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Final Report

ANALYSIS AND INTERPRETATION OF SEASAT SYNTHETIC APERTURE RADAR DATA FOR PORTIONS OF COSTA RICA, HAITI, AND HONDURAS

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16. Abstract

The utility of Seasat Synthetic Aperture Radar (SAR) data for supplying resource information to developing countries was assessed.

Seasat data was obtained and analyzed for project sites in Costa Rica, Haiti and Honduras. The study focused on the Guancaste, Costa Rica site for which Landsat, ground truth and two dates of Seasat data were available.

The results of the study indicate that the all-weather capability of a spaceborne SAR is quite useful for resource surveys of tropical areas. The Seasat data were sufficient for assessing general vegetation height but not for identifying specific crop types. Certain SAR system parameters greatly affect the utility of the radar data for any applications. Further studies should be undertaken to determine the specific SAR that would be most appropriate for AID's Assistance Programs.

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PREFACE

In July 1979 the Environmental Research Institute of Michigan (ERIM) commenced a 1-1/2 year project to study the nature of Seasat Synthetic Aperture Radar (SAR) data of tropical countries and to assess the utility of Seasat SAR-type data for supplying resource information to developing countries. The study focused on project sites in Costa Rica and Haiti, for which available Seasat SAR data was carefully examined and interpreted. Seasat data of eastern Honduras provided a useful example of a different type of terrestrial environment. This report describes the results of the project and includes a non-technical review of the recent development of radar as an earth resource sensing tool.

Thomas W. Wagner served as Principal Investigator for this project under the direction of Donald S. Lowe, Director of ERIM's Application Division. He was assisted by Jacquelyn S. Ott, ERIM Research Geographer. Other ERIM staff making significant contributions to the project include Norman E.G. Roller and Frederick Thomson of the Applications Division, and Robert Shuchman, Eric Kasischke, Alex Klooster, and Ivan Cindrich of the Radar and Optics Division.

Many other people also contributed greatly to this project, including F. Maro Rudin and Carlos Elizondo of Costa Rica's Instituto Geografico Nacional, and Roger LaFortune and Fritz Seme of Haiti's Department de l'Agriculture des Ressource Naturelles. For their interest and efforts, and that of their colleages, the authors are truly grateful. The requisite Seasat data were provided by Benjamin Holt of NASA's Jet Propulsion Laboratory.

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INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Space-acquired remote sensing data has been widely promoted as a technique for mapping and monitoring resources in developing countries (Cleveland, 1977; Conitz, 1978; Paul, 1979). While its inventory capability has been repeatedly demonstrated for such disciplines as forestry, geology, soils, and water resources, constraints on the timely acquisition of data from space and the availability of the data to users limit any truly global resource monitoring activity today.

Cloud cover is the major restriction on obtaining high quality satellite data of the earth's surface when using passive, optical sensors. Atmospheric conditions such as clouds, haze, and dust obscure terrain features and reduce the opportunities for obtaining usable photographic or multispectral scanner data. Data must be collected repeatedly from an area in order to provide a reasonable probability of obtaining suitable coverage. This constraint is true even in temperate climates, and is especially restrictive in the tropics, where clouds or haze may dominate the skies for months at a time. Unfortunately, it is during this rainy season in the tropics that resource information is most important. This is the major crop planting and growing season, the season of flooding, and the period of greatest environmental peril. An all-weather, high-resolution imaging system is needed if remote sensing is to make a significant contribution to monitoring global resources. The satellite should be able to collect high quality data during any season, regardless of weather conditions.

Radar remote sensors would seem to meet this requirement, but spaceborne radar imagery has not been available until recently. On June 26, 1978 the National Aeronautics and Space Administration (NASA) launched Seasat-A into an orbit 800 kilometers above the earth's surface (see Table 1). Seasat-A obtained 25 meter resolution Synthetic Aperture

Radar (SAR) data of the earth until early October 1978, when the satellite ceased functioning. Examples of this 23.5 cm (L-band) SAR data of portions of Costa Rica, Haiti, and Honduras provide the basis for this study.

TABLE 1. SEASAT SAR PARAMETERS
(after Thomson and Laderman, 1976)

Launched:	26 June 1978
Ceased Operation:	5 October 1978
Orbital Altitude:	approximately 800 km
Area of Coverage:	North and Central America, Western Europe
Image Swath Width:	100 km
Length of Image Pass:	1,000 to 4,000 km
Surface Resolution:	approximately 25 m x 25 m
Wavelength:	23.5 cm
Frequency:	1,274 MHz
Transmitted Bandwidth:	19 MHz
Pulse Duration:	33.8 μsec
Antenna Beamwidth, Elevation:	6°
Antenna Beamwidth, Azimuth:	1°
Antenna Pointing Angle:	20° off nadir, right side

1.2 OBJECTIVE

The objective of this study was to determine the utility of Seasat-type spaceborne radars for collecting useful data of developing countries. If spaceborne radar systems can provide useful imagery for resource monitoring, this data could contribute to AID's programs for international assistance and relief.

Seasat SAR data for portions of Costa Rica, Haiti, and Honduras were selected for this study. These sites are shown in Figure 1. The data for these three sites was collected by the Seasat Receiving Station at Merrit Island. Because agriculture is the major source of sustenance and income in most developing countries, interpretation of the data emphasized agricultural land use features. Features of topographic, geological and hydrological significance were also considered.

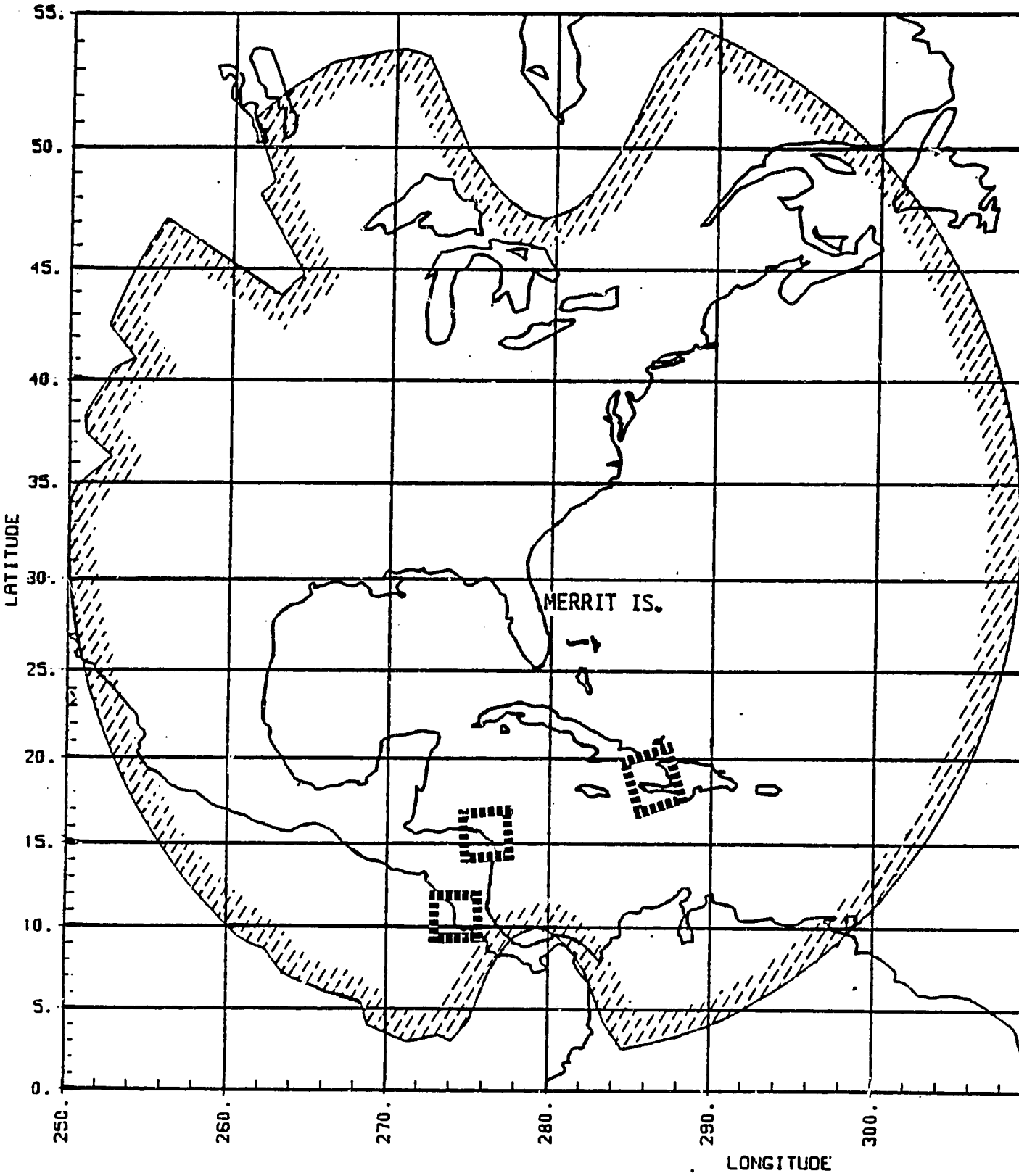

FIGURE 1. MAP OF PROJECT TEST SITES AND COVERAGE OF MERRIT ISLAND SEASAT RECEIVING STATION.

1.3 NATURE OF RADAR DATA

There are several differences between radar and conventional photograpic or scanner-type imaging systems that affect the utility of spaceborne radar data for terrestrial applications. These are more completely described in Appendix A and are summarized below.

Radars are active sensors because they provide their own source of scene illumination, and are not dependent on external energy sources to generate an image. This means that data can be collected by radar at any time, unlike most aerial or spaceborne optical systems that are sunlight dependent.

Clouds and other atmospheric constituents are virtually invisible at certain radar wavelengths, so radar data can be obtained almost without regard to weather or cloud cover conditions. These weather-insensitive radars operate at the longer radio wavelengths -- roughly 1 cm or greater. Other types of radars that operate at shorter wavelengths are actually designed to record cloud and precipitation patterns.

A third significant feature of radar is the geometry and contrast of the resulting images. Radar signals are recorded as a function of the precise time it takes for their return to the sensor from the reflecting surface. The geometry of the resulting radar image is unique and requires careful consideration in the interpretation process, especially for mountainous topography.

The strength of the returned radar signal and the consequent "tone" on the black-and-white image is dependent on a number of radar system and terrain factors. The radar backscatter is most strongly affected by the orientation and the physical roughness of a surface with respect to the radar wavelength. Color variations are important for interpreting aerial photography and scanner imagery, but have little significance for radar data. The contrasting tones of a radar image are generated in a

different manner than those of other sensors and must be interpreted with a knowledge of how the radar signals interact with various physical surfaces (Manual of Remote Sensing, 1975).

As illustrated in Figure 2, Seasat A obtained radar data from 100 km wide swaths extending for 1000 to 4000 km in a generally north-south oriented direction. It covered very large areas in a short period of time and allowed for repeat coverage of the earth's surface at intervals of several days to several weeks. As a "side-looking" sensor, the Seasat SAR viewed the surface of the earth from an angle of 20° off nadir to the right side of the satellite. Data were collected from both ascending (toward the North Pole) and descending (away from the North Pole) portions of the 800 km high orbit. Therefore, some Seasat images are "illuminated" from the east, some from the west.

