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PRELIMINARY SCIENCE RESULTS FROM THE SHUTTLE IMAGING RADAR-B

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ABSTRACT

On October 5, 1984, the space shuttle Challenger carried the Shuttle Imaging Radar-B, developed and built by the Jet Propulsion Laboratory (JPL), into orbit as part of the OSTA-3 (Office of Space and Terrestrial Applications) payload. During its eight-day mission, SIR-B gathered digital radar imagery covering 5 million square kilometers of the earth's surface between 57° north and south latitudes. Of major concern was the collection of radar imagery of the same target at different incidence angles, creating a means of classifying surfaces by their backscatter response as a function of incidence angle. Chosen by NASA to work with the data were 43 scientists representing academic, private and government interests from around the world. Study areas spanned the fields of geology, archeology, forestry, agriculture, oceanography, geography and hydrology. In spite of transmitted power problems experienced during the mission, useful imagery was obtained for all of the above interests, substantially contributing to spaceborne multiple incidence angle radar studies.

I. REVIEW OF SPACEBORNE IMAGING RADAR

The use of the radar portion of the electromagnetic spectrum for remote sensing has several advantages. The proper wavelength, L-band for instance at 23 cm, is not attenuated by water vapor, hence is capable of penetrating cloud cover. Since imaging radar is an active instrument (providing its own illumination), illumination from the sun is no longer required, allowing data to be collected around the clock--regardless of solar position. In addition, radar is sensitive to surface roughness on the scale of the illuminating wavelength. Rough, highly reflective areas appear bright on radar imagery, while smooth areas appear dark. Whereas optical sensors look at elemental chemical composition of surfaces as manifested in their color, radar sees surface textural and dielectric properties. Combined data sets of both optical/infrared and radar can be very useful, complementing each other and providing valuable information about an area.

A. PRINCIPLES

The principle of imaging radar is rather straightforward, though its implementation can be complex. The simplest system is called real aperture radar. An airborne or spaceborne antenna transmits pulses of radar energy directed at a long, narrow strip on the ground, perpendicular to the direction of motion of the antenna. Simultaneously, between transmitted pulses, the reflected radar echo from the surface is received and recorded, either digitally or on an analog recorder. By dividing the echo into discrete portions, resolution is created in the range direction, a narrow strip perpendicular to the direction of antenna motion. As the antenna moves along, more echos are collected, allowing the range element strips to be joined creating azimuth or along track resolution. However, this along track resolution is limited by how narrow the strip on the ground that can be illuminated. This is a direct function of the antenna length. The longer the antenna, the narrower the illumination pattern. To create an azimuth resolution of 30 meters, a spaceborne antenna would need to be 3 km long. Since this is not a tenable situation, the technique called synthetic aperture radar (SAR) was developed.

The synthetic aperture technique uses the intrinsic motion of the platform to create an apparent antenna of very large dimension to greatly increase the resolving power of the system. By coherently processing the returned signal utilizing the phase of the reflected radar waves and the Doppler frequency shift introduced by the relative motion of the target and platform, high resolution imagery can be generated either by analog or digital techniques. The analog method of recording data involves exposing photographic film, its density modulated by the raw signal data. The developed film is illuminated by laser light. A series of spherical and cylindrical lenses transforms and filters the data into an image format, which is used to expose the final product image film. This technique is very efficient for handling large amounts of data, but lacks the resolution and dynamic range available when using digital data collection methods. The digital technique stores the raw radar data on high density magnetic tapes. After extensive computer filtering and processing, the imagery is displayed on a graphic output device and photographic products generated, utilizing digital enhancement techniques which are capable of revealing subtle features often not visible in the optical product.

B. SEASAT

The first spaceborne SAR was flown on Seasat, launched June 28, 1978. Flown at an altitude of 800 km in a 108 degree inclined orbit, the synthetic aperture radar was one of 5 microwave instruments designed for detailed remote sensing of the Earth's oceans. For 100 days, the satellite gathered imaging radar data at L-band with an incidence angle of 23° degrees (measured from nadir) and a resolution of ~25m over North America and Western Europe. Though initially anticipated as an oceanographic tool, imagery of land areas proved to be extremely interesting to geologists and agriculturalists. All of the data were processed optically at first with selected scenes recorrelated digitally. Digital scenes covering 100 x 100 km areas provide synoptic coverage at a relatively constant incidence angle. Geomorphological differences could be mapped as textural changes in an image, augmenting Landsat coverage in the ability to discriminate terrains, especially in heavily vegetated environments. Agricultural areas could be mapped and recent rainfall detected by anomolously bright areas, saturated with water and thus highly reflective. Bathymetry of shallow water could be mapped in certain areas due to changes in ocean surface roughness as a result of current interaction with submerged channels and sandbars. The flow patterns of sea ice could be charted 24 hours a day, regardless of weather conditions.

During its short life, Seasat collected radar imagery of 100 million square kilometers of the earth's surface, emphasizing the advantages of spaceborne SAR and revealing the utility of radar for applications other than oceanography.

