar radiation (as it relates to evapotranspiration).

Extensive discussions on mointoring and mapping soils, sand dunes, and vegetation are contained elsewhere in this report and will not be discussed here.

3.2 APPLICATIONS OF PRECIPITATION ESTIMATES

Meteorological satellite observations provide the capability for direct estimation of precipitation, measurement of cloud coverage and type (a major factor in the amount of energy available for evapotranspiration), and may permit direct estimation of soil moisture levels. The data on precipitation, solar energy attenuation and soil moisture can be used independently, without integration of ground observations, or they may be used in a system concept where the satellite data are integrated with ground data. Tables 8-1 and 8-2 outline the current and future satellite systems and the sensor characteristics. These tables are also presented in Chapter 4 but are repeated here for clarity.

The methods used to estimate precipitation from satellite observations are generally based on the visible or infrared characteristics of clouds as observed by the sensors. These sensors, unlike the longer wavelength meteorological radar sensors, do not image rain directly nor do they distinguish between liquid and frozen drops. Until recently, sensor resolution would have been considered the major limitation on accuracy. However, this is no longer true with the attainment of 0.8 kilometer resolution on the NOAA-2 and NOAA-3 very high resolution visible and infrared scanning radiometer (VHRR) and the promise of improved resolution capability in the near future.

Cloud, platform and sensor characteristics are intimately related. Active convection must be isolated from background cloudiness. Thus, precipitation estimation techniques are vulnerable

CURRENT SATELLITES

Satellite	Agency	Orbit	Altitude	Period	Applicable Sensors	Observable Type
NOAA-2 °Direct Read °Tape	Commerce	Sun Synch Polar 0930L 2130L	790N.M.	115min	Scanning Radiometer (SR) Visible .5-.7 m-2N.M. Thermal 10-12 m -4 N.M. Very High Resolution Radiometer (VHRR) Visible-.5 -.7 m-.5N.M. Thermal 10-12 -.5 N.M.	Cloud Cover-Day/Night Surface(IR)Temp Day/Night Surface Albedo - Day - same -
Nimbus - 5 °Tape	NASA	Polar Sun Synch 1200M 2400	600N.M.	110min	Temperature/Humidity Radiometer (THIR) Visible - None Thermal 10-11.5 m -4N.M. 1/Electrically Scanned Microwave Radiometer ESMR Microwave - 19.35GHz 13 N.M. 1.55 cm	Color Cover - Day/Night Surface (IR)Temp-Day/Night Surface (Microwave) Temperature Day/Night Cloud Cover where the clouds are precipitating or very moist
DAPP 1-2 °Direct Read °Tape °Digital	Air Force	Polar Sun Synch 0600L 1200L 1800L 2400L	600N.M.	110min	Visible Sensor .4-1.0 m - 3N.M./2N.M. Thermal Sensor 8-13 m	Cloud Cover - Day/Night Cloud Cover - Day/Night Surface (IR) Temp Day/Night
ERTS-1	NASA	Polar Sun Synch 0930L 18 day Repeat	500N.M.	103min	Multispectral Scanner-MSS Visible .5-.6, 6.7 m .05N.M. Near IR .7-.8 1.1 m	Surface Spectral Albedo in 4 Bands day time 18 day repeat cycle

1/ ESMR is currently not calibrated.

TABLE 8-1

FUTURE 1974 - 1976 +

Satellite	Agency	Orbit	Altitude	Period	Applicable Sensors	Observation Type
NOAA-3 Launch 1974	Commerce	Sun Synch Polar	800 N.M.	115min	Same as NOAA-2	Same As NOAA-2
SMS/GOES	Commerce	Earth Synch at 100 W	19,300N.M.	24 hours	Visible/Infrared Spin Scanner Radiometer (VISSR) Visible .5-.7 m .5N.M. Thermal 10-12 m 2N.M.	Cloud Cover-Continuous Surface Albedo - Day Surface(IR)Temp-Continuous
Nimbus F 1974 (Nimbus G) 1976	NASA	Sun Synch Polar	600N.M.	110min	1/Surface Composition Mapping Radiometer Visible .8-1.1 m .3N.M. Thermal 2 Bands 8.4-9.5 m) .3N.M. 10.2-11.4 m) Electrically Scanned Microwave Radiometer(ESMR) Microwave -37 GHz -9N.M. Earth Radiation Budget (ERB) Total .2-40 m -35 N.M.	Cloud Cover-Day (Restricted Coverage) Surface Albedo Surface(IR)Temperature Day-Night Restricted Cover Surface(microwave)Temp Net Radiation for Selected Spots
TIROS N	NASA	Sun Synch Polar	900N.M.	120min	Advance Very High Resolution Radiometer (AVHRR)	

TABLE 8-2 FUTURE SATELLITE SYSTEMS

to the misinterpretation of inactive strati-form or cirro-form clouds. This factor is applicable to the disturbances or cloud clusters that are associated with the heaviest rainfalls over the Sahel.

Several exploratory studies have been accomplished to relate infrared temperature and cloud brightness to precipitation. Radok (1966) found heavy rainfall in Indochina to be related to a minima in the intensity of the 8-12 micron thermal radiation occurring a few hours later and observed from TIROS 3. Window radiation from TIROS 4 was later compared by Lethbridge (1967) for stations in the United States with precipitation 3 to 12 hours later. Precipitation probability increased 3 to 6 times with decreasing thermal infrared temperatures expressed in four broad categories. Brightness, as measured in the visible spectrum (.5 to .7 microns), performed equally well as an estimate of precipitation probability, but the strongest relationship was obtained when thermal and visible images were combined. The application of such techniques to estimating total area rainfall over large regions has shown continuing promise. For example, Follansbee (1973) showed, in test cases, daily rainfall estimates with mean absolute errors of only 1.4 inch. This result suggests that estimations of total rainfall over larger areas can be obtained with an error or 15 percent or less.

Generally the methods described concentrate on estimation of convective rainfall, a common type of rain in the Sahel region. The degree of accuracy attained by the investigations cited above suggest that the distribution and the amount of precipitation throughout the Sahel could be directly assessed on a daily basis using meteorological satellites alone.

3.3 APPLICATIONS TO EVAPOTRANSPIRATION

Calculation of evapotranspiration on a short term basis requires knowledge of cloud cover and type. The need to determine short term evapotranspiration is intimately related to the fact that the precipitation in the region is very irregular and that agricultural production and range forage development are dependent on an assessment of the short term, small area variation in the water budget. The type and amount of cloud cover can be extracted from meteorological satellite imagery. Six cloud types can generally be distinguished: cumulonumbus, nimbostratus, cumulocongestus, stratus, cumulus, and cirrus. The application of this cloud cover information to estimates of potential evapotranspiration requires calibration using calculations of evapotranspiration at ground observing stations for various surface temperatures and sky cover conditions.

Once such calibration points have been defined, estimates of potential evapotranspiration can be developed directly from the distribution of cloud cover as defined in the meteorological satellite observations.

3.4 QUALITATIVE WATER BALANCE APPLICATIONS

Daily estimates of relative water balance, using direct estimates of precipitation from meteorological satellites and derived estimates of a potential evapotranspiration, have been accomplished for arid regions of Iran by Arcese and Merritt (1973). The empirical approach utilized in the referenced study examined the distribution of four different water budget related cloud categories: clear skies, when maximum potential evapotranspiration should occur; thin clouds, when a somewhat lower level of evapotranspiration should occur; thick non-precipitating clouds, which would significantly reduce the amount of solar energy available for potential evapotranspiration; and precipitating clouds, to which a standardized precipitation amount was applied. Data derived from meteorological satellites were entered into an empirical equation utilizing the cloud categories previously mentioned as weights and a relative wetness value was derived for a 25 nautical mile grid mesh. The relative wetness value was found to correlate well with the distribution of range forage over the arid portions of Iran south of the Caspian Sea. While the procedures described in the previous paragraphs appear to yield useful information for assessing water budget distributions in arid regions, the future applications of meteorological satellites to water budget problems appear most promising when viewed in a systems concept. Figure 8-1 outlines a hydrological system concept which relates observing systems to observables, derived parameters, and applications. The following sections will examine the system approach to applying meteorological satellite data to the Sahelian water problems.

3.5 QUANTITATIVE SYSTEM APPLICATIONS

Figure 8-1 presents an integrated system applications diagram relating to water balance/hydrologic problems. Similar diagrams can be developed for agriculture, land use, forestry, etc.. This diagram shows the integrated relationships between the observing systems in the upper left hand corner and the applications on the right side of the diagram. The elbows in the diagram present interrelationships which are either direct or indirect. Direct relationships can be quite straightforward while indirect relationships require the application of a scientific or management model in order to transform one type of information to another. For example, the NOAA-2 satellite is operationally capable of mapping cloud distributions, surface temperatures, surface

	Precipitation Rate (rain)	Precipitation Distribution (rain)	Vegetal Type	Vegetal Vigor	Soil Wetness	Soil Type	Structure/Land Forms/Geology	Cloud Type	Cloud Distribution	Surface Temperature	Air Temperature
1976 - 1980 / CURRENT: WMO USGS, SCS & State Survey	1	1	1	1	1	1	1	1	1	1	1
1976 - 1980 / CURRENT: ERTSA (visible)200ft/18days	3	1	1	1	1	1	1	1	1		
1976 - 1980 / CURRENT: NOAA-2 (VHRR-visible).33mi/12hr.	2	1			1		1	1	1		
1976 - 1980 / CURRENT: NOAA-2 (VHRR-IR) .33mi/12hr.	2	1			2	2	3	1	1	1	2
1976 - 1980 / CURRENT: NOAA-2 (SR-visible) 2mi/12hr.	2	1			1		1	1	1	1	
1976 - 1980 / CURRENT: NOAA-2 (SR-IR) 5mi/12hr.	2	1			2	2	3	1	1		2
1976 - 1980 / CURRENT: NIMBUS-5 (THIR) 4.9mi/12hr.	2	2				2	3	1	1	1	2
1976 - 1980 / CURRENT: NIMBUS-5 (ESMR) 15.6mi/12hr.	2	2									
1976 - 1980 / 1974-1976: DAPP (Visible) .5mi/12hr.					2		1	1	1		
1976 - 1980 / 1974-1976: DAPP (Thermal-IR) 2mi/12hr.								1	1	2	2
1976 - 1980 / 1974-1976: NIMBUS-F (THIR) 4.9mi/12hr.	2	1				2	3	1	1	1	2
1976 - 1980 / 1974-1976: NIMBUS F (ESMR) 15.6mi/12hr.	2	2									
1976 - 1980: ERTS-B (Visible) 100ft./18days			2	2	2	2	2	2	2	2	
1976 - 1980: TIROS-N (Vis.-IR) 528/12hr.	2	2	2	2	2	2	2	2	2	2	2
1976 - 1980: EOS/NIMBUS-G (Vis.-IR)/12hr.	2	2	2	2	2	2	2	2	2	2	2

Code A: Information Sources/Outputs

1= Operation*
2= Research Mode/Future Potential
3= Not Proven
Blank=No Capability/Application

*Refer to "Conditions" for Explanation

Code B: Information Output/Forest Variable

D= Direct Input to Present or Planned Measurement of Variable

A= Ancillary Information to present or planned measurement of Variable.

Conditions:

1) Operational Means that capability is in or planned for regular usage as part of the forecast activity.

2) Basin size is 1000 $(mi)^2$ or larger.

	Precipitation Rate (rain)	Precipitation Distribution (rain)	Vegetal Type	Vegetal Vigor	Soil Wetness	Soil Type	Structure/Land Forms/Geology	Cloud Type	Cloud Distribution	Surface Temperature	Air Temperature	Seasonal Forecast	Annual Forecast	Daily Forecast
Precipitation Total (from rain)	D	A			D		A	A	A		A	3	3	3
Soil Moisture	A	A	A	A	D	D						2	3	1
Evapotranspiration	A	A	D	D	D	D				D		2	3	1
Surface Runoff	D	A	D	A	D	D	D					2	1	3
Interflow	A	A	D	D	D	D	D					2	1	3
Ground Water Flow	D	A	A	A	A	A	D			A		2	3	1

Code D: Forecast Type/Water Resources Applications

	Seasonal Forecast	Annual Forecast	Daily Forecast
Total Water Supply	X	X	
Navigation			X
Irrigation	X	X	
HydroPower	X		
Flood Warning	X		X

Code C: Forecast Variable/Forecast Requirement

3=Forecast-Highly dependent

2=Forecast-Moderate dependent

1=Forecast-Slight Dependent

FIGURE 8-1 HYDROMETEOROLOGICAL SATELLITE DATA MANAGEMENT SYSTEM

reflectance or albedo. These observables can be interrelated with precipitation distributions, soil moisture or vegetation response, through an earth science model that converts the observables derived from the satellite into estimates of the derived parameters. Similarly, the derived parameters can be converted into management information through combinations of the derived quantities in appropriate modeling techniques.

The main system problem in the application of meteorological satellite data to water balance information is in the processes of data assimilation and modeling. The data assimilation aspect of the problem is related to the collection and processing of the satellite data and ground observations into a common network. Critical elements of the input data transformations are:

- Data formats
- Data calibrations
- Objective analysis procedures
- Digital data reduction algorithms
- Data melding algorithms

Each of these critical elements has already been separately solved by one or more organizations. For example, meteorological satellite data are assimilated daily by the National Environmental Satellite Service of the National Oceanographic and Atmospheric Administration of the Department of Commerce in the United States. The NOAA program, however, does not attempt to integrate the satellite data directly in the computer. Extensive work must be undertaken in order to effectively combine the ground point observations with satellite observations in a systems approach.

In the context of an international water balance analysis activity, the logistics problems associated with melding of ground data and satellite data can be overcome by centering such an activity at one of the data centers established by the World Meteorological Organization.

One of the initial problems that must be faced in the systems approach to the use of remote sensing data for evaluation of water balance over the Sahel is the dissimilarity of formats for satellite data and ground data. Satellite data are arrayed in a complex coordinate system as a function of sensor type, satellite, altitude, and earth rotation. The ground point data are referenced by latitude and longitude. In order to meld these two data types, a uniform reference system must be established with both arrays referenced to the new system.

Objective analysis schemes which will accept randomly distributed point observations and transform those observations into a grid mesh are readily available and in standard use in numerical prediction. The principal problem is related to the type of ground observation. For example, cloudiness and precipitation are not continuously distributed over the surface of the earth and therefore, cannot be spread uniformly using standard objective analysis techniques. However, if we assume that the satellite observations can provide an estimate of those regions where cloud cover and precipitation are uniformly distributed, we can then apply objective analysis techniques to those regions. Temperature, humidity and possibly wind speed can be assumed to be continuous functions which are readily distributed using standard objective schemes.

The models required to determine precipitation, soil color, vegetation distribution, and temperature at grid points from satellite data, are generally available. For example, an approach to define precipitation distribution could draw on techniques outlined by Follansbee (1973) for visible data and Woodley (1972) for infrared data. It is anticipated that such a procedure would be very suitable for the generally cumulo-form precipitation occurring in the Sahelian region. Techniques for direct assessment of precipitation rates utilizing experimental satellite-borne microwave observations, e.g. Sabatini and Merritt (1973), are under development.

A mathematical mapping operation can be used to integrate the nearly continuous surface defined by the satellite derived grid mesh map onto the ground observation mesh. The resultant values should provide a more accurate distribution of water budget related information on a spatial distribution which has been heretofore unobtainable.

The mapped diagnoses of water budget related parameters provide a prime input to an accounting and budgeting system for water. Precipitation and radiation spatial statistics should be reasonably reliable. Evaporation and/or evapotranspiration are difficult factors but appear to be tractable in a system concept.

The water budgeting and accounting output serves as an operational input to a variety of applications. For example, water management, range management, and agriculture all are interrelated with the water budget. In a research sense, the operational system could be used to test new forage production models or range development and improvement activities. For example, predictive information could be entered to test possibilities for predicting the occurrence of the greening up of a range forage area.

A computer centered system is required for an effective system to apply remotely sensed data from meteorological satellites to water budget problems. Meteorological satellite data can provide a significant amount of the information necessary for a realistic description of time and space variability of heat and moisture budgets over the Sahel. The flexible nature of a computerized system would permit parallel operations of both a research and an operational nature, and might therefore, provide a mechanism for system learning and model improvement. The learning characteristic could permit the initiation of an operational water budget analysis system prior to the conclusion of research activities.

4.0 CLIMATOLOGICAL APPLICATIONS OF HISTORICAL METEOROLOGICAL SATELLITE DATA

Meteorological satellite data have been acquired in both the visible and thermal infrared portions of the electromagnetic spectrum since April 1, 1960. The early TIROS satellites did not provide continuous coverage but extensive amounts of data are available over the Sahel region from the TIROS, Nimbus, ESSA, ITOS and NOAA meteorological satellites for a period of 13 years.

The climate of an area is, by definition, the underlying structure of meteorological variations in time and space, on which are superimposed variations of a stable and predictable nature as well as variations which appear to be random. Climatic variations from year to year are non-uniform in space. In this sense, the drought across the Sahel is not uniform in space from year to year. The application of traditional analysis techniques to precipitation and temperature data from ground observing points will reveal this non-uniformity in space but will not effectively provide information on the actual distribution in space. While it may be appropriate to define the drought area as uniform across the Sahel from a climatic sense, it is not appropriate for short and medium term policy and management decisions. Application of meteorological satellite data to develop a climatology in space and time should provide some broad insight into the year to year variability and persistence of certain cloud cover and inferred precipitation, and evaporation and evapotranspiration distributions. The application of historical meteorological satellite data for climatological applications requires knowledge of the existence of the data, its location, its limitations, and an understanding of the application of cloud data in precipitation analyses and evapotranspiration estimation. Each of these elements has been discussed in previous sections.

Most of the meteorological satellite data since 1960 have been archived by the environmental data service of NOAA at Asheville, N.C. These data are stored in 35mm roll film format. The early data, prior to 1965, were acquired with a space-oriented, spin-stabilized satellite (TIROS), where the cameras viewed earth only during those periods when the spin axis was parallel to the plane of the orbit and the camera systems were oriented toward the earth. A further limitation, not critical for Sahel studies, is the fact that the early TIROS satellites were launched into inclined orbits of approximately 48 degrees inclination and therefore did not provide global coverage and were not sun-synchronous, i.e., they did not cross the equator at the same sun time each day. While the orientation of the TIROS vehicles often introduce some severe limitations on geographic referencing, the area coverage of the images over Africa in the Sahel region generally permits orientation by reference to landmarks. All satellites since TIROS 9 contain earth-oriented camera systems and the limitations of coverage have been eliminated by sun-synchronous polar orbits.

The magnitude of data handling to accomplish a climatological study using hard copy film is large. An effective study for the Sahel region would require approximately four man-years of effort. Such a study could be carried forward using indigenous technician-level meteorologists or junior scientists after a suitable training period and after acquisition of the necessary data and supporting materials. Since 1967, meteorological satellite cloud and window infrared data have been stored in low resolution formats on magnetic tape. The use of the magnetic tape format for a climatic study would expedite the analysis process, but would limit the potential data availability to approximately seven years.

The application of climatological/meteorological satellite data on clouds, and in a broad sense on surface albedo, combined with more conventional ground observations, permits an extension of the standard climatological observations, e.g., rainfall and cloudiness, over much larger areas than is possible with the ground observations alone. This latter fact is important to considerations of dynamic change in the drought condition in the Sahel. The standard observing network is not sufficient to describe the highly variable characteristics of precipitation and cloudiness in space or in time; consideration of this variability should provide an improved understanding of the temporal and spatial variations of agricultural and range forage production.

5.0 SUMMARY AND CONCLUSIONS

It is clear that knowledge of the water cycle on a time and space basis appropriate to range and agricultural interests is a most important subject for considerations of mid and long term improvement in the Sahel region. Even in the short term, i.e., in the current year 1974, knowledge of the spatial variations in precipitation and evapotranspiration would provide information, heretofore unavailable, for assessments of current forage and agriculture conditions. The ground observations available in the region are not adequate to describe the water budget at a scale which would assist range planners or permit direction of nomadic herders into appropriate areas.

The remote sensing techniques described in this chapter utilizing meteorological satellite data represent a new technology that has not been in general use in operations or research throughout the world. However, the techniques do build on existing knowledge and represent a natural culmination and integration of research activities on the applications of meteorological satellites that have been proceeding on a broad front over many years. Limited tests of the work, in Iran and in portions of the U.S., demonstrate that relative water budget information can be derived and that the derived information is reasonably correlated with actual conditions. The most quantitative results may be expected when the techniques are applied in a rigorous systematic manner, i.e., combined in a computer utilizing generally accepted and tested modeling techniques. However, even relatively simple qualitative applications of the techniques discussed yield useful information, particularly in the context of the problems facing the Sahel.

Principal recommendations arising from the foregoing discussions include:

1. Current year meteorological satellite data should be analyzed and applied to the derivation of a range forage potential assessment in the Sahel. This recommendation can be implemented immediately at relatively low cost with minimum start-up problems.

2. A longer range examination of the potential use of meteorological satellite information should be initiated through an evaluation of the historical meteorological satellite data available on magnetic tape since 1967. This evaluation should address the potential for assessing the dynamic spatial and temporal variation in the water balance over the Sahel for the period from 1967 to the present time.

3. Data for the Sahel from both operational and research meteorological satellites should be routinely acquired and analyzed. The availability of high resolution observations, in different portions of the electromagnetic spectrum at different times of day, that are available on newer satellites would permit more accurate analyses of the factors influencing the water budget than are possible using the generally available NOAA low resolution information.

4. Consideration should be given to the establishment of a Sahel water balance evaluation center which could provide invaluable knowledge on the variation in water balance over the entire region. The center could also provide the kinds of information necessary to forecast regional variations of range carrying capacity and regional variations in agricultural production. The data developed in such a center would be

directly applicable to relief planning operations since they would assist in predicting in a timely manner, which areas might require emergency distributions of food products.

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CHAPTER 9

EVALUATING SURFACE AND SUBSURFACE WATER RESOURCES

1.0 INTRODUCTION

Water in the Sahel as in any arid region is the basis of life itself. Most of the regional concerns with water ultimately stem not only from the area's shortages of fresh water, but also from its striking maldistribution in amount, in space, and in time: There were floods in the Niger and Chad drainages in 1972 at the same time that the region-wide drought, now in its seventh year became more serious.

The Sahel region is hot (mean annual temperature 23°C) with the wet-dry rhythm found on the borders of subtropical deserts. Annual rainfall is about 1000 millimeters in the south and 50 millimeters in the far North, 90 percent of which falls in mid-June to October. Evaporation rates are high, and moisture deficits are severe. Rainfall comes in patchy, intense but brief showers and a whole season's rain can come in a few storms. Reliability of rainfall is thus very low.

In this difficult, if not intractable environment, water is demonstrably a most precious commodity. There is a pressing need for a substantial improvement in the data now available on Sahelian water resources. This report discusses how remote sensing can aid water resource management and planning through the inventorying and monitoring of these maldistributions of water, and through the provision of key information for: 1) short-term, emergency action; 2) long term water usage modeling; 3) significant strengthening of existing data; and 4) development of long term plans for improved distribution, storage, and consumption patterns.

2.0 THE NATURE OF SURFACE AND SUBSURFACE WATER RESOURCES INFORMATION

An understanding of water distribution in an area is best approached through analysis of the local characteristics of the hydrologic cycle: the process which defines the flow of water in and on the earth and atmosphere. In the hydrologic cycle of the Sahel, water evaporated from the oceans, from lakes, rivers, moist soil, and transpired from vegetation becomes part of the atmosphere. The evaporated moisture is lifted, transported, condensed and in due course precipitates to the earth. Precipitated water may be intercepted by plants, flow over the ground surface into perennial and non-perennial streams, temporary and permanent lakes, or out to the Atlantic, or may percolate into the soil. Much of the intercepted water and some of the potential surface runoff of the land returns to the air through evaporation and transpiration.

Standing water may percolate downward into groundwater basins where it may be temporarily stored only to flow out at the earth's surface as springs, seep into streams as runoff to oceans, or evaporate into the atmosphere at a later time and complete the cycle. Thus, the flow of water through the hydrologic cycle undergoes multiple processes: evaporation, precipitation, interception, transpiration, infiltration, percolation, storage, and runoff: All of these processes are amenable in part -- and with some definable accuracy -- to remote sensing techniques.

The question of accurately measuring surface and subsurface water with remote sensing is paralleled by concerns on measurement accuracies and limitations in the existing methods for collecting water information in the Sahel. The accuracy of measurement in water management is, essentially, a function of the ease with which the measurement can be made, and the degree of confidence that can be inferred from the measurement in the context of the surrounding environment. The degree of confidence of such extrapolation is, in turn, related to the two principal types of hydrologic measurements involved, namely those which are static or predictably dynamic in a spatial or temporal framework, and those which are unpredictably dynamic.

The most deceptive measurements in tropical arid areas are unpredictable dynamic measurements of soil moisture and evapotranspiration. These measurements are not only difficult to accurately assess in a temporal context, but vary widely over a given area mainly because the initial rainfall distribution is quasi-random on a much finer scale than that of the point ground observation network (weather stations, soil moisture readings, etc.). Conventional point measurements thus are rarely accurate or reliable due to the fact that areal distributions are not accurately known but, rather, are statistically derived on the assumption that a few point measurements may be extended over a large area using linear interpolation and extrapolation. Because of the cost of point ground observations, and their wide spatial distribution, it is important to develop procedures for more accurately extrapolating from and interpolating between ground sites than are now available. There is growing and significant evidence that the combination of aerial and orbital remote sensing with ground point observations can provide the improved data needed. <u>It is in this ability to increase the value of scattered ground observations that remote sensing offers a major contribution to water resource management.</u>

3.0 REMOTE SENSING SYSTEMS AND THE COLLECTION OF SURFACE AND SUBSURFACE WATER RESOURCES INFORMATION

Satellite or aircraft sensors not only may be useful in monitoring continuously and unpredictably changing variables, but also may provide substantially more detailed and unique spatial measurements of static phenomena than existing measurement procedures. For example, relatively static features such as the water surfaces of lakes, rivers, playas, springs, and seeps are readily apparent on remotely sensed imagery. Indicators of water availability such as dry drainage channels (wadis), alluvial fans, floodplains, tectonic disturbances (fractures) and vegetation types and densities may also be observed. Sequential coverage by orbiting satellites allows the dynamics of water occurrences to be monitored over seasonal and annual cycles. Consumptive water demand information (population centers and irrigated or irrigable cropland) can also be identified and related to the location of water supplies on remotely sensed imagery to permit more useful allocations of water over designated areas.

