Spaceborne and Airborne SAR for Target Detection and Flood Monitoring

Huadong Guo

Abstract
The Spaceborne Imaging Radar—C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) mission was a cooperative endeavor of the United States, Germany, and Italy. The SIR-C/X-SAR scientific research program was a large international cooperative program of radar for Earth observation in which 13 countries participated, including China. SIR-C/X-SAR, with the ability to acquire polarimetric SAR and interferometric SAR data, was the first spaceborne radar to operate simultaneously at several frequencies and polarizations, representing the most advanced civilian SAR system for Earth observation. This paper will present some results of the SIR-C/X-SAR program made in China. The emphasis is placed on aerial and ground synchronous experiments with SIR-C/X-SAR overpasses, SAR penetration studies for dry sands, and SIR-C/X-SAR data applications in relevant fields and different areas, e.g., discovering the volcanoes of the Kunlun Mountains, detecting geological features underneath vegetation canopies, and revealing the Great Wall segments of the Ming and Sui dynasties. The paper also introduces the use of the Chinese airborne L-band SAR system, developed by the Chinese High Technology Program, for flood monitoring in 1998.

Introduction
The Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) was placed aboard Space Shuttle flights in April and October 1994 and successfully conducted two 10-day missions for Earth observation with 107 terabits of data returned (Stofen et al., 1995). Up to now, all other spaceborne imaging radar systems were characterized by single band and single polarization, including Seasat SAR, SIR-A, SIR-B, Almaz-1 SAR, JERS-1 SAR, ERS-1/2 SAR, and Radarsat. The SIR-C/X-SAR has the following distinct characteristics: (1) the first multifrequency imaging radar system to be simultaneously operated in Earth orbit, (2) the first multipolarization imaging radar system, and (3) a system with interferometric measurement ability. This system largely utilizes wavelength, polarization, magnitude, and phase information of electromagnetic waves, enabling further exploitation of electromagnetic resources in the microwave bands. The multifrequency, multipolarization capability creates a new and powerful tool for detecting surface targets more accurately and efficiently.

As an integral part of the SIR-C/X-SAR research program, the Chinese team has conducted multidisciplinary research work for Chinese test sites. A simultaneous experiment with airborne SAR imaging and ground measurements was carried out during the Shuttle Endeavor's overpass. With the advanced SAR data, detection and analysis for terrain surface and subsurface as well as man-made features were conducted. The unprecedented flood disaster of 1998, which occurred along the mid and lower reaches of the Yangtze River, was successfully monitored with an L-band airborne SAR system developed by the Chinese High-Technology Program.

SAR System Characteristics and Chinese Test Sites
SIR-C/X-SAR System Characteristics
SIR-C/X-SAR was operated at L-, C-, and X-bands, which can acquire data for the same target at the same time. There are four polarization combinations at the L- and C-bands, i.e., HH, HV, VH, and VV polarizations. In addition, SIR-C can provide phase-difference images of four polarized echoes, from which a full scattering matrix can be derived and full polarimetric SAR information can be obtained. X-band SAR has VV polarization only (Table 1). The viewing angle is adjustable aboard and ranges from 15° to 60°. The acquired SIR-C/X-SAR data were mainly recorded and saved onboard; a small amount of data were sent to the ground via the Tracking and Data Relay Satellite System for real-time data processing.

SIR-C/X-SAR developed and applied four advanced techniques. These are interferometric SAR, ScanSAR, calibration, and SAR data real-time processing techniques. Based on the repeated-pass interferometric imaging principle, interferometric SAR data collection was performed during the last three days of the second SIR-C flight, obtaining a great deal of interferometric SAR data including China's test sites. To meet the needs of a large-scale study for natural resources, environment, and technical experiments, ScanSAR images were acquired during two flights of the SIR-C/X-SAR missions with a maximum swath width of 200 km. The radiometric calibration was performed for the SIR-C/X-SAR data. Thus, this allowed the use of the SIR-C/X-SAR data to directly derive radar backscattering coefficients and to conduct a quantitative remote sensing study. Another key technique developed was a real-time SAR processor on the ground, which is a high-speed processor with data rate of 45 Mbps and is capable of continuously outputting SAR image data. Data strips of 7 km can be processed per second.

