Overview of the Shuttle Imaging Radar-B Preliminary Scientific Results

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The Shuttle Imaging Radar-B experiment consisted of a large number of scientific investigations in the earth sciences. Nine oceanographic experiments were conducted to study the generation and propagation of surface waves, the dynamics of internal waves, oil slick detection, and the properties of southern polar ice. Stereo imaging from space allowed three-dimensional viewing of surface features. Geologic experiments were conducted to study subsurface penetration, structural mapping, and lithologic classification. Imaging radar angular scatterometry was used in the vegetation cover, forest type, and urban areas classification experiments. This article provides an overview of the scientific results, some of which are also presented in this issue.

SATELLITE IMAGERY, BASED ON THE USE OF VISIBLE AND near-infrared radiation, has been used since the 1960's for the study of the earth's surface and its cover. These investigations have provided synoptic information about the surface structure and chemical composition. In 1978, spaceborne radar imagery became available from the Seasat synthetic aperture radar (SAR). The Shuttle Imaging Radar-A (SIR-A) experiment took place in 1981. These radar sensors provided imagery that complements the visible and near-infrared data by sensing the physical properties (topography, morphology, and roughness) and electrical properties of the earth's surface (*1–9*) and, in arid regions, by imaging the subsurface features under a few meters of sand (*5, 8, 10*). The follow-up SIR-B experiment was conducted in 1984.

The main objective of the SIR-B experiment was to conduct a number of scientific investigations in the earth sciences. Forty-three international scientific teams and more than 200 collaborators participated in the acquisition and analysis of data. In spite of the problems encountered during the mission, a number of important scientific results were obtained. (i) The first radar stereo imagery obtained from space made it possible to view surface features in three dimensions. (ii) Theories for ocean wave and internal wave pattern imaging developed with SAR were verified. (iii) The presence of subsurface dry channels in the Egyptian desert was reconfirmed. (iv) Buried receivers were used to quantify the penetration effect in dry soil. (v) With multiangle imaging it became possible to use the "angular backscatter signature" to classify terrain units on a pixel-to-pixel basis.

This article presents an overview of the preliminary scientific results, some of which are also reported in this issue (*11, 12*). Details of all the results summarized here will be published in the July 1986 issue of the *IEEE Transactions on Geosciences and Remote Sensing*.

Sensor and Mission Description

The SIR-B sensor was an upgraded version of the Seasat SAR and SIR-A sensors, which operated at a fixed illumination geometry (incidence angle of 20° for Seasat and 48° for SIR-A). They provided the first capability to observe the earth's surface with radar sensors (*1–9*).

One of the objectives of SIR-B was to conduct scientific experiments to increase our quantitative understanding of the effect of the illumination geometry. This required that the SIR-B antenna be pointable and that the data be handled in a digital form (Fig. 1). Incidence angles between 15° and 60° could be selected with 1° increments. The data-handling system could selectively digitize the signal data at 3, 4, 5, or 6 bits per sample.

To acquire multiple angle imagery from an orbiting platform, we selected a slightly drifting orbit (at an altitude of 225 km). With this orbit it was possible to make surface observations of the same area at up to five different angles (Fig. 2). In addition, the bandwidth of the SIR-B sensor was doubled relative to SIR-A, thus improving the image resolution by a factor of 2.

The nominal mode for data transmission was real time via the shuttle Ku-band 50-megabit link to the TDRS (Tracking and Data Relay Satellite) system. In addition, a 32-megabit on-board recorder was used to acquire data over some of the sites.

The SIR-B experiment was launched on the space shuttle Challenger on 5 October 1985, and the mission lasted 8 days. Figure 3 shows the SIR-B antenna before deployment in the shuttle bay.

A number of problems occurred during the SIR-B mission that prevented acquisition of the complete set of planned data. The shuttle Ku-band data link antenna, in the process of unwrapping itself after tracking TDRS, lost its drive mechanism and began oscillating from side to side; it thus became impossible to track TDRS. The problem was remedied in part by disconnecting the antenna-pointing control, thus locking the Ku-band antenna into a fixed position so that power could be applied without creating oscillations. In the new mode of operation, data were acquired for 20 minutes on the HDRR (High Data Rate Recorder) and then the shuttle was put into a TDRS tracking attitude such that the entire orbiter was used to point the Ku-band antenna at TDRS. The total planned data had to be cut by about 80%, so that there were only 8 hours of data acquisition instead of 40 hours.