One example of the potential for ground water assessment has been developed by Howe (1958) and Nefedov and Popova (1972) as a series of detailed methods for locating groundwater by photo interpretation of conventional large scale aerial photographs. Both methods are similar and consist of the following steps:

- Delineation of streams, drainage lines, and surface waters on a photo mosaic of the area;
- Detailed interpretation of surface materials and delineation of soil types according to physiography and vegetation;
- Delineation of landforms and land use patterns and correlation with subsurface water conditions;
- Delineation of areas likely to possess water-bearing formations;
- Review of collateral data including well logs, geologic reports, and other information about the area; field check of the problem areas; and
- Preparation of a groundwater map and written report.

Location of groundwater in desert areas is aided by means of vegetation indicators, primarily phreatophytes which develop root systems that come into direct contact with groundwater. By determining the vigor and distribution of various phreatophyte species, it is often possible to ascertain the depth to groundwater, degree of mineralization, and sites where water-bearing horizons are discharging. Howe (1958) concluded that aerial photographs, used to identify a proper choice of sites for exploratory borings, significantly decreases the cost of groundwater exploration.

Small scale synoptic imagery from satellite sensors provides the ability to simultaneously collect hydrologic data over a much larger area and to follow the same sequence of operations as used by Howe (1958), but at a smaller scale. With small scale imagery, the interaction and response rates of dynamic events can be discerned on a regional basis to assess a water budget or water availability scheme. The key to locating surface water on small scale infrared imagery is its distinct tonal signature, the unique linear pattern of most drainage systems and associated riparian vegetation. In combination with sample large scale aircraft imagery of higher resolution and more detail, such imagery can provide a substantial amount of information for hydrologic analysis.

Hydrologic information obtained by remote sensing methods can be stored directly on the imagery (graphic form storage), on map overlays produced from individual photographs or mosaics, or it may be used as inputs to geo-based information systems for ready recall and manipulation.

3.1 SPECIFIC SENSORS AND THEIR APPLICATIONS

Remote sensing and water resources management has been the topic of a recent symposium at which some 45 papers were presented and then compiled and edited by Thomsen, Lane, and Csallany (1973). Much of the material in the following section draws heavily on this current research. It will be cited in appropriate instances to demonstrate specific sensors and applications to a number of topics relevant to the Sahel.

Meteorological satellites such as Nimbus have been applied to terrestrial hydrologic problems on a limited scale. The Nimbus ground resolution will not permit detailed hydrologic analysis, but small scale observations of dynamic phenomena (thunderstorms, cyclone, massive wind systems, etc.) are feasible over large regions. NOAA II and III meteorological satellites have higher resolutions of 0.8 km over certain portions of the earth, and 3 km over the entire earth in the 0.5 to 0.7 micron (μm) wavelength band (Wiesnet and McGinnis, 1973). A more detailed discussion of the use of meteorological satellites has already been given in Chapter 8.

Infrared imagery is of considerable utility and is available on certain satellites. For example, the Nimbus III daytime high resolution infrared radiometer (0.7 to 1.3 μm.), responding to reflected solar infrared energy, can provide a relative estimation of the near-IR reflectivity of terrestrial surficial features in certain situations. Such data can be used to monitor soil-moisture/vegetation conditions and to locate alluvium and sand deposits.

Sequential coverage (18-day cycles) provides, in many instances, the capability to assess and quantify dynamic hydrologic conditions such as flooding, droughts, seasonal changes in amounts of surface water in liquid and solid state, and soil moisture. Enhancement techniques currently being developed will make the imagery adaptable for many additional uses and refine the accuracy of present uses as well.

The data collection system (DCS) on ERTS-1 has proven to be a reliable and rapid means of providing quantitative hydrologic data for operational water resources management situations requiring near real time data. The DCS interrogates remote, automated data collection platforms and relays the data to centralized ground stations when the ERTS spacecraft can simultaneously "view" the platform and ground stations desired. Examples of ground sensors include those providing data on stream flow, water quality, snow depth, snow water equivalence, air temperature, precipitation, and soil moisture. Data from any platform can be telemetered to investigators for analysis within 24 hours of the time the sensor measurements are relayed by the spacecraft. (A ground station would have to be located in Africa in order for this system to be employed in the Sahelian region because of the distances and view angle geometry).

More conventional sensors such as aircraft photographic sensing systems provide larger scale photography and better resolution in comparison to satellite systems. Their utility, however, must be weighed against their comparatively higher cost. Applications must be designed to fit the data objectives. Panchromatic photographs at scales of 1:50,000 and 1:60,000 are useful for the analysis of stream drainage networks, lakes and ponds, and groundwater parameters, because entire landforms, and structural lineaments, are integrated to highlight features. Infrared photography is particularly good for detecting springs and seeps for groundwater analysis. Even larger scale photographs (1:3,000 to 1:12,000) must be used when specific types of indicator plants are to be identified.

Other types of imagery available include color photography, radar imagery, thermal infrared imagery and microwave imagery. Each contributes a unique form of information to hydrologic investigations and merits separate attention.

Color photographs are generally preferred for water pollution analysis. Some factors of importance to pollution studies which are interpretable on color photography are:

- Effluent points, seepage areas, and regions of possible contamination, either not visible by, or removed from, direct ground observation;

- Factors related to water quality, such as water opacity or transparency, color, the local geology, algal growth and bottom or suspended sediments;
- Flow patterns, particularly of currents, affecting the distribution and concentration of injected effluents.

Observing these factors adds a dimension to point biological and chemical tests and sampling because the implications of the point source measurements may escape the biologist if he remains ignorant of upstream or other local conditions not observable at the sampling station alone.

Radar can supplement aerial photographs as well as be the sole data source or source of preference in cloudy, remote, unmapped regions where very large areas need coverage for national water resources planning. Drainage patterns can be mapped with radar imagery. Regional variations in drainage patterns, drainage densities and other expressions of drainage composition can thus be compared visually and quantitatively. Distances and areas can also be scaled with sufficient accuracy for rapid reconnaissance hydrologic studies.

Thermal infrared imagery may prove useful in the near future for ground water exploration and mapping; in particular, prospecting for, detecting and mapping shallow aquifers. This technique is based on the comparative thermal effects of water, with a high specific heat, and geological materials. Water-saturated materials will act as a heat sink in summer and as a heat source in winter. A shallow aquifer will, therefore, cause soil temperature above the aquifer to deviate from a normal occurrence. Measurements of this thermal anomaly may be used to delineate shallow aquifers.

Passive microwave radiometers aboard the Nimbus 5 and proposed Nimbus F meteorological satellites have demonstrated the capability of measuring soil moisture to a far more specific level of accuracy than is possible using other satellite sensors. Schmugge et al. (1972) found a linear increase of 2 degrees Kelvin per one percent change in soil moisture above a soil moisture content ranging from 10 to 20 percent. The value of the lower threshold of sensitivity of the radiometer depends on the soil type and may be related to the wilting point of the soil. This ability to sense soil moisture in specific wavelengths of registration in the radiometer, however, has been found to decrease both by surface roughness and vegetative cover.

Several other sensor packages are currently operational aboard a wide variety of aircraft. These are used for geo-magnetic surveys, subsurface geologic mapping, ground water elevation, identification of mineral deposits, soil moisture monitoring, and several other applications.

Techniques include gamma ray, resistivity, and aeromagnetic sensor packages, all providing low altitude, high resolution measurements of earth resource information over specific areas.

Many applications of remote sensing technology find a multi-staged approach beginning with satellite data as a synoptic and sequential viewpoint, useful and cost-effective, particularly in geologic research and mineral exploration (see Chapter 6), and equally in water resources studies. Satellite data are first used to make a regional appraisal of water resources. Large scale, higher resolution aircraft surveys are then employed to refine and supplement the data base for those areas deemed most critical for defining the quantity and quality of surface and subsurface water resources. Using satellite data to target more detailed data collection minimizes the economic losses common to conventional site investigations which are conducted without an overview stage.

Remote sensing systems often provide surrogate information, i.e., indirect links between the phenomena measured and the management application of that measurement. Information required for the measurement of one hydrologic variable is often useful for assessing other hydrologic variables as well. For example, the derivation of evapotranspiration requires measuring soil types, soil moisture and distribution, and the type and vigor of vegetation, variables which contribute in varying degrees to the measurement of soil moisture, groundwater flow, water quality, and other hydrologic variables. The ultimate effect of this duplication permits unique inferences about processes that are not directly observable. A matrix encapsulating the more common relationships between the operational and projected satellites, the observable measurements, and water resources management objectives is presented in Figure 9-1.

4.0 APPLICATIONS OF REMOTE SENSING TO THE SAHEL ENVIRONMENT

The Sahelian region covers a vast surface area (approximately three million square kilometers) where surface water is poorly distributed. Extremes are wide regionally, seasonally, and cyclically. Generally, surface water is scarce or occurs only temporarily during the rainy season when it may cause annual flooding on the Niger and Bani River watersheds. Data concerning water resources is meager, and furthermore, the location, quantity, and quality of subsurface water is unknown for much of the region at present. Hydrologists studying its occurrence, utilization, and management have as yet been unable to develop the information necessary to effectively and rapidly improve the present conditions.

		Precipitation Rate (rain)	Precipitation Distribution (rain)	Snow Extent	Snow Density	Vegetal Type	Vegetal Vigor	Soil Wetness	Soil Type	Structure/Land Forms/Geology	Cloud Type	Cloud Distribution	Surface Temperature	Air Temperature	Water Body Extent	Water Body Depth	Water Body Transparency	Water Color
1976 - 1980	WMO, USGS, SCS, & Other Surveys	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3
	Aircraft (Vis & IR) as needed	2	2	2	1	2	2	2	2	2	3	2	2	2	3	2	2	3
1974 - 1976	ERTS-A (visible) 200ft/18days		2	2	1	1	1	2	2	2	3	2	2		3	2	2	1
	NOAA-2 (VHRR-visible).33mi/12hr.		2	2	1						3	3			3			
	NOAA-2 (VHRR-IR) .33mi/12hr.	1	2	2							2	2	2	2	3			
	NOAA-2 (SR-Visible) 2mi/12hr.	1	2	2							3	3						
	NOAA-2 (SR-I) 5mi/12hr.	1	2								2	2	2	2				
	NIMBUS-5 (THIR) 49.mi/12hr.	1									2	2	2	2				
	NIMBUS-5 (ESMR) 15.6mi/12hr.	2	2	1	1			2										
CURRENT	DAPP (Visible) .5mi/12hr.		2	2	1						3	3			3			
	DAPP (Thermal-IR) 2mi/12hr.	1	2	1							2	2	2	2				
	Goes ATS-F (Visible) 12mi/20hr.	2	2								3	3						
	Goes ATS-F (IR) 9.6mi/20min.	2	2								2	2	2	2				
	NIMBUS-F (THIR) 4.9mi/12hr.	1									2	2	2	2				
	NIMBUS-F (ESMR) 15.6mi/12hr.	2	2	1	1			2										
1976 - 1980	ERTS-B (Visible) 100ft/18days			1	1	1	1	1	1	1	3	3			3	1	1	
	TIROS-N(Vis.-IR) 528ft/12hr.	1	2	1	1	1	1	1	1	1	3	3	2	2	3			
	EOS/NIMBUS-G (Vis.-IR)/12hr.	1	2	1	1	1	1	1	1	1	3	3	2	2	1			

Code A: Information Sources/ Outputs

Blank = contribution insignificant. (future application potential insignificant.)

1 = contribution not demonstrated but promising for future applications

2 = contribution significant but requires additional verification.

3 = contribution substantial: requires no additional verification

CONDITIONS:

The applications of these relationships imply a suitability only to areas where the effects of cloud cover, vegetation, topography, size of observed area, and rate of change and annual variability of climate are not deleterious to the sensor discrimination, and vehicle frequency of coverage. Several alterations would be required in the matrices if these variables were interposed.

Figure 9-1 Remote Sensing Assisted Water Management Systems

Meeting the fundamental set of management objectives necessary for survival, such as the development, processing, storage, and transportation of water as a raw material for agriculture, industry, recreation, and domestic uses, is essential and highly important to this region. Additional management objectives, such as the protection of vegetation and control of erosion and sedimentation on watershed lands are of indirect but equal importance. Several principal data requirements are basic to understanding, managing, and protecting these water resources properly. These data requirements include: a) drainage basin morphology; b) location, quantity, quality, and timing of surface water runoff; c) timing and areal extent of floods; d) location, quantity, and quality of sub-surface water; and e) trends, sources, and rate of travel of water pollution. Each requirement will be treated separately in the following discussion.

4.1 DRAINAGE BASIN MORPHOLOGY

A map of the major drainage basins is a basic requirement in a general inventory of water resources. Delineating the perimeters of drainage basins divides a large land mass into more manageable units where estimations of runoff, flood probability and direction of water movement can be evaluated. Stoertz and Carter (1973) demonstrated the ability to map drainable divides of 184 closed basins in an arid region encompassing 440,000 square kilometers in South America, using 1:1,000,000 scale ERTS-1 multispectral scanner images. Synoptic coverage (34,200 square kilometers per frame) was particularly useful for this work. Surveys of this type are often impractical, if not impossible, by conventional methods (Salmonsen and Rango, 1973).

The geologic structure and landforms which influence the behavior of all hydrologic events in a basin can be identified. Water is not only controlled by the present landforms, but also is one of the chief agents of change of the landscape. A knowledge of drainage basin morphology, i.e., the landforms, their geologic structure and history, drainage texture and density, aids the hydrologist in explaining many of the hydrologic processes occurring within a particular basin. Some of these processes are water quality, water storage capacity, quickness of response of stream flow to storms, and areas of potential erosion.

Tueller and Lorain (1973) evaluated the capability of ERTS-1 imagery of the arid Great Basin region in Nevada to delineate mountains, valleys, playas, stream courses, canyons, and alluvial fans. Band 5 was found to be most useful for identifying general landform features. The location of water bodies is most apparent on Band 7 (Burgy, 1973), and water bodies as small as one

hectare in size can be discerned (Salmonsen and Rango, 1973). Baumgardner, Kristoff, and Henderson (1973) identified the broad soil patterns of clay loams, fine sands, and fine sandy loams on Band 5 over sub-humid Lynn County, Texas, using computer-implemented overlay techniques with ERTS data. Such information is useful for identifying the relative permeability of basin areas.

The delineation of vegetation within drainage basins provides useful hydrologic information by indicating the presence of both surface and subsurface water and the relative amounts of rainfall and soil moisture throughout the drainage basin. Lauer and Krumpe (1973) conducted a cost-effectiveness study of the vegetation inventory process using conventional black and white photography as compared to U-2 highflight and ERTS image y interpretations of the Feather River watershed in California. Application of these data suggests a potential cost-effectiveness of between 1:9 and 1:20 for ERTS in comparison to highflights and conventional methods, despite having less detailed information from the satellite imagery. A second major benefit potentially derivable from an ERTS-based inventory system is the timeliness of results created by the short time lapse (speed of accomplishment) between initiation and completion of inventory projects. These advantages are more likely to be realized when the overview is conducted by trained personnel with or combined with sufficient local experience. It has been demonstrated in many instances that local experience is indispensable in minimizing ground truth investigations before going operational with an inventory program.

The preliminary inventory of drainage basin morphology and vegetation based on ERTS described above provides a static view of surface and subsurface water containment and transitory corridors, and potential problem areas such as saline water or soils, flooding, erosion, and sedimentation. Such a survey combined with land use, agriculture, and range resource surveys would provide a rational basis for ranking hydrologic basins by their potential to yield surface and subsurface water. Larger scale and higher resolution, stereoscopic viewing capability of conventional aircraft imagery can then be used in the most important or strategic basins to add detail to the ERTS inventory. Blanchard (1973) has measured watershed runoff capability on the basis of ERTS data and Soil Conservation Service ground observation parameters, such as slope, vegetation, soil type, basin drainage configurations, and other parameters which lend themselves to ERTS and/or aircraft observation. Integrated values which he derived to reflect these conditions, plotted as C.N. numbers (curve numbers), related very closely to specified runoff volumes when known precipitation values were input to the graphs.

The implications are very promising for this research, for if it is possible to establish relationships between surface observations and runoff in well-gauged areas, it should be equally possible to extrapolate to ungauged areas with similar or known ground conditions. Assuming this research will continue and be expanded, it may be possible to develop an acceptable procedure of estimating surface runoff on the basis of satellite observed data.

Application of this research to the Sahel would be of profound importance to hydrologists for it is precisely in sparsely populated and isolated regions where many developing nations lie that ground truth data to derive the basic water balance data is lacking.

4.2 LOCATION, QUANTITY, AND QUALITY OF SURFACE WATER

The ERTS system provides two means of obtaining quantitative data on surface water volumes, quality, and timing of flow. The first method involves the data collection system (DCS) which interrogates ground systems, collects and relays information; the second is that of assessing surface water volume changes from image products (Figure 9-2). The data collection system on ERTS-1 has proven to be a reliable and rapid means of collecting and relaying data on precipitation, stream flow and water quality, so that it can be used in operational water resources management situations requiring near real time data. Schumann (1973) documents the example of stream flow information on the Verde River Watershed in Arizona being needed on an emergency basis (because of microwave telemetry failure) in order to determine the amount of water to be released from a key reservoir. The required information was relayed from the headwater portions of the watershed via satellite to Goddard Space Flight Center and, subsequently, to the Salt River Valley Water Users' Association in Arizona within 1/2 hour. As a result of this information, it was determined that excess amounts of water did not have to be released and, therefore, highway closures due to flooding were reduced by 70 percent in the Phoenix area. Applications of the DCS for ground monitoring a vast range of dynamic phenomena in isolated regions are obvious.

In other applications, data from 20 stations collecting water quality, stream flow, and observation well information were relayed in near real time from the Delaware River Watershed via the data collection system to the Delaware River Basin Commission (Paulsen, 1973). Water level and rainfall information was collected in Florida and relayed to water resources management agencies in 30 to 45 minutes (Higher, Cordes, and Coker, 1973). Areal information from the satellite and ground based information allows volumetric estimates to be made. This capability permitted definitive assessments of moisture conditions in wildland situations for

Figure 9-2: Lake Chad, Lower Chari River and Eastern Chad

Figure 9-2 is an enlarged portion of an ERTS image (scale 1:870,000) taken in December 1972. It covers part of western Chad and the eastern half of Lake Chad. The lake sits in a low part of the Chad depression, one of the largest areas of internal drainage in the world. The Chari River is shown flowing into the lake from the south. As can be inferred from the spread of water surface between sand dunes to the north, the lake is very shallow with maximum depths seldom exceeding 20 feet. The surrounding land is of gentle gradient. Seasonal fluctuations in size are the rule, and the decrease in area that follows the period of maximum runoff is closely followed by agriculturalists who raise crops and livestock in the residual soil moisture left by the receding lake.

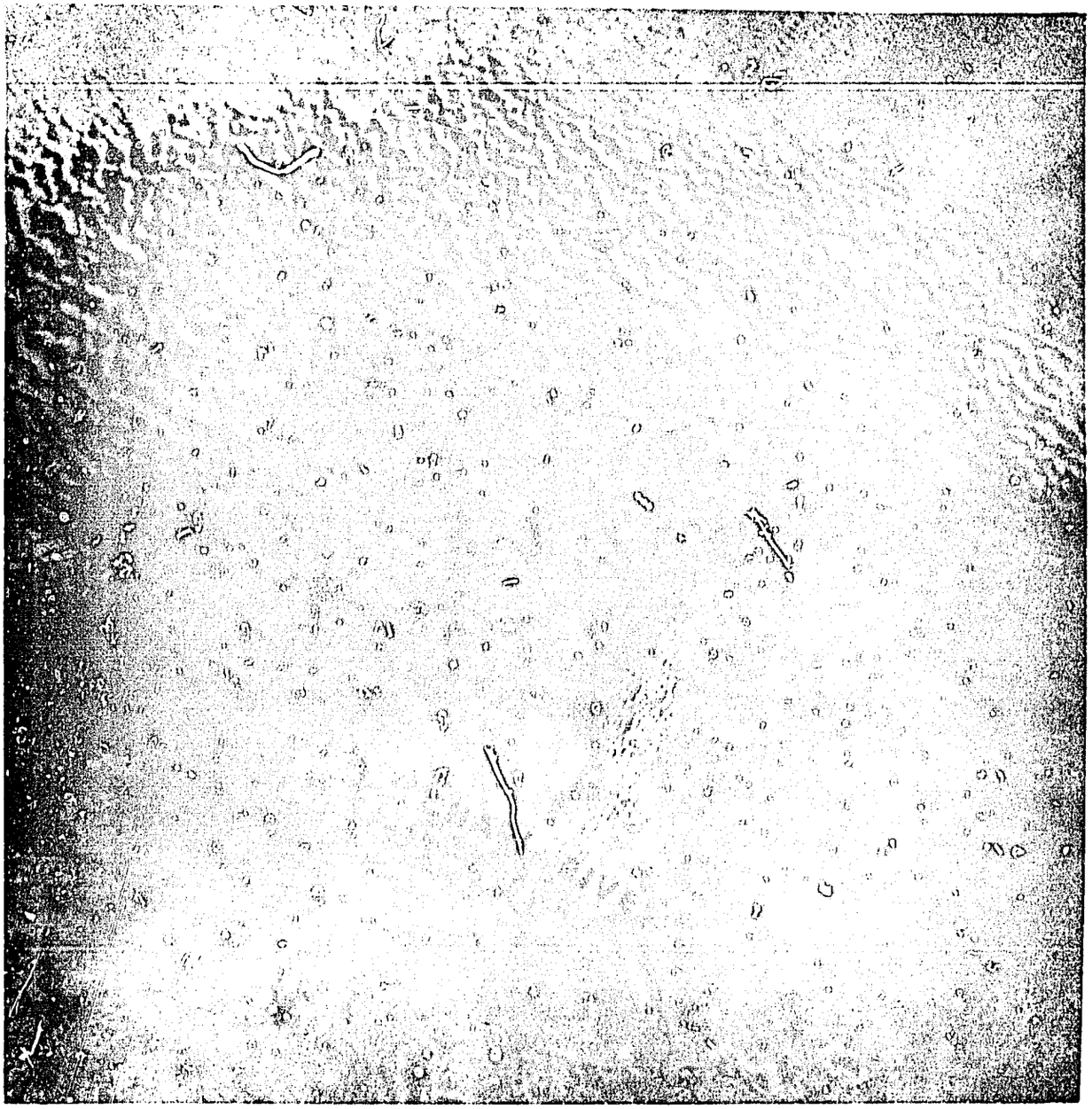
The lake shrinks and expands in a seasonal rhythm that is always apparent but never regular with respect to amounts of water or temporal periods. Usually, however, the lake decreases in size from December to July and expands from August thru November. The water surface in this image is represented in shades of red which indicates relatively high sediment content. The lake level is high as a result of heavy rains that fell to the south of the Sahel in 1972.

Green tones indicate the presence of vegetation concentrated along the lake shores and river valleys. Variations in tone which extend horizontally across the image originate in the image producing system and do not represent true environmental conditions. Yellow tones between valleys on drier upland sites do not indicate a complete lack of vegetation. Typical plant growth in these savannas away from the rivers is relatively sparse and therefore does not register on the image.

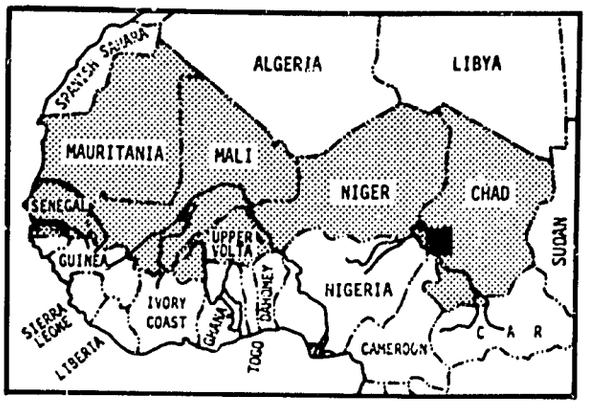
The northern and southern lake shores form contrasting environments. Lake Chad's southern edge is composed of re-worked fluvial and deltaic sediments deposited by the Chari, Logone and lesser north-flowing rivers. Textures of this material are fine, and soils are dark and heavy. The northern lake shore is composed of aeolian deposits, primarily transverse sand dunes which have been deposited by dominant north-easterly winds, and somewhat re-worked by seasonal flooding. The textures of these sands are quite coarse and colors are lighter.

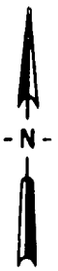
These contrasts which are apparent on the image are closely related to the way the environments are used by the people of the area. Although by generalizing one risks over over-simplifying the situation, agriculturalists to the south plant and farm the lake bed as the waters recede; wells are dug to the water table for livestock; and the entire area where soil moisture conditions permit is intensely utilized. To the north, the interdune low areas are sometimes planted, and natural vegetation growth above the water line and below the dune crests are utilized by grazing animals.

ERTS imagery, obtained at 18-day intervals in this area of largely exotic streams and lower cloud cover, can readily monitor charges in surface hydrology including lake-fill and shrinkage, as well as the parallel greening of the flooded areas. Such data can be used in forecasting amounts of available feed and foodstuff once initial calibrations were developed over several years of testing.



