RADARSAT Applications: Review of GlobeSAR Program

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ABSTRACT

Radar imagery, which can be acquired through clouds or at night, is ideal for many applications. These images, besides offering virtually guaranteed data collection, are useful for many applications on their own or in conjunction with imagery acquired in the visible and near-infrared portions of the electromagnetic spectrum. The last decade has seen a significant growth in radar remote sensing technology and applications with several spaceborne radar sensors now available for civilian use. One of these, RADARSAT, is a Canadian led spaceborne program with a flexible synthetic aperture radar (SAR) to facilitate application development and operational/commercial use of radar imagery. In order to facilitate the international use of RADARSAT data a program called GlobeSAR was initiated in 1993. This has been a highly successful international program designed to transfer technology on SAR from Canada to the participating countries and to further develop applications of RADARSAT. While the flexibility in RADARSAT's beam modes and configuration enhances the use of the SAR data for geoscience applications it also adds complexity to the data ordering and selection process. The trade-offs between swath coverage, resolution, number of looks, and incidence angle must all be considered when ordering, processing, and analyzing the data. This paper describes applications studied during GlobeSAR and makes preliminary recommendations for selecting the optimum RADARSAT operating mode for the various applications. Ancillary data requirements for successful use of the SAR data are also addressed. This is followed by a presentation of several example images from RADARSAT chosen to illustrate the discussion.

I. INTRODUCTION AND BACKGROUND

The use of remote sensing technology for mapping and monitoring resources, both renewable and non-renewable, has become well developed since the launch of ERTS-1 (renamed Landsat) in the early 1970's. The large area coverage, spatial information, repeat coverage, and timeliness have all been recognized as advantages of using the remote sensing approach. This technology has evolved to include synthetic aperture radar (SAR) sensors which offer additional advantages of an all-weather, day or night data collection capability as well as synergism between SAR imagery and optical data. There are now several civilian SAR's in space including ERS-1, JERS-1, and RADARSAT. RADARSAT, which is the first commercial SAR system, offers a flexible system configuration which maximizes data coverage and application potential. The RADARSAT program is described by Parashar et al., (1993).

GlobeSAR is an international SAR project led by the Canada Centre for Remote Sensing (CCRS) in co-operation with the Canadian Space Agency (CSA), RADARSAT International Inc. (RSI), and the International Development and Research Centre (IDRC). During GlobeSAR, more than 125,000 km^2 of multi-mode SAR data were acquired over numerous test sites in the various countries. Petzinger et al., (1994) and Petzinger (1995) provide a detailed description of the GlobeSAR airborne data acquisition program while Livingstone et al., (1995) provide a description of the CCRS airborne SAR facility. GlobeSAR started with analysis of the airborne SAR data which were then used to simulate Fine Resolution and Standard Mode RADARSAT products for further study and evaluation by the research teams. With the successful launch of RADARSAT in November, 1995, the program is now moving towards utilisation of satellite imagery for these applications. However, the optimal RADARSAT beams and modes must be determined for the various applications in order to assess their respective information requirements and meet the overall program objectives. It is also important to assess which complementary data sets will be required to facilitate the optimal utilisation of RADARSAT data. The following section provides some additional details about GlobeSAR while Campbell et al., (1995) provide a detailed description of the program.

This paper will address both of these issues. First of all, significant results will be presented on the analysis of the airborne SAR and simulated RADARSAT products. Examples from all countries and all major application areas will be presented including an identification of key ancillary data needed to support the applications. Secondly, recommendations on the modes of operation of RADARSAT will be given for the different applications in the various environments. Several examples of RADARSAT imagery over a few of these test sites are then presented to validate and demonstrate the applications studied with the airborne data. Finally, the future activities planned for the final phase of the GlobeSAR program will be outlined to indicate how these recommendations will be evaluated and modified based on the results from this and other RADARSAT validation programs.

II. GLOBESAR PROGRAM DESCRIPTION

The GlobeSAR program was described in detail in a paper by Campbell et al. (1994). However, a brief description will be given for completeness. Within the program there is close interaction between personnel at the Canada Centre for Remote Sensing and a co-ordinator within the host countries which include, China, Jordan, Kenya, Malaysia, Morocco, Tanzania, Thailand, Tunisia, Uganda, and Vietnam. This interaction is essential for the efficient operation of the program, including the development of a training plan for the country and the development of various other plans such as the ground data acquisition strategy, the analysis plan for the airborne SAR data, the RADARSAT simulated data and finally the RADARSAT imagery. This close interaction between

CCRS and the host countries has resulted in a directed analysis to address the information needs. In addition, radar analysis software has been purchased through funding from the International Development Research Centre. The necessary tools were therefore available for data analysis.

The specific objectives of the GlobeSAR program are:

1. To work collaboratively with foreign countries to assess the ability of SAR data to meet the information requirements of different application areas within tropical, moist, and arid environments;
2. To develop and transfer the technology acquired from this joint assessment to user agencies within the partner countries; and
3. To educate and train a range of users in radar remote sensing in the partner countries. In this process, and using feedback from our collaborators, user-defined workshops were presented, and training materials were further developed and updated.

The GlobeSAR program was initiated in early 1993 with planning meetings and workshops held in the various participating countries. During these meetings test sites were identified, analysis plans were developed, and contacts were made with local government agencies, universities, and scientists who were participating in the program. In the Fall of 1993, the CCRS CV-580 C/X airborne SAR collected data over the 32 selected research sites. Prior to the airborne data acquisition, workshops on an introduction to radar and on supporting ground data collection were conducted in each country. Ground data were then acquired to support the image analysis for each test site. The airborne data were processed to simulate RADARSAT data to evaluate its information content. The generation of simulated imagery was an important step in RADARSAT readiness tests and pilot projects, such as GlobeSAR. Simulations were generated by reducing the resolution of the airborne data to match the expected resolution of the RADARSAT products, and by increasing the speckle of the imagery again, to meet expected RADARSAT radiometry. The SARPAC software developed by Intera Information Technologies, under contract to CCRS, was used to generate these simulations. The methodology has been described by Wessels et al., (1986) and Wessels and Kirby (1986).

In the spring and summer of 1994, the partner countries were revisited and workshops conducted on advanced radar concepts, radiometric and geometric correction to SAR data, and information extraction. Major applications were also reviewed, in general, followed by detailed discussion on study plans for local applications. During this visit, image analysis software developed by Canadian companies (PCI and Atlantis Scientific) were installed and hands-on training provided. These workshops were followed by regional meetings held in Bangkok, Amman, and Beijing where results were presented by the various study teams. During these regional meetings, and through follow up visits to each country, plans for actual RADARSAT data acquisition and analysis were developed during 1995. With the launch of RADARSAT on November 4, 1995 the final phase of the program began.

The completed milestones of the program are:

Mid-1993	Planning meeting in the host countries. Site selection for pilot projects.
Fall 1993	Field work training in support of SAR data acquisition;

	Introduction to SAR workshop; Airborne data acquisition.
Mid-1994	SAR data processing and interpretation workshop; Hands-on PCI/Earthview training.
Nov. 1994	Bangkok Workshop, presentation of preliminary results in Southeast Asia; Application specific workshop.
April 1995	Amman workshop, presentation of preliminary results in Africa and the Middle-East.
May 1995	Review of research plan in Asia and joint workshops; Remote sensing applications for natural resources managers workshop, Kuala Lumpur.
Oct. 1995	Beijing Workshop presentation of results in Southeast Asia.
Nov. 1995	RADARSAT launch.
Mar. 1996	Beginning of GlobeSAR RADARSAT data acquisition.