Satellite-borne remote sensing systems have the advantages of (1) large area coverage, (2) almost continuous operation and (3) repeat coverage of areas of interest. Although elaborate ground stations are frequently required for data reception, satellites offer an effective way to obtain global resource information that may not be affordable by any other means. Current Seasat SAR coverage was limited to North and Central America and Europe by the lack of receiving stations in other parts of the world. This should not be considered an inevitable deficiency for future satellite systems applicable to the information needs of developing countries. Eleven Landsat receiving stations have been built by foreign countries to date, five in developing countries (Brazil, India, Iran, Argentina, and China) and others are planned in Asia and Africa. Establishment of satellite radar receiving facilities could be encouraged in various parts of the world. This would require a commitment to orbit civilian radar satellites. The Japanese government has already made such a commitment for 1986, and Canada and the European Space Agency are considering launching additional radar satellites (Ishizawa, 1981; Duchossois and Honvault, 1981).

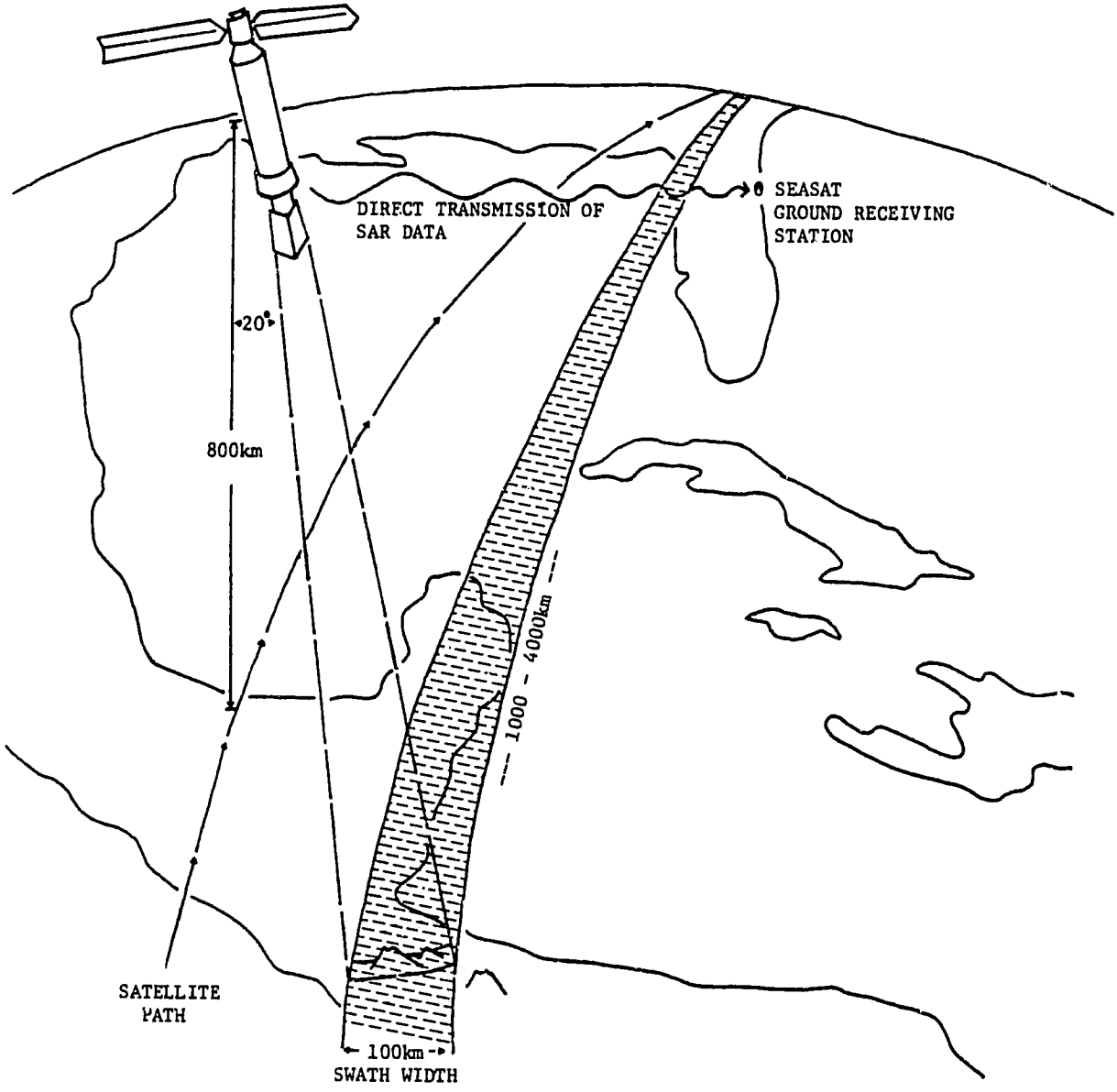

FIGURE 2. SEASAT-A SAR DATA COLLECTION

1.4 SUMMARY OF PROJECT RESULTS

The analysis of the Seasat SAR data for each test site is summarized in this section. Summary conclusions and recommendations based on those results are then presented. Details of the individual studies are presented in subsequent sections.

1.4.1 COSTA RICA

Analysis of the SAR imagery of Costa Rica included only non-mountainous regions. Detailed analysis of the agricultural land in the relatively level Vallee de Rio Tempisque, in Western Costa Rica revealed significant differences in tone and texture of the radar backscatter that could be related to vegetation height and density. Using the Seasat data, bare and newly-planted fields could be differentiated from fields with moderate crop growth, and these in turn could be differentiated from relatively tall or rough-canopied crops. Ground truth indicated the newly-planted fields to be rice or cotton, while the intermediate and tall crops were pastures and sorghum, respectively. Sugar cane is cut at different times throughout the year and was represented in all three growth stages but was particularly apparent at full height. Forests on level-slopes were similar in appearance to the tall crops.

The analysis of the Costa Rican SAR data for aggricultural information was limited by the fact that the ground truth was collected after the growing season by interviewing farmers and government officials as to the cropping patterns in the region at the time of the Seasat data collection. A more complete assessment of the utility of spaceborne SAR in monitoring crop heights would require ground truth collection at the time of the satellite over flight.

1.4.2 HAITI

Certain geological and hydrological structures were highlighted by the Seasat SAR data of Haiti although the geometry of the imagery was strongly affected by the mountainous terrain. The radar emphasized

structural features roughly oriented parallel or perpendicular to the orbital track of the Seasat. Drainage patterns and some geologic faults in this rugged area were apparent and could possibly be mapped from the SAR data. Vegetation information, including the distribution of forest cover, was interpretable only in a few level coastal and plain areas. The imagery also displayed some very interesting hydrographic and drainage outfall patterns in the Gulf of Gonave. Study of these coastal patterns was out of the scope of this project but should provide the basis for future evaluations. The Seasat configuration was not optimized for geologic or hydrologic features. Therefore, this study should not be considered definitive as to the utility of all SAR for these applications.

1.4.3 HONDURAS

Eastern Honduras presented a target of unique natural vegetation, a large tidal marsh area known as Laguna Caratasca. The detail in the Seasat imagery appeared to be related to differences in marsh vegetation and soil moisture content. Although ground truth was not available for comparison, the Seasat data represented vegetation patterns as determined by the topography and surface hydrology. This could be very useful for planning the development of this area of Honduras.

1.5 SUMMARY CONCLUSIONS

The utility of Seasat data for vegetation applications was evaluated and, for the Costa Rica study site, compared to Landsat. The SAR provided all-weather high resolution data, a capability important in monitoring crop condition and other seasonal phenomena. The black and white SAR imagery, however, was more limited for vegetation studies than the color Landsat.

The ability of SAR to crudely differentiate vegetation height may justify Seasat-type data for future agricultural resource monitoring. It is particularly applicable in Costa Rica and similar situations where

the existence of cloud cover during most of the growing season precludes the use of other remote sensing systems. Early season crop monitoring could be provided by combining vegetation height information with accurate knowledge of local cropping practices. This invaluable information was not previously available because persistant cloud cover prevented Landsat viewing during appropriate periods.

Through the season crop development could be roughly monitored with the SAR all-weather data capabaility. Some changes in vegetation canopies are apparent between the two dates of Seasat coverage of Costa Rica. Significant variations in normal crop growth could be detected early in the season and appropriate steps taken to compensate for them.

SAR is quite useful for physiographic applications, and enhances certain topographic features. This is primarily a function of two system properties: the ability to change the direction of surface illumination and the sensitivity of the radar response to surface slope (Elachi, 1981). Identification of features such as faults and drainage patterns is important to countries such as Haiti, where an understanding of the geology of remote areas could be economically important. Ocean bottom topographic features are apparent on some radar images which would greatly augment any coastal study.

Landsat imagery would provide a better source for geographic location of features in areas of high relief, where the SAR geometry can be distorted. A combination of both data sources would be optimal for geological and hydrologic studies.

Wetlands and soil-moisture patterns could be surveyed with Seasat-type data. Land-water boundaries are clearly evident on the Honduras image (Figure 11). A wide-range of wetland conditions are also apparent, and with additional information, the characteristics of each area could be identified. Several recent studies support the utility of SAR for wetland inventories (Lyon, 1981). With this and the all-weather

capabilities, a satellite-SAR would also be invaluable for real-time monitoring of the effects of flooding.

1.6 RECOMMENDATIONS

Serious considerations are now being given to the deployment of more spaceborne Synthetic Aperture Radar systems. These future sensors include the Shuttle Image Radar (SIR) for the Space Shuttle and SAR satellites proposed by Japan, Canada and the European Space Agency (Elachi, 1981; Shaw, 1981). With proper planning, these systems could be beneficial for resource mapping in developing countries, especially if the data were combined with other remotely sensed data and adequate ground truth. A SAR similar to Seasat would complement Landsat, which is currently promoted by AID as an appropriate tool for development.

Certain SAR system parameters greatly influence the radar response to a surface and, therefore the utility of the data for particular applications. An understanding of the effects of these parameters is necessary in order to determine the satellite radar system that would be most valuable for each of AID's assistance programs. These factors include the wavelength and polarization of the radar and the incident angle of the radar beam.

The wavelength of the radar signal is particularly important because it will define the surface roughness that will produce an apparent backscatter. The surface roughness threshold increases as wavelength increases. Data from multiple wavelength bands could be used to refine vegetation height (e.g., surface roughness) estimates and variations in intensity of backscatter due to vegetation condition.

Several other factors affect radar imaging of terrain features. The depression angle chosen for the SAR system will determine the geometry of the image, particularly the extent of radar foldover distortion and shadowing. Polarization of the pulses affects backscatter and could perhaps be related to differences in vegetation canopy structure.

The dynamic range of the radar data will establish the contrast on the image and which types of features will be most emphasized.

The proposed Shuttle Imaging Radar, supported by NASA (Elachi, 1981) will provide an opportunity to study the above mentioned problems, possibly within a developing country context. The SIR on-board optical recorder will permit data coverage of areas beyond the range of receiving stations. SIR will simultaneously collect data at two wavelengths - C Band (5 cm) and L Band (23.5 cm), with multiple polarizations. It will also offer multiple, adjustable incident angles and look directions. This flexible system will provide a wide variety of spaceborne radar data. SIR-A is currently in progress and SIR is planned for 1984-1986. These missions could easily be integrated into on-going AID development programs, such as the current project in Bangladesh.