C. SIR-A

As a follow on project to Seasat, JPL developed the Shuttle Imaging Radar-A (SIR-A) as part of the OSTA-1 (Office of Space and Terrestrial Applications) payload, flying aboard the Columbia on November 12, 1981, the second flight of the space shuttle. A prime objective of the mission was to demonstrate the use of the Shuttle as a platform for scientific investigations. Specifically, the SIR-A project goal was to acquire and analyze radar imagery of a variety of regions to further the understanding of the use of spaceborne imaging radar for geologic mapping applications. Utilizing much the same hardware as Seasat, SIR-A operated at L-band at an altitude of 260 km with an orbital inclination of 38 degrees. A fixed look angle of 47 degrees was used collecting optical data with a resolution of about 40 m over 10 million square kilometers of the earth's surface. The results were spectacular, proving the ability of the Shuttle as a useful platform for earth observations and dramatizing the unique nature of radar imagery. Image data were collected over parts of Indonesia, whose nearly perpetual cloud cover makes optical and infrared sensors useless, revealing the geomorphology and structural features of virtually inaccessible regions. Even in areas less remote, SIR-A imagery often assisted in structural interpretation due to the roughness properties of the surfaces imaged, allowing differing lithologies to be separated and mapped. In the field of hydrology, SIR-A imagery was used to map river morhpology in remote areas of South America, where maps are constantly changing due to the dynamic nature of these fluvial areas. Rural and urban land use patterns were plainly visible, contrasting the geometric field patterns of western cultivation and the mosaic maze of villages and fields in China. Wind and wave patterns in ocean imagery confirmed the utility of SIR-B's higher incidence angle geometry for oceanographic applications and are of much interest to hydrospheric researchers.

By far, the most exciting outcome of the SIR-A experiment was the discovery that L-band radar is able to penetrate very dry sand and image subsurface features. Imagery of the Western Desert in Egypt were being analyzed for their geologic content when it was noted that corresponding Landsat visible and infrared imagery of the same geographic area had very little resemblance to the radar data. Subsequent field work in these areas suggested that the radar was actually penetrating the thin veneer of windblown sand, which gave the Landsat imagery its uniform character, and reflecting off of coarse stream gravels. Elaborate drainage networks beneath the desert, hidden for thousands of years by drifting sands of an encroaching desert were revealed, helping to understand paleodrainage and climatic conditions. Field work also uncovered paleotools and artifacts along the buried banks of once major rivers, leading to speculation of the habitability of the areas 100,000-200,000 years ago. While very specific conditions are required for penetration of this kind, its application to archeology and hydrologic exploration in the arid regions of the world is potentially enormous.

II. SIR-B

The concept of spaceborne imaging radar was proven by Seasat and SIR-A, extending its utility to fields other than oceanography and geology. But certain fundamental questions remained to be answered. What is the effect of incidence angle on radar backscatter, how does it differ between varying surfaces, and can it be quantified? Does radar actually penetrate certain vegetative and forest canopies, revealing properties of the underlying surface? Can large areas be mapped to get regional synoptic views of geomorphology and land use? Can the phenomenon of penetration in arid regions be extended to areas besides the Western Desert of Egypt?

A. MISSION DESIGN OPERATION

In December of 1982, NASA issued an announcement of opportunity soliciting experiments using information to be collected by the Shuttle Imaging Radar-B. SIR-B differs from SIR-A in two important ways. First, the radar antenna is now moveable, allowing imagery to be collected between 15 and 60 degrees incidence angle. Second, a digital data handling system has been incorporated, allowing the data to be recorded and transmitted digitally making it intrinsically more quantitative and of higher resolution. Also of major importance to the SIR-B mission was the careful experiment design which made possible the collection of very specific data of particular areas of interest, made more valuable by simultaneous ground based measurements and observations at many sites.

SIR-B was launched October 5, 1984 as part of the OSTA-3 pallet of experiments aboard the Space Shuttle Challenger, STS 41-G. Also included were the Large Format Camera (LFC), a Feature Identification and Location Experiment (FILE) and an experiment for the Measurement of Air Pollution from Satellite (MAPS). In addition, the mission carried with it the Earth Radiation Budget Satellite (ERBS), a deployable satellite to monitor the balance of solar flux and re-radiation from the Earth, and an Orbital Refueling System (ORS) an experiment utilizing an extra-vehicular activity (EVA) to test the feasibility of transferring liquid propellant in the weightless environment.

Launch occured at 11:03 GMT, a few minutes before dawn at Kennedy Space Center, with an initial circular orbit of 352 km altitude for the deployment of ERBS. Following the ERBS deployment, the shuttle went into an intermediate phasing orbit at 256 km, dropping to the SIR-B operational altitude of 222 km 48 hours after launch.

About 13 hours after launch, a failure occured in the Shuttle's high data rate Kμ band antenna system, used to transmit the digital SIR-B data to the Tracking and Data Relay Satellite (TDRS) which was to redirect the data to a recording station at White Sands, NM. Since nearly 85% of the data had been scheduled to be collected in this mode, major replanning had to be undertaken in real time during the mission. An onboard tape recorder, capable of handling 2/3 of the SIR-B data rate and intended primarily for data collection in areas outside of the TDRS coverage, became the primary digital mode of data collection. Fortunately, near heroic efforts by the crew of Challenger enabled the partial use of the failed Kμ system, allowing about 40 minutes of tape recorded data to be transmitted to earth each day. A total of nearly 8 hours of digital data were collected, though much of it at a reduced swath width. In addition, 8 hours of optical data were also collected by the same optical recorder that was used on SIR-A.

A second problem was noted involving the SIR-B antenna's transmitted power, 6 to 10 db below predicted values and fluctuating as a function of time. Subsequent analysis traced the problem to a faulty cable between the transmitter and antenna. The digital data handling system was in most cases able to compensate for the resultant weak signal, due to its large dynamic range. The optical system, however, was not able to perform well under these conditions resulting in optical data of marginal to poor quality.

On October 13, 1984, after 197 hours in orbit, the Challenger returned to Earth landing at the Kennedy Space Center in Florida. Each of the experiments had operated successfully and, considering the circumstances, SIR-B performed well despite some potentially fatal problems.