LAKE CHAD, LOWER CHARI RIVER AND PART OF EASTERN CHAD





protection of multitudes of animals highly dependent upon water, a problem which is particularly acute in a drought situation and equally relevant to the Sahel despite its greater aridity. A preliminary cost-benefit analysis indicated that $2.5 million per year could be saved in this application alone if the availability of these data were assured from a satellite, and a management model was implemented. A data collection system in the Sahelian region that rapidly collects quantitative hydrologic data over widely separated and remote regions would greatly alleviate the lack of basic ground level data.

Delineation and measurement of the surface area of lakes, ponds, and playas on satellite or aircraft imagery is another method of quantifying surface water. Tueller and Lorain (1973) inventoried and measured the surface area of reservoirs, lakes, and ponds in arid Nevada on ERTS imagery. Each water surface was analyzed for areal changes as imagery became available. Changes could be related to water consumption, evaporation, and climatic conditions, in order to derive a continuous inventory of the amount of potential irrigation water available and the rate of use, all of which are important considerations in an arid environment. Temporal and spatial changes of water surfaces in the playas of the Texas High Plains were observed in sequential ERTS-1 coverage by Reeves (1973) and Baumgardner et al. (1973), to determine the water balance of an area, the amount of water subject to evapotranspiration, and the location of areas contributing to groundwater contamination. With several years of data collected, the areal size of playas may be used in climatological research to provide an index of how dry or wet the region is likely to be in relation to normal years.

Work, Gilmer, and Kiett (1973) compared ERTS-1 and aircraft multispectral data over North Dakota as a means to evaluate the capability of satellites to detect numbers and distributions of prairie ponds and lakes. Using a level slicing technique, recognition maps were generated from Band 7 and surface water areas larger than two acres recognized; ponds in the one to two acre range were detected only randomly.

Another application of volumetric estimates by ERTS-1 remote sensors has been suggested by Burgy (1973), for lakes and reservoirs where direct inflow is retained for substantial periods of time. While surface area increases toward maximum state and spillage or overflow is allowed to discharge to downstream channels, inflow volumes may be determined and correlated to watershed runoff for yield estimation during the time period. Sequential coverage by remote sensing

platform can thereby augment the data base for yield prediction in undeveloped areas, or where little hydrologic information is available.

The ability to delineate water depth on ERTS-1 imagery is still in the experimental stage. By taking advantage of the various spectral bands and image enhancement techniques, Burgy (1973) reported that differences between Bands 4 and 5 may be used for sounding water depth since the 0.5 and 0.6 μ wavelength (Band 4) penetrates water more deeply than the 0.6 and 0.7 μm length (Band 5). This technique (sounding of water depth), when developed, would be particularly useful in remote areas in the Sahelian region for obtaining accurate volumetric measurements of water bodies.

4.3 TIMING AND AREAL EXTENT OF FLOODS

Repetitive ERTS-1 coverage allows rapid appraisal of the areal extent of flood inundation for up to seven to ten days after flooding. Those areas affected by severe sediment deposition and erosion following large floods may also be observed and delineated on ERTS-1 imagery. Hallberg and Hoyer (1973) compared the capability of satellite imagery with low altitude aircraft imagery and ground methods for mapping late summer floods in southwestern Iowa. ERTS and low altitude aircraft interpretations were comparable at a scale of 1:250,000 with complete agreement on 80 percent of the area mapped. Since inundated areas have sharply reduced infrared reflectance caused by surface water, excessive soil moisture and stressed plants, flooded areas were readily apparent on the near-infrared Band 7.

Following a severe flood in the Gila River in Arizona, Morrison and Colley (1973) found the inundation limits mapped from ERTS-1 imagery agreed well with those obtained by aircraft imagery and ground surveys during the flood. Areas of severe erosion and sediment deposition were identified on Band 5 as light-toned strips inside the inundated belt which appeared dark on the infrared bands.

In both the Iowa and Arizona flood studies, the time required to map the flood inundated area was an order of magnitude smaller than that required by low altitude aircraft surveys. ERTS-1 area coverage also permitted flood mapping to be extended to areas and rivers not covered by aircraft surveys. Satellite imagery can also be used to inventory regional implications of flooding for flood planning purposes, to assess floods and to determine where relief operations are required, and to evaluate conditions in the source areas. Deutsch, Ruggles, Guss and Yost

(1973) demonstrated capability to rapidly inventory the extent of flooding along a 1,200 mile reach of the lower Mississippi River. Such capability may make satellite remote sensing an important tool in the poorly mapped, inaccessible areas of the Sahel.

In the Sahelian region, two operational applications of flood inundation mapping from satellite imagery have been reported. Rabchevsky (1971) reported that tonal variations brought about by soil moisture and vegetation changes in the Niger River Valley observed on the Nimbus III infrared imagery correlate well with regional climatic and meteorological conditions. He also delineated flooded areas of the Niger River delta during the wet season through increased soil moisture and vegetal growth recorded in the 0.7 to 1.3 μm band ranges.

MacLeod (1973) has obtained good ERTS-1 imagery of the maximum flood stage on the Niger and Bani River watersheds and assessed the size, timing, and areal extent of the annual flood -- data of particular interest to nomadic herdsmen, who bring their cattle to the Inland Delta each year to forage; to fishermen, who harvest 50,000 tons of fish from the Niger each year; and to cultivators in the Delta. Final results of MacLeod's analysis have not as yet been published.

4.4 LOCATION, QUANTITY, AND QUALITY OF SUBSURFACE WATER

A primary resource management problem in the Sahel region is identifying the location of groundwater so that it may be developed for livestock production, cultivation, and domestic use. Groundwater surveys normally are initiated by surveying the surficial geology to identify and delineate local geologic materials important in water storage, and their transmission and chemical qualities. The general lithologies which may be discerned are indicative of type and sorting of the sediments present and, thereby, the water transport mechanism. These can often be inferred through accurate identification of the landforms in the area. Vegetation vigor of phreatophytes, as related to the soil moisture regime, provides important additional inputs into hydrogeological mapping efforts.

Several procedures for utilizing satellite data in operation groundwater surveys were tested by Moore and Myers (1972) in sub-humid South Dakota. They concluded that both manual (visual) and automated (machine) analysis of ERTS and ITOS-type satellite data can be used effectively to discern surficial deposits. Ninety-four percent correct recognition of data from six different geological materials was accomplished with the techniques of data averaging, multispectral analysis, and assessments of reflectance change with time.

Satellite data have many applications in hydrogeologic mapping and can be acquired at minimal expense to the user. While aircraft data provides better resolution characteristics than satellite data, the cost of broad coverage may be too great for operational programs in an area as large as the Sahel. A choice among sensors and combinations of sensors (e.g., multi-stage approach) must be based on cost-effectiveness in specific applications. The sequential coverage and synoptic view of satellite imagery has often been found to be of greater value to the interpreter for hydrogeologic mapping than the better resolution of limited areas in a non-sequential pattern provided by aircraft imagery (Moore and Myers, 1972).

The inventory of natural resources in the Republic of Mali in Sahelian Africa using ERTS-1 imagery has already begun. MacLeod (1973) has reported preliminary results which demonstrate that stream beds, lake beds, lineaments and drainage patterns can be observed on ERTS-1 imagery and used for mapping potential groundwater resources. In one area of Mali, he found no surface drainage ways of any substance, indicating very porous soils for this region. The absence of surface drainage ways may suggest the presence of shallow aquifers which could be developed for livestock watering points for nomadic herds. Another application was the delineation of zones of potential recharge for groundwater supplies. Delineation of such recharge zones would aid in more efficient management of water quantity and quality.

Thermal infrared imagery may provide a means of locating shallow groundwater aquifers within the Sahel but this technique is at present operationally untested. In South Dakota, Moore and Myers (1972) evaluated remotely sensed thermal data with the use of a theoretical model of the soil thermal regime and temperature observations in a deep well. A map of sand and gravel thickness of the Sioux Basin was prepared by interpreting predawn, August thermal data. Predawn thermal missions were employed to obtain minimum interference from surface characteristics such as surface soil moisture, evapotranspiration, ground shading, slope aspect, and albedo. Significant correlations (at the 0.05 level of confidence) were obtained when comparing well-log temperatures with surface thermal emittance for the thickness of sand and gravel in the 0 to 15.3 meter profile.

4.5 LOCATION AND SOURCES OF WATER POLLUTION

Reflectance variations of water bodies due to variations in depth, suspended sediments, pollutants and biological activity of various kinds, are readily observable on ERTS-1 imagery with the state-of-the-art technology. Such variations have been repetitively observed over

rivers and water bodies, particularly in Bands 5 and 6 observations. Representative results for Lake Ontario (United States - Canada) were reported by Falconer et al. (1973) and Pluhowski (1973). Other results, by Burgy (1973), concerned turbidity in Lake Berryessa (California) and algal growth in Clear Lake (California). The turbidity patterns at a given time were found to be qualitatively associated with the discharge of rivers into larger lakes, to circulations within the lakes themselves, and to shoreline erosion processes. Changes in the extent and shape of turbidity patterns were related, inferentially, to variations in wind flow direction and drainage variations in rivers.

Except for certain controlled research studies, aerial water quality measurements to date have been restricted almost exclusively to qualitative or semi-qualitative observations of relatively large scale effects. The reason is the inability to remove masking effects that obscure the true reflectance of water bodies, effects such as source effects, atmospheric effects, and surface reflections (principally skylight reflection). Piech and Walker (1971) developed the scene color standard (SCS) technique which allows for removal of these peripheral effects in water quality surveys. The SCS technique utilizes natural objects of known reflectance, coupled with certain characteristic shadow areas within the scene, to remove the aforementioned peripheral effects. As a result of this procedure, accurate reflectance for many water bodies can be determined inexpensively and over large geographical areas. Strandberg (1967) gives detailed methods for aerial water quality surveys, but these are too voluminous to include in this report.

In summary, aerial photographic interpretation techniques add to, but do not replace, existing field and laboratory water quality analysis methods. Critical areas which require field work can be located rapidly with aerial reconnaissance, thereby reducing the time and money spent on field work, and leaving more for laboratory analysis and corrective action. The techniques of locating and monitoring sediment-produced turbidity in the rivers, lakes, and reservoirs of the Sahelian zone would permit sources of erosion to be isolated and, hence, contribute towards an understanding of the hydrologic processes in the region.

5.0 PROBLEMS AND LIMITATIONS

Several problem areas of remote sensing for hydrological analysis in the Sahelian region are listed below. Each problem applies mainly to one sensor, primarily the photographic remote sensors. In many cases, the sensors unaffected may offer supplementary data.

1. Cloud cover, by obscuring the surface of the earth, easily comprises the most serious limitation to water resource assessment from space imagery in the visible and infrared spectrum; primarily the photographic remote sensors are affected. The more arid portions of the Sahelian zone would probably be relatively cloud free; however, in the more humid regions, important hydrologic events may be masked by cloud cover during the rainy season. Nightime thermal IR on a possible ERTS-C satellite, modest resolution meteorological satellite imagery at several times each day, and in the future possible radar imagery from Shuttle may reduce this problem substantially.

2. The Harmattan haze, which extends over the region in varying proportions through nine months of the year consists of dust storms that block out the shorter wavelengths of visible light which are normally recorded by several satellite and aircraft remote sensors. The problem occurs sporadically and has an undefined nature requiring further definitive research.

3. The 18-day repetitive coverage of ERTS is considerably longer than the optimum for study of dynamic hydrologic events. Runoff and stream flow from precipitation, and its effect on the environment (increased soil moisture and vegetal bloom), may be missed depending on its timing in relation to orbital passes of ERTS.

4. The low spatial resolution of satellite imagery, although advantageous where regional analysis is of major importance, is a limitation in acquiring detailed information. It is, however, not a barrier to applying the imagery as a targeting device for higher spatial resolution imagery from aircraft supplemented still further by limited ground observations.

5. The volume of water in lakes and reservoirs is more important than the surface areal extent information currently available from remote sensing means. Other means of estimating water body volumes in remote, unsurveyed, or inacessible regions need to be explored. One possible means of doing this would be to establish area/volume empirical relationships that apply to topographically well-defined areas.

national assistance. In many instances -- such as non-technical applications where identification is important -- the imagery, once interpreted for basic parameters, could be distributed and interpreted with minimum training on a more localized level for use within a specific community. The ultimate effect of this would be to encourage, in an open and fruitful manner, the kind of activity that is most sought after: development with self-initiative, using indigenous skills, encouraging national solidarity and ultimately international cooperation, rather than international dependence.

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CHAPTER 10

SOIL SURVEYING AND MAPPING

1.0 INTRODUCTION

In planning agricultural development and range improvement programs, information on soils and their relationships to vegetation growth is essential. When such information is available, it can be used to plan more detailed studies for specific agricultural and range programs, such as irrigation projects, improved forage areas, and potential agricultural areas. The essence of reconnaissance scale soil mapping utilizing very small scale black and white photography, trimetrogon photography*, and now ERTS imagery is that there are explainable and rational relationships between soils and their distribution over the landscape. These relationships enable experienced soil scientists with a small amount of field work to map soil associations -- soils repeatedly found together -- at scales of 1:200,000. The amount of field work necessary is a function both of the training and experience of the soil scientists and of the complexity of the landscapes. The simpler the landscape, the more supporting material available, and the greater the experience of the soil surveyor, the more modest the demands for field work at reconnaissance scales.

The spatial relationship between soils, and geologic and geomorphic patterns has repeatedly been observed. This association has led to the establishment of distinct landscape units which may be mapped in the physical environment. Examples of representative soil and landform associations follow:

1. A small mesa or table-like plateau can form a soil association. The flat top of the mesa may be gently undulating and contain two or three soils intimately related to position on the slope and the varying drainage conditions. If the association is a simple one consisting merely of three soils from the crest and midslope to lower slope positions it is often referred to as a catena, the succession and association of soils along a slope, following the terminology introduced by Geoffrey Milne in East Africa in the mid-1930's.

2. Another quite common soil association is that found on sand dunes; again in a rather simple catenary pattern (see also Chapter 7), running from the denuded and frequently blowing dune crest through mid-and lower slopes. The lower slopes often contain phreatophytes and merge into the inter-dune troughs where small saline ponds may be found.

* Trimetrogon photography consists of three photographs obtained by three cameras, one vertical and two mounted obliquely in order to photograph both the horizon and a small part of the area covered by the vertical camera. These are exposed simultaneously and thus photograph a strip of ground extending from horizon to horizon.

3. Extensive areas of dissected hilly acid basement rocks, with a suite of soils reflecting the various positions available for soil development;

4. Areas of basic intrusive or extrusive rocks which tend to have either high base status or high iron status soils;

5. Areas mantled with fine loessial dust from the working of sand dunes;

6. Areas mantled with saline materials derived from the wind working of salt pans and scalds with downwind accumulation of salty materials;

7. Areas of residual lateritic ironstone material dismembered and dissected in various ways.

The examples given above indicate typical soil and landscape associations which make mapping unit designation feasible. Notice that these associations consist of either a geomorphic unit such as a relict mesa surface, or an ancient alluvial fan, or a major geologic rock type which is dissimilar to the surrounding rocks and on which different dissection patterns are observed. All of these components show an orderly and understandable relationship between the landscape mapping unit and the soils contained within that unit. The designation of the soil association mapping unit, however, requires extensive field work in order to build up knowledge and assurance that the mapping unit is legitimate.

Before considering the details of remote sensing experiments and soil association mapping it is appropriate first to consider some of the peculiarities of the Sahelian area with respect to soil development: the area is indeed complex and parallels the complexity found in the fringes of the Kalahari Desert in South Africa and the desert fringes of central Australia. All three areas have been characterized by striking climatic changes which have left a distinctive stamp on the region's soils.

2.0 SAHELIAN FACTORS OF SOIL FORMATION

It is widely known that many parts of the world have been subjected to major climatic changes over the last million years or so and to a greater or lesser extent these changes are evidenced in the relict soils. The effect of these changes has been most striking on the fringes of the subtropical desert areas, like the Sahel. These regions have experienced rainfalls distinctly heavier and lighter than those of the present. These violent swings in rainfall and accompanying vegetation cover have produced a complex mosaic of landform types and associated soils of different ages.

If the soils in the Sahel had formed on fresh parent materials during the last few thousand years a simple pattern would be found from south to north. In the southern areas where rainfall averages around 1,000 millimeters, basic rocks such as calcareous sedimentaries and basalts, would have soils possessing high iron content and in the lower slopes dark colored soils containing calcareous concretions would likely occur. More acid rocks found in this area, such as sandstone and granite, would likely have leached acid soils comparable to the lateritic podzols of northern Australia. In the subhumid zones with an annual rainfall between 750 to 500 millimeters, soils developed on basic rocks would contain calcium carbonate and have high general fertility levels. On the desert fringes, 250 millimeters or less of rainfall, salinization would be common, and saline clays and mobile sand dunes and sheets would be observed. In broad outline this sequence of soils is observed today, because the most significant factor in soil development is that of the present climate. However, the picture is more complex due to the striking changes in climate and in erosion, dissection, and valley filling that occurred on the diverse rock types in the Sahel during the Pleistocene and Early Recent geological periods. Thus, superimposed on a simple south to north gradient in rainfall with a change from acid through calcareous to saline soils is a complex landscape and soil elements which mark earlier episodes of climate and erosion.

The evidence of these changes is widespread. In the Tibesti Massif cave paintings of deer are found along with acid, high iron soils that cannot form under today's arid climate. Nearby there are saline soils which could not have formed at the time when the high iron soils were formed. In many areas of the southern part of the Sahel there are extensive dune fields which are fully vegetated today but which could never have arisen in the present environment.

The interlacing in time and space of these humid-arid cycles on varying rock formations, and resulting landscapes is further complicated by dust accretions from Harmattan winds during late Pleistocene and Recent time and the redistribution by wind of saline materials from interior drainage basins. In combination these influences have produced a complex group of soils in the Sahel. While general soil associations can be obtained from remote sensing applications, detailed soil mapping requires the skill of the soil geneticist, geomorphologist, and Pleistocene geologist to unravel.

Thus the soil surveyor, in developing his mapping procedures must be conscious of the present and past climates in an area, the present vegetation and other organisms that help to make up

soil, the patterns of topographic dissection and relief, the nature of the soil parent materials, and the length of time over which any soil forming process has continued. He must also observe the relics of past conditions shown in fossil soils, and the abundant examples of soil polygenesis.

The experienced soil surveyor in the Sahelian region will use this intimate knowledge of the various ways in which the factors of soil formation have operated, region by region, to map soil associations. This intimate knowledge can only be gained by field work.

3.0 THE NATURE OF SOIL ASSOCIATION MAPPING AND SURVEYING

A soil surveyor confronted with the task of reconnaissance soil mapping and evaluation would go about his work in much the same manner whether he used Earth Resources Technology Satellite color-combined images, black and white trimetrogon photography, or radar imagery. His work would be easiest with the Earth Resources Technology Satellite images because they may be readily mosaicked, and because the color combination images provide a high quality, uniform mapping base which sensitively displays the natural landscape units. Trimetrogon and vertical black and white photography which would normally be used in the absence of ERTS-1 images suffers from the disadvantage of the obliquity of the photography and inability to effectively and simply map and mosaic large areas at suitable working scales (1:1,000,000 to 1:200,000). Radar imagery has been used in the Amazon Basin primarily as a mapping base for designating natural landscape units. Its value in the Sahel would be marginal for soil mapping, since the whole area has already been covered with ERTS imagery.

The first step in using small scale imagery would be the preparation of a large mosaic. Clearly, ERTS offers the opportunity for a unique broad area coverage mosaic to be prepared where soil boundaries can be delimited. Scales between 1:1,000,000 and 1:200,000 are appropriate for producing large area maps with ERTS depending on the detail of the mapping program.

The next step would be to designate mapping unit classes which appear to be distinctive landscape units for later field sampling. Existing soils data plus vegetation maps of the area would be used to develop the preliminary legend.

The third step would be to judiciously field sample as many of the landscape units as necessary to verify the boundaries and to establish the within-landscape-unit soil associations. With the ground observations in hand the map could then be revised, extended, updated and finally brought to publication. The essential features of the process are to use ground observations

to confirm the within-class characteristic of the mapping units, to modify the mapping units, and to break out internal subdivisions within the mapping units. The role of the photographic or spacecraft data is simply to provide the broad overview and perspective necessary to map effectively these spatial associations. Very small scale imagery, such as ERTS, is demonstrably more satisfactory for reconnaissance scale evaluation than conventional black and white photographs at scales of 1:20,000 to 1:60,000.

Field work is carried out in a manner quite different than that in detailed soil surveys in which observations are spaced only hundreds of meters apart. The essential feature of the field work is to employ sparse sampling to extrapolate over the entire area, using the broad picture to designate areas which are important for closer scrutiny at a later time.

The most judicious way of integrating the office mapping and field work will vary from location to location. In some areas with adequate roads, jeeps may be used to rapidly reconnoiter an area and obtain observations not only on the soils but on associated plant communities. In other areas -- this applies to large sections of the Sahel where roads are both widely scattered and of very poor quality, and where off-road travel is notoriously difficult and slow -- it may well be much more advantageous to use a helicopter survey. Though helicopter surveys initially appear expensive, a well-trained crew of scientists can move quickly from sample point to sample point covering large areas of repetitive topography and soil associations without the lost hours of land travel. In the Sahel a mixture of jeep and helicopter sampling would be feasible. Several hundred to a thousand sites viewed carefully in their soil catenary and association relationships as displayed on ERTS-1 imagery would form an acceptable basis for later more detailed work.

4.0 REMOTE SENSING DATA AND SOIL MAPPING

Over recent years some tests of remote sensing applications in soil mapping have occurred. In the United States the traditional procedure in soil mapping is to enlarge three times 1:20,000 black and white photography for use as a base for soil series level mapping. A survey is ordinarily of a county -- some 1,000 square kilometers -- and takes several years to map at scales of 1:15,840 or 1:20,000. Such detailed mapping is appropriate in the Sahel only in those areas where observations at the soil series level are necessary for detailed irrigation project planning. (Both reconnaissance and detailed soil surveys are available for parts of West Africa.) The black and white photographs principally provide a mapping base where field

observations are entered: It is well known that many soil boundaries are not seen on black and white imagery, particularly where there is extensive cultivation and the natural landscape is fragmented by rectilinear field patterns.

In other areas such as Northern Australia where reconnaissance scales are used, much smaller scale black and white photographs are used. The question then arises as to whether some of the newer remote sensing systems -- very high altitude color and false color photography, space photographs of the Shuttle era, radar imagery and multispectral scanner images from aircraft, and the ERTS-1 multispectral scanner -- have new roles in mapping soils at a reconnaissance scale suitable for preliminary planning in developing countries. The answer is undeniably "Yes -- the newer sensors do offer some capabilities which are cost effective in comparison with the older techniques". These capabilities may now be reviewed.

The ERTS-1 multispectral scanner (MSS) is the only remote sensing system that offers comprehensive coverage of the Sahel region. No radar images have been obtained and black and white aerial photography including trimetrogon photography is dated (most coverage is at least a decade old). Very little false color or color photography is available from any altitude. Finally, multispectral scanner imagery from aircraft has not been flown in the Sahel, since the mobilization costs are prohibitive. The ERTS-1 images thus provide the most viable base for landscape unit or soil association mapping.

A number of studies have been made using color and false color photography in detailed soil series mapping. (The soil series is a smaller unit than the soil association and consists of a single soil. Several soil series associated geographically constitute a soil association). Studies in Canada, particularly by Crosson and Protz (1973) and Parry (1969), show that color and false color photography is more useful than conventional black and white in soil boundary delineation but unambiguous identification of soil series is not feasible: Soil color is imperfectly correlated with the other variables which make up a soil profile. Yet soil color, either dry or moist, is the principal basis for photographic discrimination of different soils. Furthermore, if the entire areas is not flown at a time when cultivated land is bare the association that one must use is that between natural plant communities and the soil boundaries.

The possibility of separating soil mapping units on airborne color imagery was considered by Cihlar and Protz (1973). They pointed out that particle size distribution influences moisture retention by the soil as well as soil structure (the soil with greater retention capacity for

moisture will darken most strikingly with added moisture); organic matter decreases the total amount of reflected radiation; and ferric iron affects the slope of the spectral reflectance curve between .5 μ and .6 μ (ferric iron imparts a reddish cast to soil). They found that these four soil properties are indirectly related to airborne imagery through the influence they have on reflectance characteristics of bare soils: "Laboratory data indicated that none of the soil properties measured differed sufficiently among soil mapping units to distinguish each mapping unit from all others." Time of image acquisition in relation to soil and moisture was important. Greatest differentiation among the classes occurred when the soils were wetted. There was relatively little spectral differentiation among the dry soils. In another study, Cihlar and Protz (1972) found that color film was three times more accurate in recording individual soil mapping units due to averaging all layers of the color film which produced unique film density values as compared to a hypothetical black and white panchromatic film. This evidence suggests that in the normally dry state of soils in the Sahel relatively little spectral differentiation among the soil mapping units would be discernible at the soil series level. Color film would be most useful immediately following rainfall which would enhance the utility of color-combined ERTS images from ERTS-B and ERTS-C, where shortening of the 18-day interval is being considered.

These results with color film suggest that the establishment of soil association level boundaries using small scale imagery may be the greatest contribution of remote sensing in the general area of soil surveying and mapping. Since the soil mapping unit is not the soil series for which spectral differentiation is critical, but is the soil association, many other features can be used for mapping including: spatial distribution of reflectance values, fabric of drainage dissection, meso-scale textural arrangements, and orderly arrangements of geomorphological units. The strength of mapping at the soil association level is therefore much increased over that of mapping at the soil series level.

Radar imagery has been extensively used for unpublished reconnaissance soil mapping in the Amazon Basin using landscape units as a basis for delineating broad soil associations. Soils information within the landscape units is highly differential and has been extrapolated from very sparse field observations. Earlier studies by Simonett (1968) and by Morain and Campbell (1972) have shown that many, but not all, soil units delineated on conventional U.S.D.A. county soil maps may be observed on radar imagery of semi-arid and arid areas. The study by Simonett was carried out in Oklahoma and southern Kansas in badlands, sand dune and Flint Hills type cuesta topography. That by Morain and Campbell was carried out in arid areas of California and Arizona.