Satellite SAR is potentially quite valuable for resource monitoring. To maximize the utility of the data, the specific applications that would be most beneficial to developing countries should be identified. Then a detailed study should be undertaken to determine the radar system parameter settings that would best support the chosen applications, and how they would affect the usefulness of the data. Detailed ground truth should be collected during the SAR over flights so that changes in data characteristics could be correlated to changes in parameter settings. The exact SAR system that would be most suitable could then be identified. Recommendations, supported by the results of such a study, could be made for optimizing future satellite SAR systems for specific applications. The actual SAR data collection could possibly be coordinated through NASA, at little cost to AID. AID could then provide the supporting data processing and ground truth efforts. The establishment of a mechanism for obtaining real-time SIR coverage for monitoring natural disasters should also be considered.

2

COSTA RICA

In cooperation with Costa Rica's Instituto Geografico Nacional (IGN), a site-study was undertaken to determine the utility of Seasat SAR data for agricultural and land-use monitoring. Seasat completed two passes over western Costa Rica during the 1978 summer growing season. At the outset of the project it was not known how terrain features would appear on the images. The primary objective was to determine the ability of the SAR data to discriminate different crop and natural vegetation conditions in this developing country environment.

2.1 GUANACASTE PROVINCE

Guanacaste Province is adjacent to Costa Rica's northwest Pacific coast at approximately 11° North latitude and 85-1/2° West longitude (Figure 3). A variety of terrain features are present in the province including volcanic mountains, rugged hills, level plains, and a long rocky coastline. Of greatest interest for this study was the relatively level Vallee de Rio Tempisque. The valley has large fields of cotton, sugar cane, sorghum, rice, and pasture-land and many smaller fields of corn and tree-crops. It is an important crop and cattle producing region for Costa Rica. Some scrubby forests remain on the hills and in the poorly-drained areas, but the original forests have been largely harvested, leaving behind eroding slopes with rocky outcrops that are often used as unimproved pasture.

2.2 GROUND TRUTH

Guanacaste Province was visited in late September 1979 and in mid-March 1980 by a combined ERIM-IGN ground truth team. The team photographed and recorded crop locations along major and secondary roads. Local residents and government officials were interviewed about crop conditions during the 1978 growing season, at the time of the

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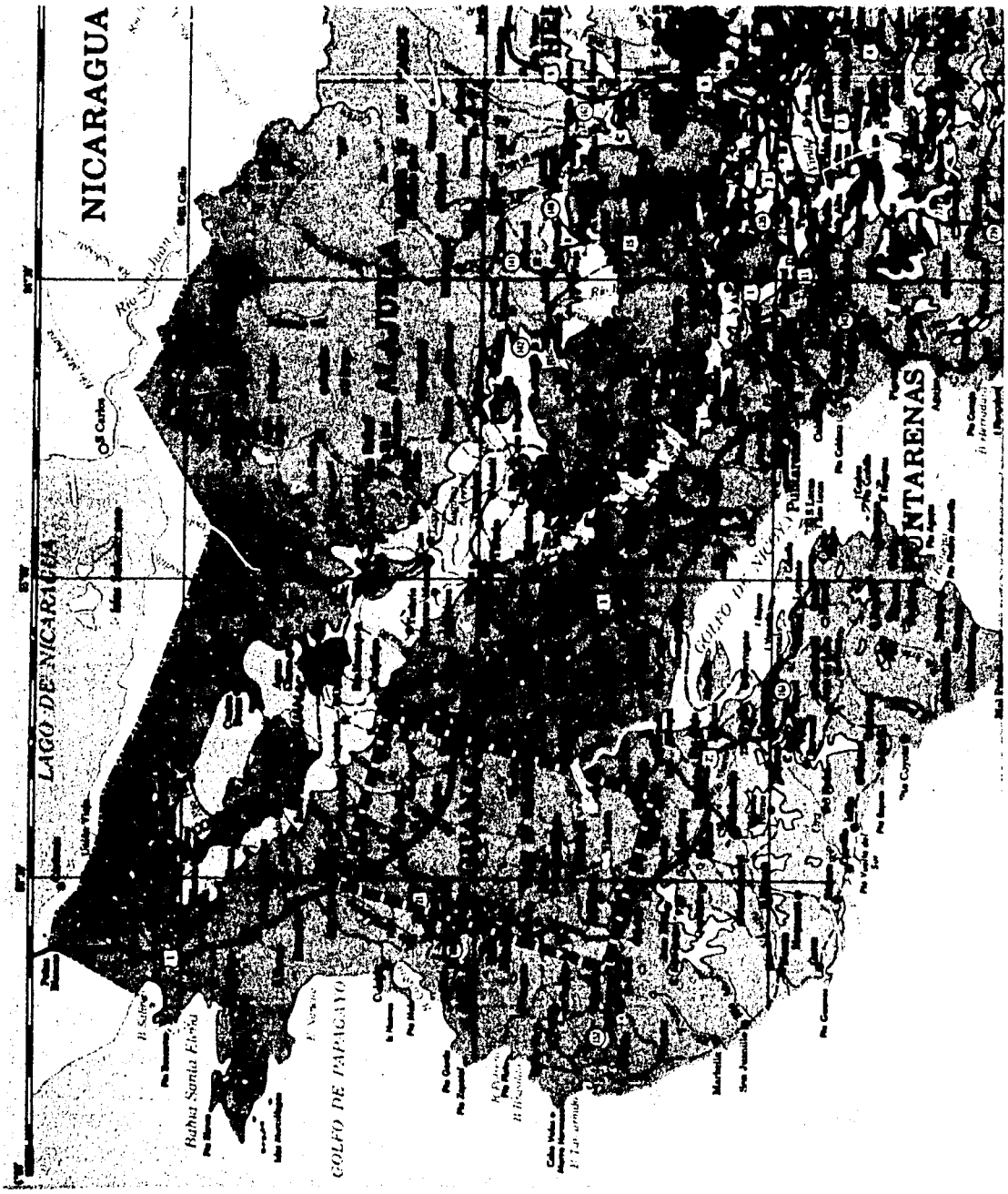

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FIGURE 3. LOCATION OF GUANACASTE, COSTA RICA STUDY SITE

Seasat overpass. In addition to 1:50,000 scale maps and 1977 panchromatic aerial photographs, the team made extensive use of Landsat scene No. 2144-15085 of Guanacaste. This image was collected on January 6, 1979, approximately five months after the available Seasat coverage of the same area. The Landsat data was contrast-stretched, resampled, and geometrically corrected to provide a high quality 1:100,000 scale image of the project site. The IGN 1:50,000 Lambert conic conformal maps of the region were reduced to a 1:100,000 scale and merged with the Landsat image (see Figure 4). This provided an excellent locational reference for working in the field.

During September of 1979 the study area was lush and green, with many crops growing in large angular fields of 10 hectares or more. The rivers were full and intermittent precipitation indicated that the rainy season had not yet ended. Crop heights varied greatly. Cotton and rice were usually less than 15 cm high, while the sorghum and sugar cane were frequently 100 cm high or more. The extensive pastureland occupied steeper slopes or areas of poor soil and consisted of coarse green grass of different heights.

In March the conditions were quite different. Most of the field crops had been harvested and stubble in the former rice fields was being grazed by cattle. In some areas the reddish-brown soil was being prepared for later planting but most fields were fallow. Large irrigated sugar cane fields were still green and contained cane at various heights from newly emerging to greater than 150 cm. Most of the hills were covered with yellow dry grasses and leafless brush.

Based on the above observations, a ground truth map was prepared that indicates the locations of crops present at the time Seasat data were collected in 1978. The major growing season started in late July and many annual crops were being planted or were emerging as green shoots when the SAR data was collected.

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FIGURE 4: PORTION OF PROCESSED LANDSAT SCENE OF 06 JANUARY 1979 OF WESTERN COSTA RICA.

The area north of the Rio Tempisque is occupied by a large state-owned farm of rice, sugar cane, and pasture, and a rice processing plant. This was the only area in Guanacaste where irrigation was used and two rice crops were produced per year. The following ground truth information for the 1978-79 cropping season was obtained from the staff at that farm (see Figure 5):

Field 20 - Rice. Planted in March; harvested in July and August. Planted in late July and August; harvested in November-January. Fields irrigated in August were flooded to 7 cm of water and then drained 8 days after planting. The rice stubble was used for fodder from January-February and appears white on the Landsat image (Figure 4). In late July, the first rice crop would form a continuous cover 0.5 to 1 m in height.

Field 15 - Sugar Cane. Sugar cane is normally planted in May and harvested in January-February. Such cane would normally be about 2 meters high in August and appears red on the January Landsat image. On the Seasat image, the one dark-toned field is harvested sugar cane.

Field 23 - Pangola Grass. High-quality improved pasture -- approximately 30 cm high in late July and moderately red on the January Landsat image. Jaragua Grass occupies a portion of the field. It is browner in color on the Landsat image.

Field 21 - Evergreen Forest. This forest area was still green at this time and appears light toned on the Landsat image.

Field 33 - Poor Pasture. Heterogeneous area of poor grass cover on thin soils overlying volcanic rock.

Records of crop area and production for Guanacaste Province were obtained from the Regional Agricultural office. The major agricultural land uses were listed as rice, cotton, sorghum, corn, sugar cane, and pasture. A summary of the 1977-78 season follows (see Figure 6):

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FIGURE 5. SEASAT IMAGE OF 27 JULY 1978 (REV. 443) OF GUANACASTE WITH TRAINING FIELDS INDICATED