Before discussing some of the results of the SIR-B experiment, it will be useful to describe briefly the mission design strategy and the tools used to respond to the scientific needs of the many users. As previously mentioned, 43 scientists from around the world were chosen to select sites for study and analyze the SIR-B data following the mission. Integrating their needs into a coherent data collection scheme was a formidable task. The primary objective was to collect multiple incidence angle data sets for several areas around the world. To this end, the last six days of the mission at low altitude were designed to repeat coverage of a specific target each day, or 16 orbits, with a slight westward drift, altering the imaging geometry sufficiently to allow the collection of new incidence angle each day. Input from the 43 team members helped JPL choose an orbital node, specifying which targets would be imaged. Of course, not all of the experiments dealt with multiple angle studies, so mapping and incidental coverage was also planned. In addition, the complex requirements of the orbiter and crew had to be taken into consideration, as well as the requirements of the other OSTA-3 experiments. Crew sleep periods, inertial guidance alignment, fuel cell water dumps and sun illumination requirements (for LFC and FILE) all helped shape the final data collection plan.

A unique element of the mission was the extensive collection of simultaneous ground truth by dozens of teams around the world. Groups in England, West Germany, Saudi Arabia, Egypt, Botswana, Bangladesh, Australia, Japan, Brazil, Argentina, Canada and the United States had to be directly informed of changes to the mission plan and target location. Some needed to know precise times of data acquisition to schedule ground crews, aircraft underflights and instruments appropriately. Many of the oceanographic experiments utilized shipborne measurements to be compared with the radar data, and so had to be informed well in advance of any changes to provide time to relocate if necessary and optimize their valuable ship time. Daily telex messages conveyed most of this information, though in critical situations telephone calls kept team members informed.

SIR-B operations and replanning were conducted by the JPL team operating out of the Johnson Space Center in Houston, TX. Although a pre-mission radar timeline and command plan had been prepared, software planning tools were created to maximize the instrument's flexibility and the ability to react to late stage changes. Radar parameters and shuttle position were calculated in real time using a network of IBM PC/XT computers. As the detailed shuttle position and timeline became available, new radar parameters were computed to acquire imagery of specific targets. These tools proved to be invaluable during the mission as virtually all of the SIR-B data takes had to be extensively replanned due to the digital downlink and antenna power problems previously mentioned. Command plans were then generated which were integrated by the JSC computer system and uplinked to control the radar.

B. PRELIMINARY RESULTS

Slightly less than eight hours of digital data were actually collected during the October mission. The location of these data are indicated on the world map in Figure 1, which should be used for general location only. Detailed swath locations and information regarding data availability can be obtained from the National Space Science Data Center, Goddard Space Flight Center, Code 601, Greenbelt, MD 20771 or JPL.

The first SIR-B image was produced hours after launch, during the mission, to verify the operational state of the instrument and test the correlator software. Since that time, nearly half of the data has been processed, anticipating completion of the correlation in the Autumn of 1985. In early 1986, the group of SIR-B investigators will meet to present the results of their studies utilizing the radar data. The SIR-B imagery and discussion presented here are not intended to represent final results, but to convey some examples of the data product and potential uses.

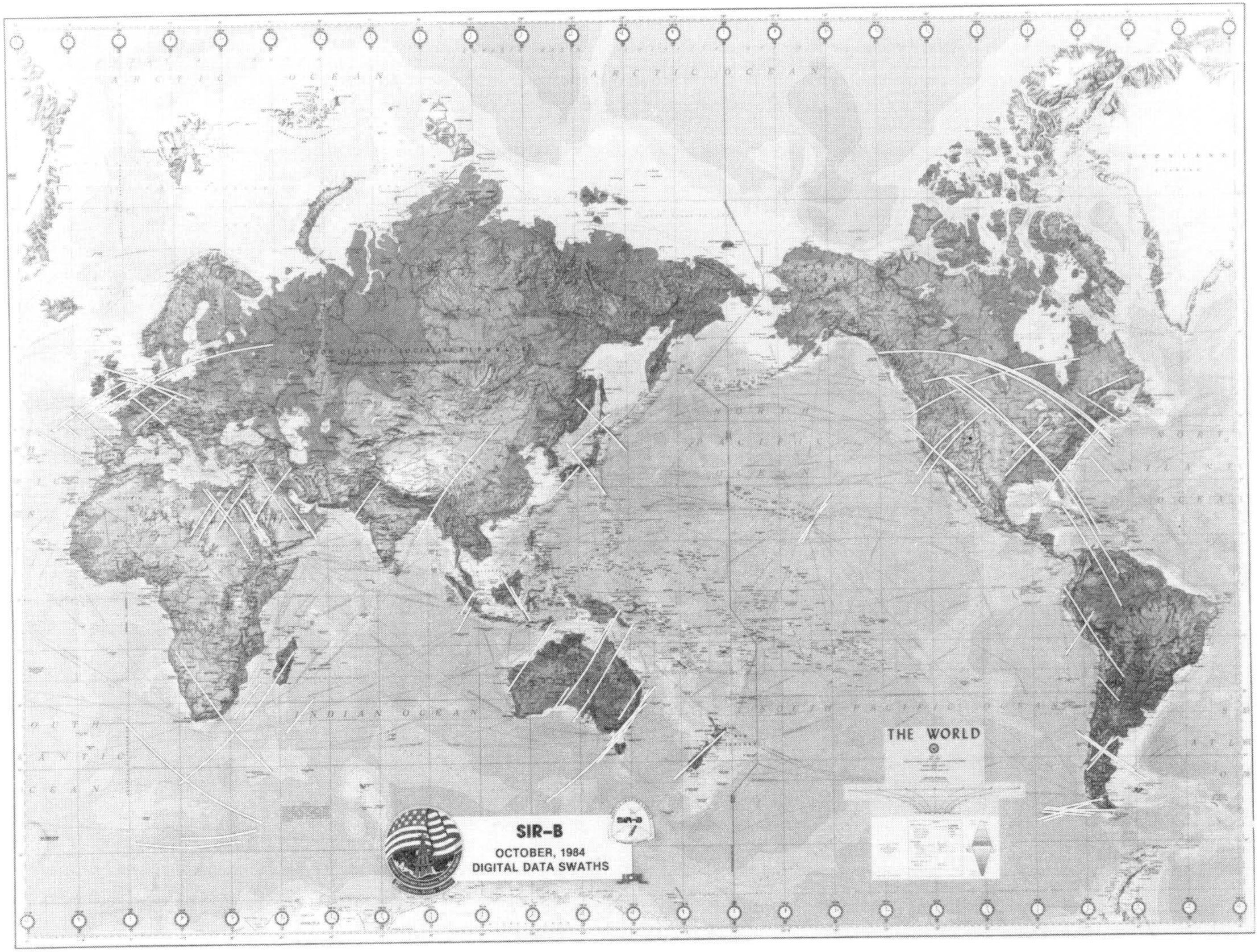
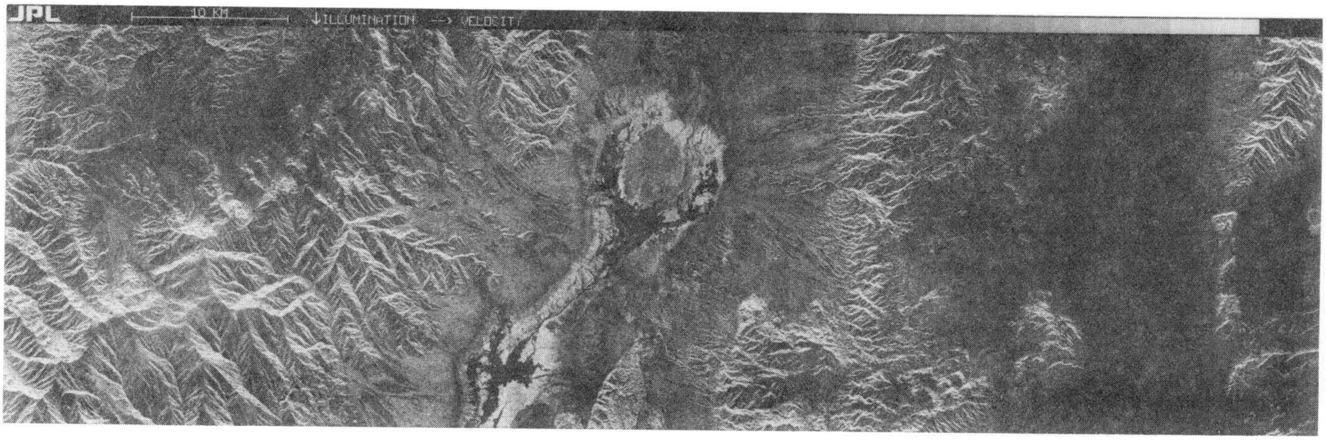