A second problem resulted in the loss of about 16 dB round trip (8 dB each way) in the antenna feed. A particle in the antenna feed was causing arcing, which reduced the transmitted power by 8 dB. Because of the dynamic range available in the digital data system, it

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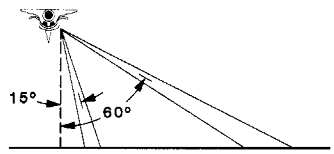
Fig. 1. Characteristics of the SIR-B sensor.



System characteristics
- Frequency: 1.282 GHz
- Wavelength: 23.4 cm (L band)
- Polarization: HH
- Look angles: 15° to 60°

Image characteristics
- Swath width: 20 to 40 km
- Azimuth resolution: 25 m
- Range resolution: 58 to 17 m
- Number of looks: 4

Instrument components
- Transmitter-receiver
- Antenna (mechanically tiltable and folding)
- Digital data handling system
- HDRR
- Optical recorder

Instrument characteristics
- Peak power: 1 kW
- Antenna dimensions: 10.8 by 2.16 m
- Bandwidth: 12 MHz
- Data rate: 30.35 megabits (through HDRR)
- Sampling: 3 to 6 bits per sample

Data collection
- Optical data: 8 hours
- Digital data: 8 hours
- Total digital processing: 5×10^6 km^2

Orbit characteristics
- Altitude: 350,272,225 km
- Inclination: 57°

Mission
- Launch date: 5 October 1984
- Mission duration: 8.3 days
- Vehicle: Challenger
- Flight: 41G (STS-17)

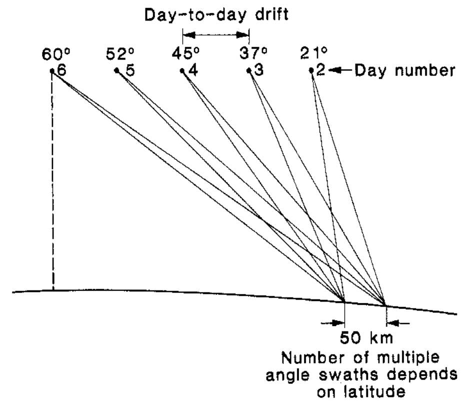


Fig. 2. Sketch illustrating the drifting orbit and the resulting multiangle-imaging capability.

was possible in most cases to boost the gain 10 dB to compensate in part for the loss in power.

In spite of these problems, a large number of SIR-B targets were imaged successfully, and sufficient data were obtained to demonstrate the value of the multiple angle capability. The final data set (Fig. 4) consists of about 8 hours of digital data covering about 6.4×10^6 km^2 of the earth's surface.

Oceanography

A ground truth campaign was conducted off the western coast of Chile to verify the ability of the SIR-B to image wave patterns. SAR ocean imaging theory indicates that a nonlinear relation leads to a rotation of the wave spectrum in the radar image and the nonlinear effect is proportional to the range divided by the velocity of the platform. Because of the low altitude of the shuttle, this ratio was significantly less for SIR-B than for Seasat (by a factor of 3). The results reported by Beal *et al.* (*11*) confirm the excellent correlation between the directional spectrum generated from the SIR-B imagery and the ground observation and verify the general behavior of the nonlinear effect. These results demonstrate that a low-altitude orbiting SAR can be used to provide the database for an accurate global surface wave prediction model.

Internal waves have been observed on airborne radar imagery (*13*), Seasat imagery (*2*), and SIR-A imagery (*3*). One of the SIR-B ocean experiments was an attempt to observe an internal wave packet simultaneously with ground truth. Such a fortunate situation occurred during one of the passes off Long Island, New York (Fig. 5). As reported by Gasparovic *et al.* (*12*), a number of internal wave packets were imaged in the immediate vicinity of the ground truth vessel while surface measurements were being acquired. The results of the application of their theoretical model to the observed situation are consistent with the SIR-B data to within a factor of 2. This finding represents a substantial advance in our ability to quantify the characteristics of the internal waves on the basis of satellite SAR data.