SIR-C/X-SAR Test Sites in China
The design of the SIR-C/X-SAR test sites in China began in 1990. After studying the SIR-C/X-SAR parameters, six test sites were selected, including the Xinjiang, Inner Mongolia, Guangdong, Hubei, Taiwan, and Hebei (Beijing, Shandong, and Hebei) areas. The major application fields were geology, forestry, oceanography, penetration studies, etc. According to the difference of terrain features and SIR-C/X-SAR data application

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objectives, viewing angles were first determined for the central coordinates of each test site, and imaging modes were then selected based on the chosen viewing angles. SIR-C/X-SAR has 23 imaging modes (Stofan et al., 1995). Apart from X-band VH polarization for X-SAR imaging, the other modes are different combinations of RH, HV, VH, and VH polarizations at the L and C bands. Modes 22 and 23 were specifically designed for interferometric SAR. In addition to different radar information being acquired at different modes, the radar information was also affected by the differences in imaging swaths.

During the flights of the Space Shuttle Endeavor in April and October 1994, SIR-C/X-SAR imaged all the test sites in China in accordance with our requirements. The imaging swath usually ranged from 15 to 90 km in width. The length of each image strip varied for each data take depending upon the imaging time. Some strips were a few hundred kilometers in length but some exceeded 2000 km. A total of 90 minutes of SIR-C/X-SAR data were acquired for the Chinese test sites. In addition, the astronauts on board the Space Shuttle Endeavor took handheld camera photos of the test sites when weather conditions allowed. These photos provided very useful data for performing a comparative study with the radar images.

**Chinese Airborne L-SAR System**

In 1997, China developed an airborne L-band SAR operational system, with the support of the Chinese High Technology Program (863-308), with the objective of conducting preliminary research for a Chinese spaceborne SAR system to be launched following the turn of the century.

The system has been placed aboard the Citation S/II aircraft owned by the Chinese Academy of Sciences. The flight altitude varies from 6,000 to 10,000 m, and the flight velocity is 550 km/h. The L-SAR system is operated at 1250 MHz with HH and VH polarizations and left and right viewing directions. Table 2 gives the operational modes of the L-SAR system.

The L-SAR system has a wide application potential for detecting targets beneath canopies forest and dry deserts, mineral exploration, offshore exploration, studying oceanic waves, mapping underwater topography, etc. The system has demonstrated its power in monitoring the flood disaster that occurred in the mid and lower reaches of the Yangtze River.

**Spaceborne-Airborne Ground-Based Radar Remote Sensing Experiment**

One quantitative remote sensing method is to make ground measurements during the flight of airborne or spaceborne remote sensing experiments. We conducted this experiment at a Beijing test site during the overpass of SIR-C/X-SAR. From 18 to 20 April 1994 when SIR-C/X-SAR imaged the test site, an X-band airborne SAR developed by the Chinese Academy of Sciences (CASSAR) was imaging the same area at the same time. Meanwhile, a truck-mounted scatterometer was measuring the ground surface's backscattering coefficients. The surface roughness was measured and samples were collected.

The CASSAR operated in the X-band and HH, VH polarizations. Its resolution is 10 m by 10 m. The flight altitude was 7200 m. The azimuth and range directions were designed to coincide with the first mission of SIR-C/X-SAR (SRL-I). The incidence angles were 73.93° to 83.12°. CASSAR included both an optical processor and a digital real-time processor for data processing. However, during the operation the optical mode was used, and the data were not calibrated. The truck-mounted scatterometer operated in the X-band with four polarizations. The antenna was fixed on a boom about 12 m high. It could illuminate at any azimuth direction and elevation angle from 0° to 84° with a 6° interval. A Lunenburg sphere was used for external calibration prior to measurement. The measured distributed targets included bare soil, winter wheat, rice staple, water bodies, etc. During the observations, vegetation and soil parameters such as biomass, soil moisture, and surface roughness were measured in real-time (Wang et al., 1996).