Figure 1. The above map of the world shows the general location of SIR-B digital coverage. Nearly 8 hours or 5 million square kilometers of imagery were collected. Detailed information about data location and availability can be obtained from the National Space Science Data Center, Goddard Space Flight Center, Code 601, Greenbelt, MD 20771.



Datatake 98.2 Incidence angle: 44°

North

Figure 2. The above image of Death Valley, California shows the response of radar to differing geologic targets, from the slope dominated returns from the Panamint Mountains to the salt flats of the valley floor.

Several areas around the world were targeted as multiple incidence angle test sites. It is hoped that by coregistering imagery from these sites, a pixel by pixel comparison of the radar reflectivity can generate backscatter curves as a function of radar incidence angle. These curves can then be used to help classify the surface utilizing its radar reflectivity properties (Figure 3). For geologic applications, differing rock types may have different radar reflectivity responses as a function of incidence angle. A limestone may weather differently than a sandstone for instance, producing surfaces of differing roughness, discernable by this multi-incidence angle approach. A quantification of this effect is the subject of several SIR-B investigations utilizing volcanic terrain in Hawaii and the Cascade Range of the western United States.

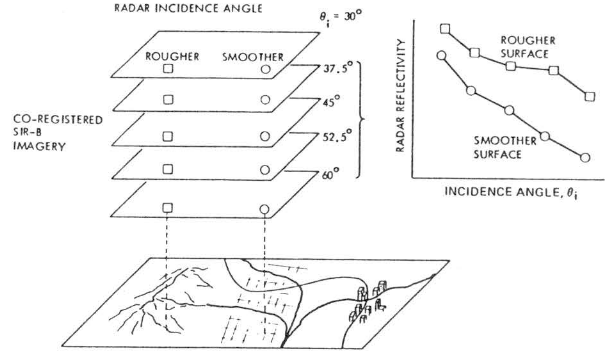


Figure 2. Co-registered imagery can be used to generate radar backscatter curves as a function of incidence angle.

Though not a multiple angle site, Death Valley in California (Figure 2) provides a fine example of radar brightness as a function of surface roughness. The roughly circular feature in the valley floor at the upper center of the image is Cottonball Basin. The dark area which partially encircles the feature is a smooth mud flat, sometimes filled with water. The brighter areas, however, are blocky deposits of evaporated salts and sulfates, much more highly reflective at radar wavelengths.

Surface roughness can also be used to discriminate alluvial fans of different ages. In the center of the image is a fan deriving its material from the Panamint Mountains to the west. Darker areas are visible in the fan, correlating to older smoother surfaces where soils were able to form without being destroyed by more recent erosional activity.