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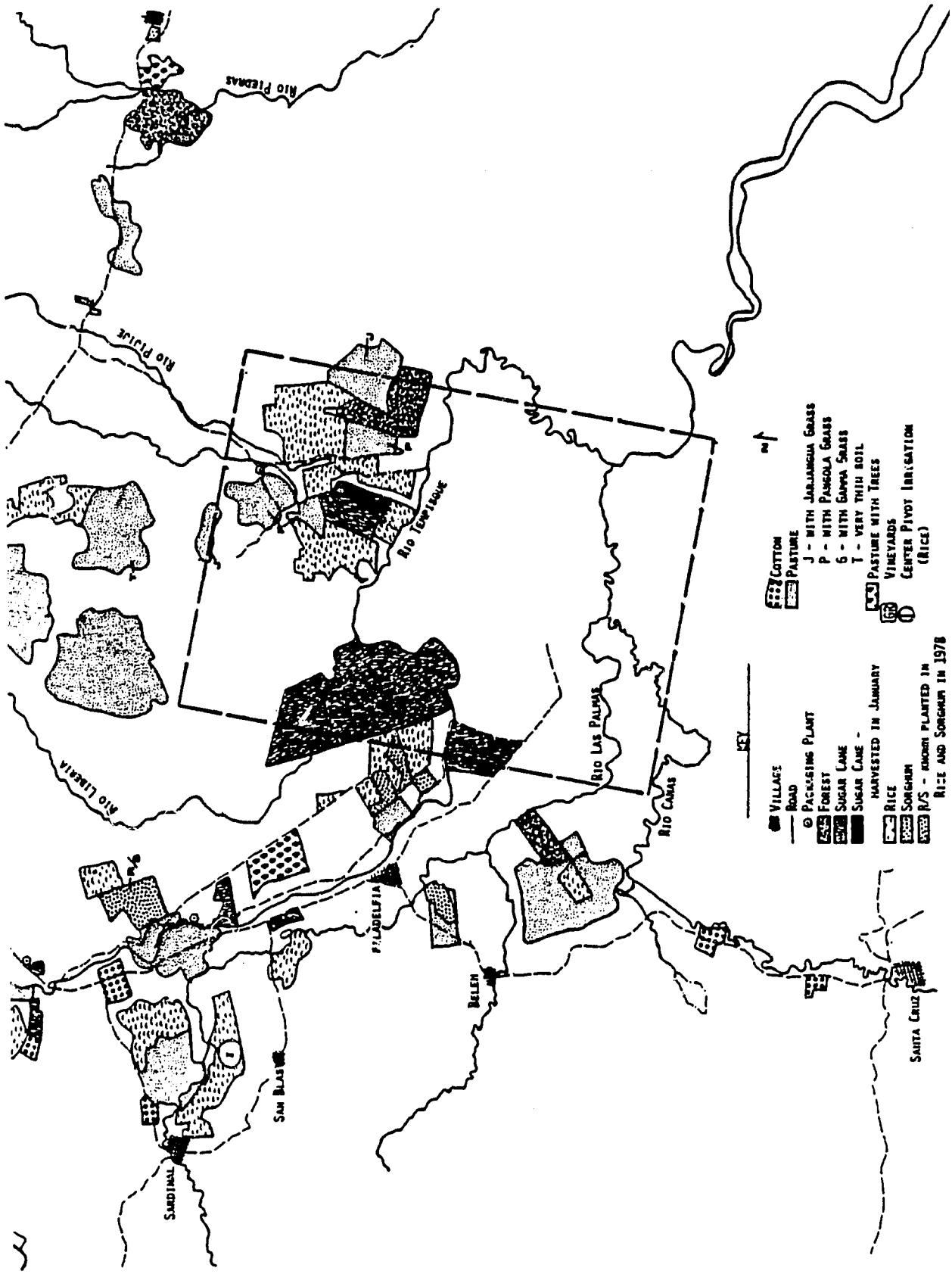


FIGURE 6. GROUND TRUTH MAP OF GUANACASTE

A. Rice. Approximately 40,000 ha were planted in 1978. Rice is usually planted from 20 June to 20 July and harvested from 15 November to 15 December. In late July the rice would be 20-25 cm in height. Approximately 11,000 ha is grown in the Filadelpha District (the central portion of the study site). During the December to February period the rice stubble is used for fodder or sprayed with insecticide. One circular field with center pivot irrigation, was used for rice production.

B. Cotton. Approximately 7,500 ha of cotton were planted in 1978. (Cotton fields identified on the Landsat image have a non-uniform purplish appearance.) Cotton is normally planted in July and harvested in late December and January. By late July the cotton plants would be 10-15 cm high and 4 cm in diameter. Since they are planted in 1 m rows, most of the fields would appear bare in late July. Normally the rows run in the long direction of the field to facilitate aerial dusting.

C. Sugar Cane. Sugar cane is planted in May and harvested in January-March. A single rattoon may last for 4 or 5 cuttings. (Most sugar cane fields are a distinctive uniform light red on the January Landsat image.) These plants would be approximately 2 m high in late July.

D. Corn. Approximately 10,000 ha of corn were planted in 1978. The corn would be about 80 cm high in late July. Corn is usually planted in small fields -- average 3 ha -- and is usually planted in May and harvested in December.

E. Sorghum. The Government of Costa Rica was trying to discourage sorghum planting in Guanacaste -- 8,000-8,500 ha in 1978. It was recommended that sorghum be planted in humid areas further south in Costa Rica. Sorghum is often planted after the rice crop has been harvested in December and is usually harvested in March. (The ground truth team observed sorghum harvesting during the March trip.) In some areas sorghum may be planted in September and harvested in January.

A number of fields of each crop type were located on the Landsat image. As nearly as possible, the cropping practices and current field conditions were verified. A variety of pastures and forest/savanna conditions were also noted.

2.3 SEASAT DATA

Seasat SAR data of western Costa Rica were obtained on 27 July (Rev. 443) and 14 August (Rev. 687) 1978. Both were collected on descending, west-looking orbits. High-density digital tapes of the radar signal data for the July pass and positive image transparencies of the August data were obtained from NASA's Jet Propulsion Laboratory (JPL). Subsequently, the July data were converted to signal film and optically processed into an image film at ERIM. The SAR data were converted to digital data using ERIM's Hybrid Optical-Digital processor. Operation of the processor is described in Ausherman, et. al. (1978). Thus both JPL and ERIM optically processed images were available for comparison.

2.4 DATA PROCESSING

A portion of Rev. 443 was selected for computer processing. The first of the four subswaths of the pass was selected because it covered most of the Guanacaste study area. The signal film was transposed into an image plane and digitized onto a computer compatible tape by the ERIM Hybrid Optical Processor. For this project, the output data were optimized for terrestrial features rather than the oceanographic features generally emphasized on JPL Seasat SAR image film.

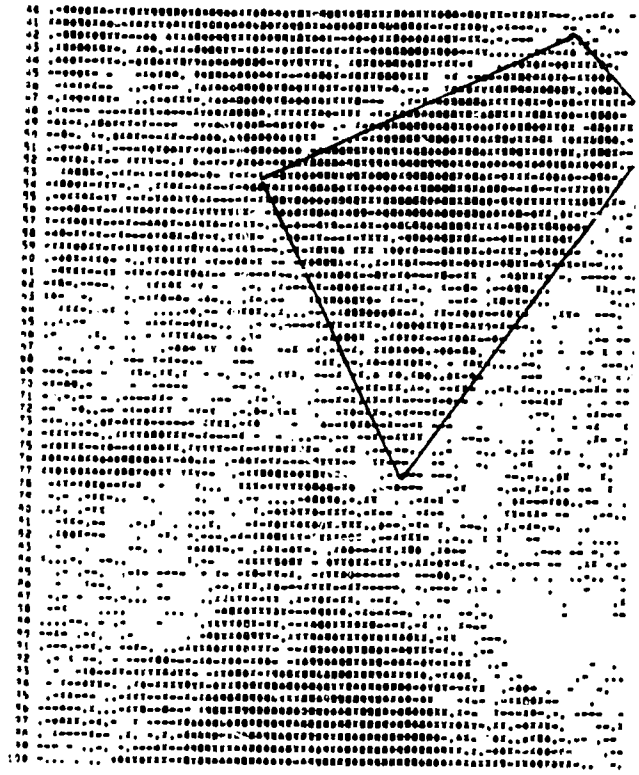
Several corrections were applied to the SAR digital data to facilitate the analysis. A slant to ground range conversion was applied, to correct for the side-looking geometry of the radar system. This capability was previously developed at ERIM on its special purpose ARIES computer system (Feldkamp, 1978). The range (i.e., ground distance) distortion occurred only in the cross-track direction so that the correction could be applied scan line by scan line. The output pixel

spacing chosen for Costa Rica was 12 meters in both the cross track and azimuth directions.

A small compensation for change in antenna gain across the swath was also applied by the ARIES facility. Although the tonal variation caused by the antenna pattern was not noticeable on the uncorrected imagery, the improvment in the contrast on the output data was significant for digital analysis. Both corrections were useful in normalizing the SAR digital data and reducing the system variables that affect image interpretation.

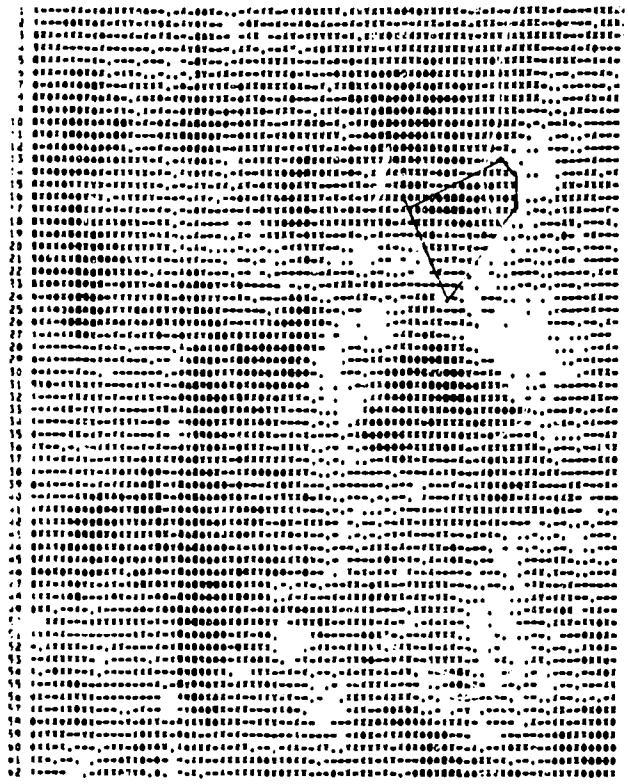
The speckle inherent in "coherent" SAR data was found to be detrimental for small area detailed interpretation. A conventional spatial filtering technique was used to "smooth" the data (Morgenstern, 1977). Pixel values within a moving window were averaged to create a new output pixel value. Windows of different sizes, from 2 x 2 pixels to 10 x 10 pixels, were tested on the Costa Rica data. The 5 x 5 (25 pixel) average was chosen because it was judged to offer maximum feature clarity with a minimum reduction in detail. Also, the output pixel size of 60 meters x 60 meters was compatible for subsequent resampling and combining with the Landsat data.

Figure 7 provides a comparison of digital alphanumeric printouts of the unsmoothed data and various smoothed data. Greymap printouts are standard methods of displaying such digital data. Several discrete levels of data values are designated and all values within a given level are printed with the same symbol. On these greymaps the dark areas represent low radar signals or "backscatter" returns such as harvested rice fields; the brighter areas represent high returns from such features as forests. The known crop fields that had been visited on the ground were located on the greymaps. The pixel coordinates that uniquely defined each field within the digital data were determined. Thus one or more "training sets" were created for each surface feature that consisted of the group of pixels representing that area. The mean,



3 x 3 pixels

5 x 5 pixels



10 x 10 pixels

FIGURE 7. COMPARISON OF GRAYMAPS OF SEASAT DATA WITH DIFFERENT SMOOTHING WINDOWS

standard deviation and variance/mean of the pixel values within each training set were calculated, creating a quantitative "signature" for each field. These are summarized in Table 2 and discussed in the next section.

2.5 INTERPRETATION AND ANALYSIS

Interpretation of radar imagery requires some understanding of how certain radar system parameters affect terrain backscatter and the contrast on the resulting imagery. Rayleigh's criterion of roughness may be used as an approximation of the vertical variation from a level surface. According to the theory, a surface with roughness (h) or greater will return some radar energy to the sensor. Given the parameters listed in Table 1, the Rayleigh Roughness Criterion (h) can be calculated:

where λ = radar wavelength, and

θ = incident angle

$h \geq \lambda/8\sin\theta$

for Seasat SAR

$\lambda = 23.5$ cm and $\theta = 70°$, therefore

$h = 3.2$ cm.