During the first SIR-C/X-SAR mission, the truck-mounted scatterometer data acquired in real-time were used for calibration of the Chinese airborne CASSAR data and SRL-I survey image in the Beijing test site. In the image linear range, the regression precision is less than 2 dB (except for the L-band data). However, due to the limited dynamic linear range of dis-

### Table 1. SIR-C/X-SAR System Characteristics (After Jordan et al., 1995)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>L-Band</th>
<th>C-Band</th>
<th>X-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Altitude (km)</td>
<td>23.5</td>
<td>225</td>
<td>3.1</td>
</tr>
<tr>
<td>Wavelength (cm)</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH, HV, VH, VV</td>
<td>HH, HV, VH, VV</td>
<td>VV</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>30 x 30</td>
<td>10 x 20 m</td>
<td>15 ~ 60</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>13 and 26 m</td>
<td>13 and 26 m</td>
<td>15 ~ 90</td>
</tr>
<tr>
<td>Swath Width (km)</td>
<td>20 ~ 55</td>
<td>10 ~ 20</td>
<td>20 ~ 55</td>
</tr>
<tr>
<td>Look Angle (°)</td>
<td>33.17, 8.5 μsec</td>
<td>40 μsec</td>
<td>33.17, 8.5 μsec</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>6.4</td>
<td>6.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Transmit Pulse Length</td>
<td>1240 and 1736 pulses per second</td>
<td>1240 and 1736 pulses per second</td>
<td>1240 and 1736 pulses per second</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>90</td>
<td>90</td>
<td>45</td>
</tr>
<tr>
<td>Data Rate (Mbps)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Acquisition Time (h)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NB: except as specified in the table, other parameters in the L and X bands are the same as those in the C band.

### Table 2. Operational Modes of the L-SAR System

<table>
<thead>
<tr>
<th>Modes</th>
<th>A</th>
<th>B1</th>
<th>B2</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (km)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Slant range (km)</td>
<td>6.4 ~ 10</td>
<td>9 ~ 18</td>
<td>9 ~ 27</td>
<td>15 ~ 24</td>
<td>15 ~ 33</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
<td>3 x 3</td>
</tr>
<tr>
<td>[Image produced on the ground]</td>
<td>3 x 10</td>
<td>6 x 10</td>
<td>3 x 10</td>
<td>6 x 10</td>
<td>6 x 10</td>
</tr>
<tr>
<td>Resolution (m) [Image produced aboard in real-time]</td>
<td>3 x 10</td>
<td>6 x 10</td>
<td>3 x 10</td>
<td>6 x 10</td>
<td>6 x 10</td>
</tr>
</tbody>
</table>

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Target Detection and Recognition have received a lot of attention from geologists in the world. For many years they have performed for the samples collected from the two sites. By measuring the experimental penetrating depths and determining the penetration conditions, the following conclusions have been drawn:

1. The theoretical maximum penetrating depth of SIR-C/X-SAR is 2.2 m for dry sands in Inner Mongolia (Shao et al., 1995); and
2. The reason for selecting site 2 was to study the attenuation process of microwaves in dry sands. Two corner reflectors were placed on the surface of the Gobi Desert. Because the penetration depth of SAR is closely related to the moisture of the materials on the ground, the measurement for the moisture and complex dielectric constant of sands was performed for the samples collected from the two sites. By measuring the experimental penetrating depths and determining the penetration conditions, the following conclusions have been drawn:

(1) The theoretical maximum penetrating depth of SIR-C/X-SAR is 2.2 m for dry sands in Inner Mongolia, but it is possible to detect objects deeper than 2.82 m (Shao et al., 1995); and
(2) The reasons for selecting site 2 were: (a) to observe the penetration capability of microwaves in natural conditions, and (b) to understand the process of microwave attenuation in natural sands. Site 2 was selected in an area of the Gobi Desert where about 20 cm layer of dry sand covered the unconsolidated Cenozoic aluvium. Here, six corner reflectors were buried in the spaces to depths varying from 0.93 to 2.73 m with dry sands taken from other places. The reason for selecting site 2 was to study the attenuation process of microwaves in dry sands. Two corner reflectors were placed on the surface of the Gobi Desert. Because the penetration depth of SAR is closely related to the moisture of the materials on the ground, the measurement for the moisture and complex dielectric constant of sands was performed for the samples collected from the two sites. By measuring the experimental penetrating depths and determining the penetration conditions, the following conclusions have been drawn:

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Detection of Lithology Beneath the Vegetation Canopy In a subtropical region, it is very difficult to carry out geological surveying and mapping due to the depths of soil and dense vegetation cover. Poor coherence of field data within the vegetation cover is therefore the main problem. Synthetic aperture radar images, especially the multi-parameter SAR, may detect geological features beneath vegetation cover (Guo et al., 1996). Some of the information extracted from SAR images is impossible to obtain from visible remote sensing data. On 18 April 1994, the SIR-C/X-SAR flew over the Zhao Qing region in the Guangdong Province of southern China and acquired one data take at mode 11 (L-HH, L-HV, C-HH, C-HV, and X-VV). The research work in Zhao Qing with SIR-C/X-SAR data demonstrates the advantages of multi-parameter SAR technology in detecting the geological structures and lithology beneath a vegetation canopy. This study was aimed at providing fundamental information for geological surveying and mapping at scales of 1:106,000 and 1:200,000.

It is difficult for color infrared imagery to distinguish sedimentary rocks and determine their strike and dip orientation, which are essential elements for geological surveying and mapping. The difficulties in multi-frequency, multipolarization color composite SAR images for the Zhao Qing test site reveals the beds of sedimentary rocks beneath the dense vegetation cover. On a false-color SIR-C composite image using L-HH (R), L-HV (G), and C-HV (B), there are large bands of cyan, and magenta to grayish brown stripes. The stripes are parallel to each other and have clear boundaries and a sawtooth shape. These are only visible
in the SAR image: no traces of the stripes are found in the Landsat TM image or in the color infrared airphoto at a scale of 1:35,000 due to vegetation cover. The distribution pattern of these colored stripes is the same as the occurrence of sedimentary clastic rocks of the Devonian Guitou Formation (D2-3) on the north slope near Zhao Qing city. These color stripes can be identified as beds of Devonian sedimentary rocks because of the V-shaped outcrop of two adjacent formations, shown in the SAR image in a sawtooth pattern. A V-shaped outcrop of a geological boundary represents a line along which a contact between two adjacent formations or beds intersects the Earth's surface. Field-work confirmed that these color stripes represent beds of sedimentary rocks of the D2-3 formation. There are a few outcrops of these Quartzose sandstones and siltstones covered with dense vegetation growing in a thin layer of soils.

The formation of the color stripes comes mainly from the L-band image. Sun and Ranson (1995) pointed out that the backscatter received by the SAR system from a vegetated area is composed of five components. One is the trunk-ground component. L-band microwave penetrates the crown layer of the trees and reaches the ground, so there are distinct variations of intensity from the top of the slope to the bottom in the L-HH and L-HV images. It is not clear in the C-band image and there are no variations in the X-VV image. L-band SAR images show the geological features beneath a vegetation canopy better than does the X-band image. The vegetation canopy is comparable to an enveloping surface over the land surface conforming to the topography. The radar return from the X-band image comes from the top of the tree canopy whereas the longer-wavelength microwave penetrates through the vegetation layer and collects the sub-canopy information.

Archaeology
The Great Wall segments in a desert region of north central China, within the boundaries of Ningxia and Shanxi provinces, were revealed by the SIR-C/X-SAR images (JPL, 1996). Three Walls were unidentified, two of them built in the Ming dynasty and one in the Sui dynasty. The Great Wall of the Sui dynasty was built in the year 585 with rammed earth. It is now discontinuously elongated, about 4 m in width and 1 to 3 m in height. The Great Wall of the Ming dynasty was built in 1531 with rammed earth. The remnant wall is about 6 to 8 m in height and 6 to 8 m in basal width.