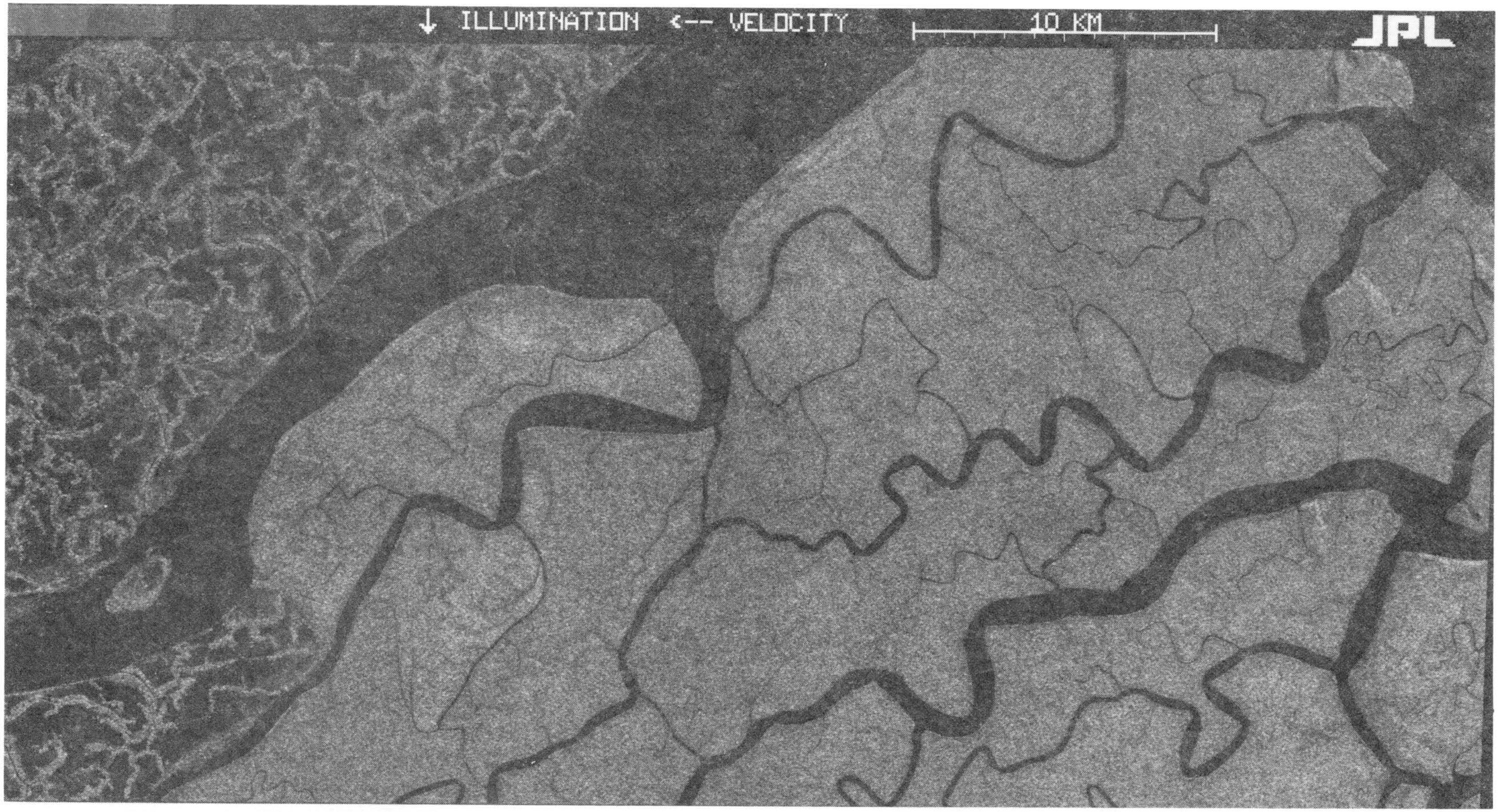
There are also agricultural interests in multiple angle radar studies. Differing crops have different radar signatures, depending on crop height, structure, moisture content and stage of growth. It is hoped that data from SIR-B will be able to help to better quantify these variables by adding the effect of incidence angle and identifying the optimum geometries for different conditions. The same techniques can be extended to forestry applications where several experiments are being conducted using SIR-B and Landsat data to assess stand characteristics and forest management practices. Radar is particularly useful for discerning clearcut areas of forest by its sensitivity to the differing textures and reflectivity properties of new growth and mature trees. It is hoped to eventually be able to determine when a clearcut area has the same radar signature as the surrounding mature trees in order to better put bounds on clearcut rates and detectability.

Of prime concern are studies relating to the penetration of radar through forest canopies in areas such as the Ganges floodplain in Bangladesh (Figure 4). As the illumination geometry changes, so should the amount of penetration, where steep near vertical angles should penetrate the most. However, it is not always clear whether or not the canopy completely attenuates the signal regardless of incidence angle. This can be important, especially if it is desireable to image properties of the surface beneath the trees and to know whether surface or canopy effects are dominating an image. The right hand, brighter portion of this image is a coastal forest preserve or sundarban. Tonal variations in this area do not appear to be related to vegetation specie changes. Possibly they are due to variations in the extent of standing water on the forest floor. Three images at differing look angles were obtained by SIR-B of this area, hopefully to aid in the solution of this problem. The left, darker portion of the image shows heavily cultivated flooded croplands connected by a series of canals. These images were collected during the monsoon season under heavy cloud cover. Farther upstream, the areal extent of flooded conditions can be mapped, again proving the utility of radar in an area where optical and infrared sensors would not be able to provide useful results.

An interesting application of multiple angle radar data sets is the creation of stereo imagery. Several different viewing geometries are available, but the most satisfactory seems to be imaging a target from the same side at two different incidence angles. The optimum separation between the angles is related to the topography of the area being imaged, and the extent of vertical exaggeration desired. Utilizing standard photogrammetric techniques, the digital topography of an area can be generated and used to create maps such as the axonometric plot of Mt. Shasta in Figure 5a. Creating an accurate and registered product requires a detailed knowledge of spacecraft position and imaging geometry. The potential exists for mapping remote regions of the world quickly, efficiently and at a resolution adequate for most applications. Once the data are in a digital format, computer graphics techniques can be employed to present an area in a perspective view, from any angle with any vertical exaggeration (Figure 5b). This can be a useful tool, especially if implemented interactively with the user, who can virtually "fly" anywhere in an area of interest, examining morphological features and relationships. Again, this technique would be especially appropriate for remote unexplored portions of the Earth.