For level surfaces, such as agricultural fields, the primary source of Rayleigh's roughness would be variation in vegetation height. If the height reaches 3.2 cm or more, the field will act as a diffuse reflector at the Seasat wavelength and will produce some apparent brightness on an image. Surfaces with a roughness of less than the estimated 3.2 cm would appear specular, or mirror-like to the radar and most likely dark on the image. The backscatter from relatively <u>level</u> terrain would be greatly affected by the height and canopy geometry of existing vegetation. It would not be greatly influenced by the underlying

TABLE 2. DIGITAL ANALYSIS OF SEASAT SAR DATA FOR COSTA RICA (27 July 1978)

Vegetation	Field Number	Mean	S.D.	$\frac{(SD)^2}{M}$	Estimated Height In Late July 1978	Manual Description
Sugar Cane	11	40.6	7.1	1.3	Harvested	Smooth texture; even, dark tone
Sugar Cane	13	56.9	10.4	1.9	2 meters	Mod. speckled; uneven, mod. bright tone
Sugar Cane	15	58.2	8.3	1.8	2 meters	Mod. speckled; uneven, mod. bright tone
Sugar Cane	12	58.6	8.4	1.2	2 meters	Mod. speckled; patchy, mod. tone
Sugar Cane	16	74.8	12.5	2.1	Max-2-1/2 m.	Very smooth; very bright tone-this was harvested the following January
Rice	10	38.5	5.3	.7	Newly planted	Finely speckled; even, mod-dark tone
Rice	34	40.9	8.0	1.6	20-25 cm	Smooth texture; uneven, dark tone
Rice	19	40.7	6.4	1.0	Newly planted	Smooth texture; even, dark tone
Rice	20	41.1	9.5	2.2	Newly planted	Patchy texture and dark tone
Rice	35	41.1	6.6	1.0	Mixed	Patchy, finely speckled; dark tone
Rice	18	50.4	7.4	1.1	.5-1 m	Mod. speckled; uneven med-dark tone
Rice	17	52.2	12.1	2.8	.5-1 m	Mixed field-smooth texture with clear fields of med to dark tone
Rice	27	55.5	7.2	9.3	20-25 cm	Quite speckled; even medium tone
Rice	3	56.0	8.9	1.4	20-25 cm	Mod speckle; mod bright tone
Sorghum	4	37.3	4.6	.5	Stubble 10 cm	Smooth texture, very dark tone
Sorghum	24	49.2	7.0	1.0	Stubble 10 cm	Mod speckle; mixed, med-dark tone
Sorghum	9	56.4	7.2	.9	?	Very finely speckled; even, med. tone
Pasture	5	39.0	6.2	1.0	15-25 cm	Smooth texture; dark tone
Pasture	26	47.8	8.3	1.4	15-25 cm	Patchy, mod. speckle; patchy med tone
Pasture-J	32	40.3	5.0	.6	15-25 cm	Jarjangua grass; smooth; dark tone
Pasture-J	22	45.0	7.4	1.2	15-25 cm	Jarjangua; Mod. smooth; med-dark tone
Pasture-P	23	41.5	6.8	1.1	30 cm	Pangola grass; finely speckled; uneven, med dark tone
Pasture-P	14	41.6	6.2	.9	30 cm	Pangola; mod. smooth; dark tone
Pasture-P	36	46.2	6.9	1.0	30 cm	Pangola; smooth texture; patchy, dark and bright tone
Pasture-P	31	52.7	8.7	1.4	30 cm	Pangola; finely speckled; even, med tone
Pasture-T	33	47.4	10.4	2.3	20-30 cm with trees	Thin soil; mod. speckle; mixed Med. tone
Pasture	28	59.1	7.2	1.0	20-30 cm	Smooth texture; very bright tone -- grass field-not used for grazing?
Pasture	1	45.2	7.2	1.1	20-30 cm	With trees: Mod. speckled; med. tone
Cotton	29	31.9	3.0	.3	10cm widely spaced	Smooth texture; mixed dark tone
Cotton	37	40.6	5.7	.8	10cm widely spaced	Very fine speckle; mixed dark tone
Cotton	30	46.3	7.2	1.1	10cm widely spaced	Very fine speckle; mixed dark tone
Cotton	8	47.9	5.9	.7	10cm widely spaced	Fine speckle; medium-dark tone
Forest	25	51.1	6.0	.7	all leaf covered	Quite speckled; mixed, medium tone
Forest	39	51.4	7.5	1.1	all leaf covered	Mod. speckle; medium tone
Forest	40	53.9	6.5	.8	all leaf covered	Mod. speckle; medium tone
Forest	38	54.3	6.8	.8	all leaf covered	Mod. speckle; mixed, medium tone
Forest	21	56.6	7.6	1.0	all leaf covered	Mod. speckle; mixed, medium tone
Village	2	53.1	9.2	1.1	all leaf covered	Mod. speckle; mixed, medium tone

surface because these radar wavelengths do not effectively penetrate heavy vegetation canopies.

Changes in the angle of the incident radar signal also affect the backscatter. This is an important consideration in the interpretation of airborne side-looking radar data. Because the depression angle of the Seasat SAR is consistent across the 100 km wide swath (17° to 23° from the vertical), it has little impact on satellite collected data.

The Guanacaste study area provided good opportunity for evaluation of SAR imaging of vegetation. The level terrain, large fields and simple agricultural patterns helped to limit complex scene variables. The Landsat imagery was useful for separating pasture, forest and mature sugar cane from other agricultural areas, but was not available during the vital crop growing season because of cloud cover. Using image interpretation, there is some confusion on the SAR imagery between cropland and pasture or forest areas. The most effective method of analysis was to delineate general areas of pasture, forest, and cropland with Landsat data and then to separate each of those into areas of different vegetation heights with Seasat data.

For example, several of the fields clearly identified as sugar cane on the Landsat had much different appearances on the Seasat imagery, indicating different stages of maturity at the time of the Seasat overpass. That may be a useful tool for monitoring sugar cane area extent and development, because the sugar cane fields are traditionally planted at different times throughout the year. Many differences are visible on the Seasat image within the agricultural areas that appear uniformly fallow during the dry season on the Landsat imagery. Some differences on the Seasat were related to irrigation.

A portion of the July Seasat image is shown in Figure 5, with the training fields indicated by number. Many terrain conditions can be interpreted by referring to Table 2 while comparing the Landsat image

(Figure 4) with the SAR image (Figure 5). Several interesting situations are noted, including:

1. Fields 15 and 16 provide a good example of monitoring differences in height of similar crops. It was determined from the ground truth, that both fields were sugar cane, yet field 16 is much brighter (i.e., more mature) than 15, which was most likely planted at a different time. By January, only 15 was mature enough to harvest as apparent on the Landsat image.

2. Forest areas cannot always be distinguished from pasture and rice in SAR data, by using image interpretation. However, when delineated first with the Landsat the group of signatures for the forest areas were more consistent than those of the other training sites. Computer categorization should be able to separate out these forest areas.

3. Slight differences in heights are apparent within several rice fields. This is visible in fields 10, 19, and 20. This could be useful, given precise ground measurements, for monitoring differences in crop planting times or growth rates.

4. Pasture areas exhibit variable tone, but relatively consistent speckle (see fields 23 and 26). This could possibly be developed as a means of monitoring grazing practices. Note that field 28 is particularly bright. Grazing had not been allowed on this field before the ground truth visit -- the grass was much longer than the surrounding fields, possibly causing the high backscatter.

5. In July, the cotton plants were quite small, leaving much of the soil exposed. This created a dark, but mixed appearance on the image. It is separable from other areas, particularly fallow areas where stubble creates a somewhat brighter backscatter.

6. The villages in the area were not visible on the SAR imagery. They were all low population density, with low buildings surrounded by much vegetation -- the corners that might produce the bright point returns to the radar were usually buried in long grass. Those bright specular reflections that were apparent on the image were from metal bridges and isolated processing plants that had, without exception, metal roofs -- each plant, always in the middle of an agricultural area, was clearly locatable as a bright spot on the SAR image.

Eighteen days separated the two Seasat SAR passes over Guanacaste Province. Some changes in the vegetation occurred during that period. Figure 8 provides a comparison of a portion of the two Seasat images and the Landsat image. While specific ground truth observations are not available to document the nature of changes from one date to the next, it is evident that the Seasat SAR is sensitive to changing vegetation conditions. The tone has changed from dark to medium or light grey in each area marked on the radar images. This suggests that the vegetation has developed from less than the threshold canopy roughness (approximately 3.2 cm) to greater than that in height. Such a change would indicate rapid vegetative growth and a transition from a mixture of bare soil and young plants to a closed canopy. In several cases the image tone changed from light to dark, suggesting a plowing of weeds or harvesting operation. The intensity and texture of the tones also changed. Information about the vegetation cover could be more refined, if those changes could be quantified.

2.6 DISCUSSION

The correlation of SAR response and vegetation height was postulated in this project, but since there were no detailed records available for the times of the Seasat overpasses to substantiate it. If the correlation was established, crop type could be inferred by relating estimated height at the time of the overpass to the local crop calendar.

27 July 1978

Seasat SAR

14 August 1978

6 January 1979
Landsat Band 5

↙ Area of change
F - Forest
P - Pasture
S - Sugar Cane
R - Rice
T - Rio Tempisque

FIGURE 8. COMPARISON OF SEASAT AND LANDSAT IMAGES OF VALLEE DE RIO TEMPISQUE

Records from the Guanacaste Province Regional Agricultural office provided estimates of various crop heights for July 1978.

The geometrically corrected Landsat image provided an effective field map. Because of the date of the Landsat image, it was possible to delineate pasture, forest and sugar cane fields from other types of fields, e.g., sugar cane was the only crop green in January. The verified areas were then located on the SAR image and carefully examined for differences in tone and texture.

Digitization was an efficient method for managing the large amount of data collected by the radar sensor. It also helped to reduce the subjectivity inherent in manual image interpretation. Digitization is particularly effective for Seasat SAR data because of the large dynamic range of the raw data. An appropriate range of signal values can be extracted from the digital data and maximized for a given task. Only a portion of that range can be effectively reproduced on photographic film, so that all the possible information cannot be presented by a single photographic image.

The following conclusions were reached:

1. Large agricultural fields are generally identifiable by their regular shape and uniform tone, but smaller fields are often indistinguishable from their surroundings. Adjacent fields with the same crop usually appear as a single entity.

2. The image tones of agricultural fields range from very dark to light, but three general tones are distinguishable:

   Dark (specular reflectors) - bare fields, low crops (cotton, rice, beans), surface water.

   Medium grey - moderate vegetation cover including pastures, sugar cane, sparse woodland.

Light (highly diffuse reflector) - heavy vegetation including forest and some crops (sugar cane and sorghum), east-facing slopes.

3. Drainage patterns can be traced for long distances due to the high (bright) return from the east-facing slopes and the trees lining the banks of the rivers. The Rio Tempisque provides a locational reference for other features.

4. Rolling terrain and rocky outcrops are evident by a bright speckly return. These areas are often used as unimproved pasture.

5. Some buildings, bridges, and large farm machines could be identified as very bright points on the radar images, but generally man-made structures (including major roads and towns) were not evident.

6. While described more fully in the Haiti test site analysis, the general trend of geologic structures, especially ridges and valleys, is evident, but considerable geometric distortion occurs in mountainous areas.

3

HAITI

In cooperation with Haiti's Remote Sensing Unit in the Department de l'Agriculture des Resources Naturelles et du Developpement Rural, ERIM conducted a study of available Seasat synthetic aperture radar imagery of Haiti. This project augmented previous remote sensing experience gained from a USAID small grant study of Landsat data for agricultural-land use mapping in the Cul de Sac Plain. As a result of the interest created by that project, a modest remote sensing unit was created in the Department of Agriculture and Natural Resources to pursue operational remote sensing work in Haiti.

