SPACEBORNE IMAGING RADARS FOR EARTH'S REMOTE SENSING

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SUMMARY

Spaceborne synthetic aperture radars (SARs) generate high resolution, wide-swath coverage maps of the surface which resemble aerial photographs. Since SARS are active, microwave instruments, they can operate in day and night situations and are nearly independent of cloud and weather conditions. in the past two decades, SAR imagery had been applied to numerous Earth's remote sensing studies. This paper provides an overview of some of the spaceborne SAR activities that are on-going at the Jet Propulsion Laboratory. The potential scientific applications of SAR imagery are discussed and the recent development of a Shuttle imaging Radar-C (SIR-C) is described. Finally, the development of the associated data processing systems that are used to convert the radar instrument signal into imagery for several SAR missions is summarized.

INTRODUCTION

Spaceborne synthetic aperture radars (SAR) generate high resolution, wide swath coverage maps of the Earth's surface which resembles aerial photographs. Since SARS are active microwave instruments, they can operate in day and night settings and in nearly all weather and cloud conditions. in the past two decades, a number of spaceborne SARS have provided such imagery for various Earth's remote sensing studies. This paper provides an overview of the spaceborne SAR activities that are on-going at the Jet Propulsion Laboratory (JPL) under the sponsorship of the U.S. National Aeronautics and Space Administration.

One measure of the "goodness" of an imaging instrument system is its ability to discriminate spatial details in the scene being observed. High resolution systems are those which can differentiate two closely spaced objects, an ability generally achieved only at the cost of a large viewing aperture. For a given angular resolution, the required aperture size Increases with the wavelength employed and to achieve a spatial resolution of several tens of meters operating at a large range from the scene for a spaceborne system, the use of a traditional large physical aperture in a microwave radar would require an real-aperture antenna size that is prohibitively large. A SAR overcomes this aperture size problem by forming a large, virtual aperture by coherently combining multiple radar echoes as the SAR is carried along Its flight path by the spaceborne platform. Fig. 1 illustrates the basic principle behind the operation of a SAR. In the cross-track dimension, the radar achieves high resolution by transmitting short radar pulses. The different arrival times of the return from the scene can be used to separate targets in the cross-track dimension. Due to limitations of peak transmit power and in order maintain the required signal-to-noise ratios, most spaceborne SARS utilize longer radar pulses with wide bandwidths. Pulse compression techniques are then used to process the radar returns to generate results that effectively correspond to those from radars with very short pulses. In the along-track dimension, the radar echoes at multiple along-track positions are coherently recorded and, in a subsequent data processing step, coherently combined together. This step synthesizes a large, virtual aperture which leads to the high along-track resolution desired. In this way, an antenna only, say, 10 meters long can lead to image resolution comparable to that available from a real antenna that would have to be 10 kilometers in length. Further discussions on the operation and design of SAR systems can be found in Elachi(88) and Tomiyasu(78).

The first civilian spaceborne Earth's observation mission that carried a SAR was SEASAT (Jordan), which operated from July to September 1978. It was a hallmark achievement in that it demonstrated the technical feasibility of spaceborne SAR operation and the radar results showed promise in many areas of Earth's remote sensing. Since the SEASAT mission, we at JPL have flown two additional SAR systems on the NASA Space Shuttle. These two systems, referred to as Shuttle Imaging Radar-A and -B (SIR-B), were flown in 1981 and '84 respectively and they provided imagery for a number of scientific investigations (Special Issue on SIR-B (86)). Table 1 shows a brief summary of the performance characteristics of the SEASAT SAR, SIR-A and SIR-B. In the remainder of this paper, we will illustrate some of the potential environmental remote sensing applications of SAR data in Section II, describe the design and characteristics of the next shuttle-borne SAR, SIR-C in Section III and discuss SAR data processing issues in Section IV. It should be noted that although this overview paper draws mainly on the activities at JPL, a number SAR systems are being flown and planned to be flown on multiple space missions by many different countries and world agencies. All told, these multiple missions represent a multibillion dollar international Investment in Earth's observations using SARs. A collection of papers describing these international efforts can be found in a Special section on spaceborne radars (Proc. IEEE (91)). It Is expected that this international set of SAR missions will provide global radar imagery throughout the 90s and beyond.