As a result of the discovery of buried river features by SIR-A, several of the SIR-B experiments were focused on attempting to extend this phenomenon to other less arid regions of the world. Preliminary analysis of the SIR-B data seems to indicate penetration of up to a meter in dry sands in Saudi Arabia, with similar results in Egypt. Certainly, the lowpower transmitted by SIR-B did not help these penetration studies, but work continues in data analysis and Landsat comparison. One experiment, however, had exciting results indicating that penetration may occur in areas far from hyperarid. Small, portable ground receivers, built by SIR-B team members from West Germany, were deployed in the desert of western Nevada. The receivers were tuned to the L-band frequency of SIR-B, and were interfaced to a microcomputer which recorded the received signal strength as a function of time. Several receivers remained on the surface during the mission, but others were buried to depths of up to 74 cm at two separate sites. The SIR-B signal was detected by all receivers even though subsequent measurements indicate greater than 5 weight percent water in the soil. Though the two way attenuation of the signal would almost certainly preclude the imaging of subsurface features in this environment, the experiment has shown that penetration can occur in areas that are not hyper-arid. The information obtained can be used to extend the depth of penetration expected in truly dry environments.

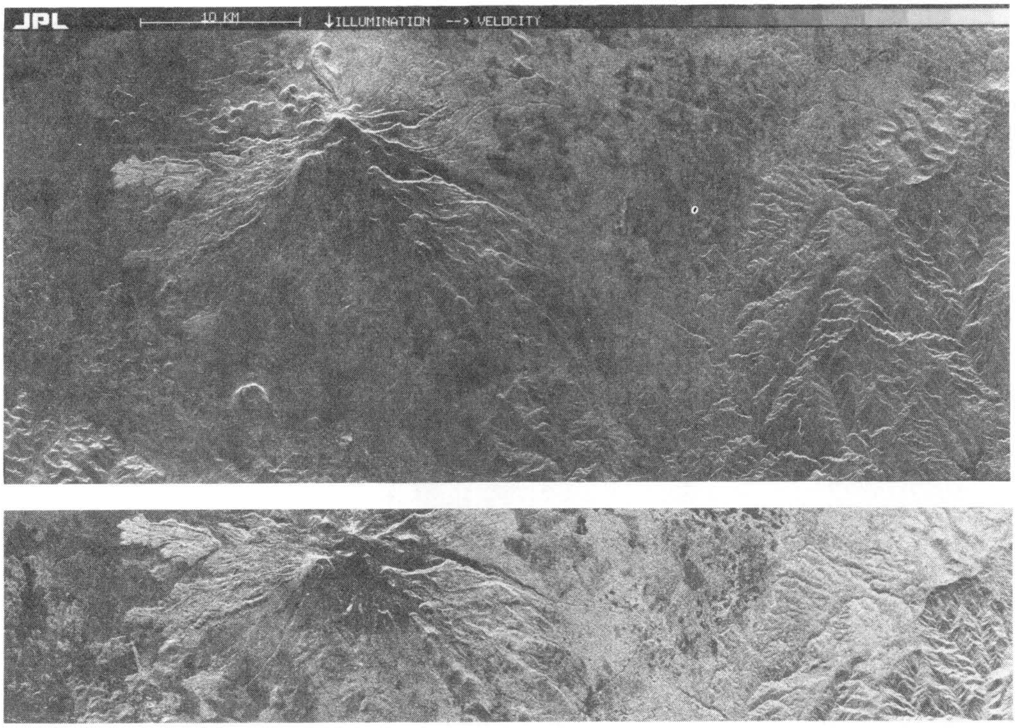
Finally, we look at imagery of the Rio Japura, a tributary of the Amazon in Brazil. Figure 6a,b shows a comparison of the digital SIR-B data and optical SIR-A data of the same area, at a slightly different scale, as imaged in November of 1981. The superiority of the digital SIR-B product can clearly be seen both in resolution and dynamic range. Though no major changes had occured in the river between the dates of acquisition, both images differ greatly from Defense Mapping Agency maps of the area produced in 1975. Of interest to SIR-B team members working on this data is floodplain dynamics as it applies to the carbon biogeochemistry of the river and the possible penetration of the forest canopy



Datatake 104.2, Incidence angle: 46°

↙ North

Figure 4. Shown above is the floodplain of the Ganges River in Bangladesh. The image is dominated by coastal mangrove forest or sundarban. Tonal variation in the forest may represent varying amounts of standing water beneath the trees. In the upper left darker portion of the image are flooded fields connected by a series of canals. This image was acquired at a local time of 3 AM under heavy cloud cover.



SIR-B Datatake 87.5
Incidence angle: 30°

SIR-B Datatake 55.4
Incidence angle: 54°

Figure 5a. Two views of Mount Shasta in northern California are shown here, creating a stereo pair which was used to generate a digital topographic data set and the axonometric plot below.