A fortuitous situation occurred on the last day of the flight when the shuttle orbit crossed Hurricane Josephine off the U.S. East Coast. SIR-B was able to acquire images of the ocean surface wave patterns close to the hurricane eye, under extensive cloud cover. These data were used by B. Holt and F. I. Gonzalez to identify two wave systems generated by the hurricane that underwent significant spatial and directional variations, and provided some insight into the generation of waves around the eye of the hurricane.

Ocean oil spills were detected on Seasat and SIR-A imagery but without corroborating evidence. In one of the SIR-B experiments off the coast of Japan, N. Fugono *et al.* discharged oleyl alcohol, a biodegradable alcohol that simulates the dampening effect of oil on ocean capillary waves. About 1 hour after the discharge, the spill was imaged by SIR-B over an area 1 km by 2.5 km.

Because of the high orbital latitude, it was possible to acquire radar imagery at the edges of the ice zone in the Weddell-Scotia Sea off the coast of Antarctica. This was the first time that the southern polar ice margin was imaged with a radar system. The analysis by F. Carsey *et al.* showed that ice flows were imaged as a mixture of piecewise linear and rounded edges, analogous to arctic flows in summer. In the band region of the ice margin, the ice-water contrast was reversed, an indication that the ice reflectivity was weaker than the open-water reflectivity. A number of icebergs (up to about 1 km) were imaged, the larger ones showing ocean waves diffracting around their edges.

Stereo Mapping

One of the key scientific objectives of the SIR-B experiment was to demonstrate the capability of stereo imaging. Stereo images were used to generate a digital topography database of Mount Shasta. Computer processing allowed the generation of perspective views of the mountain from multiple-look directions (Fig. 6). This result demonstrates the potential of spaceborne stereo radar data for three-dimensional analysis of the surface structure of the earth and the other planets. The data in Fig. 6 were generated by M. Kobrick and F. Leberl, using some human interaction for stereo merging. Automatic techniques for stereo merging have been developed by H. K. Ramapriyan.

Geology

Good coverage was acquired over the central section of the islands of Borneo and Sumatra. Because of intensive cloud cover, these areas have been only partially imaged by Landsat, even after a decade of observations. The analysis by J. P. Ford and F. F. Sabins of the SIR-B images over the tropical rain forest area shows a number of major geologic structures that can be discerned in the images, even with the subdued eroded topography. Their analysis verified that the interpretation techniques and classification schemes developed for the geologic analysis of SIR-A data in tropical areas (*4*) are broadly applicable.

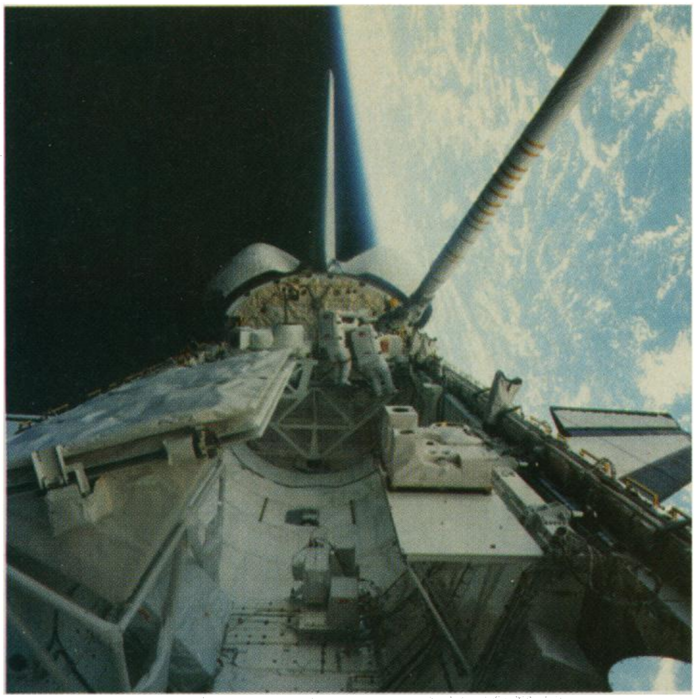


Fig. 3. Photo of the SIR-B antenna (before deployment) in the shuttle cargo bay.

One of the most dramatic results of the SIR-A experiment was the imaging of old buried river channels in the Egyptian desert. This led to a number of field investigations, which verified the presence of these channels, and theoretical studies, which confirmed the ability of the radar sensor to image morphological features through a few meters of dry sand cover (*5*). During the SIR-B mission, only a small area of the Egyptian desert was observed because of data transmission problems (*6*). One of the areas imaged by SIR-A was imaged again on SIR-B, reconfirming the capability of the radar to image the buried channels and identifying new areas of buried drainages (*8*).