Figure 2 shows a small portion of the Great Wall in four black-and-white images representing SIR-C's four radar channels. The radar beam was perpendicular to the Great Wall, resulting in a corner reflector effect which enabled the SAR to detect two generation walls effectively. In the area where sand covers the Wall segments, long wavelength SAR's penetration ability reveals the Wall's features and displays them on the SAR images. In terms of wavelength, the L-band is obviously better than the C-band for revealing the Wall's features. In terms of polarization, HH polarization is better than HV polarization. On the L-HH and C-HH images, the Great Wall of both the Ming and the Sui dynasties are shown, but it is difficult to see that both of them existed simultaneously. Figure 3 shows visualization models of radar backscattering intensity for the two generation's of the Great Wall (on the right of the L-HH image) and the roads to the left of the Wall (only seen on the L-HV image). Trees lining a road parallel to the Wall show up as bright rectangles because the L-HV and C channels are sensitive to complex vegetation structure.

L-SAR Applications
The Chinese airborne L-band SAR system has demonstrated its capability in monitoring natural hazards, especially the unprecedented flooding events of the Yangtze River. When the third flood peak passed through Jiu Jiang City of Jiangxi Province, the L-SAR system was flown over the area, acquiring 27,700 km² of real-time, high-resolution data for the Poyang Lake area, which experienced the highest flood stage ever recorded. SAR images of the Dongting Lake area were also acquired from 27 to 31 July, 1998. Researchers at the Institute of Remote Sensing Applications, Chinese Academy of Sciences promptly processed and mosaicked the SAR images. On the basis of human-computer interactive analysis, the total
flooded area and the individual flooded areas by county (city) were calculated in detail. The inundated area was further classified into farmland, towns, residential areas, grassland, and damaged fish ponds (Plate 1). Maps of the inundated areas were produced and provided to decision-making authorities.

**Conclusions**

This paper presents research work on the applications of SIR-C/X-SAR data in the test sites of China as well as the applications of Chinese airborne L-band SAR data for flood monitoring. In the spaceborne-airborne ground-based remote sensing experiment, a linear relationship was derived for terrain features and image gray level. In the SAR penetration experiment for desert sands, it was found that the long wavelength SAR is able to penetrate dry sands from a depth of several centimeters to a few meters. Five volcanoes and two types of lava flows have been discovered with SIR-C/X-SAR data. Geological structures and rock types beneath a forest canopy were detected by SIR-C/X-SAR data in a subtropical region. The Great Wall segments of the Ming and Sui dynasties in a desert area were revealed with SIR-C/X-SAR data. An airborne L-band SAR system developed in China was used for monitoring flood events which occurred in the middle and lower reaches of the Yangtze River in 1998. Our study indicates that SAR data is a powerful tool for detecting the Earth’s resources, studying the Earth’s environment, and monitoring floods and other natural disasters.

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Plate 1. Chinese L-band airborne SAR imagery showing the flooding situation of Poyang Lake in 1998.
Sciences, the Hi-Tech Research and Development program of China, and the National Aeronautics and Space Administration of the United States of America for their support.

References


(Note: The customary western practice of listing author’s family names last, except in the list of references where only the first author’s name is listed family name first, is followed herein.)

Special Session on ASPRS/NASA-CRSP
Ten-Year Remote Sensing Industry Forecast

Wednesday, May 24
3:30-5:00 PM

Mark your calendar to attend a special session on the ASPRS/NASA-CRSP Ten-year Remote Sensing Industry Forecast. The session, to be held during the ASPRS Annual Conference in Washington, DC, will be moderated by ASPRS Primary Data Acquisition Division Director Charles Mondello, EarthData Technologies.

ASPRS and the NASA-Commercial Remote Sensing Program are conducting a 10-Year Remote Sensing Industry Forecast, which began in October 1999. The study will provide a baseline to determine the current state of the remote sensing industry, and advance during the next 5 years to establish a “rolling horizon” of forecast data for remote sensing applications, business development, technology opportunities, and investment guidance.

The panel session will report the progress of the study:

Study Group Organizations and Staff
Industry Definitions
Forecast Study Areas
Definitions of Customer Segments
Forecast Framework
Review of the ASPRS Membership Survey Document

Panelists:
Ron Rabin, Lockheed Martin Space Operations-Stennis Prog.
William Piper, NASA-CRSP
Mike Renslow, ASPRS President
Nate Boyer, Eastman Kodak
Mindy Brown, Space Imaging

Alan Mikuni, US Geological Survey
John Schott, Rochester Institute of Technology
Len LaFeir, Autometric, Inc.