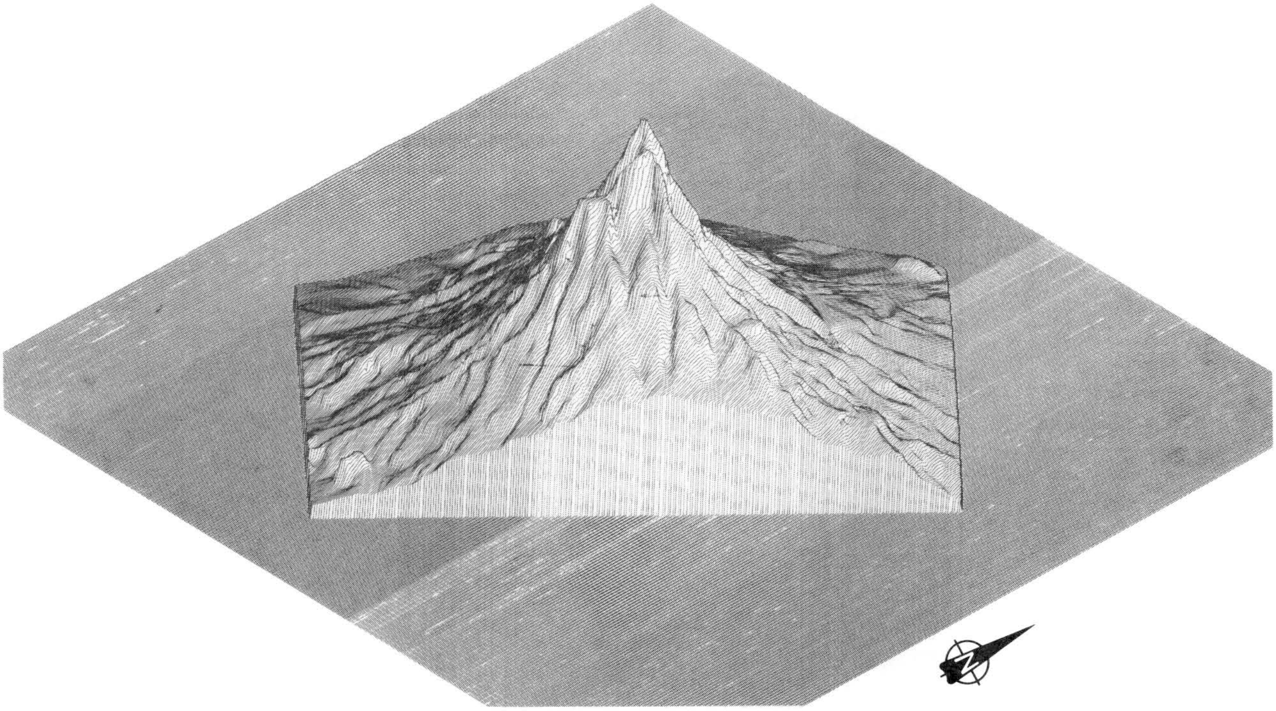


Figure 5b. A digital topographic data set can be used to generate a computerized perspective view such as this one of Mount Shasta. Any viewing geometry can be used, assisting in the visualization of morphological features, especially in remote areas.

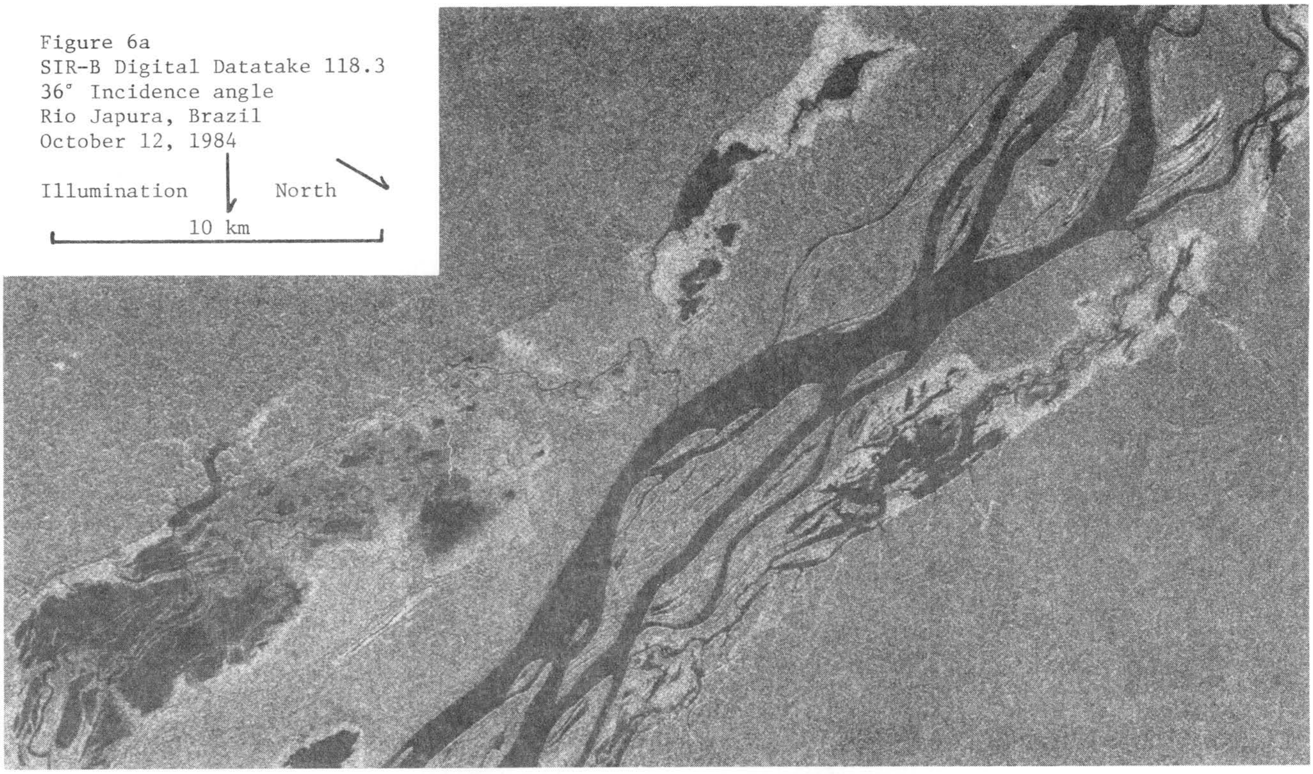


Figure 6a
SIR-B Digital Datatake 118.3
36° Incidence angle
Rio Japura, Brazil
October 12, 1984