3.1 HAITIAN BACKGROUND

Haiti is a mountainous country that forms the western one-third of the island of Hispaniola in the central Caribbean. The Dominican Republic occupies the eastern two-thirds of the island. Haiti is about the size of the State of Maryland and the poorest country in the western Hemisphere. Although located in the humid tropics, Haiti is troubled by both droughts and floods. Precipitation is highly variable and effects different parts of the country at different times. Extensive forest cutting and grazing have left most of the mountainous slopes eroded with little soil to support vegetative growth. Rapid runoff from the steep slopes also contributes to the recurring cycles of flood and drought. For this reason Haiti has received special attention in connection with a NOAA project to provide weekly weather assessments using meteorological satellite photos (AID PASA CC/CARB-9991-77).

3.2 SEASAT DATA AND GROUND TRUTH

Several Seasat passes included coverage of portions of Haiti. At the time of this project, two of the passes were available in 1:500,000 scale positive transparency form from the Jet Propulsion Laboratory

(JPL). Digital tapes were also ordered but were received by ERIM too late to be processed for this project.

Rev. 493, collected on 31 July 1978, covered the central portion of the country and Rev. 694, collected on 14 August 1978 covered the western tip of the long narrow southern peninsula (Figures 9 and 10). Both were obtained on descending satellite orbits. The first pass covered much of the northwestern and southeast part of the country, although it did not reach the border with the Dominican Republic. This very excellent pass included major mountainous and level portions of Haiti, including the western-end of the Cul de Sac Plain and Port-au-Prince, the capital city. The August image showed only a small part of the country, but a remote area that is quite mountainous and poorly known.

Both images were reproduced and interpreted as black-and-white positive prints at several scales. Topographic maps at scales of 1:250,000 and 1:50,000 were available for comparison and Landsat images obtained at the same time (± one day) were obtained. Additionally, two land use maps of the Cul de Sac Plain produced from 1975 Landsat data were also used to help interpretation.

The Seasat images showed striking contrasts and patterns in the nearshore coastal regions. These appeared to be associated directly with coastal currents, river and stream outfalls, and bottom topography near the coasts. Principal interpretation efforts concentrated on the terrestrial portions of the imagery. Unfortunately, it appears that image contrast was optimized for water variations, and some of the terrestrial features were over-exposed and lacking in detail. It is believed that special processing would have recovered some of the terrain details from these areas.

Two visits were made to Haiti by ERIM personnel to obtain ground truth and to consult with the two EROS-trained remote sensing specialists in the Remote Sensing Unit. The initial visit was made in

FIGURE 10. SEASAT IMAGE OF 14 AUGUST 1978 (REV. 694) OF SOUTHWESTERN HAITI

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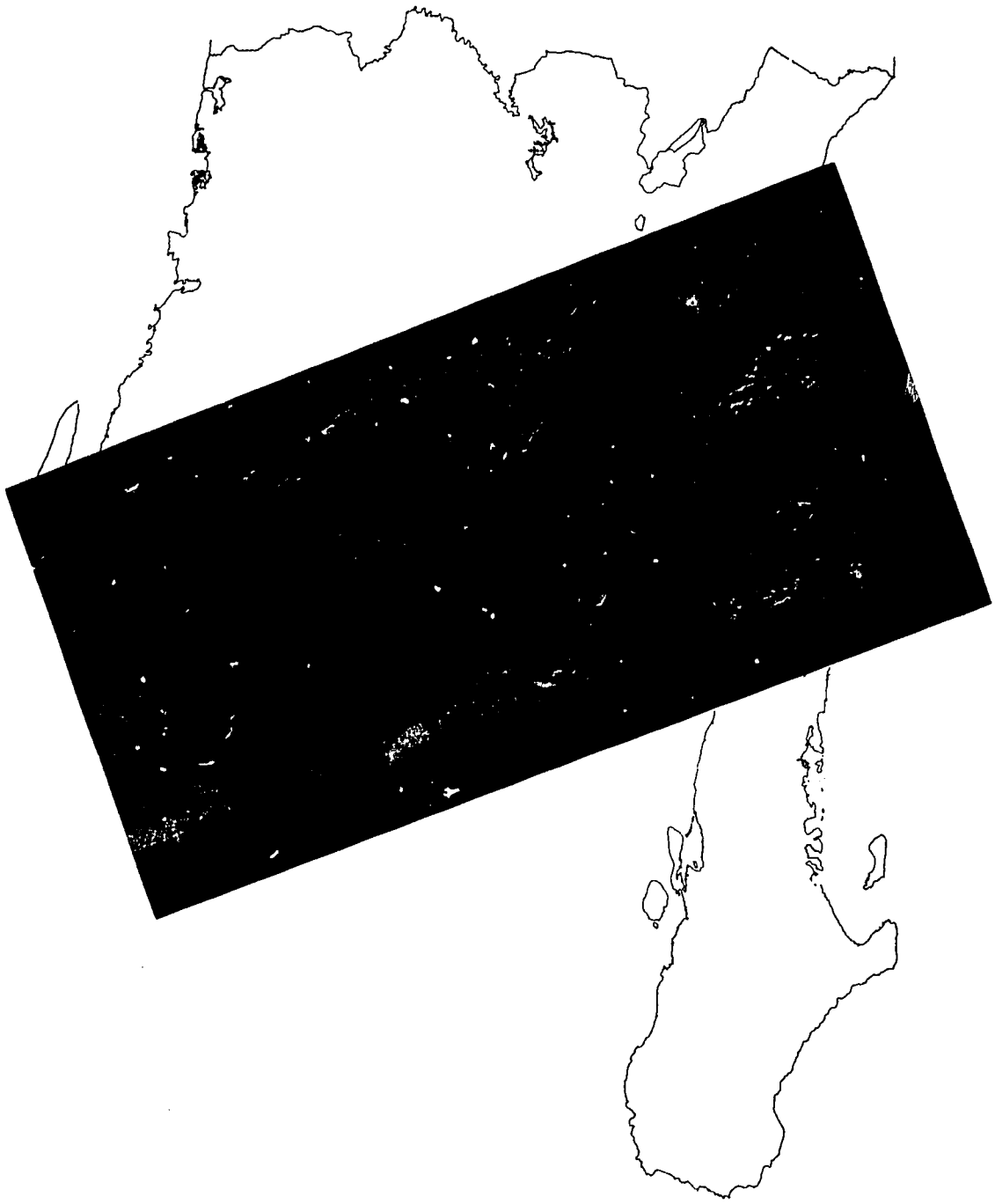

FIGURE 9. SEASAT IMAGE OF 31 JULY 1978 (REV. 493) OF CENTRAL HAITI

August 1979, before the Seasat data were obtained by ERIM. Ground photographs were taken that represented the same season as the Seasat data, but one year later. The second trip occurred in June 1980 to conduct follow-up analysis efforts.

In addition to visiting several known areas of the Cul de Sac Plain, ERIM personnel met with representatives of USAID, the Department of Geology and Mines, and the Topographic Survey. Although it was not possible to visit some of the more rugged areas, several distinctive geological patterns were noted and discussed with local experts.

3.3 IMAGE INTERPRETATION AND DISCUSSION

Interpretation of the Seasat SAR data centered on the Cul de Sac Plain and the mountainous portion of the tip of the southern peninsula. The Seasat imagery of the plain (Figure 9) showed the same types of phenomena that were documented for Guanacaste Province, Costa Rica. Although the contrast was much better on the Costa Rica images, Seasat data of the Cul de Sac Plain showed high growing vegetation to be very light-toned. The sugar cane along the coast was particularly visible. Most of the crops had been planted in May, so there was less variability in crop development and more closed green crop canopies than in the Costa Rica case. Unfortunately, some of the highly saline soil areas in the eastern part of the Plain were not covered by the Seasat image. The effect of saline soils on vegetation growth was clearly evident in the Landsat imagery obtained at the same time and would have made an interesting study with the Seasat SAR imagery.

Large area linear patterns oriented in the direction of the Seasat path are particularly enhanced by the radar. A major east-west trending fault zone is apparent in the southern peninsula (Figure 10). The lack of high peaks along that fault and the difference in peak heights on either side of it make orientation unmistakable and significant for geological applications. Landsat also provides some indication of the fault, with better locational representation of the terrain features.

FIGURE 11. SEASAT IMAGE OF 27 JULY 1978 (REV. 443) OF NORTHEASTERN HONDURAS

Again the most information is gained by a combination of the two data sources.

Drainage patterns oriented perpendicular to the Seasat SAR signals (parallel to the actual satellite orbit) are frequently enhanced by the differential slope illumination if layover is not too severe. This is apparent on the Seasat image of the Ile de Gonave. Regional drainage patterns are usually obscured by the interference of radar layover effects.

It should be noted that multiple looks at the same area with radar can sometimes be used to produce stereoscopic imaging. It was originally hoped that stereoscopic coverage could be exploited for Haiti, but the lack of two different Seasat looks of the same area prevented doing so within the timeframe of this project. Additional high quality Seasat data has just recently become available. An in-depth study of these data, particularly emphasizing physiographic and coastal features could provide invaluable resource information for Haiti.

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4

HONDURAS

Seasat Rev. 443 (27 July 1978) covered northeastern Honduras, an area of coastal wetlands about which little is known. No ground truth or detailed maps were available to augment the SAR data, but analysis of the imagery did show good potential for the initial overview of the area for development planning.

A preliminary interpretation was made of the Honduras image (Figure 11), based on previous Seasat experience, gained in the analysis of Seasat imagery of Costa Rica and Haiti. Many interesting phenomena were noted and most appeared to be related to wetland vegetation or soil moisture patterns. No cultural features were identified.

Open water was clearly evident by the dark tone and smooth texture on the SAR image. The Pacific coastline is visible across the top of the image, as is the large Laguna de Caratasca in the upper center. The linear "stringy" patterns of tone parallel to the coast could possibly be related to tidal influences. Two rivers can be identified in the west, Rio Kruia in the north, and the larger Rio Wangki Coco o. Segovia in the south. Many oxbows and meanders are also apparent.

Areas of relatively homogeneous tone and texture can be delineated, although not identified. Ancillary information could be used to characterize each area. The wide variety of patterns, particularly in tone, appear to represent different vegetation and moisture regimes. The darker tones seem to indicate wetter conditions; the brighter tones and more speckled texture, denser vegetation, dryer conditions, or a combination of both. The interesting pattern of bright spots in a dark background in the extreme left center probably represents islands of dryer land within a marsh.

The brightest, finely textured areas, such as the one in the left center of the image, are probably densely vegetated and the dendritic-

like pattern of some of these areas suggests heavy vegetation along drainage channels. A large area in the upper right portion of the image has a similar appearance, but is somewhat darker in tone and finer textured. This could be the difference in radar response between different wetland forest communities.

The Seasat data could provide valuable resource information if substantiated with ground truth or other remote sensing data. The unique capability of SAR to partially distinguish different moisture regimes is especially useful for mapping wetlands and the extent of flooding. It provides a good basis for a resource survey of this remote region of Honduras.