The soil unit boundaries were in both instances quite well detected for some associations and some series but were very inadequately detected for others. Similar conclusions were reached with color photography and radar. Certain series boundaries associated with striking topographic features are easily delineated, whereas those more diffuse are often not readily detected either on radar or color photography.

The multispectral scanner (MSS) is still an experimental instrument in soil mapping and no convincing cost/benefit analysis is available. Results are ambiguous with respect to extrapolation over large regions even though in small areas, boundary delineations do often show improvements in soil boundary and unit delineation. Where multispectral scanner data is available, high resolution photography is a useful adjunct in soil mapping and undoubtedly will be used to some degree in developing countries. However, it would be difficult to justify a flight of an MSS unit in the Sahel even as part of a detailed irrigation soil survey let alone a reconnaissance survey. Existing techniques using ground observations and color or black and white photography are more than adequate to map soils for irrigation projects. These projects require a very close network of ground augerings, and photography is used more as a mapping base than for its value in mapping soil unit delineation. MSS is currently being used for studying the relationship between iron and organic matter content in soils, between soil boundaries as previously mapped by soil survey and for delineation using training sets, or multispectral clustering routines (Cipra, Baumgardner, and others, 1973).

As noted by Cihlar and Protz (1973) in "Surface Characteristics of Mapping Units Related to Aerial Imaging of Soils": the "successful detection of boundaries of soil mapping units using differences in spectral characteristics of the surface soils requires that any given mapping unit appears homogeneous but different from all other soil units as viewed by a recording device." They assessed the surface soil characteristics affecting the aerial images and the degree to which they differ among soil mapping units, using soil samples collected along four transects crossing eleven units at ten meter intervals.

> "Munsell color coordinates and organic matter, oxalate iron, sand, silt, and clay contents were subjected to a statistical analysis. The results showed that except for Munsell hue, more than fifty percent of the total variability occurred among the soil mapping units. Distinct groups of soil mapping units were defined on the basis of Munsell value, organic matter, sand, and silt content, but in no case were all soil mapping units distinguished from one another. This, and related studies suggests that these soils could not be mapped accurately on the basis of their spectral responses but that spectral differences would provide additional information on soil distribution. Since soil reflectance characteristics are described in terms of Munsell color coordinates and into various areas with similar soils."

In soil series mapping, extensive use is made of photo stereoscopy using the relation between topographic position and soil type. However, in monoscopic imagery -- high altitude strip aerial photography, MSS aircraft imagery, ERTS-1 MSS, and radar images without sidelap -- there is no stereoscopy and one is forced to use spectral characteristics more than would ordinarily be the case, even though it is clear that spectral characteristics of soils are not adequate for discrimination between series: No competent soil surveyor would anticipate carrying out a soil survey based upon soil surface color alone!

There is now significant evidence that soil association maps may satisfactorily be compiled using ERTS images or space photography. Among the earlier studies with Gemini and Apollo space photographs are those by Morrison (1969) in the arid southwest of the U.S.. He delineated major geomorphic soil association units in a very large area and reported favorably on the improved knowledge of geomorphic/soil units distributions. The space photography enabled known mapping units to be extrapolated over very large areas. Similarly, Poulton, Schrumph, and Garcia-Moya (1971) in Arizona found that natural land system mapping was not only facilitated with Gemini and Apollo space flight photography, but was the mapping system of preference. Unpublished studies by Simonett compared mapping units derived from Gemini photography in the Alice Springs area of central Australia with soil associations distinguished by Jackson (1962). A very close correspondence was noted between the Jackson map and that prepared using the space photography. Some units were not discriminable on the space photographs and would require field work.

Numerous investigators have made passing reference to the ability to map soil associations or landscape units with ERTS-1 imagery. For the Sahel, three are particularly relevant since they are detailed and were carried out in areas with some similar soils. These papers are: 1) F. C. Westin (1973) "ERTS-1 MSS imagery: A Tool for Identifying Soil Associations"; 2) Seevers and Drew (1974) "Evaluation of ERTS-1 Imagery in Mapping and Managing Soil and Range Resources in the Sand Hills Region of Nebraska"; and 3) Westin and Smith (1973) "ERTS Mosaic of South Dakota".

Westin has, in a series of publications, demonstrated the value of ERTS imagery in improving soil association boundary mapping in South Dakota. The abstract from his 1973 publication summarizes his views:

> "Soil association maps show the spatial relationships of land units developed in unique climatic, geologic and topographic environments, and having characteristic slopes, soil depths, textures, available water capacities, permeabilities, and the like. From these characteristics of

the soil, broad interpretations can be made such as how the soil is suited for various agronomic and engineering uses. ERTS-1 was found to be a useful tool in the identification of soil associations since it provides a synoptic view of an 8 million acre scene, which is large enough so that the effect can be seen on soils of climate, topography, and geology. A regional view also allows soil scientists to observe most, if not all, of their extent. This aids in selecting typical sampling sites and provides a check on the homogeneity of the associations. ERTS-1 MSS imagery also provides four spectral bands taken every 18 days which gives data on relief, hydrology and vegetation, all of which bear on the delineation and interpretation of associations. Enlarged prints derived from the individual spectral bands and shown in gray tones were useful for identifying soil associations."

An even stronger statement of the value of ERTS-1 imagery could have been made if Westin had worked with false color images made either with single date/multiband or multi-date ERTS imagery.

Westin and Smith (1973) in their published map of soil associations and land values were able to divide South Dakota into eleven major land classes containing 53 principal soil association mapping units. These mapping units employed the integrated land system relationships of soil associations with geology, geomorphology, soil surface texture, and details of agricultural utilization. In designating the topographic components, Westin and Smith used snow enhanced low sun angle photography to show the topographic texture of the areas. Within the Sahel similar low angle photography could not be obtained because of the low latitude of the area, but where side-lap occurs (15 percent between successive daily ERTS passes) gross topographic units can be distinguished through stereoscopic observation.

In compiling an ERTS mosaic of soil association valuations Westin observed that many of the soil association boundaries of previously published maps could be sharply refined, some new soil association units could be designated, and that the compilation was rapid and relatively inexpensive through use of judicious sampling to establish the internal characteristics of a mapping unit.

The third major study on soil association mapping, by Seevers and Drew (1974), has already been quoted extensively in the section on sand dunes and dune migration (Chapter 7). Some of this material is repeated here because of its importance. Their most significant conclusion was as follows:

"Relationships established through comparison of ERTS-1 imagery with published soil association maps of McPherson, Hooker and Thomas counties permitted construction of a soil association map for Cherry County, Nebraska, and adjacent Sand Hill County, for which no comparable soil association map is available. Comparisons of the soil association map constructed for Cherry County with data obtained from field observations and from high altitude color infrared aerial photography indicated a high degree of accuracy for the soil association mapping interpreted directly

from ERTS-1 imagery (MSS bands 4, 5, 6 of image 1295-16562 and MSS band 6 of image 1170-17013). Because of unique combinations of vegetation and land surface configuration within the Sand Hills region, ERTS-1 imagery is suitable for interpreting soil units and range sites at a level of generalization intermediate between county soil association maps and standard soil surveys made for observations of soil profile and landscapes on the ground."

5.0 APPLICATION OF SOILS DATA

Soils data, coupled with vegetation, agriculture, climate, and population information, can provide a method for developing an integrated approach to solving some of the critical problems facing the Sahel region. Remote sensing techniques present an alternative, cost-effective method for obtaining these data, and stratifying the Sahel region for effective resource planning.

The development of accurate soils maps is an essential element for analyzing three significant resource problems:

1. Delineation of potential agricultural (including range) lands;
2. Control and detection of agricultural problems, such as saline soils and moisture stress; and
3. Development of population range carrying capacity estimates.

5.1 POTENTIAL AGRICULTURAL LANDS

The physical environment of the Sahel and the continual fluctuation of climate in this environment has severely restricted the lands available for agriculture and herding. The present drought situation has introduced added stress on existing land resources through overgrazing of rangelands and lessening of fallow periods for agricultural soils. Many areas have been so overgrazed that continued use under present environmental conditions seems improbable, without an effective monitoring program. To solve or alleviate these problems, a number of steps is necessary:

1. Establishment of a comprehensive data base, including soils, vegetation, human and animal population and water distributions;
2. Delineation of potential areas for agricultural or rangeland development based on analysis of soil-vegetation-water associations;
3. Delineation of environmentally stressed areas that could be improved through controlled usage or soil enrichment methods or areas that should be removed from the production economy.

An integrated approach to stratifying the Sahel region into productive and non-productive zones can be effectively accomplished through the application of ERTS, since it provides the overview for further detailed analysis with aircraft and ground surveys.

5.2 STRESS DETECTION

In semi-arid regions such as the Sahel, the early detection of conditions that affect plant growth would aid in developing quick response methods for alleviating stress conditions before serious damage occurs. Two types of stress conditions that relate to soils are soil salinity and moisture stress.

In those portions of semi-arid areas where water tables are high, (e.g., inter-dune troughs, irrigated areas) the problems of soil salinity increase. Detection of saline areas and the degree of salinity can be obtained through remote sensing techniques, since saline conditions can be observed by the reflectance level of the plant. Numerous studies using infrared photography and thermal imagery have shown that saline soil conditions affect plant appearance and spectral characteristics (See Myers (1970) for an extensive review of thermal and infrared techniques for detecting soil salinity).

Moisture stress also affects the physical and spectral appearance of the plant. In a number of studies reviewed by Myers (1970), infrared and thermal techniques provided the best methods for moisture stress detection. ERTS has added value in moisture stress detection because of its synoptic and repetitive coverage.

Although detection of moisture stress conditions is not specifically related to soils, the physical properties of soils that affect moisture retention are. A knowledge of soil retention capabilities and plant tolerances to moisture stress can become a crucial element during conditions of drought. Drought areas can be stratified by soil retention capabilities and plant tolerance to aid assistance agencies in planning phased relief programs.

5.3 CARRYING CAPACITY ESTIMATES

The effects of population pressure on scarce resources is of growing concern in the Sahel. Decreasing water supplies and grazing land due to the drought have caused a migration of the nomadic populations into sedentary agricultural areas and larger cities. Declining soil fertility and increasing populations in the agricultural areas have caused shortening of the fallowing periods and an increase in marginal land for crop production.

An assessment of human population pressure is dependent upon the amount and type of information available on land carrying capacity, human resources, and the social and cultural variables that affect man's use of the land.

Human carrying capacity of soils in West Africa has been studied by Allan (1965). Allan determined human carrying capacity of certain soils to be:

Soil Type	Human Carrying Capacity (per km^2)
Weakly developed lithosols	19
Weakly developed regosols	11
Brown sub-arid soils	22
Tropical ferruginous soils on recent sands	16
Tropical ferruginous soils with granites	38
Hydromorphic alluvial soils in the Niger floodplain	40
Hydromorphic alluvial soils in the Upper Volta floodplain	80

Comparisons of existing population with present human carrying capacity would help determine the degree of overpopulation by each soil type. Demonstrating this relationship is essential, given that most people rely on soil directly as farmers or indirectly as grazers. Animal carrying capacity estimates are discussed in Chapter 12.

Soils data provide a critical input to comprehensive resource planning. A knowledge of the distribution and characteristics of soils, their interrelationship with topography, climate, vegetation, water, and population can assist the effective development, utilization and management of the soil resources of the Sahel.

6.0 SUMMARY AND CONCLUSIONS

To our knowledge there is no large region outside the United States which has been covered so repeatedly with ERTS-1 imagery and under such generally cloud free conditions as has the Sahel. The National Aeronautics and Space Administration at the request of international agencies, and during a time when the ERTS tape recorder was malfunctioning, devoted a very substantial part of recorder time to obtaining these repeated images of the Sahel.

These ERTS images represent a unique resource suitable for soil association mapping. Their judicious use can aid substantially in constructing soil association maps of the entire Sahelian region. There is no other image data base of such quality, relative inexpensiveness, recency, and

overall utility for this purpose. Merging of existing published soil data and maps with ERTS imagery, together with carefully designed ground sampling procedures to establish the homogeneity and internal characteristics of the soil association mapping units, is the recommended approach for this task.

The whole of the Sahel could be prepared as false color ERTS mosaics for less than $50,000. The use of these color mosaics in soil association mapping, as the base for interpretation of plant communities and in hydrologic and general agricultural and rangeland planning would be invaluable. They would provide a broad region-wide uniform view. Such data in the hands of many operating agencies would serve as one of the most powerful integrative tools for coordinating planning on region-wide basis.

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Chapter 11

CLASSIFICATION OF NATURAL VEGETATION AND EVALUATION OF RANGE QUALITY

1.0 INTRODUCTION

Livestock grazing dominates the subsistence economies of the Sahel. Human and animal populations have so balanced their numbers against the availability of water and vegetation that any variation in the water supply, the driving force, is counterbalanced by variations in animal and human populations. One of the characteristics of marginal economies is their elasticity, their tendency to fluctuate in direct relation to environmental conditions.

Goals formulated in regard to managing, improving, or developing renewable range resources in Sahelian countries must include flexible procedures that can cope with the periodic fluctuations of their two most important resources -- water and vegetation. The first prerequisite to meeting policy, resource allocation, and management goals which perpetuate these resources is an inventory of vegetation and range quality conditions. Seasonal and spatial variations in vegetation make inventories difficult if not unattainable without a cost-effective survey technology. It is not a question, "Does remote sensing have a role to play?" in the Sahel but, rather, "How and where is remote sensing technology needed?" This chapter serves one basic purpose: to present organized excerpts and proven methods from key literature that combine plant ecology with remote sensing to achieve the goals of range vegetation management.

2.0 APPLICATIONS PROBLEMS IN THE SAHELIAN ENVIRONMENT

A primary problem in inventorying the vegetation of the Sahel is the documentation of existing vegetation cover and the abusive land use practices and climatic variables that affect vegetation growth and increase desertification in this sub-Saharan region. There is little accumulation of knowledge concerning man's practices and his specific impacts on vegetation and soil resources which can provide an adequate basis for interpreting inventory information in terms of local problems of land use, resource allocation, and management. This deficiency must, and can best be dealt with, by assigning highly capable and experienced people to perform the inventories in the Sahelian region, or to cautiously extrapolate from their experience in other arid regions of the world. This experience can be supplemented by selective observations while the region is being inventoried.

A second concern is the lack of detailed knowledge and understanding of plant ecology in the region. A refined knowledge of vegetation communities, their potential on various sites, plant successional patterns, and autecologies of the important species is needed. If this information is available, inventory projects can progress rapidly in collecting detailed information suitable for local problem solving. Though excellent, general works of the region's plant geography, such as the UNESCO-FAO "Plant Geography of the Mediterranean Zone" exist, they do not provide sufficient information on characteristics and distributions peculiar to the Sahelian portion of the area.

Problems of urgency and cost prohibit conducting ecological research prior to the implementation of an operational inventory program. Methods must be devised for rapidly improving existing information at modest cost and with a feasible and financially allowable amount of additional ground work. These problems virtually dictate that an action program to inventory the vegetation resources and range quality of the Sahel place strong emphasis on remote sensing technology.

Finally, inventories of any type -- vegetation, soils, geology, or land use -- have little value until the basic inventory information is interpreted in relation to specified problems. As Philips (1970) indicates, some of the most valuable expertise on the Sahel may not be found solely by importing foreign scientists but by having these people wisely draw on the knowledge and experience of the native population. Many types of research, particularly soils and vegetation analyses, have benefited from drawing on the wealth of information held by indigenous peoples on their natural environment. The aerial photograph has proved an effective catalytic tool in obtaining this information, the importance of which cannot be underestimated.

The utility of inventorying vegetation by remote sensing is most seriously limited by the sparseness of vegetation in arid and semi-arid regions. The natural vegetation density is so low, that even when vegetation is in good condition, image characteristics are determined in surrogate fashion, i.e., soil, rock type, and landform supported inferences, that are based on relationships that exist between these features and vegetation. In the absence of detailed research, vegetation inventories develop this interpretive knowledge by first determining ecological provinces within which a high degree of vegetational, landform, geological, soils and climatological homogeneities are known to prevail, and then by subdividing these areas for analysis, much as the Australians have done by creating land systems in their excellent resource inventory program (Christian, 1958; Gibbons and Downes, 1964). Surficial geology, landforms, and vegetation are thereafter treated as interrelated components in an environmental system or model.

This analytical procedure clarifies useful vegetation/environmental relationships as keys identifiable on remote sensing imagery, emphasizing the need for interpreters who are knowledgeable ecologists and are familiar with the region.

Any vegetation resource inventory program that maximizes the rapid survey and cost-effective capabilities of remote sensing must include a very carefully designed sampling program for the acquisition of relevant ground information, the assemblage of qualified ecologists as interpreter, and the opportunity of obtaining selected ground-based information.

3.0 EVALUATION OF RANGE QUALITY

A prime reason for performing an ecological resource inventory is to provide for a national analysis of forage productivity, range improvement potential, and animal carrying capacity. However, good inventories are not easily conducted, particularly in a region like the Sahel, where the serious deterioration of resources, the rigor and variability of the climate, and the nomadic management of animals pose great difficulties for resource inventories. Nomadism, an adaptation to environmental constraints, makes it difficult to acquire information about animal numbers and movements. Such information is essential for carrying capacity projections and estimates.

3.1 RANGE IMPROVEMENT POTENTIAL

Range improvement potential can be identified from a comprehensive resource inventory of Sahelian rangelands. An initial projection of candidate areas for improvement can be effectively outlined, but improving such candidate areas under existing circumstances is a much more difficult task. The projection can be performed by using 1:250,000 scale space-acquired images supplemented by sub-sampling aircraft underflights or digital data analysis. Both must be supported by appropriate ground checking. This type of analysis will not provide the information required for an action program that will, so to speak, "tell where to put the plow in the ground," in the Sahel. It can, if properly performed, provide the statistical and cartographic information necessary for an initial assessment of the capacity for improvement and for the identification of candidate areas where more intensive study and a complete inventory can be justified.

3.2 FORAGE PRODUCTIVITY

Estimating forage productivity presents a different, much more complicated array of problems. If current production is the sole interest, the problems are simplified. For purposes of range

management programming, however, current production in the Sahel cannot represent what is ecologically optimal, nor give any indication of climax-form vegetation without sequential observations over long periods of time.

Traditional practices of productivity inventorying begin with a vegetation map. The map is assessed at the ground by visiting either all major vegetation delineations or sampling each kind in order to acquire direct estimates in productivity units (kilograms per hectare). Often other environmental variables such as soil moisture, structure and texture which relate to production are measured at the same time. Techniques under development are making use of multi-stage proportional probability sampling to approach the problem in a manner somewhat paralleling the approach of foresters in measuring timber volume (Langley, 1971).

Productivity indexing techniques used in the past developed a hypothetical forage factor based on plant composition and density. Through this approach a carrying capacity figure is derived by collecting accurate information on past animal use of well-managed areas. Such a method is not usable in the Sahel because technical information is lacking on the physiological and ecological tolerance of various plant species to grazing. Accurate information on animal stocking and season of use in properly grazed ranges is also scarce.

It would seem a simple matter to directly measure or estimate range production in kilograms per hectare by well-established sampling and statistical procedures. However, under pressure for urgent action one can only think in terms of a single year inventory. This restriction poses many problems. Because of climatic variability, single year inventories are grossly inadequate. Secondly, in a heavily grazed and abused region it is problematical and extremely unlikely that the ground examiner would visit a designated sampling site before a herd of animals. He would thus obtain unreliable estimates of even the current year's yield. These statements are particularly true if one is concerned about a projection of the absolute yield parameter. If, on the other hand, one can be content with relative yields, useful data can be obtained by a multi-stage sub-sampling procedure that is conducted in a cost-effective manner.

Projections of current relative range productivity for a number of countries with large arid and semi-arid areas have been produced under commercial agreement (Earth Satellite Corporation, 1973). The information is to be used in designing and projecting a master plan for range improvement in each country. The basic resource information for these projections is derived

from space imagery, two stages of aircraft photography, and ground examination. Based on this experience, it would not be difficult to design a better, more appropriate analysis of the Sahel, provided that: 1) users of the information were fully aware of the inherent, unavoidable problems in making reliable projections of the absolute yield parameters; and, 2) users recognized the obvious biological fact that an inventory based on a single year's measurement is likely to miss the long term average by an indeterminant amount. Year-to-year variation of forage yield in arid and semi-arid regions is commonly known to exceed 50 percent, and may, on occasion, exceed 100 percent of the long term norm. What this means is that forage production in arid areas is inherently variable, an inescapable condition that must be accepted and managed accordingly.

Some indirect methods for estimating biomass production from space acquired data have developed out of the space applications program. Spectral band ratioing techniques have been developed for grass steppe regions where vegetation density is relatively uniform and high (Rouse et al., 1973). Ratioing estimates, if reliable, could be related to forage production in the region after a vegetation resources inventory is completed. Whether or not they would be applicable to the arid and semi-arid Sahel remains to be seen. The probability of usefulness of the concept is low in arid areas, except where, under favorable climatic conditions, a flush of annual vegetation coincides with the warm rainy seasons, or in regions where a vegetation cover still exists.

Other studies have shown significant relationships between optical image density and ratioed reflectance data in the visible and near infrared spectral regions with the biomass of rangeland vegetation (Driscoll et al., 1972; Pearson and Miller, 1972). The relationships can be well defined in areas of uniformly dense ground cover. Additional studies have attempted to develop predictive models of forage production based on bi-directional reflectance properties of plant canopies (Smith and Oliver, 1972; Colwell, 1974). Additional studies are needed, however, before these techniques can become operational.

3.3 ANIMAL CARRYING CAPACITY

Determination of animal carrying capacity in the Sahel would be premature given the unique difficulties and drought problems that now prevail. Ideally, a resource inventory should precede any attempt to derive carrying capacity estimates.

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Many biological and management related reasons explain why an estimate of carrying capacity is unnecessary as an initial step toward corrective action. First, the Sahel presently contains a greater population of animals than the food supply can sustain. Only a portion of the indigenous population would take corrective action where it means voluntary reduction of animal herds. A more viable approach would be to identify areas for potential range improvement and embark upon a program of growing more feed. This approach seems preferable to one of downward adjustment in animal populations over and above what losses occur from drought. An agronomic improvement program would allow animal agriculture and cropland agriculture to be more effectively integrated with the allocation of agricultural production capacity (where it is surplus to direct human food needs) to fodder production.

Furthermore, it is well known among range scientists that actual carrying capacity is the last element determined in the application of range technology since it is strongly a function of the specific details of management. In other words, it cannot be calculated unless the management technique first is specified. Carrying capacity is influenced by the season of forage removal by grazing animals, the rate and intensity of removal, and the cycling of removal: whether forage is removed in a single rapid flush, more slowly over a long grazing season, or in a series of increments with allowance for intermittent regrowth.

An estimate of carrying capacity made on domestic animal or wildlife ranges is at best an initial estimate of a safe stocking rate, not of a carrying capacity. Carrying capacity is derived through the careful manipulation, adjustment, and delicate balancing of the relationship between the animals and their feed and cover supply. Carrying capacity estimates are essential to: 1) maintain vigor of the preferred forage plants and to insure their continued productivity; and, 2) obtain the maximum continued yield of forage. Sound principles of plant physiology, plant ecology and animal nutrition are applied with the technology of grazing management to arrive at a carrying capacity of a specified region or management unit. The judgements are tempered by monitoring forage utilization and range condition and trend (the state of ecological health and the direction of successional development in the vegetation).

A wise approach to the carrying capacity problem is to study and document management of grazing regions, specific ecosystems developed from an ecological resource inventory, and the impact of grazing on ecological conditions and on successional trends induced in the vegetation. From such studies and technological applications, the production limits of each ecosystem when in excellent, good, fair, poor, or very poor condition can be understood. One can often determine characteristics of the ecosystem best through actual practice: the number of hectares required to sustain an animal unit and the potential for improvement and regeneration.

A useful body of statistics can be generated if knowledge of each ecosystem -- field experience, research and data accumulation -- is tabulated for ready reference. It would be preferable to compile data in this manner than to spend equal energy on a single inadequate determination of carrying capacities through survey procedures. The primary objective of rangeland surveys should not be to directly determine carrying capacity, but to define ecological characteristics and the nature of the resources so that physical and biological bases can be established for monitoring responses to man's action.

The Soil Conservation Service in the United States has effectively pioneered an approach to ecosystem management whereby a body of knowledge specifically relevant to individual ecosystems is developed. Examples of this work include that of E. J. Dyksterhuis in the Great Plains steppe region, and E. W. Anderson in the complex shrub steppe, grass steppe, and mountainous, forested grazing regions of the Northwest. In these examples, the concept of range site was the basic unit of classification. Following an ecological resource inventory (range site and condition survey), site guides and handbooks were compiled and updated through periodic revision as a compendium of knowledge relevant to each ecosystem (Anderson, 1959). These handbooks treat information similar to that of Poulton et al., (1971) but only in tabular and narrative form.

4.0 REMOTE SENSING SYSTEMS FOR VEGETATION AND RANGE INVENTORY

4.1 VEGETATION INVENTORYING

The requirement for urgent action to deal with Sahel resource management problems underscores the need for simple, quick-access remote sensing systems such as those which have already been demonstrated operational. The most appropriate remote sensing system for inventorying Sahelian vegetational resources is a combined Earth Resources Technology Satellite (ERTS-1)/ aircraft system. ERTS has already been demonstrated operationally feasible for large area

ecological resources inventories that require highly generalized, broad scale data. Langley (1971) demonstrated the value of satellite imagery as an important first step in a multi-stage approach that provides useful resource information in a cost-effective manner.