The final workshop will be held in Ottawa in May 1997 at the Geomatics in the Era of RADARSAT symposium which will be a joint meeting of the 19th Canadian Remote Sensing Symposium, the 9th International Geomatics symposium, the 4th GlobeSAR Workshop and the ADRO mid term meeting.

III. APPLICATIONS REVIEW AND RADARSAT RECOMMENDATIONS

Due to space constraints in this publication, the following discussion is brief and is only meant to highlight the most promising applications and make preliminary recommendations on RADARSAT modes and beam choices. An additional GlobeSAR application review can be found in Brown et al., (1995) with specific studies described in detail in the proceedings of the various regional meetings, as well as in other papers in the Geocarto International special issue on GlobeSAR. Many of these citations are included in the following sections to facilitate the pursual of additional details by the reader.

Agriculture

One of the most promising applications in agriculture for RADARSAT will be rice mapping and monitoring (Brisco et al., 1995; Ewe et al., 1995; Chantothai et al., 1995; Yun et al, 1995; Le Toan et al., 1989). The characteristic dark signature of flooded paddies followed by increased radar backscatter as the crop grows and develops offers the ability to monitor rice growth using multi-temporal imagery. This is demonstrated in Figure 1 with an airborne C-HH image from the Kedah test site in Malaysia. The Standard Mode RADARSAT simulation is also included for comparison purposes. The variations in return from the rice paddies has been related to growth stage and condition of the rice crop. The underlying water surface tends to simplify the scattering process as little or no direct surface backscatter is included in the total backscatter. The larger angles have repeatedly been shown to be superior for this type of application and due to the fragmented land cover, Fine Mode data may be required. Larger incidence angles (i.e., greater than 40 degrees) eliminate or reduce row direction effects which often reduces the accuracy of identification or monitoring applications. For regional studies and areas of larger field size Standard Mode or even

Wide Mode data may be preferred, but once again larger incidence angles. GIS layers on land cover and field boundaries will facilitate the identification and mapping applications. Ancillary data on weather conditions and yield models for integrating the remotely sensed data within the GIS will be needed to obtain final productivity estimates.

SAR data has been shown to be very useful for crop type mapping applications especially if multi-temporal data is available or VIR data are used synergistically (Brisco and Brown, 1995). Fragmented land-use resulting in small field sizes and the effects of topography need to be overcome before the SAR data can be used effectively in many parts of Southeast Asia (Nordin, 1994; Chantothai et al., 1995; Yusoff and Yasin, 1996) although the use of multi-parameter SAR (Yun et al., 1995) and the combination of SAR and VIR data (Merzouk et al., 1995; Harahsheh, 1995; D'Iorio et al., 1995) has demonstrated improved information content for crop type discrimination. Figure 2 shows an C-HH airborne SAR image example of an agricultural area in Morocco (Merzouk et al., (1995) which illustrates the information content for crop type mapping and agricultural applications. Bare dry surfaces, such as the bare fields or harvested crops are quite dark in the image. Higher biomass crops like sugar cane appear quite bright while crops of intermediate amounts of vegetation are various shades of grey. Note, one can also easily map the irrigated fields from the dryland crops on the SAR data including a soil wetting front due to irrigation (see next paragraph). Incidence angles larger than 40 degrees are preferred for crop mapping applications with the best RADARSAT mode being a function of the geographic coverage requirements and the average field sizes in this area.

Soil moisture estimation is also a very promising RADARSAT application (Boisvert et al., 1996; Brown et al., 1993; Dobson and Ulaby, 1986) as the very high dielectric constant of water at microwave frequencies (approximately 70) causes a significant increase in radar backscatter as water is added to the soil (which has a dielectric value of from 3-5). The use of airborne SAR for mapping soil moisture has been demonstrated in both Canada (Geng et al., 1996) and China (Xingchao and Xiaoming, 1996) as well as many other countries. Subsequently, the methods developed are being applied to satellite systems to develop operational programs. The information extracted from the SAR data can be used in many applications such as yield estimation in agriculture, or distributed watershed modelling in hydrology. The results have demonstrated that the smaller incidence angles are preferred for this application, as the contribution to the total measured radar backscatter from vegetation and soil roughness is less at these angles. This implies Standard Mode beams 1 and 2 as the preferred RADARSAT configuration, although once again more regionally orientated applications may make use of the Wide or even ScanSAR Modes. GIS overlays of soil type, land cover, topography, etc. will benefit this approach as will suitable models for each particular application.

The airborne SAR data have shown very good potential for mapping and monitoring various type of agro-forestry plantations. For example, Hai and Khang, (1994) were easily able to map the location of rubber plantations in Vietnam. Rubber was also easily separable from natural forest in most test sites in Thailand although rugged topography and fragmented land-use were problems lowering the accuracy of identification (Chantothai et al., 1995). The smooth texture generated by the plantations which have same-aged, regularly spaced trees allows for discrimination from natural vegetation which has a coarser image texture. Similar results were reported for Malaysia by Nordin (1994); Yusoff and Yasin (1996). Some research has also focused on surface evaluation of olive tree plantations in Southern Tunisia (Talbi, 1995). Olive tree plantations are a dryland crop with the trees often standing on almost bare soil. By selecting a shallow angle image acquisition, the bi-directional component of the soil reflection becomes predominant leaving only the bright olive tree backscatter. Olive trees are spaced according to a rigorous pattern dictated by moisture conditions. Trees can almost be counted individually using the simulated Fine Mode RADARSAT or airborne SAR data. Figure 3 shows a rubber plantation from the Quang Binh test site in Vietnam and a olive tree plantation from a test site in Tunisia showing the characteristic image texture and pattern of agro-forestry plantations. A DEM will be very useful for correcting the effects of topography on the local incidence angle which causes variations in backscatter not related to target conditions. The shallower angle data, as mentioned above, will be preferred for this application with the resolution requirements a function of the mapping scale and area coverage.

In most environments, but more specifically in dryland environments, soil erosion monitoring has been an endless challenge. SAR data associated with ancillary information describing topography, soil type, and other landscape information can provide a pictorial view of the local geomorphology and support erosion risk assessment (Bacha et al., 1995; and Merzouk et al., 1995). Due to the impact the erosion has on surface roughness conditions areas of significant erosion are easy to identify, generally being brighter and more variable than non-eroding surfaces. Models can also be employed to use the SAR data in conjunction with other landscape parameters such as slope, aspect, and soil type to predict erosion potential. First results have shown that images acquired from two opposite perspectives provide the best results. The shallower angle beams are also preferred.

Archaeology

Archeological exploration in Southeast Asia have often been hampered by numerous factors including dense vegetation, human re-settlement, difficult terrain, political changes. The use of optical imagery was also very difficult because of the frequent cloud cover. The SAR data are becoming an important tool to discover and inventory those sites (World Monuments Fund and Royal Angkor Foundation; Supajanya et al., 1994).