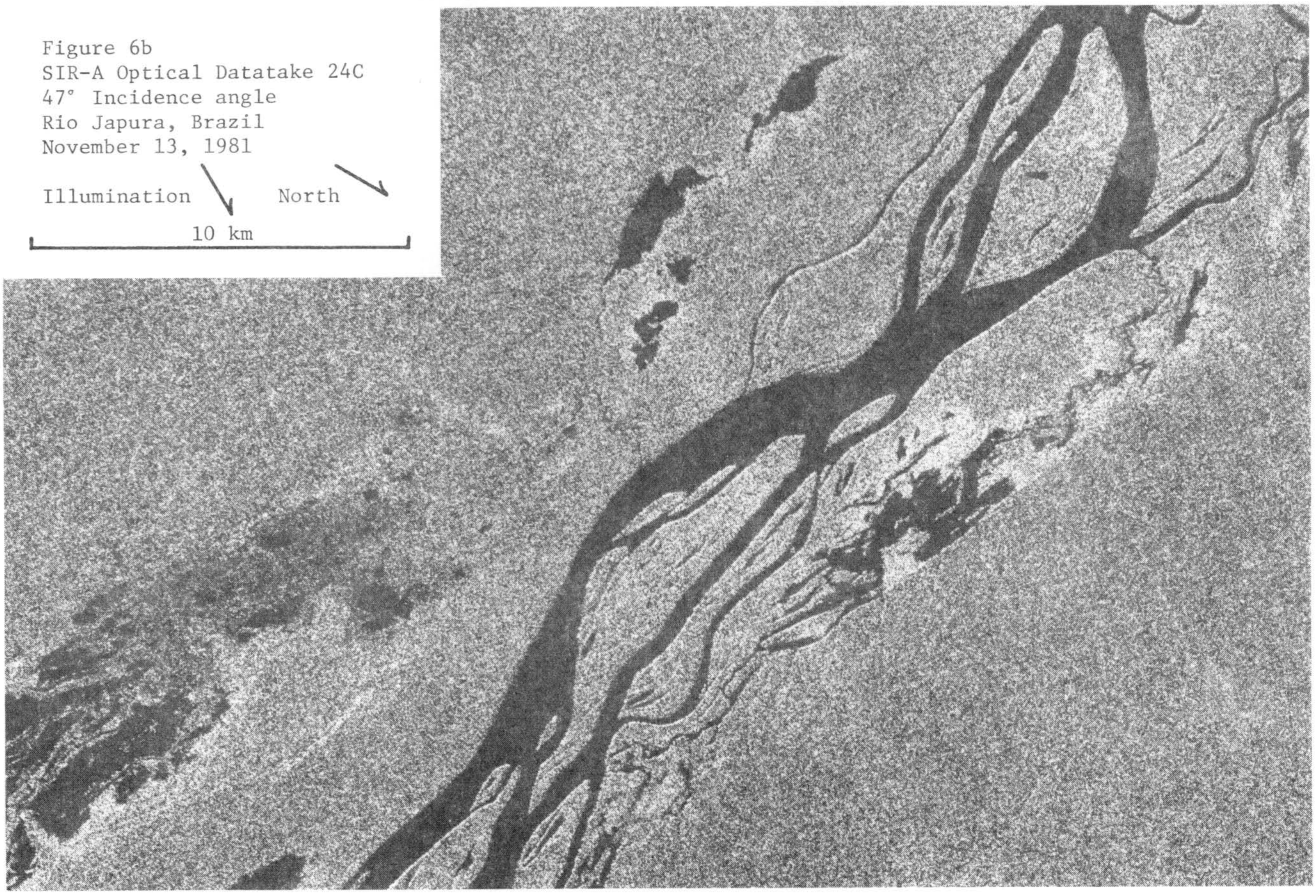


Figure 6b
SIR-A Optical Datatake 24C
47° Incidence angle
Rio Japura, Brazil
November 13, 1981

to reveal the presence of standing water. Though differences in look angle, look direction and time of year make a comparison of the images less than straightforward, there are marked differences in the appearance of bright "halos" surrounding some of the cut off lakes and eddies of the river. The SIR-B image, acquired with a look angle of about 36 degrees shows the effect much more clearly whether the result of changes in water height, a steeper look angle penetrating deeper into the canopy or the increased dynamic range. Ground truth conducted in similar areas during the mission will help to answer some of these questions.

III. CONCLUSIONS

SIR-B has proven to be a useful instrument by collecting multiple incidence angle data sets over a broad range of targets. Analysis continues to extract information from the imagery and optimize radar parameters such as look angle for future missions. Since much of the mission was substantially altered by the failed high rate data link, a reflight of SIR-B is being planned for the Spring of 1987. The group of investigators would remain the same as would the primary areas of interest. However, a polar orbit will allow for the first time spaceborne radar imaging of the Arctic and Antarctic regions of the planet.

In addition, the next generation of spaceborne SAR, SIR-C has been approved for flight in 1989 or 1990. This instrument will image the surface using L-band, C-band (about 5 cm wavelength) and perhaps X-band (3 cm wavelength) in four polarizations. The antenna will be electronically rather than mechanically steerable. It is expected that the increased information content will be useful for vegetation and geologic studies. SIR-C will also act as the prototype of a permanent spaceborne SAR to be flown on the Earth Observing System scheduled for the mid 1990's. An announcement of opportunity soliciting SIR-C experiments is scheduled to be released in early 1986.

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BIOGRAPHY

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