II. POTENTIAL APPLICATIONS OF SAR IMAGERY IN EARTH'S REMOTE SENSING

A number of key Earth's system science studies utilize SAR measurements. An excellent summary of these potential applications is given in a NASA EOS SAR panel report (88). For example, SAR imagery have significant applications in ecosystems dynamic studies. Atmospheric carbon dioxide flux from deforestation is a key unknown parameter in determining the contribution of the carbon cycle to global warning. Estimation of this flux requires measurement of the extent of areas of deforestation and the biomass of the existing forests. The spaceborne SAR systems have the potential of measuring both the green (leafy) biomass and total biomass. The SAR results can also help to determine vegetation water content and canopy structure. Another key area of potential SAR application is the measurements of soil moisture. It has been difficult to use traditional remote sensing Instruments to measure soil moisture as surface roughness and vegetation confuse the measurements. New advances using multi-frequency, multi-polarization radar measurements may help to separate soil moisture effects from other geophysical parameters. In fact, the soil moisture measurements may best be obtained by a combination of SAR radar results and other remote sensor data.

SAR imagery collected in the polar regions have been used in many polar ice research studies. Since SAR imagery can provide fine-scale mapping of sea ice extent, the data can be used to follow the formation, deformation, breakup and motion of sea ice. It has also been shown that the radar return can be used to evaluate the ice type (Le. ice age) and Ice concentration. These results are crucial ingredients in the studies of ice dynamics, heat flux and other polar region modeling. issues. The SAR results also contribute to the understanding of the solid Earth's geophysical processes. With its sensitivity to surface structure and roughness, the SAR imagery will provide global perspective of the Earth's crust and the processes that influence its evolution. With the potential ability of the radar signal to penetrate dry soil, the SAR is an essential tool in determining the geological evolution of many of the highly arid regions of the world. The data can be used to measure the extent, rates and conditions indicative of desertification and soil erosion, both human and climate induced.

Many of these potential application rely on the physical mechanism of the interaction of the radar signal with the terrain under study. The wavelength used for these spaceborne SAR systems typical ranges from 3 to 30 cm. The backscatter return originates from interaction of the radar signal with surface structure that has spatial sizes similar to the radar wavelength. In addition, the backscatter process also depends on the relative geometry of the "scatterers" and the polarization state of the radar signal. Finally, the relatively long wavelength allows the signal to penetrate, to some degree, surface-cover layers such as canopies, snow or arid soil. All these physical properties are crucial to the exploitation of SAR results.

Another significant potential application of spaceborne SAR is in the area of high resolution topography mapping. Such high resolution topography data of global land mass are essential input to many studies in geophysics, hydrology and ecology (see Topographic Science Working Group report (88)). Typical spatial resolution required for such a data set is 10 to 50 m with height resolution of 1 to 5 m. A very promising technique to generate such a global topography data set Is a spaceborne Interferometric SAR. This type of SAR system utilizes two antennas to observe the same area with the two antennas separated by an appropriate Interferometric baseline (Li and Goldstein (90)). The difference in the phase values measured for a given image pixel between the two antennas can be converted to topographic information. A number of airborne and spaceborne Interferometric SAR concept demonstration experiments were conducted in the past 15 years and topography measurement accuracy matching those required was demonstrated to be achievable. It is expected that this potential application will be addressed by future spaceborne SAR missions.

III. SIR-C SYSTEM DESCRIPTION

One of the key on-going SAR activities at JPL is the development of the third in the series of shuttle-borne imaging radars, SIR-C. As mentioned in Section 1, SIR-A and SIR-B flew in the 80s and obtained L-band radar imagery for different regions around the globe. SIR-C consists of an L-band and a C-band, multi-polarization radar system. In addition, an X-band SAR (XSAR) that is developed by Germany/Italy will fly in conjunction with SIR-C. The combined SIR-C/XSAR system will provide simultaneous radar imagery over a decade of radar wavelength. It Is envisioned that the results from these wavelengths will be highly complementary in terrain geophysical characterization.