Northern Thailand has a number of ancient moated cities which are now agricultural areas or larger urban centres. Remnants of archaeological sites often appear as man-made patterns on SAR images (Wara-Aswapati, 1995). The moats of these cities are seen, typically, as circular patterns on the imagery. They are particularly visible if they are still filled with water, but still detectable when empty or backfilled.

The canals associated with the ancient cities are important archaeological markers as they testify to the chronological evolution of that area and to the extent of development. Some canals are still used for irrigation but most have been built or grown over or filled and used as roads They are often visible or detectable with SAR (Supajanya et al., 1994; 1995). Archaeological features are linked to the geomorphology of the area, which will dictate the primary appearance of RADARSAT data. The larger angle Standard Mode beams will be most useful for this application (Brown et al., 1996). In addition, the GlobeSAR simulations indicated that Fine Mode data will be an asset in detecting and adding to the archaeological inventory. Additional investigations of smaller incidence angle data will assess its potential for ancient canal mapping, which can be identified through soil moisture effects.

Coastal zones

Coastal zones include the marine and terrestrial near shore area. Its assessment and monitoring is crucial in matters of sovereignty, environmental monitoring and protection, and hazard mitigation. Sensitive areas, such as mangrove forests, are protected in most countries as they are threatened by human activities and by tropical storms which erode coastlines (Thongchai et al., 1995). The expanding shrimp farming industry requires a near-shore salty or brackish water environment, an ecosystem similar to that of mangroves, which results in a monitoring requirement to prevent encroachment into these forested areas (D'Iorio et al. 1995; Gordon et al.; 1995; Musigasarn, 1995; Musigasarn et al., 1994). Figure 4 shows an airborne C-HH SAR image of the Songkhla Lake test site in Thailand which has been used for coastal application studies. Note the important land cover types, as discussed above, are easily identified in this airborne SAR image. RADARSAT Fine and Standard Mode data are being acquired for those types of studies. Preliminary results from analysis of airborne SAR and RADARSAT data suggest that incidence angle variations will not have a significant impact on interpretability of the data for primary landuse. Instead, a combination of several Standard Mode beams may be used to obtain timely spatial coverage.

Ship detection and tracking from SAR data offers potential solutions to illegal shipping and fishing. This is an instance where the steerable beam of RADARSAT is a great asset by providing timely information and more useful large incidence angle data. Ancillary data on wind and wave conditions and shipping lanes will facilitate ship detection applications. Oil spill detection and mapping is another promising application being investigated under the GlobeSAR and RADARSAT Announcement of Opportunity which was called the Application and Development Research Opportunity (ADRO) projects. The RADARSAT beams acquired at smaller incidence angles and the Fine Mode can be important tools in evaluating the extent of spills and the potential environmental impact, respectively.

The detection and mapping of ocean features represent the final discipline in coastal zone monitoring. Radar data has proven its usefulness in this field with airborne SAR and data from the ERS-1 satellite (Arid, 1995; Rabia, 1995; Weigen, 1995). Mohd et al. (1994) reported the use of GlobeSAR data for mapping ocean features and oil slicks. Oceanography will be further investigated by various participants under ADRO projects. The results have shown that these features can be detected using Standard mode data, especially at the smaller incidence angles. More detailed studies may require Fine mode data while regional investigations can make use of the Wide mode products.

As shown in Figure 5, monitoring of Sebkhas is another coastal feature for which SAR capabilities are emerging (Boussema et al., 1995; Rabia, 1995). Sebkhas are flat, seashore areas up to few kilometers inland, flooded occasionally by the sea. When the water evaporates, there remains a concentration of residue i.e., evaporites. Many coastal areas around the world have Sebkhas, particularly in the Middle East and the Mediterranean basin. First results have shown that RADARSAT has excellent potential to identify ring effects of evaporation thus supporting a chemical type evaluation. It is worth mentioning that while SAR data cannot identify chemical properties, there is a relationship between the type of evaporite and the surface roughness. By using images acquired at a grazing angle, and by applying roughness criterion, it is possible to discriminate between various surface roughness which in turn helps identify surface mineral type. Research is ongoing on this topic, which has rarely been investigated using remote sensing.

Forestry and Land Cover Mapping

General land cover mapping at the primary level (i.e., forest, water, urban, agriculture, etc.) and sometimes at secondary or higher levels of classification is quite effective with SAR data and in most cases the larger incidence angles are preferable. Due to the importance of land cover mapping to many different disciplines and the need to periodically update land cover or land use maps, this application has been studied in every country. A partial list of references is Yun et al., 1995; Ewe et al., 1996; Chantothai et al., 1995; Hai and Khang, 1994; Merzouk et al., 1995; Talbi, 1995; Oroud and Harahsheh, 1995; and Selmi, 1995. Many other papers describing land cover classification approaches and results can be found in the proceedings from the Amman, Bangkok, and Beijing Regional GlobeSAR Workshops. The appropriate mode of RADARSAT will depend on the area of interest and the desired mapping scale. In areas of rugged topography, a DEM will be needed to account for variations in local incidence angle, which is the first-order parameter governing radar brightness. Other ancillary data, especially visible and infra-red data from the optical satellites, combines synergistically with the SAR data to improve identification accuracy. Texture is also very useful in SAR interpretation for separating natural from cultural vegetation types, as the randomness of the natural vegetation generates rougher textural signatures. The image of Lake Nakuru in Kenya will be used to illustrate land cover mapping with SAR (Figure 6).

Lake Nakuru is one of a string of lakes on the floor of the Rift Valley of Kenya, north of Nairobi. The area around Lake Nakuru is a National Park and wildlife refuge containing a saline lake with millions of flamingos and a variety of wildlife, including giraffe, water buffalo, waterbuck, baboons, etc. The highly reflective area just north of the lake at A (in Fig. 6) is a residential area whose roof tile size and roof alignment cause high radar returns. Grasslands and larger agricultural fields surrounding the lake and the outskirts of the town appear dark (B). Strong returns come from shelter belts of trees and some fences around some of the large holdings. In this area many of the large fields associated with large holdings have been transformed into small owner-occupied holdings. These appear in a mottled texture north of the townsite (C) and east of the Menengai crater (E) in the upper left corner of the image. The Menengai Crater is a volcanic remnant containing dense low shrub growth. Lava flow patterns are visible on the airborne imagery as are roads, rail lines and hydro transmission lines. Coffee, which tends to be brighter, is found throughout the small holdings. The darker fields tend to be harvested grain (wheat) fields, while the lighter are often coffee.

North of the lake in the park the bright forested areas within the park are acacia trees (D) as tall as 30-40 metres, up to 50 cm. in diameter, with 30-65% crown closure. Some are also found south of the lake. Areas of variable moisture as one moves away from the lake are clearly discernible. While different types of vegetation are seen within the park, there is some confusion caused by the sharpness of the local relief. The slopes on the east side of the lake are dominated by succulents (euphobia) in the north and by a small willow-like shrub known locally as leleshwa. SAR data has also been shown to be very useful for monitoring clear cuts, forest regeneration, and infrastructure developments (i.e., roads and buildings). The airborne SAR data from GlobeSAR has been used for forest type mapping and forest map updating in most countries participating in the program

(Bao, 1994; Yusoff and Yasin, 1994; Thongchai et al., 1994; Merzouk et al., 1995; Selmi, 1995; Chantothai et al., 1995; Guo et al., 1995; and Jingjuan et al., 1996). In general, the shallower angles are preferred for these applications, and in some cases the higher resolution Fine Mode data may be required to accurately identify the location and size of the feature(s) of interest. Due to the all-weather day or night capabilities of SAR data collection, RADARSAT will be very useful for change detection approaches to support these applications. The information content at C-band is low for forest-type mapping and biomass estimation. However, the data can be used synergistically with other data (including other SAR frequencies and polarizations) to improve forest mapping capabilities. The longer wavelengths, such as P- and L-band, are more suitable for these applications, especially biomass estimation (Dobson et al., 1992; Li et al., 1996).