The role of ERTS in a vegetation inventory begins with a color mosaic at 1:1,000,000 scale. From this perspective one can quickly stratify the region and classify gross features of landforms, geology, tone, texture, and patterns of the image on the basis of selected criteria of similarity into ecological provinces or land and resource systems. After identifying and mapping gross features, enlarged ERTS imagery (1:250,000 scale color enlargements) and human and machine aided interpretation can be used to obtain more detailed, second level data. Various density slicing techniques using the original 1:1,000,000 scale and single spectral bands can support human interpretation of vegetation and vegetationally related features. Identified and classified features can be appropriately mapped at a scale of 1:250,000.

This scale of mapping allows broad physiognomic-structural and, on occasion, floristic levels to be identified directly from the ERTS interpretation. Each level, however, is largely determined by the ground familiarity of the interpreter. With such mapping, one can prioritize areas of concern, and/or pinpoint areas of probable high, medium, and low productivity for a more detailed study at the third level.

At the third, more detailed level, either digital analysis of the ERTS data or photo interpretation of aircraft data can be performed. Digital data analysis is a specialized subject that cannot be treated adequately in this chapter. It need only be said that it is possible to look uniquely at each 0.4 hectares of land at a scale approximating 1:24,000 from digital information and to classify and identify certain unique vegetation-soil systems. This assumes that the resource scientist is, in fact, highly knowledgeable about an adequate sub-sample of the region to be inventoried. Remote sensing techniques cannot be meaningfully used without correlative information. It has not yet been determined whether digital data analysis is cost-effective against the human interpreter for large area coverages. At present, it is not yet cost-effective except for detailed analyses of carefully specified high priority areas where critical and important problems exist.

An alternative method may use aircraft imagery as the third or fourth level of information source to obtain highly detailed data. The technology in this area is well developed and has been operational for many years. Scales appropriate for vegetation inventory have varied and been found useful from 1:4,000,000 to 1:3,000,000 scale for crude inventory purposes, to about 1:8,000. Some range vegetation monitoring problems require scales as large as 1:1,000 to 1:600, all of which are operationally feasible, well demonstrated, and extensively used in vegetational applications.

The scientist also has a wide choice of film-filter combinations in aircraft systems. The information content of color and color infrared film is so great that their high absolute cost, compared to black and white, and their proportion of total acquisition cost, is usually accepted in reconnaissance surveys. The greatest problems are those of controlling quality on the products interpreted when color, and especially color infrared, is used.

The actual selection of film-filter combinations, lens types, focal length and flight altitude are all a function of the characteristics of the region photographed and the purposes for which the images are to be interpreted. Further discussion in this section is, therefore, inappropriate except to point out that difficulties and costs of interpretation increase markedly with the number of film-filter combinations. In the interest of project efficiency, the increase of information content over conventional color or color infrared photography must be justified against the total cost.

4.2 MONITORING RANGE QUALITY

For many years range scientists and managers have used ground photography -- both oblique and vertical, monocular and stereo -- to document and study vegetational conditions and change (Wells, 1971). Stereo photography greatly increases the information content and analytical capability even of ground photography. One of its prime values is permanent, visible documentation of resource conditions at a known point in time. Old aerial photography should not be overlooked as a source of information for documenting change in vegetation and range conditions in the Sahel.

Range scientists and foresters have recently turned to fast cycling 70 mm cameras as a monitoring device. These cameras can obtain stereo photography in 70 mm format from fixed wing aircraft at a variety of scales. This permits identification of many species and numerous

photogrammetric measurements of vegetational parameters which are important in monitoring vegetation and soil conditions that result from imposed management practices. In the United States and Australia this approach to vegetation study has been pioneered by a small group of research scientists (Carneggie and Reppert, 1969; Driscoll and Reppert, 1968; Tueller et al., 1972; Carneggie et al., 1972; Driscoll and Coleman, 1974; Poulton, 1970).

Observations from Apollo space photography first indicated the capability of small scale space imagery as a range monitoring system. With the advent of the Earth Resources Technology Satellite System (ERTS) and its theoretical 18-day repetitive sequence, some of this capability has been further developed. A capability to detect the gross extent of heavy versus light utilization has been demonstrated. The ability to follow the vegetation green wave as it relates to the seasonality of growth and development has been documented in ERTS experiments (Carneggie and DeGloria, 1974; Bentley, 1973; Rouse et al., 1973). While most of this work has been done with photographic analysis, computer analysis of the digital tapes (when it becomes cost-effective), shows substantially greater potentiality for monitoring applications.

Evaluation of range quality and changes in range conditions over time requires an accurate inventory of vegetation and range conditions, animal grazing characteristics, and supplementary historical information -- photography and/or reports -- to establish a base for future monitoring and planning of range resources.

5.0 VEGETATIONAL CLASSIFICATION FOR REMOTE SENSING APPLICATIONS

The biological disciplines have produced a voluminous and active literature dealing with vegetational classification concepts, philosophies, and methodology. This section will seek to avoid the academic, scientific, and philosophical jargon and suggest an approach to vegetation classification that will contribute to resource inventorying in the Sahel.

The world literature on vegetation classification and mapping has been drawn together effectively by Kuchler (1956, 1967, 1973). Other important contributions include the comprehensive United Nations Educational, Scientific and Cultural Organization work in press on "a framework for the classification of world vegetation" (UNESCO, 1972). Its applicability for vegetational resource inventory by remote sensing has not been tested, owing to the recency of this work. Many systems work well for visually classifying vegetation on the ground, and for classifying vegetation from tabular data that display the criteria for classification. Since the classes are based

on morphology or visual appearance of vegetation and often on the vertical structure of the plant community, all classes cannot be expected to correspond to image classes that a remote sensor sees in the same vegetation mosaic. The need to have a classification related to remote sensing is evident.

It became apparent early in the development of remote sensing technology that a new approach to vegetation legend systems was required (Carneggie et al., 1967). A fresh look at classification of natural and man-altered features of the landscape that would be compatible with satellite and aircraft imagery, was needed. Also, a system was needed that would be computer compatible for data management without conversion or transposition, and that maintained a consistent logic among all classes throughout the hierarchy. Experimental work began with Gemini IV photography, and reached a successful plateau of reasonable accomplishment by 1969 in the mapping of vegetational resources with Apollo 9, SO-65 experiment imagery (Poulton et al., 1971). Applications to vegetation classifications have culminated in recent work with ERTS-1 and Skylab experiments which have been useful in applications in Canada, Iran, and five states in western United States. The system still required improvement, but it is now operationally effective, easy to apply, and highly adaptable to vegetational resources, landforms and land use analysis in the Sahel.

The concept and philosophy of the legend system has evolved since 1966 through many iterations and practical field applications (Poulton, 1972). Table 11-1 displays the legend hierarchy to show its total information content; and Table 11-2 shows a partial listing of the vegetation breakdown showing a system that blends remote sensing analysis with conventional vegetation classifications.

An inventory by this hierarchical classification system has many kinds of utility: information is provided that can be more meaningfully interpreted by knowledgeable scientists for land use planning, resource rehabilitation, resource allocation, agricultural development, and the integrated management of all the natural resources in the planning area or region. Such an inventory also provides a stratification basis upon which to determine forage productivity, and to project carrying capacities for animals and even humans; it also contributes to an understanding of the constraints the environment places on the activity of man and his animals.

TABLE 11-1

The following classes fit the highest possible level in the useful generalization of images that we are able to delineate and/or identify from space:

PRIMARY SURFACE FEATURE CLASSES

100 - BARREN LANDS (other than crop fallow)
200 - WATER RESOURCES (free water surfaces)
300 - NATURAL VEGETATION
400 - CULTURED VEGETATION
500 - AGRICULTURAL CROP AND IDLE LAND
600 - URBAN, INDUSTRIAL (manufacturing and processing) AND TRANSPORTATION
700 - EXTRACTIVE INDUSTRY
900 - OBSCURED SURFACE (not visible, atmospheric obstruction)

TABLE 11-2

VEGETATION CLASSIFICATION TO ECOSYSTEM LEVEL

300 - NATURAL VEGETATION
- 320 - Shrub-scrub vegetation
  - 324 - Microphyllous salt tolerant vegetation
    - 324.1 - Saltsage (Atriplex) prominent vegetation
      - 324.11 - Shadscale/Budsage (Atco/Arsp) communities
        - 324.111 - Atco (4-5)-Arsp (3-4/Sihy (3-5)-Brte(0-3)
        - 324.112 - Atco (4-5)-Arsp(3-5)Grsp (2-3)/Sihy(1-5)-Brte(0-5)
        - 324.113 - Atco(4-5)-Save(2), Chvi, Chn(2)/Sihy(3-5)-Pose(2-3)-Brte(0-5)

Natural vegetation subjects, from the broadest to the most specific ecosystem level, are used for the example. At higher levels, the Table is fully self-explanatory. Alpha symbols derived from scientific names characterize specific plant community types at lower levels. Numbers in parentheses indicate the prominence of the species in the communities on a scale of 5, from 1 being extremely rare and often absent to 5 meaning dominant.

6.0 SUMMARY AND CONCLUSIONS

Inventorying vegetation and evaluating range quality is essential to the effective utilization of these resources in the Sahel. Remote sensing, including ERTS or high altitude aircraft imagery (1:120,000 scale or smaller) and possibly meteorological satellite data, can be used to inventory vegetation and range resources, and to provide a cost-effective method for defining critical areas for further evaluation.

A vegetation inventory is the initial step in the development of a comprehensive plan for effective range quality control. This inventory coupled with existing collateral data (old photography, grazing characteristics, etc.) for the region provides a mechanism for evaluating range resources, assessing the quality of the range, and estimating potential forage areas.

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CHAPTER 12

LIVESTOCK INVENTORYING

1.0 INTRODUCTION

Pastoral nomadism is the principal economy of the Sahel, reflecting the productivity of the natural and physical environment. Animal grazing, the dominant land use and human activity, represents a way of life with an entire set of complex traditions and cultural values that has evolved over centuries. One characteristic of this environment is well-known: wealth is symbolized in the number of animals one possesses. The dominant concern among owners is thus to increase animal numbers; bettering their condition is of less consequence because livestock in a subsistence economy only marginally enter the cash economy. Productivity of the range regulates herd size, and the problem of maximizing herd numbers is only exacerbated by the environment's low productivity.

Herd management in a contemporary sense is virtually absent. A solution if it is to come about must cope with cultural traditions, resource limitations, and available technologies. Modern herd management practices, while giving a role to animal censusing or inventorying (survey of the distribution, characteristics and numbers of animal populations), generally begin with an inventory of the range resources and forage and browse conditions.

Carrying capacity -- a management concept that allocates animal and plant resources -- relates range conditions to the timing and number of animals on the range. Means for determining range condition, animal censusing, and the practice of herd management are thus interrelated. Three basic methods for inventorying wild animal and highly transient domestic animal populations, which are common in the Sahel, are:

1. To use very small scale photography to monitor dynamic range conditions that attract grazing animals over large areas;
2. To use various large scale techniques that count and estimate animals themselves in small areas;
3. Various combinations of the above.

The following chapter describes why an agronomic range improvement program in the Sahel is essential, and shows how remote sensing technology can provide the necessary information. It clearly identifies the limitations of present technology and shows where improvement is likely and promising; it further shows which techniques are in the research and development stage.

1.1 BACKGROUND TO LIVESTOCK INVENTORYING

This section treats the basic problem of managing populations of large herbivores -- sheep, goats, cattle, camels, horses and asses, and wild animals. Man is variously dependent on these animals for protein, other useful products, and for work and transportation. From the point of view of resource management the question is, "How many animals are there; what is the herd composition and condition of the animals; and what is their population trend?"

The fundamental problem in managing animal populations and the ranges which provide food and cover is one of balancing the nutritional requirements of the animal with the physiological/ecological requirements of better forage and browse plants. There is an inherent conflict in this plant/animal relationship. It is not the purpose here to explain the ecological and physiological requirements of plants nor the nutritional requirements of the animals. It is sufficient to say that the time of ideal harvest from the animal point of view is when the vegetation is lush, green and growing; it is generally most nutritious at that time. There are two particularly critical periods in the annual cycle of plant growth, one is near the initiation of growth and the other is at the time of flowering and seed set. Thus the reason for the plant/animal conflict is obvious -- the most profitable grazing period and the period of highest susceptibility of plants to grazing damage coincide.

Extensive and intensive animal and range management have one common goal: to strike a biologically safe balance between what the plants require to maintain productive growth and reproduction, and nourishment needed by the animals. To achieve this goal it is important to know, or have a reliable index to, the animal population level and other related facts. Animal inventory is relatively simple where complete or sample enumeration methods are feasible; but in extensive pastoral areas where records are either not kept by owners or herdsmen and not compiled by any centralized authority, reliable data are difficult if not impossible to obtain. In arid and semi-arid regions where nomadic grazing is dominant, problems of enumeration are made difficult by the low animal density and opportunistic grazing patterns that often prevail.

While at first glance a remote sensing solution may appear simple and straightforward, it is not the case. Present technology is not fully suited to solving the problem. Continuing research and development has yet to produce a simple formula to apply to animal inventorying in regions like the Sahel. The only advantage of such arid regions is the generally higher visibility of animals in areas of short stature, open growing vegetation. Areas of savanna, forest,

and tall dense scrub, reduce the usefulness of remote sensing in animal detection and inventory to where it is virtually infeasible at the present state of the available art. This is true for both photographic and thermal sensing methods since neither "sees" effectively through the tall vegetation. Despite this discouraging initial picture some feasible approaches can be suggested.

2.0 THE NATURE AND USE OF ANIMAL INVENTORY DATA

The ideal animal data for an intensively managed range area includes total animal numbers, herd or flock composition, and animal productivity. For wild animal populations, only relative statistics on numbers of/and population trend indices are available. In domestic animal management it is essential to obtain as near absolute data as possible to support intensive management of the forage resource. The types of animal data most useful follows:

1. Number of animals by breed, sex and age class;
2. Percentage by sex at birth, and at ages of weaning and maturity for marketing;
3. Replacement rate of the breeding stock of managed herds;
4. Death losses by causes, where known;
5. Weight and condition of animals at marketing or slaughter;
6. Efficiency or performance in feed conversion.

Admittedly, many of these data are unobtainable in primitive, agrarian or pastoral societies; but even relative judgments related to these factors find application and usefulness in striving to upgrade animal management as an initial step toward restoration of rangeland resources.

Acceptance of the meaning and importance of animal management practices is difficult where social customs attach high and equal value to each and every animal, where mere numbers owned is an important symbol of status and power. In some instances, the first step toward improved resources management has to be agronomic improvement of sites with high productive potential. This approach quickly supplements more widespread and basic feed resources so that some form of management procedure -- rotation, deferment or resting of the native areas -- can be accomplished without disturbing areas not as readily susceptible to agronomic improvement, thereby minimizing economic shock to the individual herdsman. Unless herd sizes around each potential improvement site are known and recognized in an agronomic program, the entire investment may be lost when

unanticipated numbers of animals move into the improved areas. Planning an agronomic range improvement program presupposes some knowledge of animal consumption in each grazing region, a function of the annual cyclic movements of the animals, their types and numbers.

Range carrying capacity is a function of nearly every variable in the natural system plus the management program. Carrying capacity can be determined or "fine-tuned" only if animal numbers and time and period of grazing are all considered in relation to the animal impact on the forage resource. These impacts are measureable through actual amount of forage removed (utilization) and the accumulative, physiological/ecological impact of various levels of use over time (condition and trend).

Finally, it is necessary to know when animals move onto the range, the distribution of the animals over the range area, and when they move off the range, in order to apply management or herding techniques for bringing animal demand into balance with feed supply. This is not required for managing natural pastures alone. To balance a livestock economy by integrating agricultural fodder and feed grain production with crop aftermath grazing, it is essential that animal numbers and herd composition are known. The first step toward general improvement of range condition and animal protein production in areas of nomadic herding may well be the integration of the animal crop production economies as far as custom and human understanding will allow. Even in relatively primitive pastoral grazing, planning adequate feed supplementation begins by determining animal numbers and their feed demand. Lacking this information forces management by expediency and happenstance rather than by purposeful design.

3.0 REMOTE SENSING AND ANIMAL INVENTORIES

A remote sensing system for animal inventory must first have a resolution that permits the registry of the unique energy return of "signature" of an individual animal body -- whether recording visible light or invisible energy. The second requirement is that the system permit discrimination of the animal body from its normal background. Without these discrimination capabilities the omission/commission error rate will be so high that the data are meaningless. A third requirement is that the system be functionally operational in either a complete coverage or a sampling mode. Complete surveillance of any sizeable area for animal inventory is unfeasible because large scale, high-resolution photography is required, and it is virtually certain that unknown numbers of animals would move from scene to scene. Fourth among the requirements

is that animals must be found in the open and visible when the sensor can record their presence. Finally, the fifth requirement is scene related; namely, the ground environment must meet certain conditions. These are: 1) all of the animals can be seen; 2) ratios of observed to obscured animals can be developed in a cost-effective manner; and 3) reliable indices of relative population density and trends must be established from observations of animal habits made in clearings.

Some alternative information sources for animal inventorying should be put into perspective before discussing applicable sensor systems and reporting experiments and operational projects. These alternatives include:

1. No data, or an incidental accumulation of "guesstimates";
2. Complete ground enumeration by interviews, questionnaires, and/or direct counts;
3. Enumeration by ground sampling methods similar to "2" with suitable expansion to estimate parameters;
4. Counting by observation (daytime or at night with spot light, eye counts) along fixed transects to develop relative population trend data;
5. Counting by direct aerial observation over the entire area and developing ratios of observed/obscured animal numbers to correct estimates;
6. Same as "5", but in a sampling mode rather than complete coverage;
7. Counting by direct aerial observations as in "5" and "6", supplemented by oblique photography for confirmation, or for double sampling to correct observer estimates;
8. Counting by sampling from aerial photography plus some ground confirmation to develop detected/non-detected ratios;
9. Thermal sensing on sample strips.

When neither existing records nor the collective knowledge of herdsmen can provide animal inventory data, some form of sampling by direct aerial observation is the only solution to having no information. Unless animals are herded, corralled at night, or so migratory that they can be counted, ground counts are rarely accurate, particularly when animals are congregated in large herds. Direct counts, from the air can also be inaccurate because it is difficult to tally which animals have and have not been counted. In such instances the observer frequently resorts to an ocular estimate of numbers, e.g. the censusing of birds. Bird enumerators have successfully used photographs of large, densely clustered flocks, accurately photo-counted, as a training aid to check against ocular estimates (Leedy, 1960). This idea has paralleled appli-

cations to large animal counting and estimating; the present practice is, however, to make accurate photo-counts because little confidence is placed in gross ocular estimates of numbers in large, high density herds.

The problem of domestic animal inventorying in developing nations, where economies are organized around nomadic or partially sedentary animal forms of agriculture, is similar to inventory problems associated with large, wild animal populations. Solutions may, therefore, be drawn from technology developed by wildlife experts. These suggestions will be brought forth in the subsequent analysis.

Philips (1970), writing about animal agriculture in the Sahel, stressed the importance of the full spectrum of wild animals: birds and reptiles, animals in ecosystems, and animals in the human food chain. He identified placing wild animal populations under a significant degree of management as a long term goal. Convincing indigenous peoples and government officials of the need and ways of game herd management requires inventory data or population trend indices. Range management applies fundamentally to improving and maintaining a forage and browse resource. Where that resource is used in common by domestic and wild herbivores is a basic consideration in range improvement and management. The remaining sections of this chapter address the more promising remote sensing methods for both domestic and wild animal inventory.

3.1 A BASIC PREMISE

A goal of complete coverage by remote sensing is unfeasible over extensive areas of semi-arid and arid regions where animal populations are quite sparse. The only operational alternative has to be a sampling scheme that gives reliable statistical estimates of animal numbers or animal densities per unit area. This approach generally assumes the use of ground estimates as an integral part of the technique -- an ideal problem where multi-stage sampling could be applied. Basic techniques have been developed, but the synthesis of a complete sampling design for multi-stage sampling is still experimental and has not been specified nor operationally tested. In this presentation the goal is to describe a synthesis which, subject to further refinement and testing, may represent an effective method for dealing with Sahelian resource and animal management problems.

4.0 APPLICATION OF REMOTE SENSING SYSTEMS TO ANIMAL INVENTORYING

Since a sufficiently detailed description of satellite and aircraft remote sensing systems has already been presented elsewhere in this report, this section discusses the most appropriate role of each feasible system in animal inventory.

4.1 SATELLITE SYSTEMS

The resolution of available satellite systems is obviously inadequate for inventorying animals, but ERTS and Skylab type imagery has a potential role in a multi-stage sampling approach to the problem. One of the initial problems in animal inventory is to predict animal locations and the likelihood of their presence. Satellite imagery of the ERTS and Skylab type can contribute this essential information. Animals tend to move either naturally or under the guidance of herdsmen to better forage areas. Detection, or prediction of greening and drying vegetation, can isolate land areas where the likelihood of detection is best. Capability to chart this "green and brown wave" with ERTS-1 data has been documented for both summer-green and winter-green climatic regions (Carneggie and DeGloria, 1973; Rouse et al., 1973a and 1973b; Bentley, 1973a and 1973b). The sequential monitoring capability of the ERTS system enables one to detect areas of lush plant growth, an important factor in predicting where animals are most likely to be found at any given time. Areas of lush plant growth can be determined quickly by visual human interpretation of false color infrared photographic composite products from ERTS at a suitable scale.

The availability of water also aids in isolating areas where prediction is best. In as much as ERTS MSS Band 7 (0.8 to 1.2 μ.) displays free water bodies and, often, moist areas contrasting from the generally light backgrounds of many arid and desert soil environments, information from visual interpretation can readily be obtained from suitably enlarged photographic ERTS products. The main problem is that resolution precludes human interpreters from consistent detection of small ponds (3 to 6 acres), small springs, wells, and narrow, flowing streams. Most water sources in the Sahel unfortunately are such small point sources -- namely, wells. Nonetheless, ERTS Band 7 does contain valuable information in other arid regions for stratifying landscapes (i.e., to divide into different levels of information or detail) on the likely presence of animals that can be extrapolated to other regions. For small data points, refinement by digital analysis of selected areas permits water bodies to be classified nearly to the resolution limit of the system, approximately 0.4 hectares (Nelson et al.,

1973). Although water turbidity and other factors confound signature recognition, water is one of the first features successfully classified from multispectral scanner data. The cost-effectiveness of this latter approach, however, remains to be demonstrated in this type of application.

4.2 AIRCRAFT SYSTEMS

Livestock ranchers in many developed nations have made extensive use of light aircraft to monitor animal distributions on rangelands. This method has been found more economical and feasible for ground surveillance than the four-wheel drive vehicle or the sterotyped horse and cowboy. Horse and vehicle travel have not been replaced entirely, however; the plane has made their work much more effective. By aircraft observation, checks can be made on distributions and grazing patterns, conditions of reservoirs and water facilities, animal health and condition, and the distribution of males where range breeding is practiced. Spot counts are often made to determine if animals are distributed according to plan.

Aerial counts of game animals by direct observation, first made in the United States in 1931 (Olsen, 1945), have become common practice in many parts of the world where game are managed. Users of this method soon began to employ aerial oblique photography to confirm direct counts. Large groups of animals are counted more easily and occasionally more accurately by photographing the group and making the actual count from the photography than by attempting it by aerial observation. In performing photographic counts, one commonly enlarges the photography and counts with binocular magnification or a lens. Stereo pairs have had limited use (Leedy, 1953). Animal movement between exposures is a problem, but animals can be identified by the fact they did move. Stereoscopic interpretation often facilitates detection in terrain backgrounds or vegetation cover where animals do not contrast sharply if the animals are taller than the vegetation.

Success in wild animal censusing by aerial photographic interpretation has been reported many times in recent years (Banfield, 1956; Bear, 1970; California Department of Fish and Game, 1946; Evans, Troyer, and Lensink, 1966; Gilbert and Brieb, 1957; Gill, 1969; Leedy, 1948, 1953; Pennycuick, 1969; Sniff and Skoog, 1964; Thomas, 1967; Watson and Scott, 1956; The Wildlife Society, 1969). Recent work in the United States on the inventory of domestic animals by aerial photographic methods has been done at the University of California at Berkeley (Huddleston and Roberts, 1968).

One of the most serious problems in animal censusing, regardless of method, is the error resulting from unobserved individuals. This problem is well recognized, and in some instances (e.g., in the case of caribou aerial counts), has been estimated at 22 percent of the population (Watson and Scott, 1956). It is extremely difficult, and often impossible, to determine a reliable observed/unobserved animal ratio to develop a parameter for general application. This is one of the main arguments in favor of a method that establishes a reliable index of relative, rather than absolute, population density. This concept becomes important with domestic livestock inventory, and particularly so in nomadic regions where a complete count is impossible.

The combined method of direct aerial count with photographic support is relatively simple to apply if one disregards the complexities of rigorous, well designed sampling schemes. One merely flies a specified route, counts all animals observed directly, and takes periodic or frequent photographs to be interpreted to confirm the count or determine biases and directions of bias for applying an adjustment ratio; and, to provide counts of large groups difficult to obtain from a moving aircraft. Such photographs are usually taken as low obliques with a hand-held camera. Various grid devices have been successfully used to facilitate accurate counting of animal numbers where animal density is high and herds are large; assessments of age and size classes and, in some cases, sex ratio determination has been possible using appropriate scales (Kalmbach, 1949; Leedy, 1960).

The most sophisticated method to date for aerial photographic animal inventory was described by Huddleston and Roberts (1968). The procedure is described as follows: complete stereo coverage was obtained with a high quality mapping camera (Zeiss RMKA) having a 6 inch focal length lens with panchromatic film at a scale of 1:5,000. Seventy millimeter color transparencies were also obtained for sub-sample areas with a Hulcher camera having a 14 inch focal length lens at a scale of 1:2,140. Both cameras were bore-sighted to the same ground point and simultaneously triggered from a single intervalometer. In this way, the color strip sampled the center of the larger frame area. The camera was triggered for 60 percent stereo overlap to insure a 10 percent overlap and continuous strip sample with the 70 mm color photography. Sample strips were flown by these two cameras. Animal counts from the color strip and its matching panchromatic film were ratioed to correct interpretation results from the smaller scale panchromatic photographs. A scale of 1:8,000 was found to be near the limit for reasonably good results, but a minimum scale of 1:5,000 maintains consistent accuracy when counting domestic livestock. Scales as large as

1:2,000 are recommended in instances where animals are tightly bunched or otherwise difficult to count.