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APPENDIX A

REVIEW OF TERRESTRIAL APPLICATIONS OF IMAGING RADAR SYSTEMS

This is a brief review of the development and use of imaging radar systems for earth resources inventory applications. It provides a short overview of the development of imaging radars (1900-1964) followed by a selected review of the work of the next ten years (1965-1975) which focused on determining the optimum configuration of radar systems for different uses, and which eventually culminated in several large-scale mapping projects. Finally, a survey of some recent applications of airborne radar is presented, describing the types of information which can reliably be extracted from radar data. The extensive list of references from which this appendix was compiled is presented at the end of this section.

DEVELOPMENT OF IMAGING RADARS

The term "RADAR" is an acronym for RAdio Detection And Ranging. In contrast to other types of remote sensing systems, radar is an active sensor, i.e., it supplies its own scene illumination. In simple terms, radar allows us to learn something about the environment by analyzing the way the environment modifies radio waves which we send out. The differences in the reflected waves (due to scattering by the terrain) are detected by comparing the form of the initial wave transmitted with the form it has assumed after being returned to the sensor. Because of the portion of the electromagnetic spectrum in which they operate, radar systems have special advantages as remote sensing devices. Chief among these is the ability of radio waves to penetrate cloud cover and usually precipitation. Combined with the fact that it is an active-sensor, the atmospheric penetration capability makes radar the only truly all-weather, 24 hour remote sensing system available. This capability generates great interest in radar because of the need to produce maps for many places which are frequently cloud-covered, such as mountainous

areas, the humid tropics, or the arctic. Radar has other capabilities which will be discussed as well.

The first use of radio waves was as a form of wireless telegraphy, first demonstrated in 1901. The earliest use of a radar-like sensing system came several years later in the mid-1920's, when Appleton in England and Breit and Tuve in the U.S. experimented with radio waves for measuring the height of the ionosphere. Shortly thereafter, during the early 1930's reflections of radio waves from passing aircraft were observed during experiments with a high frequency radio link. Subsequently, a U.S. patent was issued in 1934 for a "system for detecting objects by radio".

During World War II many countries developed plan position indicator (PPI) radars for detecting and locating ships and aircraft. The image quality of these systems was limited, however, and unsuited for observation of terrain characteristics more subtle than such things as land-water boundaries, mountains, and large urban areas. Nevertheless, steady progress was made during the war toward improving radar image quality, although their uses remained strictly military.

The first terrain feature map derived from radar data was made in 1947 by U.S. Army Air Force Lieutenant H.P. Smith, stationed in Greenland. He used photographs of a PPI radar screen to construct a map of a portion of the coast of Greenland that was more accurate than the existing aeronautical charts. Similarly in 1949, a British officer used PPI radar to fill in gaps between air photos caused by cloud cover and white-outs over a portion of Antarctica.

These results prompted the U.S. Army Corps of Engineers to conduct a classified project in the early 1950's called TERAIN to map the Antarctic landscape. In this project radar proved especially useful in detecting shelf ice versus land ice, floes and glaciers, crevasses and seracs [4]. Later in the decade the first Side-Looking Airborne Radar

(SLAR) systems were developed for military reconnaissance by Goodyear and the Autometrics Corporation.

The first reports on civilian applications of SLAR began appearing in the open literature about 1960. These early reports can generally be classed as belonging to one of two types: The first type explained how radar systems worked, including how the terrain influenced the signal that was reflected back to the sensor; the second type was more discipline-oriented, and discussed the types of resource information one could obtain from radar images. Information most frequently discussed in the discipline-oriented reports were the interpretation of geological and geomorphological features, and cultural "land use" patterns [4,5,6].

Perhaps the first significant study involving the use of SLAR to identify and map natural vegetation was performed by Morain and Simonett at Kansas in 1964 [7]. They studied vegetation in three different types of environment: a sparsely vegetated desert, a forested region, and an arctic delta. They concluded that both tone and texture were required to identify different vegetation, and also noted that the polarization of the radar signal could also be used to aid in the interpretation process. For example, forested areas were found to be most distinct on images generated by sending waves out in a horizontal plane and sensing their return in a vertical plane (HV polarization). They also observed that marsh and grass areas were most easily identified using HH like-polarized images. On this basis, they concluded that future radar systems should have the ability to collect simultaneous, multipolarized data.

These findings encouraged several large-scale projects. The first was the well-known Darien Province Project, in which a radar mosaic of the entire province was prepared in 1967 for the U.S. Army Corps of Engineers in cooperation with the Government of Panama. In eight hours of flying time the province was imaged from four different directions. For a quarter century prior to this project, attempts to map the area

with aerial photography had failed due to the nearly continuous cloud cover. A contour map, with topographic intervals of 100 meters, was prepared from the data.

In 1970, Brazil initiated a similar project, Project RADAM (RADar for the AMazon), that covered a much larger area and included coordinated field studies. This study was designed to produce imagery that could be made into semi-controlled 1:250,000 scale mosaic maps covering 1° in latitude and 1.5° in longitude. The Goodyear Electronic Mapping System (GEMS) X-band radar system was used. The imagery was acquired so that opposing views of the same area were obtained. This permitted 'stereoscopic viewing' of the terrain [9]. A similar project was initiated in 1971 in Venezuela, also using the GEMS X-band radar. Both studies featured interpretation of the imagery for hydrology, geology, soils, and forestry. Interpretation of the data was performed by visual analysis coupled with the use of regional image analysis keys. The keys were developed by correlation of land use, vegetation types and soils to regional geomorphology and geology. Total cost for the Venezuela project which covered 210,000 sq. kms. was approximately $5-6/sq. km. This included data acquisition, ground control, field work, interpretation and map preparation. This data is still being used in Venezuela.

Other similar projects have been conducted in various parts of the world. Two of the more recent projects resulted in maps for Nigeria in 1976 (Project NIRAD) and for Togo in 1977. Both used an X-band Motorola SLAR system. Contextual image interpretation was again found to be the most useful form of analysis for these projects. In the Nigerian project it was possible to map several important categories of land use including: annual crops, fallow cropland (including shrubland), plantations, closed woodlands and grasslands [11]. In Togo, distinctions were made between deciduous and semi-deciduous forest, savanna, seasonally inundated grasslands, and marshes and swamps. Several categories of

cultivated vegetation were also identified including: oil palms, coconut palms, teak and areas of intensive mixed crops [12].

These and nearly all similar projects used one of two commercial X-band radar systems, the Goodyear GEMS and the Motorola System. It is estimated that between 1967 and 1977, the GEMS system alone had mapped 12 x 10^6 km sq in 11 countries on 4 continents. Both of these commercial systems and most radars in civilian use until the early 1970's were "real aperture" systems. The along flight track resolution is determined by the ratio of radar wavelength to antenna aperture size. The radar signal returned to the system's receiver can be displayed directly on a screen or recorded on film without additional processing. The most common wavelengths at that time were the K-band (2 cm) and the X-band (3.33 cm), which were limited by the physical size of the antenna that an aircraft could carry. Several investigators urged the development of longer wavelength radars in the belief that longer wavelengths would allow the penetration of vegetation cover and permit topographic mapping of the ground surface. The real aperture radar systems were only effective at relatively short wavelengths.

A breakthrough in radar signal processing in the mid-1960's paved the way for longer wavelength systems -- the development of "Synthetic Aperture Radar" (SAR) systems. In effect, SAR systems use a standard length antenna with a wide beam to "synthesize" a very long antenna with a narrow beam by taking advantage of aircraft motion. The process is described as follows: the short real antenna transmits pulses at regular intervals as the airplane moves forward. As the airplane passes a specific terrain feature, the feature enters the antenna's beam pattern, moves through the pattern and finally leaves it. During the entire time the terrain feature is in the beam pattern it reflects a series of wave pulses. Thus, the farther the distance from the airplane to the object, the longer that object remains in the antenna's beam pattern. Viewed from the ground, the synthetic antenna is effectively longer for more

distant terrain features and shorter for closer objects. Since resolution is proportional to the range, these two effects compensate for each other in SAR systems. Thus, it is possible with SAR to obtain high resolution images almost independent of range.

Recent advances in radar technology allow improvements in the speed and accuracy with which we can analyze the data. For example, the capability to digitize radar returns so they can be analyzed with standard pattern recognition algorithms, and combined with other forms of remote sensing data, such as Landsat MSS data is significant. One of the main advantages of digital processing of SAR data over optical processing is that the entire dynamic range of the data can be maintained. Color composite images, which combine the radar data with other remote sensing data or which permit simultaneous display of the different frequencies or polarizations of radar data, are also now possible. This may make the data more interpretable than the older technique of analyzing separate black-and-white images [14].

REFINEMENT OF RADAR SYSTEMS

Research has been undertaken to determine optimum radar wavelength for various applications. Initially, the K-band (.8-2.8 cm) and X-band (3.33 cm) systems were developed in the early-mid 1960's. Although one study showed a potential for measuring soil moisture using a variable frequency C-band (5 cm) system [15], work proceeded on developing an L-band (24 cm) system, because it appeared to have greater potential for penetrating vegetation. ERIM, then Willow Run Laboratories of The University of Michigan (WRL), was part of this effort and conducted the first flight of an experimental L-band SAR in 1970 [16].

Concurrently, radars were developed that were able to transmit and receive signals with a variety of polarizations. Differences in signal returns between like- and cross-polarized signals had been observed for many terrain features in studies done during the late '60's [3,8,18].

In the early 1970's WRL pioneered in this area and produced an X-band system that was capabale of sending and receiving simultaneous signals with two polarizations. It was not until April of 1973, however, that both concepts were integrated into a single system. At that time WRL flew the first dual frequency (X- and L-bands) radar system capable of simultaneously transmitting and receiving dual polarization -- marking the advent of a truly multispectral radar [16].

The first major study reporting on the analysis of data from the WRL/ERIM X-L radar system was published in 1974 [19]. Examples of imagery from two types of environments were examined, Florida wetlands and Michigan croplands. This study compared the information content of the radar data to that of panchromatic B&W photography and thermal infrared MSS data. Comments were made regarding which band/polarization mode offers the most discrimination potential for many of the common vegetation types in these areas, including aquatic and emergent vegetation types, grazed and ungrazed pasture and palmetto, shrubland, and pine forest in Florida, and corn, alfalfa, and soybeans in southeastern Michigan. A significant conclusion was that only trees could be reliably identified without developing an interpretation key specific to the project. An advantage of the two-wavelength radar system is the ability to differentiate marshes by the lack of X-band penetration of the grasslike canopy and the L-band penetration to the underlying water (not the case when soil underlies the grass). L-band does not entirely penetrate a dense tree canopy so that the signal returned is not from the ground surface but from within the canopy. Also X-band data appears to mdap land/water interfaces and drainage patterns better than L-band.

These and other findings point out the advantages of a multispectral radar system which can simultaneously image terrain in several bands and polarizations using identical imaging parameters, covering the same swath, subject to the same motion errors, and collecting data under the same environmental conditions. Other investigators have continued

to refine an understanding of how such systems can best be employed various applications. Brief summaries of the findings associated with selected disciplines are presented in a following section.