Geology

Geological applications of SAR data are well proven and many researchers have successfully integrated information layers of mapping agencies and exploration companies (Singhroy et al., 1993). The primary objective of a mapping / exploration exercise is the recognition of physical structures expressed in SAR images (Haji, 1994). The physical features expressed in SAR imagery are directly related to structural geology (e.g., faults, synclines/anticlines), extent of lithological units, and erosion and weathering patterns (Figure 7). SAR imagery is particularly useful in tracing the extent of structures and lithological units both in arid environments (Budkewitsch et al., 1996) and in tropical environments (Cu, 1995).

In tropical areas, boundaries between resistant and recessive units are frequently visible due to erosional escarpments at their contacts, which correspond to changes or gaps in the forest canopy. High precipitation rates and warm temperatures facilitate chemical weathering of bedrock and the pattern of erosion seen from SAR data can be a diagnostic indicator of rock types (D'Iorio et al., 1995 . SAR imagery was successfully used to trace bedding and update existing maps in tropical forested areas (Cu, 1995). Fold axes were mapped and the principal phases of folding were easily recognized. The airborne data used in GlobeSAR confirmed that acquisition at high incidence angles gave optimal results in rugged terrains such as those of Sarawak, Malaysia (Ling Nan Ley, 1994; and Cao Bang, Vietnam (Cu et al., 1994). The use of RADARSAT simulations indicated that resolution and data quality were appropriate to successfully update geological maps at a scale of 1:50,000 using Fine Mode and 1:100,000 using Standard Mode. On-going work with RADARSAT data will verify these findings and assess the value of ScanSAR Narrow data for regional mapping.

Second-order information is extracted from SAR texture analysis, revealing terrain attributes and extent of domains related to general geological units. The final step in SAR data analysis is integration with other data types such as geophysical, optical, geochemical, and rasterized maps. The SAR data is often combined with colour images as the intensity component of an IHS colour transform (Harris and Murray, 1989). The data integration is a critical step for geologists as it allows the interpretation of SAR data in the context of more "classical" data sets. Many imaginative processes can used to complete data interpretation and replace radar shadows in areas of high relief (Cu and Huy, 1994). The final product of the geological analysis will be a map product using GIS to plot out extracted information (Noor and Lai, 1995; Haji, 1994; Nordin, 1994, Ley, 1994).

Geomorphology

Geomorphology is the study of landforms, of their surface expression, of surficial deposits and their genesis. As such, the first- order interaction and backscatter of microwaves with terrain will be closely tied to the geomorphology of the area (Merzouk et al., 1995). Most of the review of geomorphology has been covered in the previous sections. Indeed, the terrain morphology is the basic parameter determining landuse and therefore indirectly controlling the type of imagery and viewing configuration necessary in order to best analyse the applications.

The GlobeSAR data in all countries were classified into geomorphologic classes such as flood plains, terrace, erosional valleys, dissected highlands, solution depressions, etc. The geomorphologic information provided by the SAR data is often useful in determining and explaining landuse and agricultural practices (Mihntam et al.,1994). For example, under given environmental conditions, gently undulating topography is easily identified in SAR imagery by the dryer (darker) crest and wetter (brighter) trough (Mongkolsawat et al., 1994). RADARSAT investigations require incidence angle analysis to determine optimal information content for various terrain types. Features tied to soil moisture effects may be best mapped using steep incidence angles, whereas those marked by topographic or roughness attributes may be best highlighted by mid- to high-incidence angles. The study of RADARSAT simulations suggested that Standard Mode data were best suited to extract and study the geomorphologic features.

Hydrology

Soil moisture and distributed watershed modelling was discussed in the agricultural section. Other notable hydrology applications include flood mapping, hydrology network mapping, and wetland identification and monitoring. The GlobeSAR data of the Zhao Qing test site in China has been used for a variety of hydrological studies including mapping the hydrology network, mapping the paleo-channels and flow obstructions for flood monitoring and mitigation, and flood mapping (Wei et al., 1994; Guo et al., 1995). Figure 8 shows the airborne C-HH SAR image of a portion of the Zhao Qing test site with land cover and hydrology attributes identified on the image. The flood mapping was done by comparing the GlobeSAR collected during non-flooding conditions to airborne SAR data collected by the Chinese Academy of Sciences during flood stage. This comparison allowed the flood extent to be delineated. The Chinese Academy of Sciences uses an airborne SAR for operational flood monitoring and disaster relief (Jiahong and Xinnian, 1996) and will continue to evaluate RADARSAT for this application. The GlobeSAR C-HH SAR data of the Quang Binh test site in Vietnam was also used for flood mapping (Hai and Khang, 1994).

Due to the specular nature of radar scatter from water bodies, which creates a very dark image, the hydrology network and the presence of standing water is easy to map. This is best done at the larger angles as the contrast with the land targets is maximized. The enhanced backscatter from flooded vegetation further enhances the ability to map floods and the hydrology network. The choice of mode (Standard, Fine, Wide, etc.) depends on the area flooded or the area to be mapped and what scale is desired. For many applications the Wide Mode may offer the best compromise between swath width and resolution. As with most other applications a GIS overlay of water boundaries, land cover, etc., will benefit the approach.

Due to the sensitivity of radar backscatter to moisture variations in both soil and vegetation, wetlands can be readily identified on SAR images (Hess et al., 1990). The references cited above for land cover mapping studies also addressed wetland classification. The larger incidence angles are preferred with the choice of mode dependent on scale and land cover fragmentation issues. The use of GIS overlays and ancillary data, such as optical imagery, further enhances classification abilities. Due to the seasonal variations which most wetlands experience, the use of multi-temporal RADARSAT data is particularly useful for this application.

Hydrogeological mapping is fundamental to the economic development of Jordan. GlobeSAR C-HH SAR images have been shown to provide geological base information for hydrogeological map revision. (Waynakh, 1995; Singhroy et. al., 1996; Saint-Jean et. al., 1996). Figure 9 shows the airborne C-HH SAR image of the Azraq test site in Jordan which was used for studying this application, with a geological interpretation. Note the rock types can be easily discriminated on the SAR image as well as the location of the wadi. This information is very valuable for directing ground resources to exploit the ground water. In Jordan, the pumping of groundwater is already in danger of exceeding levels at which the resource cannot be renewed; and water quality is rapidly declining (World Bank, 1994). One of the main problem is to optimise the utilisation of ground water resources, and protect them against depletion and pollution. The shallow aquifer in Jordan is the most hydrologically significant in terms of the quality and quantity of groundwater. It consists of coarse fluvial deposits, lacustrine clays, fine eolian sands, and a caprock of basalt. The groundwater is of very good quality. In the Azraq basin, the aquifer is extremely permeable, producing large quantities of water. In this basin, more than 550 water wells have been drilled, of which 350 wells supply water for local agriculture.