Several practical considerations and problems in animal inventorying can be added:

1. Generally speaking, color or panchromatic minus-blue photography is best for most purposes; color infrared film may increase animal background contrast under some conditions (Driscoll and Gill, 1972).

2. The strongest contrasts between animals and background can be obtained by a judicious selection of the season of the year.

3. Stereoscopic interpretation increases the accuracy of counts.

4. Diurnal habits of the animals must be carefully considered in planning photo missions. Many animal populations forage in the cooler parts of the day: early morning, late afternoon, and early evening. This creates some severe problems of photographic exposures and often limits the selection of film type.

5. It is always desirable to have an observer aboard the aircraft when taking animal census photography.

6. There are presently no systems permitting detection of animals through the screening effect of tree limbs or shrubbery.

7. Careful delineation of the project area would eliminate the waste of large amounts of film used in traversing unpopulated areas.

8. In the final analysis, the best method at the present state-of-the-art may still be direct aerial observation and counting supplemented by low oblique aerial photography.

Using satellite imagery for an initial stratifying of the region into populated and unpopulated areas is an attempt to circumvent this last problem as well as to provide a better basis for expanding estimates into the regional context. If this can be done successfully, the feasibility of an innovative, dominantly photographic method with minimum ground data becomes more cost and time effective than present practices of aerial observation and ground count.

4.3 THERMAL SENSING OF ANIMALS

Infrared <u>is not</u> the sensing of emitted heat or radiant energy (a common misconception), but sensing reflected energy (return of light from the object sensed) just beyond the visible red (0.7 μ to 0.9 μ).

With the advent of sensitive <u>thermal</u> infrared detectors operating in the 3.5 to 5 μ and 8 to 14 μ spectral regions, (which do sense radiant energy, or "heat") and scanning devices for the use of these sensors, questions are asked about their usefulness for animal inventorying.

Trials and basic research on problems of thermal detection have been conducted from aircraft platforms and a significant literature has been developed. The general consensus is that these systems are not yet operational for comprehensive animal inventories, although specific applications do exist, (Croon, 1967; Croon et al., 1968; Garvin, Beatty, and Zanon, 1964; Marble, 1967; McCullough, Olson, and Queal, 1969; Moen, 1968; Parker, 1972; Parker and Harlan, 1972). Thermal infrared scanners have been used successfully to detect some wild game and domestic animals, such as deer (Croon et al., 1968; Parker, 1972), moose (Garvin et al., 1964), and cattle and sheep (Carneggie, 1967). A host of problems must be solved in going operational with presently available systems under most environmental conditions. The theory and potential applications, however, appear promising. The following problems stand in the way of an operational system:

1. Thermal radiation cannot penetrate vegetation; therefore, animals beneath even a partial cover of vegetation are not clearly discerned.

2. The probability of detection is related to the thermal contrast between the effective radiant temperature (ERT) of the animal and its background, a contrast which is often unobservable. (Marble, 1967; McCullough et al., 1969; Moen, 1968; and Parker, 1972).

3. The effective radiant temperature (ERT) of different species varies and is also strongly affected by direct-beam solar radiation. ERT variation of up to 20°C has been reported for deer (Parker, 1972).

4. Problems of detection under scattered clouds are significant; some authors have suggested that working under complete overcast is more advantageous (Croon, 1967; McCullough, et al., 1969; Parker, 1972).

5. The ERT of vegetation, soil, and rocks may exceed that of an animal under direct-beam solar radiation; even as late as 2100 hours it may exceed that of deer (Parker, 1972).

6. Rocks and some plant species protruding above the snow level will tend to give false signals just as do warm rocks in the early evening (a potential problem one can ignore in the Sahel, however).

7. Sensing animals requires that their diurnal movements from the open to to cover or shade be thoroughly understood.

8. Thermal contrasts over a snow background are greatest, particularly from altitudes of 500 to 1,000 feet (152 to 305 meters), and, therefore, better for sensing; snow cover is not present in all environments, however, and the variability of snow cover presents special problems if it is not complete.

9. The coarse resolution of currently available scanner systems (approximately 3 milliradians (0.9 square meters) from 300 meter flight altitude) makes the detection of small animals difficult. The size of the animal must be sufficiently large in relation to ground resolution to provide an emitted temperature greater than the background ERT. Parker (1972) suggests the best compromise on timing other than snow cover is in the predawn hours when the ERT of the background is lowest and there is sufficient light for safe aerial navigation.

The primary advantage of a thermal scanning system is that it has diurnal capability, i.e., it can be flown most times of the day since it is not dependent on reflected energy. A second potentially significant advantage is that the data can be fed directly through an analog to digital converter to create a computer tape record for quick handling and calculation of inventory data. Cost-effective, operational systems for practical application to management oriented problems, however, are still remote. The potential advantages with higher resolution systems do appear to justify investment in research and development, particularly if the system is used in a multi-stage sampling design that reduces the number of samples.

5.0 STATE-OF-THE-ART-EVALUATION

The animal inventory problem in Sahel region should be directed toward determining reliable indices of animal density per unit area by subregions and areas where they are likely to occur. In summary:

1. Ground enumeration is probably infeasible and, in fact, unnecessary for the general attainment of resource management goals.
2. A complete aerial enumeration and an absolute count by methods other than ground enumeration is completely unrealistic.
3. Remote sensing technology should be part of the determination of animal population densities. Any animal inventory program in the Sahel region should initially be directed toward determining reliable indices of animal density per unit area.
4. These statistics should be collected for natural subregions determined from an appropriate ecological inventory (see Chapter 11); and,
5. Animal density data on both domestic and major wild species should be related to those regions and areas with highest priority for resource management concern.

It is not possible to provide reliable estimates of the cost of implementing an animal inventory program without knowing the characteristics and topical animal management practices appropriate to individual subregions. Therefore, an ecological inventory of the Sahelian region begins with land use, and vegetation and soil resources. Basic data would thus be provided to design and cost a sound remote sensing approach to animal inventorying. This would undoubtedly be the most cost-effective approach on an operational basis once the approach and concepts were specified, refined, and pilot tested. The advantages of full cost-effectiveness cannot be expected if the various inventories and studies are done piecemeal by separate, uncoordinated agencies.

The correct design and implementation of this particular kind of multi-stage inventory requires experience and a sound methodological basis. Multi-stage inventory requires sampling at each stage proportional to the probability of occurrence of magnitude of the specified parameter. In other words, the procedure requires that numbers, densities, or predictive models be developed. Such an approach would seem particularly appropriate to the animal inventory problems in the Sahelian region.

6.0 PROBLEMS AND LIMITATIONS

For the most part, this subject has been covered in the discussion of various systems and alternatives. It is important to realize that many techniques for animal inventory are available. Some use remote sensing, and some do not. All have certain deficiencies, and none appears entirely suited to the Sahelian environment without substantial adaptation. One of the greatest problems with all present techniques is in the methods and formulae for extrapolating counts back to the land with reliable predictions. The Sahelian livestock inventory problem parallels wild animal censusing and probably calls for a similar approach. This environment and the uniqueness of its problems creates situations calling for creative approaches and adaptations that increase the reliability of estimates of animal numbers or density per unit area.

7.0 SUMMARY AND CONCLUSIONS

The Sahelian region needs reliable data on animal populations, both domestic and wild, to solve its resource problems. These data can be obtained for ecological units of the region in terms of density per unit area, and methods also could be developed to estimate the total numbers. Modern remote sensing, including ERTS or highflight aircraft imagery (1:120,000 scale or smaller), and possibly even meteorological satellite data, could be a part of a system for initial stratification, sample design, and sample data extrapolation back to the land. The most viable final stage in sampling would be direct aerial observation supplemented with aerial photography subsampling. Whether to follow the conventional oblique support photography approach or the method of Huddleston and Roberts (1968), is still questionable.

An integrated ecological resource inventory and analysis should be performed before an animal inventory is attempted. This analysis should contain vegetation, landforms, and land use features at a scale of about 1:250,000 for the entire region (preferably from good quality ERTS photographic imagery, if available). Such an interpretation should focus on initial environmen-

tal areas and areas of high probability of animal occurrence. These areas of concern should be inventoried more intensively to provide a basis for land use and resource management planning. Efficiencies would be realized by doing the resource inventory prior to an animal inventory. This would eliminate an intermediate stage between sample design and initial stratification and subsampling and provide time for the research and development work required in refining the animal inventory methodology. Small scale, preferably 1:120,000 in 9" x 9" format, high resolution aircraft photography would be suitable.

Full achievement of comprehensive and effective management of Sahelian resources and stabilization of animal and cropland agriculture requires improvements in animal and range management (Kassas, 1970; Phillips, 1970). A better knowledge of animal populations, both domestic and wild, is an essential ingredient for development and implementation of effective programs to reverse or arrest desertification and provide a reasonable standard of life for the peoples of the region.

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CHAPTER 13

ASSESSING SAHELIAN AGRICULTURAL PRODUCTION AND DEVELOPMENT POTENTIAL

1.0 INTRODUCTION

The assessment of Sahelian agricultural production begins with the compilation of the basic data on present agricultural needs to answer questions such as:

1. How much of the land is currently cultivated?
2. What crops are grown?
3. What is the condition of the crops?, and
4. What is the expected regional food production for the present year?

In addition to questions on the existing conditions, others must be answered to provide information from which to formulate new agricultural policies and sound development plans. These additional questions include, but are not limited to:

5. What are the ecological characteristics of the landscape with respect to potential agricultural expansion?
6. How can the natural landscape be partitioned into meaningful agricultural development units?
7. What would be the optimum allocation of crops within the potential agricultural units?
8. How could the performance of agricultural endeavors be checked after the implementation phase?

The design of new agricultural policies and schemes for further implementation is complex. In the Sahel, as in other areas, decisions must take into account not only economic and physical matters pertaining to land use, but relevant social, cultural, and historical matters as well. The human aspect of agricultural development must be given close attention since people in these areas must secure their livelihood mostly from livestock production and from farming (FAO, 1973; NAS, 1974): south of the 14th parallel the bulk of the population is engaged in farming; north of the 14th parallel nomadic pastoralism dominates.

In the latter portions of this chapter, these two groups of questions are examined for ways in which remote sensing may aid decision makers. Before doing so, some introductory comments on the nature of Sahelian agriculture are proper.

1.1 CHARACTERISTICS OF SAHELIAN AGRICULTURE

The value of remote sensing in inventorying, monitoring, and aiding in the management of agricultural production and development varies from locality to locality depending on the mix of physical and cultural factors encountered.

There are major differences in agricultural practices between the Sahel and North America, and these must be considered in appraising the roles for remote sensing for crop identification. First, field sizes are very small relative to the U.S. except for a few large plantations and agricultural research stations. The typical field size reported by FAO (1972) is in the vicinity of 0.6 hectares in Senegal and is much the same as the other Sahelian countries. The FAO report notes that the average rural Senegalese family consisted of 12 persons of whom six tend to agricultural duties. The main factor which reduces agricultural fields to the status of gardens, is the amount of work required in each plot. Small field size can be related to the customs and experiences of local growers and reflects the amount of land they know can be cleared and kept free from weeds. Weeding requires nearly full time attention through the growing season, and sets the limit on field size: it is possible to clear and plant much more than can be actually worked during the growing season.

Second, the planting operation is by broadcast sowing of locally-maintained, low quality, weedy seed. Third, field boundaries are determined by the lay of the land and the nature of the clearing operation and are therefore generally irregular. Fourth, the crops in the Sahel are subsistence species such as millet, sorghum, maize, ground nuts, and certain root and tuber species. Some dry land and irrigated rice is also grown. These crops are often found in mixed plantings consisting of one principal crop with inter-row planting of a second crop or crops.

Fifth, Sahelian agriculture is generally a low technology, "hoe and machete" oriented system with little or no animal traction applied (FAO, 1973). Government efforts to promote the use of animals or machines for agricultural operations have not generally been successful, and reflects the nature of the agricultural systems which are not prone to rapid change (Grove, 1970). Some success has been achieved, however, when the new technologies have been applied to cash crops.

Sixth, much of Sahelian agriculture is of the "shifting agriculture" type, with irrigated land and a few experimental stations being the major departures from this pattern. Thus land in all stages between recently cleared and fully reverted bushfallow is intimately mixed.

It should also be emphasized that the agricultural environment of the Sahel Zone, if not entirely hostile, is at least very marginal. Rainfall is scanty, irregular in timing and amount, and of very low reliability. Thus drought from both the intense type, coinciding with sensitive periods such as flowering, and long sustained drought, spanning several years is ever-present. Adverse conditions, when they occur, impartially destroy the worse and best-kept fields. The knowledge of this fact also tends to hinder the acceptance of new technology: it is typical of subsistence economies that only substantial improvements in yield are sufficient to lead to the adoption of new practices.

Because of basic dissimilarities between agricultural practices, crops, and environmental conditions in the Sahel and those in the United States, where most of the remote sensing technology has developed, serious questions are raised with respect to the transferability of many of the remote sensing applications and procedures. For example, most research in highly advanced techniques such as automatic image processing is tied very closely to the characteristics of the environments examined. In addition, remote sensing applications in areas of large fields with uniform dense stands of well-fertilized plants are simply <u>not</u> extrapolatable to the developing world, and to subsistence agriculture. Only experimental applications within the developing countries will be meaningful. At present, very few applied studies for developing nations exist. This is not to discount all possibility of using remote sensing, especially ERTS, for acreage/field boundary delineations and crop identification in the near term. It may be feasible in particular circumstances: one simply must be cautious about extrapolating remote sensing techniques developed in other areas.

2.0 LITERATURE REVIEW

Despite the caution one must have in extrapolating remote sensing analyses outside the United States into areas of small field agriculture, there are a number of studies on agriculture using ERTS-1 images which are of special interest from the point of view of the techniques employed. These interpretation techniques may be applicable with high altitude aircraft photography even if they cannot be applied with ERTS imagery, since the resolution of ERTS is

unsuitable for small scale agricultural practices in the Sahel. The techniques would certainly be usable with Space Shuttle photography of the 1980's.

The principal papers of interest in this area are by Thorley et al. (1973), Simonett et al. (1974), Landgrebe et al. (1973), Baumgardner et al. (1973), Morain and Williams (1973) Wigton and Von Steen (1973), and Wiegand et al. (1973). In addition to these ERTS-1 analyses, a valuable source of information on remote sensing in agriculture is to be found in the National Academy of Sciences sponsored publication "Remote Sensing with Special Application to Agriculture" (1970). The latter provides particularly useful information on aircraft applications.

The principal concerns in the study by Thorley et al. (1973) entitled "Regional Agricultural Surveys Using ERTS-1 Data" were to: 1) delineate agricultural land on ERTS-1 images using manual techniques (The accuracy with which agricultural areas can be differentiated from other land use categories on a periodic basis needs to be known for the monitoring of land use change and for the planning of more detailed surveys); 2) assess the feasibility of performing periodic tabulations of the predominant agricultural use of each area within the general agricultural region, (this necessitates breaking down the agricultural areas into general crop types or use groups); 3) inventory the crops in each subregion and determine the accuracy with which the acreage of selected crops can be estimated by sub region; and 4) review the comparative costs and accuracies of various combinations of manual regionalization (stratification), followed by within-region automatic digital crop classifications. The authors note that:

> "Up to the present time agricultural inventories have required a tremendous effort on the part of on-the-ground-enumerators, and have presented a formidable compilation task. However, a satellite sensing system, with which large areas of land can be surveyed in their entirety on one image, and which can provide uniform worldwide coverage with a relatively small number of images, offers great promises as a data collection tool for alleviating these problems. Furthermore, the dynamic nature of agriculture requires not a single evaluation in most cases, but rather a continual updating of conditions. In fact, it has been shown that desired information about agricultural crops can often be obtained only by capitalizing on a knowledge of the patterns of change exhibited by particular crop types under various growing conditions. Again, this suggests that a satellite sensing system such as ERTS, which makes possible regular, frequent observations of each spot on the earth's surface, can provide a service which is both highly desirable and totally infeasible using conventional techniques."

An important conclusion was that "A much more detailed and up-to-date agricultural area delineation was produced from the ERTS image than is currently obtained by the Statistical Reporting Service of the U.S. Department of Agriculture." Crop identification accuracies were higher when the field boundaries were manually determined and then followed by computer

assisted crop identifications. Multi-date imagery enabled higher accuracies to be obtained in crop identification, and accuracies for certain crops at different times of the year were as high as 95 percent while the others hovered around 60 percent. The value of multi-date imagery was stressed, since time as a discriminant has been used in increasing the accuracy of crop identification even in areas where many crops are grown. However, this may not be quite so feasible in a monsoonal regime in the Sahel where almost all crops are planted and come to maturity at the same time. The differences in the rate of progress throughout the growing season and in the planting dates (which is one basis for crop discrimination) would not be applicable to the same degree in the Sahel.

Simonett et al. (1974), in a study for the U.S. Department of Agriculture, in cooperation with the Canadian Department of Agriculture and Canadian Center for Remote Sensing, analyzed fourteen test sites using ERTS-1 imagery in the spring wheat areas of the United States and Canada. A great variety of ground and other observations on crop type and condition were merged with the Earth Resources Technology Satellite data through overlay into a computerized data base. This computer based system enabled relationships to be established between final crop yield as estimated by farmers and field observers in the various test sites and the great diversity of input variables. These input variables included weather conditions, presence or absence of fertilizer, percent ground cover, crop height, soil type, and varietal differences of wheat. By mid-1974, this study had clearly shown that a useful tool for evaluating the contributions to final crop yield of various input variables had been developed. The most significant aspect of the analyses of the first site studied -- Williams County, North Dakota -- was that selected ERTS-derived variables, particularly percent of fertilized wheat and percent prairie grass contained within a wheat field (a measure of the uniformity of stand), were significantly connected with final crop yield.

In terms of crop yield prediction, models are now being developed and tested using historical data, crop phenology, meteorological and stress variables, ERTS and other imagery for predicting crop yields in the U.S. and Iran. While direct transfer of the equations to the Sahel environment is questionable, the models employed should provide an accurate framework for crop prediction analysis.

Landgrebe et al. (1973), investigated machine processing techniques of ERTS-1 applications. Quite high accuracies were obtained in crop identification with single date ERTS imagery in

agricultural situations where a rather simple array of crops were found or where one crop at that time was sharply differentiated in its stage in the agricultural cropping cycle from others. In addition, they showed that multi-date imagery, while generally more useful than single date imagery was not always as valuable.

Morain and Williams (1973), developed a prediction model for ERTS-1 imagery to project 1973 wheat yield for a ten county area in southwest Kansas. The results obtained were within 3 percent of the pre-harvest estimates of the same area prepared by the USDA Statistical Reporting Service. The projection from ERTS data was "based on a visual enumeration of all detectable wheat fields in the study area and was completed while the harvest was in progress. Visual identification of the wheat is readily achieved for a field of 80 acres or larger by using a temporal sequence of images (Band 5, September-October; Band 5 December-January; and Bands 5 and 7 for March-April). Identification can be improved by stratifying the project area so that the sub-regions have more or less homogenous agricultural practices in crop mixes. By doing this, small changes in the spectral appearance of wheat related to soil types, irrigation, etc. can be accounted for". The study also noted that the interpretation rules developed by visual analysis can be automated for rapid computer surveys. Thus, in their study, Morain and Williams came to much the same conclusions as Thorley et al. (1973) that accuracy is improved by means of agricultural stratification using the ERTS imagery as a basis for grouping the agricultural landscapes into agriculturally homogeneous areas. In the large field agriculture of southwestern Kansas, ERTS imagery thus was very successful.

In a somewhat similar study using machine processing, Wigton and Von Steen (1973) found quite variable results in portions of Kansas, Missouri, Idaho, and South Dakota. The major crops were wheat, cotton, corn, soybean, sugar beets, potatoes, oats, alfalfa, and grain sorghum. In Missouri, winter wheat was planted in much smaller fields that in western Kansas. The crop mixture was also much more complex. This led to distinctly lower accuracies of automatic identification than had been achieved manually by Morain and Williams in western Kansas. These differences related not so much to the difference between machine and human processing but rather to the complexity of the agricultural landscape. In addition, Wigton and Von Steen found that the use of a priori statistics enable higher accuracies of identification to be obtained.

Essentially these results had been forecasted for areas such as Missouri and eastern Kansas in an earlier study by Brooner and Simonett (1971) using high altitude aircraft imagery. They

noted that a priori statistics will improve the accuracy of results. At the same time they pointed out that in areas of very complex crop mixtures, or where all crops were in flush growth (as in the wet tropics), identification accuracies were likely to be quite low with ERTS. The eastern Kansas areas they studied is very similar to the region in Missouri studied by Wigton and Von Steen.

Wiegand et al. (1973) of the Agricultural Experiment Station in Weslaco, Texas have carried out studies of vegetation density using ERTS-1 multispectral scanner data. They observed that:

> "Reflectance from vegetation increases with increasing vegetation density in the .75-1.35 μ wavelength interval. Therefore ERTS-1 bands 6 and 7 (.7-.8 μ and 7 .8-1.1 μ) contain information that should be related to the probable yield of crops and the animal carrying capacity of rangeland. On the other hand, reflectance of vegetation is typically less than that of bare soil and is essentially constant in the visible wavelengths as vegetation density increases; consequently, the decreased response observed in ERTS Band 4 (.5-.6 μ) as vegetation increases, is mainly due to the soil that is obscured by vegetation. Because the ERTS MSS responses recorded under variable ground cover conditions are mixed signals for soil and vegetation, ratios of Band 5 to Band 7, or Band 7 minus Band 5 are practical indications of vegetative cover and density for users of ERTS data."

The results of the overall study support the utility of ERTS data for explaining variability in yield, biomass, harvestable forage and other indicators of productivity.

These results by Wiegand and co-workers and the similar results obtained by Rouse et al. (1973) at Texas A & M University indicate that a real potential may be possible with ERTS in monitoring range conditions in Sahel. This potential, however, will be very difficult to realize with an ERTS resolution system for crop monitoring -- though it will be quite adequate for monitoring pastures -- and will await the development of somewhat higher resolution systems in the future. If the potential is realized in the United States, higher resolution multispectral scanners carried on Space Shuttle in the 1980's could very well provide data that could be used to assist in yield prediction in the Sahel.

The question of the applicability and costs of ERTS analyses in the Sahel are important. At this time application of digital analysis in the Sahel does not appear likely to be cost-effective. Computer processing with sequential computers is very costly even in the U.S. and nowhere are such procedures used routinely in an operational mode. With the development of parallel processing type computers and hard wired devices, such as the G.E. Image 100, the cost may be significantly lowered in the future.

Manual interpretation is more likely to be cost-effective for some time and early ventures should emphasize the manual approach in the Sahel.

Results of agricultural crop identification with aircraft scanner data are very numerous in the U.S., but are at this time essentially inapplicable in the Sahel because of the costs of aircraft flights and of computer processing, particularly as applied to subsistence crops. Total costs would represent a large proportion of the annual budgets of the departments of agriculture of the Sahelian countries, especially if repeated surveys were required. In addition, the low percentages of crops of the region which enter the exchange economy represent a major constraint on the use of such procedures. A great deal of technical information may be found on these topics in Remote Sensing: With Special Application to Agriculture (NASA/NRC, 1970), in the proceedings of symposia on remote sensing sponsored by the University of Michigan, and in the reports of several symposia conducted by the University of Tennessee.

It is perhaps to the 1980's and Space Shuttle that the Sahelian area must look for truly operational systems, or even to a higher resolution ERTS-type satellite. Space Shuttle is likely to carry multi-frequency, multi-polarization radar, multi-resolution photography and higher resolution multispectral scanners than ERTS. All will have applicability for crop surveys in the Sahel.

The extensive series of studies by Simonett et al. (1967), Haralick, Caspall and Simonett (1970), and Morain and Coiner (1970) at the University of Kansas on crop identification with various radars, and unpublished studies on the use of the Goodyear X-band Radar in the Amazon Basin, suggest many roles for operational radar systems; including crop detection. Aircraft systems will not be feasible, nor cost-effective for these sensors, since repeated looks are required during a growing season.

A quinquennial or decennial survey with high altitude aircraft photography to establish the regional framework for an agricultural census sampling frame is, however, likely to be very cost-effective -- particularly when all the feasible uses for the high altitude photography are considered. Consequently, a uniform, Sahel-wide high altitude false color photographic data base may be useful to develop at this time.

2.1 AGRICULTURAL CROPS AS REMOTE SENSING TARGETS

Over the last decade, research on the use of remote sensing for crop identification and the assessment of growth stage, crop condition, and stress, has enabled some of the complexities of the intertwined factors which contribute to crop image appearance to be deciphered. Table 13-1 summarizes the major sources of crop appearance variation.

Despite these complications, a number of relevant characteristics of crop stands have now been documented as being measurable. Table 13-2 summarizes: (a) those parameters or attributes of crops which are measurable; (b) the required sensor capabilities for detection and quantification; (c) examples of existing sensor systems which can provide required data; and (d) brief comments about each item. The information in this table provides a summary of possible future applications of aircraft and spacecraft sensors in the Sahel.

3.0 QUESTIONS ON PRESENT AGRICULTURAL PRODUCTION

In the introduction, nine questions of concern to policy makers in agriculture were raised. The first five relate to present agricultural production, and were arranged in order of increasing difficulty with respect to the ability of remote sensing to provide the requisite information. The sequence, beginning with the amount of land cultivated, and running through its location, the crops planted, their condition, and ending with estimates of the expected regional food production for the current year, are questions for which answers must be available if the Sahelian countries are to make appropriate decisions on food supplies. In order to answer the first question, one must be able to distinguish between cultivated and uncultivated land. The last question on food production not only requires knowledge of the cultivated land but also of the crop types, their stages, status, and of the prior conditions to which the crops have been subjected, as well as the expected likely future conditions so that yield as well as acreage can be taken into account. The last question thus involves a much wider range of information sources and remote sensing systems.