RADAR GEOMETRY AND IMAGE INTERPRETATION

Radar imagery has several unique geometric characteristics that effect its utility for terrain mapping, especially for moderate to high relief. These effects are (1) radar shadows, (2) radar foreshortening, and (3) radar layover and relief displacement. Each of these geometric effects is functionally related to the depression angle of the radar signal and the relief and aspect of the terrain surface. Radar shadowing, the obscuring of some portion of the terrain surface by an intervening projection, is not a problem with depression angles for Seasat SAR of between 65° and 70°. Unlike aircraft radars, Seasat illuminated the surface from a high angle and only nearly vertical cliffs would block the signal and shadow small terrain areas.

Radar foreshortening is not a serious problem with Seasat. The period of time a slope is illuminated determines its physical length on radar imagery. Except in cases of steeply sloping surfaces, little foreshortening occurs due to the fact that the Seasat SAR illuminates foreslopes (facing the direction of the satellite) and backslopes (away from the satellite) for relatively equal periods of time. The percent of radar foreshortening (F_p) is defined as, $F_p = (1 - \sin\phi) \times 100$, where ϕ is the angle of incidence of the radar signal [1]. Seasat foreshortening will be 0 to 1.5% for a 20° foreslope and 13.4 to 23.4% for a 20° backslope (20° being a fairly strong sloping surface).

Radar layover and relief displacement has a strong effect on Seasat SAR imagery. Because the SAR measures the range to an object, placement on an image is directly related to the actual radar to surface distance. When the radar has a high depression angle, as with Seasat, the tops and upper surfaces of terrain features are imaged before the bottom or lower

slopes. Consequently, the tops of mountains are all located closer to the direction of the satellite than either the lower foreslopes or backslopes. Consequently these slopes are recorded in approximately the same location on the image. This layover effect confuses terrain detail from mountainous, or even hilly areas, and creates some very unusual patterns. With Seasat data, slopes of 10° or greater can cause layover effect, rendering the data of little utility for locating specific topographic or vegetational features in rugged terrain.

SURVEY OF APPLICATIONS

In this section the use of radar data for a variety of terrestrial applications are discussed. The disciplines associated with these applications include agriculture, soil mapping, hydrology, geology, geography, and the mapping of natural vegetation.

AGRICULTURE

Most studies concerning agricultural remote sensing with radar have been performed in the U.S. corn belt. Several principles have been demonstrated and some conclusions have been reached regarding the use of radar in agricultural projects.

Most agricultural crops appear to behave like diffuse rerflectors at radar wavelengths; furthermore, for the shorter wavelengths (K- and X-bands) the returns are from the top of the canopy. Other factors that affect signal return are the percent vegetation cover of the crop, crop height, row direction, plant moisture content, and soil moisture. Where these factors vary significantly between adjacent fields, the field boundaries can be identified, even though there may not be a consistent relationship between image tone and texture vs. crop type [21]. Crop type appears to be an important overall factor which determines image characteristics.

Some crops are better distinguished at one wavelength than another. Corn, for example, in one study was distinguished from soybeans at L-band, but not at X-band. Part of the explanation for this may be the fact that the row structure of corn is readily detected by longer wavelengths. HH polarized data is more sensitive to row spacing regardless of wavelength, than HV polarized data. Accuracy of results with radar data are variable, and none are considered high. Typically, accuracies of identification vary between 60% and 70% for single-date trials, and the use of dual polarized data tends to increase accuracies. In a study using L-band data, three cover types were correctly identified 65% of the time using HH polarized data. When HV data was also included, accuracies for corn, soybeans, continuous cover crops, and woods increased to 71% [23]. Another general conclusion is that data collected using a very low incidence angle produces more interpretable results by minimizing the chance of seeing the soil (between 30° and 64°), and thus reduces the possible effects of varying soil conditions on the signal return. In a study where radar data was digitally merged with Landsat data the overall accuracy of crop discrimination of the composite data set was 10-15% better than when the radar data was used alone (Ulaby, 1980 and Goodenough, 1979) [25].

Several investigators have agreed that it is useful to use radar data in a repeat-look mode to monitor the development of a given crop. Several attempts have been made to show how a unique time/vegetative cover development profile can be established for each crop and that such a profile aids in crop discrimination. Presumably data from a satellite radar that obtains multiple looks could be used to exploit this characteristic, as with Landsat data.

SOIL MAPPING

The four factors that affect radar returns from soil are: (1) soil type, 2) soil moisture content, 3) surface roughness, and 4) vegetative cover. The first and second factors affect a soil's radar cross-section

by determining its dielectric constant; the third factor affects radar cross-section by scattering; and, the fourth factor affects it by a combination of scattering and attenuation. Traditional soil type mapping using radar data has relied on developing keys that partition the scene into regions where one or more of the last three factors remain constant. The remaining factors are then inferred from the signal strength observed on the image and a likely identification of the soil type. For example, soil profiles are usually collected from the major physiognomic zones in the study area. Soil type is then determined for each profile, and the surface roughness and general moisture retention capabilities noted. An image interpretation key is then prepared that (1) takes advantage of the association of a given soil type with a particular region or geomorphological feature, (2) assumes a soil moisture content at the time of data collection (either on the basis of weather data, average conditions, or apparent topographic position), and then relies on the actual recorded radar signal to indicate surface roughness and particle size which leads to a probable soil type identification.

Where another form of remote sensing data, such as air photos or MSS data, is available to provide information on soil color, radar data is often used to provide an estimate of surface roughness. This information can be used to help distinguish between soils with a similar color, or to help determine slope and aspect differences.

In other situations, where soil type is already known, the information of most interest may be soil moisture -- especially where it is important to monitoring crop stress or irrigation requirements. For soil moisture, several investigators have found that the longer wavelengths are more useful under both vegetated and non-vegetated conditions. X-band cannot penetrate even small amounts of vegetation. L-band, on the other hand, penetrates low density vegetation cover fairly effectively, although the vegetation also affects the signal [26].

Another investigation found that variation in signal due to surface roughness decreases with longer wavelengths. The same study also noted that errors in soil moisture estimation because of slope effects are less at longer wavelengths. In addition, both studies concluded that vertically polarized data is better because the return is less affected by surface roughness.

The influence of vegetation cover on ability to determine soil moisture was also evaluated. In a test of three common radars with increasing wavelengths (X-, C-, and L-bands) it was found that L- and C-band data were not affected by the field orientation of row crops. In this test the C-band data in HH polarization was considered most effective and was able to predict soil moisture accurately 83% of the time. Another conclusion of this study is that performance is enhanced by using incidence angles close to nadir (between 7° and 17°) [24].

HYDROLOGY

One of the earliest clear applications of radar data was in mapping drainage networks in detail over large areas. Soviet hydrologists have found that observing surface moisture and drainage patterns from radar data can best be done in the spring, following snowmelt, but before deciduous vegetation has leafed out.

The mapping of land-water boundaries can also be done effectively using radar, particularly shorter wavelength systems, such as X-band and K-band. However, for wetlands the longer wavelength systems, like L-band, are better because the longer wavelengths are capable of indicating the presence of water under the vegetation canopy [14].

Glaciologists have found the mapping of glaciers, ice shelves, etc., is facilitated using radar because of the contrast between ice, rocks, and water. Furthermore, different types of ice can often be discriminated, as well as features such as flow lines, pressure ridges, and crevasses.

GEOLOGY

Radar for geologic mapping was one of the first successful survey applications and continues today as the single most important one. As previously mentioned, PPI images of the Gaspe Peninsula were systematically photographed and the flightlines arranged so that "stereo viewing" of the terrain was possible. From analysis of the linears and patterns observed in the images various geological features were identified for the first time using radar data. These features included thrusts cutting across folds, a collapsed basin, and ancient lava flows.

Later studies led to the general conclusion that radar is a superior sensor system for detecting lineaments and that the interpretation of these features can reveal much about the subsurface geology of an area. Different frequencies and polarizations can also provide some information on lithology [6]. For example, because of their different dielectric constants, highly mineralized deposits surrounded by other rock types can sometimes be detected.

In a recent study in the American southwest desert it was found that L-band radar could discriminate between areas covered by smooth "desert pavement", and gravel fans, one of Pleistocence and one of recent origin, but that it was not possible to distinguish between the two types of alluvial fans. The same radar data also proved useful in discriminating between different classes of evaporate deposits, which were characterized by different surface roughness.

GEOGRAPHY/LAND USE/ARCHEOLOGY

Several studies have addressed the usefulness of radar data for analyzing urban environments. One recent study concluded that radar data provided a good way to define the limits of the urban environment and determine its direction of growth and rate of change. This same study also concluded that within an urban area several Level II land use categories could be detected by visual analysis, including (1) single

family residential areas, (2) recreation and open space, (3) major commercial-service areas, and (4) components of the transportation network.

Another investigator studied the usefulness of radar for detecting human settlements. His conclusions were that (1) settlements of 1000 persons or more can be detected on radar data at scales of 1:400,000 or larger; (2) settlements less than 100 persons cannot be identified unless the scale of the imagery is greater than 1:200,000; (3) the type of surrounding land uses and/or surrounding natural terrain features influences the detectability of settlements, but not in a predictable fashion; and (4) there does not seem to be much difference in the performance of K- or X-band radar data for this use [31].

A similar study found that 78% of all population centers over 7,000 persons in New England could be detected using K-band data and that 80% of the settlements between 800 and 7,000 persons were also detectable, as were 50% of the settlements between 150-800 persons. This same study also concluded that all ponds and other bodies of water larger than 200 sq. yards were detectable.

The question of how to optimize radar data for detection and identification of cultural patterns was addressed in a study which evaluated the effects of different polarizations of radar signals. This study concluded that HH polarization is better when linear cultural features are oriented parallel to the aircraft flightline, but that HV polarization is better when linear features are oriented at an angle to the flight.

A recent interesting use was reported as part of a test of an L-band radar system over the rain forest of Guatemala. Analysis of the L-band data, collected in 1977 and 1978, revealed a complex series of linear patterns in the jungle, which upon ground inspection, were found to be the remnants of an ancient drainage and irrigation system constructed by the Mayas between 250 BC and 900 AD.

NATURAL VEGETATION

Natural vegetation is considered to be one o ree types: forest, rangeland (including shrublands and grasslands), and wetlands. They are discussed in this order.

There seems to be agreement that forests are the one type of vegetation that can be reliably identified on airborne radar images. Generally, coarse image texture indicates the presence of forest [7]. However, it does not appear possible to distinguish between coniferous and deciduous forest types, unless grown in a plantation situation. An ERIM study [19] found, for example, that citrus groves were separable from southern pine stands in Florida on the basis of the row structure of the plantations. HV polarizations appear to be the best for mapping forested areas. A study of land use patterns in France using L-band radar indicated a capability to map forest at 86% accuracy.

Shrublands, especially if the vegetative cover is sparse, appear difficult to map. One reason for this is that reflectance from the background surface and not the vegetation itself often dominates the return. As a result, changes may be due to background differences, such as surface roughness, rather than the amount or type of shrub cover present.

Grasslands can sometimes be identified on radar data because of uniformly bright tones and fine texture, due to the even height of the grass and high percent cover of the vegetation.

Radar has some distinct advantages for mapping wetlands, as pointed out earlier in the section on hydrology. In addition to making it possible to detect standing surface water covered by emergent vegetation when a dual frequency (short/long wavelength) system is used, it is sometimes also possible to detect very sparse stands of emergent vegetation over water, such as reed grasses. Areas with this type of plants provide valuable fish and wildlife habitats, but are often difficult to

detect on air photos and MSS data. Because of their vertical height, however, they are very detectable using radar [19].

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