IV RADARSAT EXAMPLES

With the successful launch of RADARSAT on November 4, 1995 and the announcement of Initial Operational Capability (IOC) in April, 1996 images have now been acquired over a large number of the GlobeSAR test sites. Not all sites have been imaged to date and so far only a preliminary analysis has been done but the following examples have been chosen to demonstrate the validity of the results from the analysis of the airborne and RADARSAT simulations described in section 3 above.

Figure 10 shows a RADARSAT image of the Kedah test site in Malaysia which is is being used for studying rice identification and monitoring by the Malaysian GlobeSAR team. Note the similarity in overall appearance of this RADARSAT beam 7 image to the airborne and RADARSAT simulations presented in Figure 1. The Standard Mode beam 7 image is a 4-look, 25 meter resolution (nominal), C-HH image covering the 45-49 degree incidence angle range. The variations in the rice paddies are due to the stage of growth of the rice crop reflecting its planting date and growth conditions. Multi-temporal data can be used to monitor the rice crop during a complete growing season at this site as well as other sites in Southeast Asia in order to fully evaluate this application. The preliminary results from the qualitative analysis of this and other test sites has verified the utility of RADARSAT for monitoring rice.

Figure 11 shows a Standard Mode beam 6 image of the Zhao Qing region in China with the landcover and hydrology attributes identified as for the airborne data in Figure 8. Once again note the similarity in the overall information content to that of the airborne image. The variations in image brightness are strongly correlated to land cover with dark signatures being aquaculture areas or recently planted rice, the intermediate tones represent growing rice paddies, and the bright returns are from the lush banana and sugar cane crops. Once again, note how easily the hydrological network can be mapped, as discussed above. As for the Kedah site the use of multi-temporal data will facilitate both the landcover mapping and rice monitoring applications, while the all-weather capabilities of RADARSAT will support flood monitoring operations.

Figure 12 represents the Songkhla province of South-eastern Thailand, which borders on the Gulf of Thailand. This site was part of the GlobeSAR Thailand experiments. The area is very active in the exploitation of renewable natural resources. Activities include: fishing, rubber harvesting, rice agriculture, mixed orchards, and aquaculture, particularly of shrimps. Conservation areas north of Songkhla Lake include mangrove swamps and a bird sanctuary.

The inset of Figure 12 presents the changes in an area north of Songkhla Lake. The GlobeSAR data acquired November 5, 1993 are displayed in red and the RADARSAT data acquired June 3, 1996 are presented in green. Areas where shrimp farms replaced vegetation are red and the new bridge over the estuary is green.

It is interesting to note the interference pattern on Songkhla Lake. Each point represents a 0.5 m^2 fish cage built of four bamboo poles and a net. These cages and the water of the lake act as corner reflectors creating high backscatter and resulting in targets being visible though they are 1/50th of the resolution of the sensor.

Figure 13 represents two ascending RADARSAT acquisitions of Sarawak in Eastern Malaysia. As previously stated this site is covered with tropical forest, yet faults, folds and sedimentary beds are clearly visible and traceable. The image on the left was acquired in the Standard 5 mode whereas the image on the right was acquired in Standard 6 mode. There is approximately a difference of 5° in incidence angle between those modes. The images are displayed with a 6.5 cm separation to allow the user to view them with a stereoscope. The fact that the images can be viewed stereoscopically represents a great advancement for the geological applications of radar data and will open new door for exploration, especially in foreign countries.

Figure 14 shows a RADARSAT Standard Mode beam 4 image of the shallow and upper limestone aquifer of the Azraq basin with a hydrogeological interpretation. Wadis, mudflats, playas, alluvium, basalt, limestone, and fractures are delineated on the figure. The detailed mapping of the distribution of wadis and their channel characteristics provides information for the management of the wadis environment and seasonal floodwaters. Most of the wadis are very productive agriculture corridors, because of the presence of temporary surface water, fertile alluvial soils and shallow groundwater, and thus their location and status is very important.

The basalt is highly permeable and stores large quantities of potable water. The basalt areas are easily outlined on the RADARSAT image, and form a gently undulating terrain of low relief. It has a characteristic rough surface, and therefore appears as a light tone (Figure 14). This upper aquifer system has a moderate water potential, and is recharged directly from precipitation and from the adjacent basalt. Nearly all the groundwater resources of Jordan are found in hard-rock aquifers where the water moves in fractures, fissures and joints. Because of the high permeability of these aquifers, the velocity of the groundwater flow is high. Consequently, the groundwater is easily contaminated from recycled irrigation water, wastewater, human settlements and industry. The accurate delineation of surface fractures are needed not only to target groundwater exploratory wells, but to prevent pollution from the above landuse practices in the vicinity of the fractures. The fault in the limestone aquifers is shown in Figure 14. It is clear that the interpretation of the RADARSAT image provides information for improved hydrogeological mapping, in terms of wadi mapping, surface characteristics of hydrogeological units and aquifer fracture distribution .

V. ADRO/RVP RESEARCH PROGRAMS

Further assessment of the information content of RADARSAT data and which are the optimal modes of operation for that particular application are being carried out through a variety of programs around the world. First of all, the continued analysis of RADARSAT imagery through the GlobeSAR will allow for the validation of the results obtained with the airborne and simulated RADARSAT data. This is an important continuation of the initial analysis as the simulations of the airborne data can only predict the radiometric and geometric properties of the RADARSAT imagery but not fully assess the change in information content as a function of incidence angles, as this is such a rapidly changing parameter in airborne data.

Other complementary programs that are furthering the assessment of the RADARSAT data internationally are the Applications Development of Research Opportunity (ADRO) program and the RADARSAT Validation Program (RVP). The former is the announcement of opportunity sponsored by the CSA, NASA and RSI. Through this program over 350 proposals from around the world have been accepted to evaluate the capabilities of RADARSAT to deliver the required information. This program will run for about 2 years. The second major program, RVP, is a joint endeavour between CCRS and RSI to also address the use of RADARSAT imagery in immediate and commercially important application areas.

Through these and other programs, there will be considerable assessment of the capabilities of RADARSAT to meet operational requirements.

IV. SUMMARY

The review presented in this paper demonstrates the wide range of applications for which C-band SAR data is suitable either as the sole source of information or as part of an integrated data set. While continued research and development will expand the number and nature of these applications there are operational requirements by various agencies, governments, industries, etc. which can be met with SAR data. The steerable beams of RADARSAT and the different modes of operation combine to give a flexibility in data products which enhances the use of the data for various geoscience applications. This requires the user to consider trade-offs in swath width, resolution, number of looks, and incidence angle before selecting and processing SAR data. While this paper provides some general guidelines to this approach from an applications perspective, the RVP, ADRO, and GlobeSAR programs will all contribute to a better understanding of these issues. The GlobeSAR test sites will all be imaged by RADARSAT during 1996 using a coordinated plan of data acquisition to acquire a variety of beam and mode products for evaluation. This will allow a refinement of the recommendations made above.