Question 1: How much of the land is currently being cultivated?

This question is the first that would be asked by a nation concerned with establishing an agricultural census. Very unreliable data on total plowed hectareage is presently available in the Sahel; different ministries of the same government are known to use hectareage figures which differ from one another by 30 to 40 percent.

TABLE 13-1

SOURCES OF VARIATION IN REMOTE SENSING IMAGE APPEARANCE OF CROPS

1. Illumination Conditions

   Illumination geometry (sun angle, cloud distribution)
   Spectral distribution of radiation

2. Site Environmental Conditions

   General weather
   Micro-habitat weather
   Hydrologic
   Edaphic
   Anthropogenic
   Geomorphologic

3. Reflective and Emmissivity Properties

   Spatial properties (geometrical form, density of plants, and pattern of distribution)
   Spectral properties (e.g., reflectance or color)
   Thermal properties (emittance and temperature)
   Temporal changes in above

4. Plant Conditions

   Maturity
   Variety
   Physiological condition
    Turgidity
    Nutrient levels
    Disease
    Heat-exchange processes

5. Atmospheric Conditions

   Water vapor, aerosols, etc. (absorption, scattering emission)

6. Viewing Conditions

   Observation geometry (scan angle, heading relative to sun)
   Time observation (date, hour, season)
   Altitude

7. Multichannel Sensor Parameters

   Electronic noise, drift, gain change
   Accuracy and precision of measurements on calibration references and standards
   Differences in spectral responses of systems

Adapted from Polycn, F.C. et al., 1969, "How Multispectral Remote Sensing can Help the Ecologist." Remote Sensing in Ecology, University of Georgia Press, pp. 194-218.

TABLE 13-2 RELATIONS BETWEEN CROP IDENTIFICATION AND CROP CONDITION AND REMOTE SENSING PARAMETERS & SENSORS

TASK	PARAMETERS AVAILABLE TO MEASURE	REQUIRED SENSOR CAPABILITIES	EXAMPLES OF EXISTING SENSORS TO PROVIDE REQUIRED DATA WHEN CONFIGURED APPROPRIATELY	ADDITIONAL INFORMATION
CROP IDENTIFICATION	Reflectance (color)	Measure Reflectance .4 μm to .7 μm .7 μm to 1.2 μm	Multiemulsion, multiband photographic, MSS IR photographic including ERTS	MSS data more amenable to automatic processing than aerial photography.
	Thermal inertia	Measure emittance 3.5 μm to 5.5 μm 8.0 μm to 14.0 μm	Thermal IR Thermal IR	Crop separation by compative diurnal temperature cycles. Use to test moisture content in soils
	Moisture content in plants	Measure reflectance 1.0 μm to 3.5 μm	MSS (Skylab)	Useful Information when separating aquatics and crop plants.
	Phenologic development	Acquire sequential data in comparable form	Multiemulsion, multiband photographic, MSS, Thermal IR	Difficulty exists when comparing multidate MSS and/or thermal IR data.
	Physiognomy	Determine average crop height and depolarization ability, allow for evaluation of spatial configuration.	Photographic stereo, MSS, SLAR	SLAR and MSS data are without height information. Manual interpretation of texture. Poor geometric fidelity but possibly spectral reflectance value in SLAR data.
	Position in Landscape	Allow for evaluation of field site (Upland, Lowland, etc.)	Photographic, MSS, Thermal, IR, SLAR	Identification clues from field location.
	Crop Biological Dynamics	Acquire sequential data in comparable form	Multiemulsion, multiband photographic, MSS, Thermal IR, SLAR	Manually determined from data presentation and multi-date processing for application of crop calendar identification concepts.
ASSESSMENT OF GROWTH AND DEVELOPMENT DYNAMICS INCLUDING YIELD	Reflectance (color)	Measure reflectance .4 μm to .7 μm .7 μm to 1.2 μm	Multiemulsion, multiband photographic, MSS, IR photographic, MSS	Detect visual abnormalities during stress & normal phenology changes. Abnormal changes in near IR reflectance known to be a sign of stress, for example. Also detect stress through amount of bare ground during growing season
	Moisture Content	Measure Reflectance 1.0 μm to 3.5 μm	MSS	Abnormal changes in plant water balance a sign of physiological damage.
	Chlorophyll	Measure chlorophyll Fluorescence	Fraunhoffer line discriminator	Chlorophyll content increases with normal physiological development
	Temperature	Measure Emittance 3.5 μm to 5.5 μm 8.0 μm to 14.0 μm	Thermal IR	Stress conditions cause changes in normal thermal balance.
	Morphology	Measure Height allow for Evaluation of form	Photographic stereo Photographic MSS, Thermal IR	Useful to monitor seasonal size development and/or detect abnormal form due to damage or environmental changes.
	Crop stage and sequence.	Acquire sequential data in comparable form	Multiemulsion, multiband photographic, MSS, Thermal IR	Same considerations as crop identification.

The characteristics of typical Sahelian agriculture -- small fields, irregular field boundaries, random planting schemes, several crops in each field, and weedy natural vegetation mixed in with the crops -- pose serious difficulties in calculating the amount of cultivated land using available sensor systems in a cost-effective manner.

The difficulty of direct detection and recognition of each individual field under such conditions is obvious. With very high resolution imagery, locally experienced interpreters could be expected to identify fields and then map cultivated areas. However, this method, involving conventional interpretation of large scale aerial photographs, would be prohibitively expensive and time consuming. Alternatively, automated analysis of ERTS data, although extremely fast and theoretically cover vast areas, is also not applicable for this task because the field size is less than the ground resolution of ERTS sensors. Furthermore, there is reason to suspect, based on our experience with automatic identification routines, that individual fields in the Sahel may not offer sufficient contrast with their surroundings to be recognizable.

In order to answer the original question, the best approach would appear to utilize remote sensing techniques as part of a multi-stage sampling* scheme which, if correctly designed, could also assist in providing answers to other questions. Within the agricultural sector, such a survey could feasibly be undertaken to predict the total area devoted to each particular crop, and, if enough data was available, to predict the agricultural production of each mappable area using the same techniques. Multi-stage sampling techniques are discussed by Langley (1971).

ERTS-1 images, which are so useful in identifying areas of cultivation in the U.S., may not appear appropriate for crop census in the Sahel, since conventionally processed ERTS-1 images as noted earlier, are not easy to interpret for subsistence shifting agriculture. The principal objective of a multi-stage sample design is to be able to delimit the broad areas of cultivation with the coarse resolution sensors, and then progressively sub-sample with higher resolution systems. ERTS-type satellite imagery can play an important role by facilitating this first stage.

A number of different approaches may be necessary to detect small, agricultural fields in the Sahel. Experiments with special processing of ERTS show that image enhancement can emphasize the

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* Multi-stage sampling is a statistical technique which attempts to minimize the sampling error of surveys based upon the sequential examination of increasingly finer sampling units. The sampling efficiency and accuracy increases at each stage, until the hierarchical sampling stages are statistically related through an expansion of data to produce an overall value. This technique, if correctly applied, can produce survey information with the least sampling error.

texture of cultivated land so that manual interpretation of texture can be employed for mapping purposes. This is not something which is demonstrably feasible, however, and the needed testing has yet to be done for the Sahel.

An alternative would be the use of side-looking radar imagery. With stereo radar imagery, it has proven possible to identify fields of the shifting agricultural type in Brazil and in the highlands of New Guinea. However, these are areas where the natural vegetation is much denser and higher (rain forest), and there is no guarantee that the contrast between the cultivated and uncultivated lands in the savannas and steppes of the Sahel will be nearly so sharply defined. Special aircraft radar flights for this and other purposes would cost about $2.00 per square kilometer if large areas were covered. Radar on Space Shuttle will not be available until the 1980's.

Another possibility for detection of small fields will be the use of high resolution photography on Space Shuttle (5-15 meters resolution). However, it will be five years at least before such photography might be available and could be integrated into a Sahelian agricultural census.

Probably the most reasonable possibility at present is the use of very high altitude aircraft flights to obtain small scale color infrared photography for field location. This would cost of the order of $2.00 per square kilometer.

A final alternative would be to identify agricultural areas on black and white mosaics assembled from 1950 to 1960 photography and outline the areas of agriculture a decade ago. This historical inventory could be used as a basis for planning more restricted high altitude aircraft flights and thereby save costs.

The conclusion is that to determine the present amount of cultivated land in the Sahel using remote sensing techniques requires coping with problems of technology, expense, delay, or the currency of available data. The technological difficulties involve pushing the ERTS-1 images to its interpretation limits. Large expenses are associated with special radar and high altitude air photo flights. Time delays pertain particularly to the Shuttle System. Finally, existing black and white photography is dated and therefore often inaccurate. It would also be expensive to assemble and interpret very large scale, older photography.

In order to improve the design of an agricultural census for the Sahel in the near term, careful combination of manual interpretation of ERTS imagery in conjunction with existing black and white photo mosaics would appear to be the only cost-effective process that could be used. There are some textures on the ERTS imagery which skilled interpreters might be able to use as a basis for delineating cultivated areas. In the major irrigated areas associated with master alluvial streams, some fields are large enough that they may be individually discriminated. Even those which are not clearly discernible are identifiable as irrigated lands. Irrigated agriculture therefore may well turn out to be one portion of the agricultural sector that may be readily delineated with ERTS.

If the assumption is made that, by one or another of the above means, an overview of the location of cultivated lands is possible, then the remaining questions would be addressed.

Question 2: What Crops are Being Grown in Each Cultivated Area?

At this time there is not enough research information on interpretation of ERTS imagery (either manually or with digital techniques) for tropical regions of the world to determine with any certainty whether it will be possible to identify and discriminate among the many of crops of the Sahel with ERTS data. In order to prepare a useful agricultural census for the Sahelian countries, special high altitude aircraft photography will probably be required. This should be coupled with very high resolution sample photography (obtained synchronously) and sample ground enumeration.

Ground survey techniques used in the U.S. have included mail surveys of farmers, and repeated enumeration by state or federal employees of the same sample area (which represent a fractional percentage of the total agricultural area, and chosen so as to be representative of small state-sized areas). Obviously, such ground enumeration procedures cannot be directly applied in the Sahel, though training of enumerators could begin promptly to carry out operational remote sensing programs in the near term. However, at present the Sahelian countries will probably have to draw upon foreign expertise for programs design, management and data interpretation.

A full scale census, programmed for five-yearly intervals, could be initiated in the 1975 crop year using a combination of multi-stage remote sensing and ground enumeration procedures

as suggested above. The multi-stage photographic procedure might include flights at 10,000 meters with the following mix of cameras: 1) Wide area coverage, focal length 75 mm; and
2) 5 percent sample with 300 mm focal length lens.

Question 3: What is the Condition of the Crop in the Present Growing Season?, and
Question 4: What is the Expected Food Production for the Present Year and the Potential for a Yield Forecasting System?

If, through a sample enumeration procedure, the total national and regional crop hectarages were obtained in the 1975 crop year, it would then be feasible to develop crop yield production models specific to the Sahel based on sample ground crop condition reporting combined with agro-meteorological modeling. What are the necessary components of such a modeling system? How reliable are they likely to be? How might they be introduced?

The first component is a knowledge of the areas of cultivated land and the distribution of crop types within these areas. This information is likely to remain fairly representative of the region for a long period of time, and a survey taken in 1975 would be acceptable until 1985. The second component would be to institute a small sample, spot check on the changes within randomly selected areas to assess when a new full-scale resurvey would be required. Third, a small network of trained observers would need to be established to make regular observations on crop conditions at specified intervals, using agreed upon conventions. Perhaps no more than a few dozen field observers and the support of several cooperating agencies would be required in the early stages to get such a program underway.

Fourth, a system for collecting the preceding data at a central location would need to be established. This data, along with general crop performance (agro-meteorological) models would be used with meteorological satellite and ground meteorological data (as discussed in Chapter 8), to calibrate the agro-meteorological models for prediction purposes. The use of meteorological satellite data in crop production and forecasting analyses has just recently been undertaken (1973) by a number of investigators (Earth Satellite Corporation, NOAA, USDA, Canada Center for Remote Sensing, Canada Department of Agriculture), but the program is experimental and not operational.

Even in the crudest possible form such a system would significantly improve the present level of knowledge on crop conditions. The several ministries of agriculture would then have available estimates of crop condition and sample estimates of acreage to use in projecting region-by-region agricultural production.

Question 5-8: Potential Agricultural Land Development and Monitoring

The remaining group of four questions concern problems of developing an information base for formulating new agricultural policies. These questions concern the ecological characteristics of the landscape and the proportion of the suitable areas now under cultivation; the optimum allocation of crops within these potential agricultural areas; and the performance of agricultural development projects once implementation has begun.

Fortunately these needs coincide with a well defined and proven remote sensing strength, i.e. its use in the interpretation of natural vegetation communities and soil associations. Detailed discussions of soil and vegetation mapping can be found in Chapters 10 and 11. The following brief description points out the application of these soil and vegetation maps to problems of land allocation and agricultural development.

Armed with a map of existing vegetation communities and soil associations, plant ecologists can partition the landscape into units of "equal agricultural potential," by utilizing the community indicator approach. Since it is known that vegetation communities develop in direct response to ambient environment conditions (which in this context includes an integration of all factors - weather, soil, moisture, etc.), the plants themselves serve as indicators of the existing habitat. Therefore, once the natural landscape has been partitioned into homogeneous plant communities, it is possible to derive a new map which partitions the landscape into plant habitat areas. From there, known crop requirements can be matched with the indicated conditions in order to correctly assess the feasibility of introducing a particular species in a particular area. Actually, this approach is not new but has been used successfully for many years. In summary, the basic approach is:

1. Use remote sensing to generate images of the area being considered for expanded agricultural development. The higher the ground resolution, the higher the precision of subsequensteps;
2. Partition the landscape into vegetation communities;

3. Determine what environmental characteristics (soil, climate, etc.) are necessary for specific crops; and

4. Match the substitute plant requirements (crops) against the environmental conditions as indicated.

These questions thus would require a fundamental Sahel-wide resource information base. It would include not only the natural vegetation survey discussed in Chapter 11, and the soils association mapping sketched in Chapter 10, but also a number of water resource inventories and finally development of climatic histories. Such a Sahel-wide inventory would be the first and logical step in developing improved or new agricultural policies and strategies, including defining the options available for resettlement, agricultural expansion, development of major irrigation schemes, and improvement of water usage. Since the broad outlines of the processes involved in reconnaissance scale mapping of soils, natural landscapes, and natural vegetation have already been outlined, they will not be repeated here. However, integrated multi-resource mapping program involving multi-disciplinary teams of resource scientists will be required to insure cost-effective inventories.

4.0 SUMMARY AND CONCLUSIONS

From this discussion it should be clear that remote sensing does not offer a quick solution to the problems of obtaining an agricultural census or in estimating annual crop production in the Sahel. Policy makers and international agencies should not expect either easy or rapid access to the data required for broad project planning. Answers will be hard to come by and are likely to be expensive. They will rely heavily upon balancing traditional procedures for agricultural sampling and crop estimation with new remote sensing technologies. The exact mix best suited for the Sahel cannot be predicted without site specific analyses.

ERTS in combination with collateral data -- soils, vegetation, climate, crop conditions, etc., -- can, however, be efficiently applied for broad area resource analysis, including delineation of potential areas for agricultural development. Reconnaissance-level information of this type is a prerequisite for national agricultural and livestock planning, and represents one of the prime applications area for Earth Resources Technology Satellite data.

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CHAPTER 14

LAND USE PLANNING AND DEMOGRAPHIC ANALYSIS

1.0 INTRODUCTION

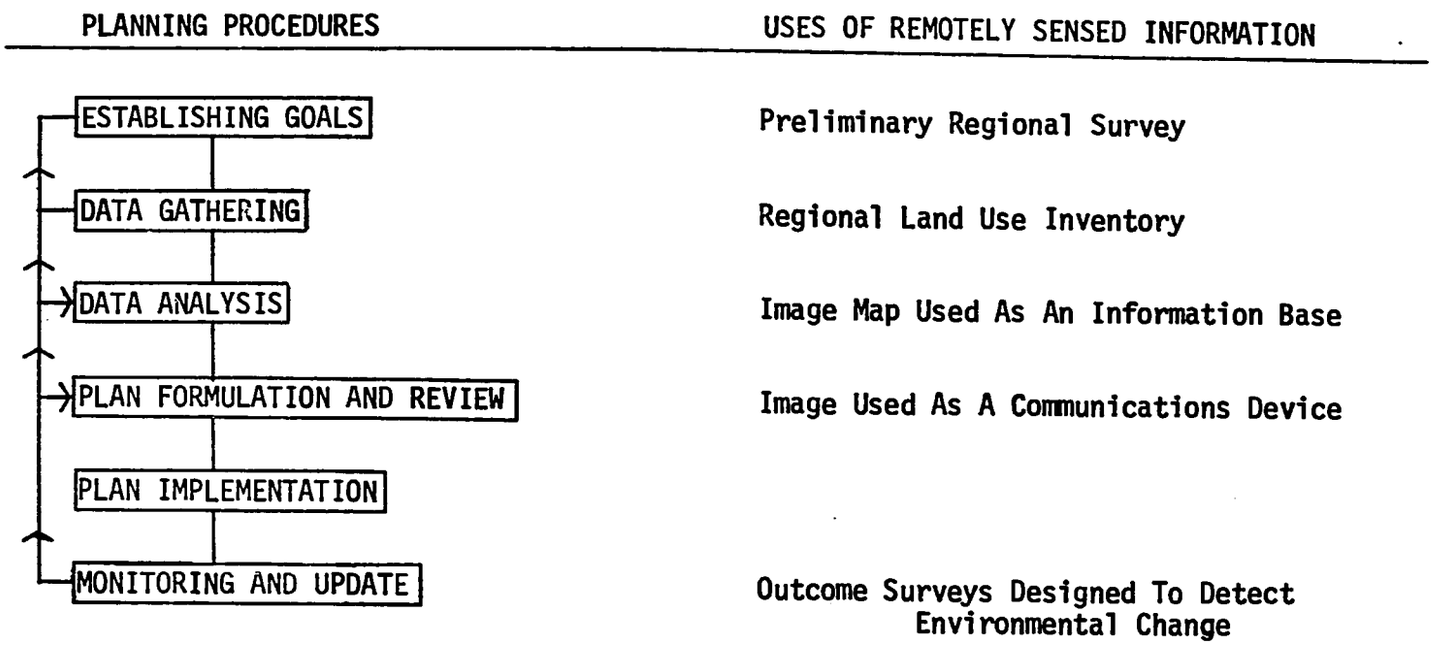
Land resource planning seeks to balance the social and economic needs of groups of people with demands on physical resources by setting policy with regard to resource allocation and regulation. Regulation of resource use is always difficult to implement. It requires that individual rights or rights of small groups be modified to achieve broader human goals. This objective is the antithesis of traditional ways of life in the Sahel which focus on short term solutions to individual needs. Pastoral nomadism and subsistence level agriculture have few mechanisms oriented to preserving the resource base in the face of increasing population pressure or decreasing environmental carrying capacities. Most recently, it has not been practical for the people of the Sahel who have been occupied with sheer survival to be concerned with preserving their resource base.

Remote sensing can be effectively employed in land management as: 1) an initial source of data; 2) a medium of communication either by improving existing maps or by helping to transmit abstract spatial relationships as a visual aid; or 3) a method to monitor changes in the resource base. One view of the land planning process is detailed in Figure 14-1. General classes of remote sensing applications are presented in the same figure. Although specific uses for remote sensing in land management can include many types of studies -- land use surveys, demographic estimates, environmental quality estimates, etc. -- the information provided is most often used in one of the ways described above.

Several unique aspects of the Sahelian region are important influences and constraints on potential remote sensing applications. Some of these are directly related to the natural environment, while others depend upon the social and cultural systems of the region. For example, atmospheric conditions well-suited to imaging sensor systems are the rule rather than the exception. Interference caused by dust transported by the Harmattan winds may be experienced in the winter season, but atmospheric water vapor and cloud cover are seldom serious problems, even in the summer season as the completeness of the ERTS coverage map (Chapter 5) would indicate. A second category of potential problems relate to the normal spatial arrangements of human populations in arid regions. In the absence of permanent water supplies, populations are sparsely

FIGURE 14-1

USES OF REMOTE SENSING DATA FOR LAND MANAGEMENT



arranged, distributed over large areas, and have natural facility for fairly rapid dispersal or migration. Because of this, environmental information concerning floral, fauna and human populations must be gathered from small scale, remotely-sensed data sources through the use of surrogates such as environmental affinities or habitat preferences.

2.0 THE NATURE OF LAND USE INFORMATION

Land use information refers to the spatial distribution of landscape variation. It reflects the characteristics of a specific region and is dependent upon the mix of natural and cultural components of the landscape. Some bias always exists in any classification system which might be used. This arises from the academic background of professionals (geography, forestry, agronomy) and from a need to emphasize certain features of an area. The following list is modified from Clawson (1969) and presents some pertinent land use characteristics that may be emphasized through classification design:

1. Location
2. Activity
3. Natural character
4. Human alterations
5. Intensity of human activity
6. Environmental quality
7. Land tenure systems
8. Price or cultural values applied to land resource
9. Human population distributions
10. Spatial manifestations of social and cultural systems
11. Interaction among natural processes on locations and between locations, and,
12. Interrelationships between economic and cultural activities.

The above represents only a partial list of various types of land use information that can be obtained from remotely sensed data. It is, however, indicative of the types of information necessary for implementation of a comprehensive land management scheme. Many existing problems within the Sahelian Zone can be addressed through the application of concepts such as man/land resource ratios or land resource carrying capacities. Actual resource allocations based on these concepts should reflect all available information about the indigenous peoples, and how they view

their resources (their cultural perceptual set). Thus, various forms or derivatives of "land use" information are necessary information inputs to a rational planning process.

2.1 LAND USE AND REMOTE SENSING TECHNIQUES

A detailed rationale explaining the value of remote sensing techniques to resource management programs was presented in Chapter 2. Some of those points relate specifically to land planning, and therefore, warrant repeating. From a positive standpoint: 1) remote sensing techniques are often the least costly* method of data collection; 2) collected information provides a unique perspective in that detailed spatial as well as statistical information can be extracted from the data; and 3) by using an optimum mix of scale, resolution, coverage and data handling procedures, the information gathered can be engineered for various types of data analysis.

2.2 SCALE AND RESOLUTION RELATIONSHIPS

In any management situation, regardless of the area of application, there tend to be several optimal scales for image acquisition and information presentation. Land use planning is no exception and although certain applications can be served by the scale and resolution character of existing maps and imagery, some special projects (e.g., land use site planning) require acquisition of larger scale imagery and production of more detailed base information.

Regional planning can be accomplished within the Sahel countries by relying primarily upon satellite imagery and existing map series (1:200,000). Activities limited by political boundaries to single countries, subjurisdictions within countries, or to local areas may require image inputs and maps at other scales. In these situations, maximum use should be made of existing 1:50,000 photos acquired under French direction before 1960. Very detailed applications require remotely sensed records at large scales (greater than 1:10,000). Table 14-1 illustrates a series of simplified scale dependent relationships between image and base map scales and different sized areas. The map and image scales appropriate for recording detailed information for a subregion of Senegal for example may be very different from a general survey for the entire Sahel. The relationships portrayed in this table should be carefully considered since they are not as simplistic as they first appear. Size of planning areas alone are not the sole factor determining map scales. Detailed information needs resulting from large population concentrations can

*In areas with acute labor surpluses, the least efficient information collection strategy, a labor-intensive census, might be the least costly.

TABLE 14-1

GENERALIZED AREA - SCALE RELATIONSHIPS

PLANNING AREA	MAP SCALE	IMAGERY TYPE
Multi-national to national 2,053,529 sq. miles (the 6 Sahelian countries) to 74,112 sq. miles (Senegal)	Greater than 1:250,000	Orbital: Apollo, ERTS, Skylab
Smaller countries 105,839 Upper Volta 74,112 Senegal to State or subnational districts	1:250,000 to 1:50,000	High altitude aircraft
Local Districts small sub-state jurisdictions to site specific studies	Less than 1:50,000	Low altitude aircraft

dictate the use of larger map scales. In practice, most jurisdictions use a number of map scales simultaneously in their planning program.

2.3 CLASSIFICATION SYSTEMS

Classification systems are devised to order the information extracted from imagery. Examples of classification systems designed for use with remote sensing imagery of various scales include the land use legend provided by Anderson et al. in USGS circular 671 (1972); Krumpe in "A Regional Approach to Wildland Resource Distribution Analysis Utilizing High Altitude and Orbital Imagery" (1973); and Poulton (1972) in "A Comprehensive Remote Sensing Legend System for the Ecological Characterization and Annotation of Natural and Altered Landscapes." These systems were developed after long iterative processes in the United States. All classification systems require modifications for region-specific applications even within the United States. A considerable effort to formulate a suitable legend system will be needed prior to any mapping project in the Sahel. The preliminary task of designing a classification system must meet the following criteria:

- It must be tailored to the particular landscapes of the Sahel.
- It should focus at a level of information detail that matches planned or existing base map scales.
- It must be complete and capable of subsuming all landscape features into aggregate classes.
- It must be sensitive to the information content of the data base.
- It must match stated user needs.

If these criteria can be met, classification schemes can be developed which are easy to apply and produce information useful to the land management process, whether as an initial inventory, as an update for change monitoring, or as part of a specialized study.