SIR-C/XSAR is mounted inside the shuttle cargo bay and is planned to launch Into an orbital inclination of 57°. After an initial instrument checkout period, the shuttle will orient itself such that the radar antenna beams will illuminate the Earth's surface and a total of about 50 hours of radar observation will be conducted over a 6 to 8 day mission. An artist conception of the deployed SIR-C/XSAR antenna system is shown in Fig. 2. As discussed below, the SIR-C system utilizes a distributed phase array and different observation viewing geometry will be accomplished by electronically scanning the antenna beam in the elevation (cross-track) direction while the whole XSAR antenna system will be mechanically tilted to alter its viewing angle. For simultaneous 3-frequency observations, the SIR-C antenna beams will be positioned electronically to match the mechanically oriented XSAR antenna beam location.

A detailed description of the SIR-C/XSAR system can be found in Jordan et al (91). A brief summary of its system parameters is given in Table 2. There are several major system characteristics of interest:

a. The system can operate in multiple modes of different polarization combination. In some of the modes, the transmit pulse will alternate between horizontal and vertical linear polarization and for each signal reception interval, the backscatter signal at horizontal and vertical polarization will be captured and recorded concurrently. It has been demonstrated by previous airborne multi-polarization experiments that data collected in this fashion will allow the generation of the complete scattering matrix for each pixel in the imaging (Zebker et al (87)). A key objective of the SIR-C experiment is to evaluate and demonstrate the utility of these scattering matrix measurements for remote sensing;

b. The system is designed to be flexible in its operation setup so that the science experimenters can optimize the system parameters for the specific experiments of interest. Options for parameters that can be selected include: frequency (L, C, or both), polarization (single, dual, or quad), transmit pulse width (3 options), range resolution (2 options), data digitization scheme (4 bit/sample, 8 bit/sample or 4 bit samples obtained from an 8-bit block floating point quantize), etc. These parameters affect the total data swath acquired, the system resolution and signal-to-noise ratio. As in many other SAR systems, the high spatial resolution typically leads to a very high data rate. For SIR-C, the raw radar data are recorded on high density digital tape cassettes on-board the shuttle. The data are then processed by a ground data processor upon the return of the shuttle to Earth (see Section IV). The limits In the rate and volume of the data recording in term impose constraints on the data collection swath. The experimenter must consider the tradeoffs between coverage and signal-to-noise ration of the final image. This choice is not typically available in other spaceborne SAR systems. Occasionally, in order to match the desired data coverage, the experimenter can select to deliberately "spoil" the elevation antenna patterns to match the areas captured by the data recording. This flexibility increases the potential scientific return of the system but also creates substantial complexity in the radar system, data processing and especially in mission planning;

c. SIR-C utilizes a distributed phase array antenna on which multiple transmit/receive (T/R) modules are populated across the entire physical antenna aperture. The phase array approach provided the capability for electronic beam steering to alter the radar illumination geometry without requiring shuttle attitude maneuvers. By placing the T/R modules at the antenna surface, the signal-to-noise ratios (SNR) for the measurements are substantially enhanced since signal losses due to antenna feed network is reduced. Finally, the multiple T/R modules provide an inherent high degree of redundancy. In traditional SAR systems, the transmitter and receiver are "centralized" and limited in number (typically, a conventional spaceborne SAR carries 1 or 2 sets of transmitter/receiver units). Failure in these units can lead to total termination of radar operation. The multiple T/R modules will allow a more graceful degradation in performance even if a limited number of them fail.

At present, the SIR-C/XSAR system is going through the final stages of integration and test at JPL. In 1993, the system will be shipped to the NASA/Kennedy Space Center for integration onto the shuttle. The first launch is expected to be in early 1994 and a second launch of this system is planned for 1995 at a different season relative to the first launch.