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VI. REFERENCES

Abdelhamid, G. and M. Tarawneh, “Mapping of Basalts and Sediments in Azraq Area, Northeast Jordan, Using SAR Airborne Images”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 24-34.

Al- Halasah, J.A., “Landslides Mapping Using Airborne C-SAR, Zarqa River Area, Jordan”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 35-46.

Arid, H., I. Ibrahimi, M. Labraimi and M. Quabi, “Complémentarité des Données Satellitales Avec les Données RADARSAT pour l’Étude des Phénomènes Hydro-Sédimentaires le Long du Littoral de Tétouan, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 47-52.

Bacha, S., A. Belguith, M. Jeddi and H. Khatteli, “Apport des Données Aéroportées RSO a l’Étude de la Dégradation des Sols Dans la Région de Menzel Habib”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 53-59.

Bao, T.Q., "Initial Application of Radar Imagery for Establishing Forest Maps in Southern Quangbinh Province, Vietnam", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 89-92.

Boisvert, J.B., T.J. Pultz, R.J. Brown, and B. Brisco, 1996, "Potential of Synthetic Aperture Radar for Large Scale Soil Moisture Monitoring", Canadian Journal of Remote Sensing, Vol. 22(1), pp. 2-13.

Boussema, M.R., R. Abdelfattah and O. Marrakchi, "Apport des Données RSO Aéroportées 🕘 l'Étude de Sebkhet el Melah Dans Le Sud Tunisien", Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 60-69.

Brisco, B., and R.J. Brown, 1995, "Multidate SAR/TM Synergism for Crop Classification in Western Canada", Photogrammetric Engineering and Remote Sensing, Vol. 61(8), pp. 1009-1014.

Brisco, B., R.J. Brown, G. Staples, and D. Nazarenko, 1995, "Potential Rice Identification and Monitoring with RADARSAT", Proceedings of 17th Canadian Symposium on Remote Sensing, Saskatoon, Saskatchewan, June 13-15, pp. 474-479.

Brown, R.J., M.A. D'Iorio and B. Brisco, 1996, "Recommendations from GlobeSAR on RADARSAT Operational Modes", Proceedings of the 18th Canadian Symposium on Remote Sensing, Vancouver, Canada, 1996, pp. 23-26.

Brown, R.J., M.A. D'Iorio, and B. Brisco, 1995, "GlobeSAR Application Review", Geocarto International, Vol. 10(3), pp. 19-32.

Brown, R.J., B.G. Brisco, F.J. Ahern, C. Bjerkelund, M. J. Manore, T.J. Pultz, V. Singhroy, and P. Vachon, 1993, "SAR Application Requirements", Special Issue of Canadian Journal of Remote Sensing, Vol. 19(3), pp. 193-203.

Budkewitsch, P., M.A. D'Iorio and J.C. Harrison, "An Examination of the Relationship Between Lithology and Radar Signatures in Arctic Environments: Preliminary Results from Bathurst Island, N.W.T.", Current Research 1996-B. Geological Survey of Canada, pp. 67-72.

Campbell, F.H.A., R.J. Brown, M.E. Kirby, D. Benmouffok and D. Lapp, 1994, "The Canadian GlobeSAR Program", Proceedings of the International Geoscience and Remote Sensing Symposium, Pasadena, California, pp. 1523-1524.

Campbell, F.H.A., R.A. Ryerson, and R.J. Brown, 1995, "GlobeSAR: A Canadian Radar Remote Sensing Program", Geocarto International, Vol. 10(3), pp. 3-8.

Chantothai, K. C. Mongkolsaawat, P. Thirangoon, W. Musigasarn, T. Supajanya, K. Vichapan, S. Chalermlarp, M. Omakupt, D. Buapradabkul, S. Chutiratanaphan, C. Jeerajunya, W. Thongma, T. Charuppat, S. Ongsomwant, T. Srisuchat, A. Srisuchat, D. Disbunchong, A. Phetcharas, S. Polngam,

C. Pornprasertchai, S. Rattanasermpong, C. Rodprom, C. Silapathong and R. Simking, "Airborne SAR Applications in Thailand", Proceedings of the Geocarto International Special Issue: GlobeSAR and RADARSAT, Vol. 10(3), September 1995, pp. 51-64.

Cu, P.V. and C.X. Huy, "Combination of SAR Data With Airphotos and 3-D Relief Data for the Detailed Geological Mapping in a GlobeSAR Experimental Area in Vietnam", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 135-138.

Cu, P.V., "Overview of the GlobeSAR Project in Vietnam - Progress and Limitations", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

D'Iorio, M.A., L.N. Ley, P.A. Budkewitsch and R. Richardson, "Geological Map Update Using Airborne and RADARSAT Simulated SAR Data in Sarawak, Malaysia", Geocarto International, Vol. 10, No. 2, pp. 43-50.

D'Iorio, M.A., S. Vibulsresth, D. Dowreang, C. Silapathong, S. Polngam and H.A. Gordon, 1995, "Identification of Agriculture and Landuse Practices in Southern Thailand from SAR Data", Canadian Journal of Remote Sensing, Vol. 21, No. 2, pp. 165-176.

Dobson, M.C. , F.T. Ulaby, T. Le Toan, A. Beaudoin, E.S. Kasischke, and N. Christensen, 1992, "Dependence of Radar Backscatter on Coniferous Forest Biomass", ", IEEE Transactions on Geoscience and Remote Sensing, Vol. 30(2), pp. 412-415.

Dobson, M.C., and F.T. Ulaby, 1986, "Active Soil Moisture Research", IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-24(1), pp. 23-36.

Ewe, H.T., H.T. Chuah, A. Ismail, K.F. Loh and N. Nasruddin, "The Suitability of Using SAR Images for Monitoring of Growth Stages of Paddy Crops", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 78-88.

Ewe, H.T., H.T. Chuah, W.Y. Chin, A. Ismail, K.F. Loh and N. Nasruddin, "Classification of Landuse in Kedah, Malaysia, Using Fractal Analysis", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Geng, H., Q.H.J. Gwyn, B. Brisco, J. Boisvert, and R.J. Brown, 1996, "Mapping of Soil Moisture from C-band Radar Images", Special Issue of the Canadian Journal of Remote Sensing on Hydrology.Vol. 22(1), pp. 117-126.

Gordon, H.A., D'Iorio, M.A., and C. Silapathong, 1995, Coastal Environmental Monitoring and Mapping Using SAR Data. Proceedings of the Sevententh Canadian Remote Sensing Symposium, Saskatoon, Saskatchewan, pp. 94-101.

Guo, H., Wang, C., Liao, J., S. Yun and Wei, C., "Dual-frequency and Quad-polarization SAR Observations in Zhaoqing Region, China", Proceedings of the Geocarto International Special Issue: GlobeSAR and RADARSAT, Vol. 10, September 1995, pp. 79-85.

Hai, P.T. and N.T. Khang, "Application of GlobeSAR Data Obtained in Vietnam to Agriculture and Hydrology", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 125-127.

Haji, M.P.H.A., "Geological Interpretation of GlobeSAR Image of Sg. Imbak Area, Sabah, Malaysia", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 128-134.

Harahsheh, H., "Agricultural Land Use Classification From Enhanced SAR Images, Madaba and Azraq Area", Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 83-99.