To quantify the penetration capability of the radar signal in natural environments, investigators buried a number of radar receivers at different depths at a site near Walker Lake, Nevada. As the shuttle flew over, the radar signals were received by the buried receivers. From these data T. Farr *et al.* were able to derive the rate of wave attenuation through the soil (14 dB/m) for one of the sites where the moisture content of the soil was about 1%. This result is consistent with the results of laboratory measurements of wave absorption in moist soil.

A number of structural mapping experiments were also conducted. A. L. Bloom and his colleagues mapped large ignimbrite sheets in the Pune-Altiplano area of the Andes. These sheets are dissected by straight, parallel quebradas (gullies), whose regional consistency was not recognized before the SIR-B mission. A comparative study of the identification of faults in Turkey as imaged by SIR-A and of

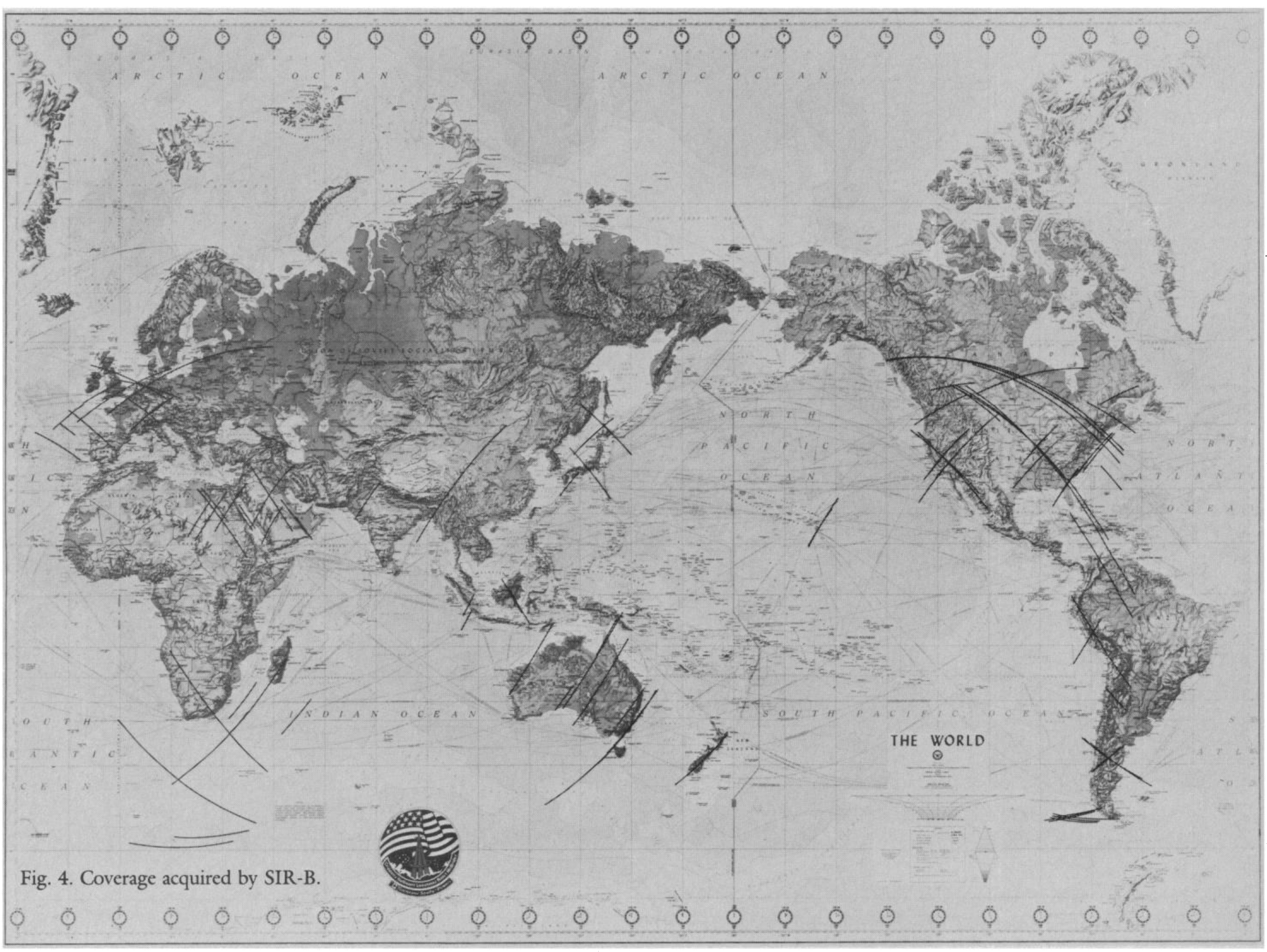


Fig. 4. Coverage acquired by SIR-B.

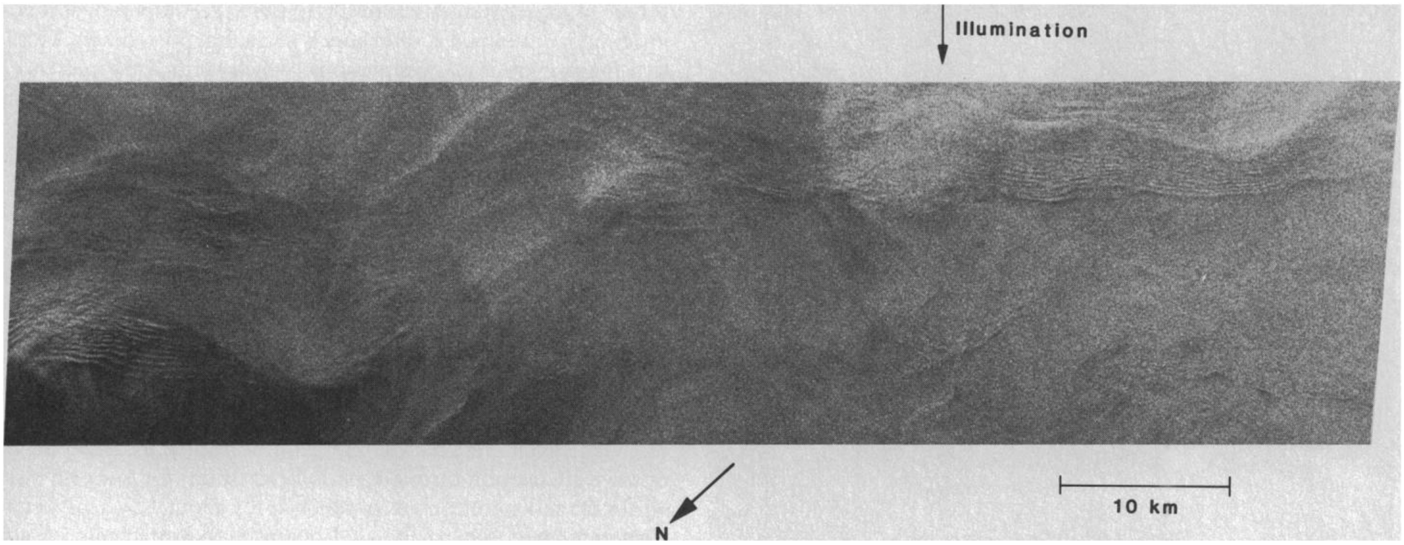


Fig. 5. Internal waves and surface wind patterns off the eastern coast of the United States near Long Island, as imaged by SIR-B on data take 96.21, scene 002. The center latitude and longitude are 40°10′N and 72°10′W, respectively, and the data were acquired at an incidence angle of 20°.

Fig. 6. Perspective view of Mount Shasta, California, generated by the use of two SIR-B images taken in a stereo configuration. A pair of stereo images acquired at two different angles was used to generate a digital topography database that was then superimposed on one of the images. [Courtesy of M. Kobrick and F. Leberl]

faults in California as imaged by Seasat and SIR-B was made by M. N. Toksoz *et al.* In both of these studies radar data were used in conjunction with Landsat data; this procedure enhanced the detection capability because of the complementary nature of these two data sets.

A number of enhancement techniques were used by M. X. Borengasser and J. Taranik to identify subtle linear features in Nevada. Textural analysis was used by S. E. Belliss and A. Oliver to identify lithologic units in the tectonically active eastern part of northern New Zealand. SIR-B data, in conjunction with Landsat data, were used by B. C. Forster *et al.* to do geologic mapping in the Amadeus Basin of central Australia.