3.0 REMOTE SENSING AND LAND MANAGEMENT INFORMATION

Documented use of conventional aerial photography (predominately black and white photography at scales of 1:30,000 or larger) for land management dates to the post-World War I period. Such photography has been used extensively, though far from universally, in urban and regional planning since the 1930's. Although it has become a standard planning tool, the list of applications includes many that are problem or task-oriented rather than part of comprehensive planning programs. Much of the past and current remote sensing work in land use planning has been documented by Branch (1948, 1971). Witenstein (1954, 1956) and Wray (1960) identify aerial photography as an integral part of the planning process; and Collins (1960), Cissna (1963),

Anschutz and Stallard (1967) have looked at various uses of air photographs in site planning and urban comprehensive planning programs. Other studies focus on specific tasks that bear on land use planning: socio-economic and demographic studies, site planning and ecological planning, transportation planning, recreational planning and urban change detection. Many of these applications have been reviewed in greater detail by Simonett (1969), Westerlund (1972), and Horton (1974).

This discussion focuses on specific applications of remote sensing which are most likely to provide important information to problems presently facing the Sahel. Therefore, the detailed review of various systems applications which follows concentrates primarily on the broad ecological interpretation of land cover and demographic analysis.

3.1 SATELLITE SYSTEMS

Satellite images of the earth's surface provide a powerful new tool for land use inventory as a result of their scale, resolution and areal coverage. Because the spatial character of this data is unique and because satellite systems are relatively new, full utilization has yet to be realized. Useful remote sensing records for parts of the Sahel have been obtained during the Apollo and Gemini programs, by ERTS-1 and by Skylab. Although the currency of these data can be questioned, the historical perspective they offer cannot. If a thorough understanding of the present Sahelian problems is to be realized, historical information, including that provided by satellites, will have to be analyzed.

Application of satellite remote sensing to land use planning had been speculated for more than a decade. Gemini photography (in color format similar to that available for portions of the Sahel) proved its worth as a data base for a regional land use mapping project in the southwestern United States (Thrower, Senger, Mullens, et al., 1970). A general purpose land use classification system was subsequently developed and used in mapping at scales of 1:250,000 and 1:1,000,000. Following this work, greater attention has been given to land use classifications and photo identification keys that are related to surface landforms rather than specific targets.

Some basis for estimating the potential utility of ERTS-1 imagery to the land management and planning processes within the Sahel is provided by several studies which specifically focus on that region, plus a number of ERTS-1 experiments in other semi-arid and arid regions of the world which concern similar applications or problems. Because so little information is yet available

from studies in the Sahel where ERTS-1 imagery has been a major information source (other than those conducted by Reining, 1973 and McLeod, 1973), much of the analysis is by analogy.

ERTS has provided its most useful input in the broad-scale, regional land use context. However, it has not been exceptionally successful in contributing to demographic studies, especially in environments like the Sahel. Reining (1973), tested the use of ERTS in identifying villages and estimating population densities in Upper Volta and Niger. By taking detailed note of the settlement locations, shapes and environmental context, Reining concluded that:

1. Compact villages and compound clusters are visible and measurable on ERTS even at 1:1,000,000 scale imagery;
2. Repetitive imagery is necessary for adequate interpretation, and dry season imagery is better for interpretation than wet season imagery;
3. Population density cannot be assumed on the basis of size of the village as delineated on ERTS imagery, irrespective of settlement pattern in the Sahel;
4. Shape and village location are relevant to its identification; and
5. Enlargements to the scale of 1:50,000 from ERTS imagery served useful analytical purposes despite the noise levels in the images.

Perhaps the most useful portion of Reining's report was the wedding of cultivation and settlement site identification to human carrying capacity estimates in which ERTS, aircraft images and ground observations all played significant, indeed essential roles. It should be noted that while her preliminary results indicated that ERTS can be used to locate villages, determination of absolute size and density were not possible. Dr. Reining used a 9" X 9" ERTS imagery and 1:50,000 photographic enlargements for this study. More refined enhancement techniques -- density slicing, additive color viewing, or digital processing of ERTS tapes -- might significantly increase the capability to extract demographic information from ERTS data.

While the resolution of existing satellite systems is not sufficiently adequate for detailed demographic analysis, ERTS and Skylab type imagery have a role in a multi-stage sampling approach. ERTS can be used to partition inhabited versus uninhabited regions and, with enhancement techniques, provide a first-level attempt at settlement location.

The work of Estes et al. (1973) demonstrates the utility of ERTS-1 in central and coastal California. In his final report to NASA, three observations were made of relevance to the Sahel: 1) the value of enlarged black and white ERTS prints as a working source; 2) the importance of multi-date coverage to improve mapping accuracies (as some features were visible only during

certain seasons); and 3) the ability to identify certain resources including perched water tables in the San Joaquin Valley which had previously been unidentified.

Bowden et al. (1973) produced topical rather than regional studies. Of the varied physical environments examined, studies in the Coachella Valley, Mojave Desert, and Peninsular Ranges best represent regions similar to the Sahel. Some important results include: the determination of plant distribution by means of photographically enhancing its growth environment; the location of pre-Colombian settlements by first identifying possible sites such as relict beaches; and the accurate detection of areas of land use change in the desert using manual techniques and enlargements of ERTS imagery at scales approaching 1:100,000.

Similar accuracies in detecting land use change were obtained by Place (1973) working in southern Arizona using automated data processing techniques. Place's work is important in that it gives some idea of the minimum detection resolution that is possible using photo products acquired from ERTS.

Simpson, Lindgren, Ruml and Goldstein (1973) produced a land use map for the entire New England area of the United States utilizing manual interpretation techniques and black and white imagery enlarged to a scale of 1:250,000. This study is of interest for future work in the Sahel since the maps produced were less than adequately accurate. New England land subdivision systems (the way individual parcels are arranged) result in small parcels with no regularity of arrangement. Many land uses are therefore difficult to recognize and identify. Assuming that Sahelian areas with sedentary populations will for different reasons reflect a similar landscape arrangement, landscape character becomes a very important determinant of imagery utility (See Figure 14-2). The very real possibility exists that if parcel sizes are finer than the resolution scale of ERTS-1 imagery and if all use types exhibit a similar spectral reflectance, there would be no application possibilities with respect to direct (rather than surrogate) land use mapping in the Sahel.

Thomas and Simonett (1973) have attempted to integrate ERTS-1 data into an operational planning program for the State of Maryland, and found a large portion of the user population (professional planners) unwilling at first to accept information derived from the data. After a period of active attempts to educate potential users, the initial barriers to acceptance were removed, and the data was applied on a statewide, countywide and subregional basis.

Figure 14-2 : Lower Senegal River, Northern Senegal and Southern Mauritania

Figure 14-2 includes the northwest third of an ERTS frame (September 30, 1972) of northern Senegal and extreme southern Mauritania at a scale of 1:830,000.

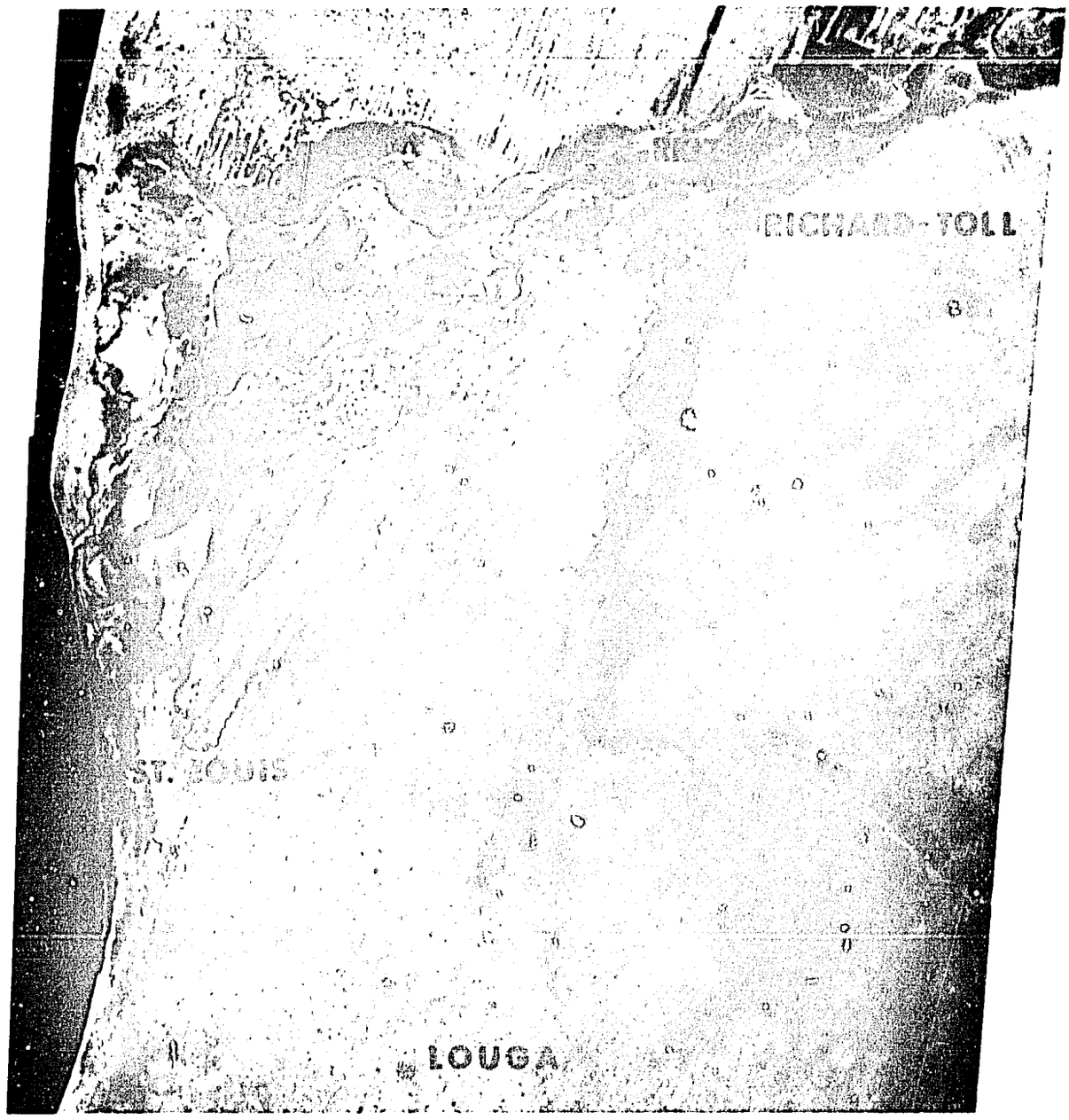
Four areas of particular interest include (from north to south): 1) southern Mauritania where active dunes encroaching on the delta and lower course of the Senegal Rivers exist along with some stabilized dunes; 2) the Senegal River valley and delta which extends diagonally across the image; 3) part of the low lying western plain of Senegal south of the river mouth; and 4) part of interior Senegal which is drained by the Fero River.

The low plateau of southern Mauritania north of the Senegal River valley is covered by active longitudinal dunes aligned in a north-northwesterly direction. These dunes terminate abruptly as they encroach upon the river valley. Sediment deposited in the estuarine delta of the Senegal through fluvial processes contains some re-worked aeolian sands incorporated into the river system during annual flooding. Economic activities north of the river valley include agriculture in the interdunal trough, during the wet season, and livestock raising throughout much of the year.

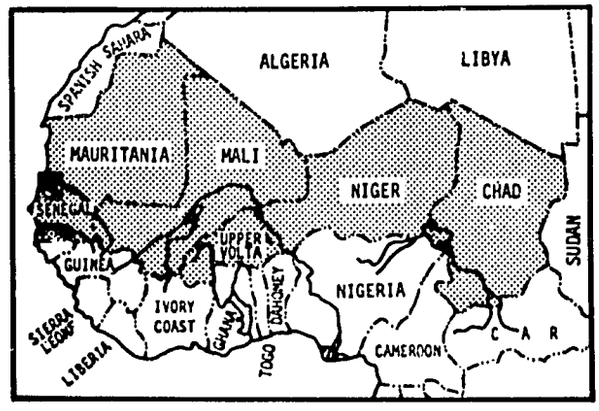
The lower Senegal River valley as seen here is a complex sedimentary environment composed of a mature river valley extending to a point 15 miles west of the Richard-Toll agriculture experiment station (south of the river in Senegal); an estuarine delta extending from there to the narrow coastal fringe; and a series of longshore barrier beaches which narrow to the south and force the river system to trend in a southerly direction. The present mouth is marked by a plume of eight blue tones extending into the Atlantic. This plume dissipates to the south as the sediment-laden river outflow mixes with the south-flowing coastal current. Lowlands associated with the Senegal River and its distributary system are the most productive agricultural areas of both Senegal and Mauritania. This region supports a higher population density than any other in either country. Planting begins immediately as annual floods recede. Once crops are harvested livestock graze the stubble. The Rkiz (in Mauritania) and Richard-Toll (in Senegal) agricultural experiment stations with large regular field patterns can be identified north and south of the river in the northeast corner of the image.

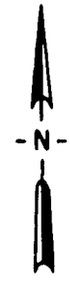
South of the delta, a narrow portion of Senegal's western plain is included on the image. A small settlement, Louga, can be identified as the circular concentration of dark tones at the bottom edge of the image. Linear features apparent both in this area and in the higher Fero desert to the east are relict longitudinal dune systems which are partially vegetated and are now inactive. Cursory analysis of this image suggests that active windblown sands once penetrated much farther to the south into the Sahel than today.

A portion of the Fero desert which occupies much of the interior of Senegal is shown in the eastern 30% of this figure. This entire area is higher than the western plains and is drained by the northeast flowing Fero River. Population is scattered in this region and grazing is the dominant economic activity.



LOWER SENEGAL RIVER, NORTHERN SENEGAL AND SOUTHERN MAURITANIA





This, of course, raises the important question of the acceptance of ERTS and other satellite acquired data by potential users within the Sahel. No one can predict accurately how an innovation such as ERTS imagery will spread through the complex mix of social systems found in Sahelian Africa. It is certain, however, that greater use will accrue from a wide distribution of ERTS and other image format data sources. ERTS and complimentary data will benefit the regional planners at the county or district level as well as policy makers in the ministries; but it can also benefit traditional groups, and coverage of their territories should be made available. In cases where political control over these groups is lacking, resource allocation decisions originating within the group will be the most important land resource management process on the Sahel's arid fringe.

If the flexibility of providing image format data to a large number of users is to be considered seriously, inexpensive and rapid reproduction methods will have to be developed. In two experiments, Hardy et al. (1973) at Cornell University in New York and O.G. Malan (1973) in South Africa, addressed the problems of user acceptance and reproduction costs as part of their research design. Hardy et al. (1973) concluded that the number of freely accepting users diminishes at a ratio proportional to the sophistication of the data presentation format. For example, more users could be found for image products than for the same data stored on computer compatible tapes. A major focus of the Cornell experiment therefore involved diazo color reproductions of ERTS composites. These are inexpensive and, once produced, can be copied photographically. Dr. Malan has organized a subscription system whereby lithographed copies of repetitive coverage of South Africa are distributed to hundreds of users at a cost of less than $1.50 per copy. Reproduction by either of these methods should be feasible in the Sahelian situation.

At the present time, the full range of ERTS-type data is not available to the Sahel countries. Since planning is an iterative process, and since active acquisition over the Sahel was limited to 1972 and part of 1973, requirements for timely data cannot be met. An important historic data record exists, and many planning objectives will be well served. The temporal limitation can be overcome once ERTS-B is launched.

Skylab has provided remotely sensed data in image and tape formats with higher resolution than is currently available from ERTS-1. Although Skylab imagery is very limited over the Sahel, it has been demonstrated to be extremely useful in land use analysis and is representative of future orbital collection systems which will be available in the 1980's on Space Shuttle. Comparative work by Rohde and Simonett (1974) concludes that the Skylab sensor systems provide

much higher resolution data than ERTS and that these systems provide complementary and not competing data types. For the Sahel, cultural data from imagery will be obtained from Shuttle not ERTS-1 imagery.

ERTS imagery is estimated to be useful as a data source for all primary (100%), some secondary (60%) and a few (5 to 10%) tertiary* land use classes in the U.S.. Skylab imagery, on the other hand, has been used as a source for all primary (100%), most secondary (95%) and some tertiary (50%) classes. Shuttle imagery will improve the tertiary level of identification of Skylab and will pick up some quaternary data as well. Comparisons dependent upon resolution characteristics alone are incomplete. It must be remembered that ERTS data, while of lower resolution, provides greater area coverage per image

3.2 AIRCRAFT SYSTEMS

Conventional aerial photography (predominately black and white photography at scales of 1:30,000 or larger) for land use planning dates to the post-World War I period. Research has demonstrated that color infrared film is generally superior to panchromatic color or black and white photography, and comparable to multiband imagery for portrayal of both rural and urban land use information (Pease and Bowden, 1969). Consequently, a major share of current applications relies on color infrared film as a data source.

Traditionally, photography and other types of imagery (e.g., multispectral scanner data) have been gathered at altitudes below 3,000 meters. Image scales are usually large and normally range between 1:5,000 and 1:20,000. Since the late 1960's, higher flights at altitudes in the vicinity of 20,000 meters have been supported by the United States Government for state and regional land use projects. Even more recently several commercial firms have acquired the capability to acquire "high flight" imagery at altitudes of approximately 15,000 meters. These high altitude systems would, because of the resultant imagery scale, be able to provide the most cost-effective, non-satellite image coverage of the Sahel. Such photography is now commonly employed by states and counties in the United States as the data base for land use information.

* References to primary, secondary, tertiary, etc. relate to the hierarchial levels in the classification systems mentioned earlier in the chapter.

Large and medium scale imagery allow more detailed consideration of any landscape (i.e., identification and analysis instead of detection and partial identification as is achieved through the use of satellite data). Because the Sahel has few large concentrations of people, and the inhabitants are dispersed over large areas, there are numerous situations where large scale imagery is necessary to provide useful information. Such aircraft imagery can be used for three types of analysis:

- Sample coverage to serve as complementary data in multiple systems surveys;
- Regional and subregional coverage for relatively large areas where satellite imagery does not provide sufficient information to satisfy user needs; and
- Focused studies for specific development objectives or detailed site evaluations.

Both low altitude, large scale conventional photography and advanced photographic techniques, such as color, color infrared (IR), multiband and space imagery have been used for demographic remote sensing analysis. Much of this work has been done with conventional color/color IR photography and some multiband imagery. For the most part, these studies have been feasibility analyses to determine the use of photography for:

- Delimiting poverty areas,
- Housing/neighborhood quality assessment,
- Dwelling unit estimations; and,
- Updating census information.

Eyre, Adolphus and Amiel (1970) for example evaluated the use of aerial photography and census data for assessing the accuracy of the Jamaican census. The 1943 and 1960 Jamaican census and historical aerial photography were used. Underenumeration, a recurrent problem in developing countries, was the most frequent error in the census data. Stereo pairs were used to make house counts and then compared with ratios of occupants per dwelling size and other available population data of similar neighboring districts to obtain a population estimate. Air photos were also used to estimate the growth of towns between censuses. The authors concluded that photo interpretation offers a method of extrapolating from accurate sample areas to areas of inaccurate census data, but caution must be used in applying these photo interpretive techniques to demographic analysis. The most promising applications of remote sensing to demographic analyses are in the following two areas: updating census information, i.e., location, distribution, size, density of the population; and integrated applications, i.e., population pressure on resources, population carrying capacity estimates; urban and regional planning.

3.3 OTHER REMOTE SENSING APPLICATIONS

The Sahel region is composed of both sedentary and nomadic populations. While most village locations are known and changes can be monitored, the location of nomadic populations is not an easy task without extensive ground survey operations. An experimental investigation using a declassified military scanner system has been used in the southeast Asia to locate nomadic settlements. Through the use of a scanner mounted on an airplane, emitted radiation from campfires at night allowed detection of nomadic locations. While this is an experimental investigation, in the future it hopefully could play a role in location of nomadic populations.

Other image producing sensor systems are commercially available and given the correct combination of environment and user demands, could be applied in the Sahel. Within this group, radar, multispectral scanners, and thermal infrared scanners offer the most promising alternative systems for use in the Sahel. Costs associated with these systems as well as the formats and character of the resulting data will make applications somewhat more difficult. Radar is very useful when clouds obscure the target, scanner data is more amenble to machine processing techniques, and thermal imagery can be acquired at night. These systems can serve special situations, but are not as flexible as photographic systems.

3.4 GROUND OBSERVATIONS AND COLLATERAL DATA

Ground observation and use of collateral data are necessary inputs in any remote sensing project. The actual mix of information sources used will depend on availability of imagery, the purpose of the survey, and existing budget constraints. In site-specific planning, the general objectives may dictate heavy dependence upon cultural or social data gathered in the field. Low altitude imagery would here serve only a supporting role. Regional surveys, while dependent upon collateral data and ground surveys for verification must utilize satellite and high altitude aircraft data to insure both the consistency and spatial fidelity of the resulting information. Maximum use, in any situation where land use or planning information is needed, should be made of historical data (existing imagery, maps, data collections, and reports) which exists in large quantities.

4.0 COSTS

The general cost figures presented in Chapter 4 are specific to data acquisition and offer little insight to the interpretation costs which might be encountered. As a general rule interpretation and data handling costs (filing, handling and cataloguing imagery) decrease in direct

proportion to decrease in image scale. Large scales increase data volume, and although information content also increases, the costs involved with handling, interpretation and cartography (map production) rise more rapidly. Chapter 5 provides additional discussions of cost variations between large and small scaled data sources.

Table 14-2 presents a range of costs for land use data organized on the basis of image scales, important characteristics of the example data sources, and final map products. The estimates presented are based upon actual land use inventories implemented in the U.S., but the actual figures presented should represent relative costs of similar work in the Sahel. Data acquisition costs are not included. Notice that decreasing the scale of the data base reduces cost per area, but the detail of the information gained is reduced also. Costs are presented as a range of values because no single estimate can be accurate for all surveys even within a given class of map and image scales. Every survey will have its own unique set of cost controlling parameters.

5.0 PROBLEMS AND LIMITATIONS

Most techniques of land use analysis have been geared to classifications based on economic criteria which require highly detailed information. For this reason, ground truth information and some low flight data were utilized. With a shift of emphasis in land use planning and management toward larger areas and more comprehensive studies, a different form of land use classification emphasizing surface form or ecological characteristics relating to population carrying capacities became important. Data requirements associated with broader objectives brought about a demand for smaller scale information where classes of land use are important. Remote sensing technology offered a means of obtaining this information at considerably less cost than ground survey.

Any remote sensor must contend with interference between the subject matter and the sensor. Dust and blowing sand can cause significant interference. The seasonal blowing of the Harmattan has the effect of reducing visibility and scene contrast in the dry season. For this reason, wet season observations might be emphasized despite other limitations, such as clouds, to eliminate gaps in the data. Reining (1973) however, determined that villages were best observed in the dry season because crops and the compacted settlement form were most distinct and less obscured by the reflection of natural vegetation.

TABLE 14-2

GENERALIZED SCALE / INFORMATION COST RELATIONSHIPS

IMAGERY TYPE	CLASSIFICATION DETAIL	MAP PRESENTATION SCALE	COSTS ASSOCIATED WITH INTERPRETATION, DATA HANDLING AND CARTOGRAPHY
ORBITAL PLATFORM ERTS-1	Regional, Landscape Units of the First Level as Indicated by Anderson, et al. (1972), Poulton (1972) and Krumpe (1973)	1:1,000,000 to 1:100,000	$0.30/sq. mile to $1.30/sq. mile
HIGH ALTITUDE AIRCRAFT	Sub-Regional Landscape units equivalent to the second level as indicated by Anderson et al. (1972), and Krumpe (1972)	1:250,000 to 1:25,000	$4.00/sq. mile to $10.00/sq. mile
LOW ALTITUDE AIRCRAFT	Local and site specific landscapes where classification detail reflects specific user needs	1:50,000 to 1:5,000	$12.00/sq. mile

Scene contrast is a continuing problem in any arid environment. Such lack of contrast is related to high albedos, low relief, sparse vegetation, and highly mixed, wind-sorted surface soil materials. For these reasons, multiple-staged surveys and multi-date coverage is essential.

The problem of observing small irregularly shaped parcels is another limitation to small scale surveys. One factor aiding identification in the American Southwest, the regularity of parcels laid out under a rectangular survey system, cannot be relied upon in the Sahel. This limitation, characteristic of ERTS' low resolution, can be counteracted by using it only as a targeting device for low level, larger scale photo surveying.

A final limitation to remote sensing in the Sahel is the high cost of obtaining detailed information for such a large region by conventional means (large scale photography and ground surveys). The solution is to determine data needs by priority as rigorously as the land use planning and management policies are determined and justified. One simply cannot afford detailed land use or demographic information which has marginal use in establishing policies. Consequently, land use policy makers must define the problems before data needs can be specified. Having accomplished these tasks, classifications and information gathering programs can be developed and employed in the most cost-effective manner.

6.0 SUMMARY AND CONCLUSIONS

The importance of accurate land resource surveys and demographic information for comprehensive resource planning cannot be underestimated. In developing regions like the Sahel, reliable data on population characteristics and land use practices are essential to developing an information base for future planning needs. The following reviews the application of remote sensing to obtaining accurate land use and demographic information:

1. An integrated ecological resource inventory and analysis should be performed immediately before a land use survey is attempted. Information so acquired would help focus detailed land use surveys and provide meaningful relationships to be derived between human activity and the environment. The analysis should contain as a minimum soil, landform, and vegetation information, and should recognize their existing conditions so that areas out of balance between human activity and land use can be determined. Such an inventory should focus on areas of prime biological productivity and high capability to support human habitation.

2. Land use information produced by classifications such as that by Anderson (1972), Poulton (1973), and Krumpe (1973), based on remotely sensed and ecological criteria, has greater likelihood of being collected cost-effectively as well as of being applied and found useful in current planning problems.

3. Demographic information can be most effectively collected using an integrated system composed of existing census data, sample enumeration/ground surveys, and medium to large scale photography.

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