Harris, J. And R. Murray, 1989, "IHS Transform for the Integtration of Radar Imagery With Geophysical Data", Proceedings of the International Geoscience and Remote Sensing Symposium, IGARSS'89, Vancouver, Canada, pp. 923-926.

Hess, L.L., J.M. Melack, D.S. Simonett, 1990, "Radar Detection of Flooding Beneath the Forest Canopy: A Review", International Journal of Remote Sensing, Vol. II(7), pp. 1313-1325.

Jiahong, L. and H. Xinnian, "Poyang Lake Drainage Area Flood Monitoring Using the Aerial Radar Remote Sensing Technical System", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Jingjuan, L. H. Guo and H. Liu, "Forest Discrimination in the Northeast of Shihui Area Using GlobeSAR Data", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

LeToan, T., Laur, H., Mougin, E., Lopes, A., 1989, "Multitemporal and Dual-Polarization Observations of Agricultural Vegetation Covers by X-Band SAR Images", IEEE Transactions on Geoscience and Remote Sensing, Vol. 27(6), pp. 709-718.

Ley, L.N., “Geologic Interpretation of GlobeSAR Image of Tuba-Bukit Lumut Area, Bintulu, Sarawak Malaysia”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 149-154.

Li, J., “Aerial Radar Remote Sensing System and Its Application in Flood Monitoring in Poyang Lake, China”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Li, Z., B. Lina, C. Xuejian and C. Erxue, “Analysis of Multi-Temporal JERS-1 SAR Data for Forest Mapping Over Zhaoyuan, Longkou Counties of China”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Liao, J., H. Guo and H. Liu, “Forest Discrimination in the Northeast of Shihui Area Using GlobeSAR Data”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Livingstone, C.E., A.L. Gray, R.K. Hawkins, P. Vachon, T.I. Lukowski, and M. Lalonde, 1995, “The CCRS Airborne SAR Systems: Radar for Remote Sensing Research”, Canadian Journal of Remote Sensing, Vol. 21(4), pp. 468-491.

Merzouk, A., A. Boukil, H. Dhaman, S. Hajjouji, H. Korkot, B. Abdelaoui, C. Prévost and L. Cyr, “Intégration des Données Radar C-Band RSO 🕐 Un S.I.G. D’Exploitation de Forêts: Application à la Forêt de Ghaba Larache, Maroc”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 100-113.

Merzouk, A., H. Dhman, H. Korkot, B. Abdelaoui, C. Prévost and L. Cyr, “Intégration des Images Radar (RSO) Avec Des Images POT pour L’Analyse Géomorphologique: Application au Bassin versant du Tangérois, Maroc”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 114-119.

Merzouk, A., H. Korkot, S. Hajjouji, B. Abdelaoui, C. Prévost, L. Cyr and M. Achkar, “Évaluation de la Télédétection Radar-RSO Pour l’Inventaire et la Cartographie de L’Occupation des Sols: Application au périmètre irrigué du Loukkos, Maroc”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 120-125.

Mohd, M.I.S., S. Ahmad and A. Abdullah, “Coastal Zone Information From Airborne SAR Data: Some Early Results”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 17-25.

Mongkolsawat, C., P. Thirangoon, C. Rodprom and K. Chantothai, "Evaluation of the SAR for Agricultural Landuse and Geomorphology", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 57-61.

Mongkolsawat, C., P. Thirangoon, C. Rodprom, P. Thirangoon and K. Chantothai, "Evaluation of SAR for Agricultural Land Use", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Musigasarn, W., S. Polngam and C. Jee-Rajunya, "GlobeSAR Input for Development Planning of Songkhla Lake Basin: TH4", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 26-31.

Musigasarn, W., "Applications of GlobeSAR Data as Input for Development Planning of the Songkhla Lake Basin", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Noor, B.E. and L.K. Hoong, "Geological Interpretation of Airborne SAR Imagery of the Cameron Highlands Area, Malaysia", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Nordin, L., "Application of Airborne SAR Data in Landuse/Land Cover, Soil Erosion, Forestry and Geological Mapping in Cameron Highlands, Malaysia", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 145-148.

Oroud, I.M. and H. Harrahshed, "Operational Significance of Radar Remote Sensing in Semi-Arid Areas: A Case Study in Southern Jordan", Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 126-134.

Parashar, S., E. Langham, J. McNally, and S. Ahmed, 1993, "RADARSAT Mission Requiremnts and Concept", Canadian Journal of Remote Sensing, Vol. 19(4), pp. 280-288.

Petzinger, F.C., 1995, "GlobeSAR: The CCRS Airborne SAR in the Era of RADARSAT", Geocarto International, Vol. 10(3), pp. 9-18.

Petzinger, F.C., C.E. Livingstone, R.K. Hawkins, F.H.A. Campbell, R.J. Brown, and W.C. Bayer, 1994, "The GlobeSAR Project: 1993 Airborne Data Acquisition with the CCRS Convair 580", Proceedings First International Remote Sensing Conference, Strasbourg, France, 11-15 September, pp. 305-316.

Rabia, M.C., "Analyse de la Zone Intertidale de la Presqu'île de Zarzis: Géomorphologie Côtière et Bilan Sédimentaire. Complémentarité des Données Optiques et Radar", Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 144-153.

Saint-Jean, R., V. Singhroy, S. M Khalifa. 1996. Geological interpretation of the integrated SAR images in the Azraq area of Jordan. Canadian Journal of Remote Sensing, Vol. 21 (4) pp. 511-517.

Selmi, K., “Cartographie des Ressources Forestières Par Interprétation Visuelle D’Images RSO: Cas du Site de Nefza”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 165-169.

Singhroy, V., R. Saint-Jean, M. R Momani. 1996. Mapping Surface Characteristics of Aquifers in Jordan from Integrated SAR Images. Proceedings ERIM Exploration Geology. Las Vegas, Nevada. pp. 691-697

Singhroy, V., R. Slaney, P. Lowman, J. Harris and W. Moon, 1993, “RADARSAT and Radar Geology Applications in Canada”, Canadian Journal of Remote Sensing, Vol. 19(4), pp. 338-351.

Supajanya, T., K. Vichapan, S. Chaleamlarp, T. Srisuchat, A. Srisuchat and J. Pornpraseertchai, “Sukhothai and Its Hydraulic Past, A Demonstrative Project for RADARSAT”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 110-118.

Supajanya, T., K. Vichapan, S. Chalermlarp, T. Srisuchat, A. Srisuchat and C. Phonprasoetchai, “Archaeo-Geomorphic Feature Observation Using SAR Imagery in Sukhothai, the Ancient Capital City of Thailand”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Talbi, M., “Contribution de L‘Imagerie Radar Aéroporté 🕒 l’Étude D’un Paysage Aride: Le Cas du Site Mareth, Tunisie du Sud-Est”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 177-187.

Tam, L.T.M., N.X. Dao and D.V. Khae, “Using Airborne Image Data for the Compilation of a Geomorphological Map of Thatkhe Area, Caobang Province”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 162-167.

Thongchai, C., S. Ongsomwang, S. Rattanasermpong and C. Silapathong, “Forest and Coastal Zone Monitoring Using Airborne SAR Image (TH-5)”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 159-161.