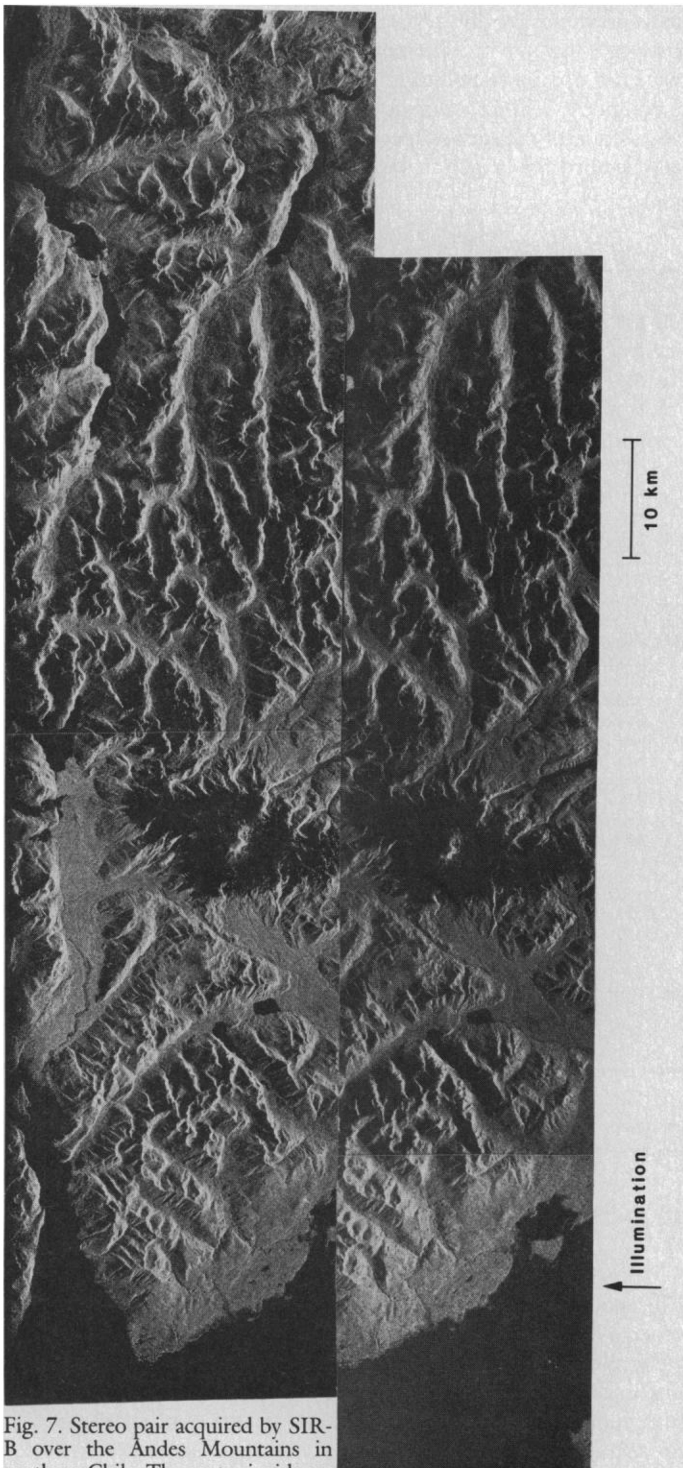


Fig. 7. Stereo pair acquired by SIR-B over the Andes Mountains in southern Chile. The center incidence angles of the images are 59.5° (data take 104.4, right image) and 45.1° (data take 72.4, left image). The images are placed such that they may be viewed in stereo with an airphoto supply stereoscope.

Multi-Incidence Angle Imaging

Multi-incidence angle imagery of a number of sites was used to classify terrain units by deriving their "angular signature." J. B. Cimino *et al.* used this technique to derive vegetation maps in the Cordon la Grasa region of western Argentina, and R. M. Hoffer *et al.* used this technique to classify forest cover at their test site in Baker County in northern Florida. Their results suggest that it may be possible to use "imaging radar angular scatterometry" in a manner similar to visible and infrared-imaging spectroscopy, for surface unit classification. The three-dimensional viewing capabilities available with the multi-incidence angle data sets are also useful for structural interpretation of geologic features. The capability is being assessed by A. L. Bloom for an area in the Andes Mountains of Chile, northwest of Cordon la Grasa (Fig. 7). The image angular signature was also used by T. Farr and D. Massonet and by V. Kaupp *et al.* to classify the lava flows types near Kilauea Volcano in Hawaii.