Thongchai, C., S. Ongsomwang, S. Rattanasermpong and C. Silipathong, “Forest and Coastal Zone Monitoring Using Airborne SAR Imagery”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Wara-Aswapati, P., “An Archaelogical Application of Synthetic Aperture Radar (SAR) in Thailand”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Wara-Aswapati, P., “Preliminary Study of Airborne SAR for Land Identification in North-Eastern Thailand”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 46-52.

Waynakh, Iz aldeen. M., “The Use of Synthetic Aperture Radar for Mapping Ground-Water Recharge Zone in the Madaba Area”, Proceedings of the First Regional GlobeSAR Seminar in Middle East and North Africa, Amman, Jordan, April 23-25, 1995, pp. 188-203

Wei, C., B. Zhu and T. Yu, “CCRS SAR for Hydrological Analysis in Zhaoqing Region of Southern China”, Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 93-100.

Weigen, H., “SAR Observation of Coastal Ocean Features in China”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Wessels, G.J., R.T. Lowry and R.K. Raney, 1986, “Validation and Simulation of RADARSAT Imagery”, Proceedings of the Tenth Canadian Remote Sensing Symposium, pp. 841-853.

Wessels, G.J. and M.E. Kirby, 1986, “SARSIM - A Spaceborne SAR Simulation Package”, Proceedings of the International Geoscience and Remote Sensing Symposium, IGARSS’86, Zurich, Switzerland, pp. 1655-1660.

World Bank 1994. Agriculture Sector Adjustment Loan, Project 5JORPA072. Ministry of Planning.

World Monuments Fund and Royal Angkor Foundation, 1995, “Radar Imaging Survey of the Angkor Eco-Site”, Report of the First Scientific Roundtable , Published by the World Monuments Fund and Royal Angkor Foundation, New York, March 1995.

Xingchao, L. And Xiaoming, Y., “A Study on Soil Moisture Monitoring Using Airborne SAR Data”, Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

Yun, S., H. Guo, H. Liu and B. Brisco, "Multi-Frequency, Multi-Polarization GlobeSAR Data for Land Use Mapping", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 32-45.

Yun, S., H. Guo, H. Liu, J. Li and X. Lu, "Effect of Polarization and Frequency Using GlobeSAR Data on Vegetation Discrimination", Proceedings of the Geocarto International Special Issue: GlobeSAR and RADARSAT, Vol. 10, September 1995, pp. 71-78.

Yusoff, W.Z.W. and M.H. Yasin, "Verrification of the Suitability of GlobeSAR Data for Forest, Land Use and Topographic Mapping in the Endau Region, Peninsular Malaysia", Proceedings of the First Asia Regional GlobeSAR Workshop, Bangkok, Thailand, November 28-December 2, 1994, pp. 101-109.

Yusoff, W.Z.B.W. and M.H.B.M. Yasin, "Preliminary Results of Airborne Synthetic Aperture Radar Applications for Forest, Land Use and Topographic Mapping in the Endau Region, Peninsular Malaysia", Proceedings of the Second Asia Regional GlobeSAR Workshop, Beijing, China, October 9-12, 1995 (in press).

List of Figures

Figure 1. Airborne C-HH and RADARSAT Standard Mode Simulation of a portion of the Kedah test site in Malaysia which is being used to study rice monitoring applications. Note the variations in grey tone which are related to the stage of growth and condition of the rice crop. The backscatter from paddy rice increases as the rice plant grows reaching a maximum at peak growth conditions.

Figure 2. Airborne C-HH SAR image of an agricultural region in Morrocco used to investigate crop type and land cover information in radar data. Note, the variations in radar return from various agricultural targets as well as the delineation of irrigated crops based on the soil moisture response.

Figure 3. Airborne C-HH from a rubber plantation in Vietnam's Quang Binh test site and an olive orchard from Tunisia showing the characteristic pattern and texture of agro-forestry plantations on SAR imagery.

Figure 4. Airborne C-HH SAR image of Songhla Lake in Thailand with various features related to coastal monitoring and land cover mapping identified. This image is also used for the change detection example using actual RADARSAT data (see Figure 13).

Figure 5. Airborne C-HH SAR image of the coastal region of Tunisia showing the location of Sebkhas which can be monitored using the image data.

Figure 6. Airborne C-HH SAR image of Lake Nakuru, Kenya illustrating the type of landcover information available from radar imagery. Note the ability to easily map urban (A), agricultural (B) and forested or shrub covered (D & E) areas. See text for detailed discussion.

Figure 7. Airborne C-HH SAR data acquired in Sarawak, Eastern Malaysia, in November 1993. This area is covered in tropical forest yet, the SAR image clearly maps the folded sandstone beds. The stratigraphic beds, the folds, and the faults are easily traced throughout this image. Two phases of folding are identifiable from the SAR data.

Figure 8. Airborne C-HH SAR image of a portion of the Zhao Qing site in China being used for hydrology studies. The hydrology network is easy to map on the radar image (ie. rivers, canals, etc.) which provides for timely flood monitoring capabilities. This image was also used to identify the flow obstructions in the rivers and the paleochannels,which helps to identify sensitive locations along the rivers for flood mitigation and monitoring.

Figure 9. Airborne C-HH SAR image of the Azraq test site in Jordan. This image was used to provide a geological interpretation of the region which was then used for evaluating potential sources of ground-water for irrigation purposes. Note the bright appearance of the basalt (which provides a source of ground-water recharge) compared to the darker sandy limestone. The wadi and mud flats can also be easily mapped.

Figure 10. RADARSAT Standard Mode beam 7 image of the Kedah test site in Malaysia which is being used for rice studies. Note the variations in grey tones in the paddy region which is related to the stage of growth and crop condition. As on the airborne image newly planted rice appears dark while growing rice is brighter. A comparison of the actual RADARSAT image in this figure with

Figure 1 demonstrates the similarity in information content. Image © Canadian Space Agency, 1996.

Figure 11. RADARSAT Standard Mode beam 6 image of a portion of the Zhao Qing test site in China showing hydrological and landcover mapping information similar to the airborne image information content (see Figure 8). The hydrology network is still very easy to map which when coupled with the "all-weather" capability of RADARSAT provides for operational flood mapping and monitoring capabilities. This site is also being used for geology, forestry, and agriculture application studies. Image © Canadian Space Agency, 1996.

Figure 12: RADARSAT image of Songkhla Lake in South-eastern Thailand. The image was acquired June 3, 1996. The large body of water on the right side of the image is the Gulf of Thailand of the South China Sea. Image © Canadian Space Agency, 1996. Inset: False colour composite of airborne C-HH data acquired November 5, 1993 (displayed in red) and RADARSAT data acquired in June 3, 1996 (displayed in green).

Figure 13 RADARSAT images of Sarawak, Eastern Malaysia. . The image on the left was acquired on an ascending pass, in the Standard 5 mode, May 28, 1996. The image on the right was acquired on an ascending pass, in Standard 6 mode, May 19, 1996. Corresponding features on each of the images are separated by 6.5 cm to facilitate viewing under a stereoscope. Images © Canadian Space Agency, 1996.

Figure 14. RADARSAT Standard Mode beam 4 image of the Azraq test site in Jordan being used for hydrogeological studies. Note the ability to map the rock types, wadi location and characteristics, the mudflats, and the faults. See text for detailed discussion. Image © Canadian Space Agency, 1996.