Land Ecosystems

A variety of land ecosystems experiments were also undertaken. The south central region of Bangladesh was the site of an experiment on the possibility of radar imaging through tropical vegetation cover. The Ganges River Delta was imaged (Fig. 8) on three successive days. M. L. Imhoff *et al.* observed penetration at all incidence angles and concluded that the soil surface and flooded areas under a mangrove canopy could be mapped. P. J. Mouginis-Mark carried out the first part of a comprehensive long-term study of delta systems, using Seasat, SIR-A, and SIR-B data. J. Wang *et al.* conducted an experiment to determine the relation between the radar image brightness and soil moisture, and to assess the effect of surface roughness and vegetation cover on the accuracy of measurements of soil moisture. Their results showed that the radar image albedo increases by about 2.3 dB per 0.1 g of soil moisture per cubic centimeter of volume; however, the contributions of surface roughness and vegetation cover are substantial.

The radar signature of different terrain cover in the Black Forest

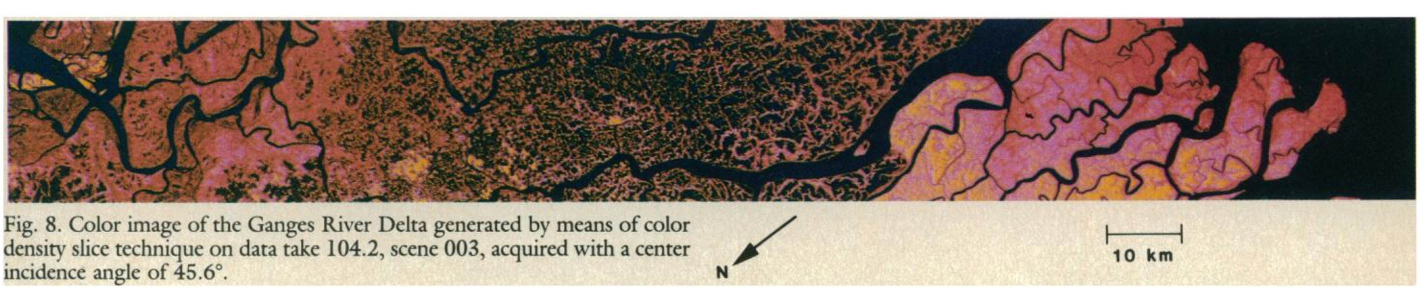


Fig. 8. Color image of the Ganges River Delta generated by means of color density slice technique on data take 104.2, scene 003, acquired with a center incidence angle of 45.6°.

of Germany was studied by A. J. Sieber *et al.* using SIR-B as well as airborne radar and truck-mounted scatterometer data. Their results showed that the high resolution of the airborne sensor made it possible to distinguish between coniferous and deciduous trees. In addition, they deployed a number of receivers on the ground to measure the SIR-B antenna pattern.

A study of the specular or cardinal reflections from urban and agricultural areas around Montreal, Canada, was conducted by A. L. Gray. He investigated a number of theories in an attempt to explain the higher sensitivity of SIR-B than of airborne radars to specular returns from well-organized coherent targets. These theories included the effect of the wave sphericity and the effect of beam width relative to the target directionality.

Sensor System Performance

To assess the performance of the SIR-B sensor during flight, a number of corner reflectors and transponders were deployed at numerous sites around the world. The results of A. Barber *et al.* show that the imaging resolution achieved from their test site in England is within 10% of the theoretical resolution. Three-meter corner reflectors and a variety of transponders were imaged.

Conclusion

The preliminary results of the SIR-B experiment demonstrate the significant scientific capability of such a remote sensor. The problems encountered during the mission seriously restricted the data coverage and quality. The next-generation instrument, SIR-C, will have the capability to image the surface at three frequencies (1.2, 5.6, and 9.2 GHz) and at all polarizations, thus allowing the acquisition of the surface spectral and polarimetric signature. SIR-C is scheduled for launch in 1990.

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