IV. SAR DATA Processing ACTIVITIES AT JPL

In many SAR systems, the raw radar echoes are digitized and the aperture synthesis process is performed by a separate data processing system. For the free-frying satellite-borne systems, the data are relayed to the ground through high rate data links and in the case of SIR-C, the data are recorded on high density digital data tapes that are retrieved after the landing of the shuttle. In all these systems, the radar echo data are then transferred to dedicated ground data processors which convert them into high resolution SAR imagery.

A key reason that the process of conversion of radar raw data into imagery is performed on ground data systems and not as part of the spaceborne sensor system is the large computational rate required. Consider an example of a spaceborne SAR system that has a 100 km data collection swath. For a typical spatial resolution of 50 m x 50 m, the rate of image pixel acquired is -280,000 per second. For a SAR system that utilizes pulse compression, signal processing in the cross-track dimension is required in addition to the along-track aperture synthesis processing. The number of arithmetic operation required for each pixel typically ranges in the hundreds to thousands in each dimension. The required computational rate is in the range of hundreds of mega-floating point operations (FLOR) to several gigs-FLOPs per sec. This imposes a tremendous demand on the SAR data processor. It should be noted that, in addition to high computation rate, SAR processing also requires high i/O rate and large data volume storage. In order to reduce the computational load, many ingenious algorithms have been developed. Balmer (92) discusses the relative performance of a number of these algorithms. They typically employ Fast Fourier Transforms (FFTs). However, even with these algorithms, the SAR processing is still too computationally intensive for on-board processing. indeed, the SIR-C data processing is performed on the ground with a general--purpose, commercial machine with multiple, parallel processing units. Many commercially available peripherals are used for housing the data at various stages of processing and for the recording and printing of the final imagery products. We have also developed special purpose hardware that allows the transfer of the raw radar data from the high density data tapes to the processing system. This processor system is near its final stage of development and is planned to be integrated and tested prior to the launch of SIR-C.

in addition to using commercial computers for SAR processing, we have also developed SAR data processing systems based on special purpose, custom-designed processing units. An example is the system for the Alaska SAR Facility (ASF). ASF is a joint effort between JPL and the University of Alaska at Fairbanks, sponsored by NASA. Its purpose is to track and collect SAR data from a number of international spaceborne SAR systems and process the data into radar imagery. The primary application of the SAR imagery is in areas of polar ice research. Fig. 3 is a block diagram for this processor facility. The “workhorse” of the system is a special purpose, custom-designed pipe-line SAR processor. The system design relies heavily on FFT for the correlation processing of the data. Special-purpose FFT circuit boards and large memory boards for matrix transpose are utilized. This system has been routinely tracking and processing data from the European ERS-1 and the Japanese JERS-1 SAR systems in the past year. The processed imagery has been distributed to the science community for geophysical studies. The details of this facility can be found in Hilland et al (91).

V. DISCUSSION

This paper presents a brief overview of some of the spaceborne SAR activities at JPL and some potential applications of SAR data in Earth remote sensing. Although the multi-frequency, multi-polarization data that SIR-C/XSAR will generate represent a substantial improvement In the quality and completeness of radar measurement of the Earth’s terrain, the limited duration of the shuttle missions will not allow a long term observation and monitor of the global surface. We are in the process of planning for a potential series of free-flying spaceborne SARS that will be launched in the late 90s or early 2000’s. This series of SAR systems is envisioned to be an element of the NASA Earth Observing System and will provide large scale, long term, continuous studies of the Earth.

V1. ACKNOWLEDGMENT

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REFERENCES

Balmer, R., "A Comparison of Range-Dopplw and Wavenumber Domain SAR Focusing Algorithms", IEEE Trans. Geos. Remote Sensing, Vol. 30, no. 4 pp. 706-713, July, 1992.

Elachi, C., " Spaceborne Radar Remote Sensing: Applications and Techniques", NY: IEEE Trans., 1988.

Hilland, J., T. Bicknell, and C. Miller, "The Alaska Synthetic Aperture Radar (SAR) Facility Science Data Processing Architecture", International Astronautical Federation, 42nd Congress Proceedings IAF-91-155, October 1991.

IEEE Trans. Geos. Remote Sensing, Special Issue on the Shuttle Imaging Radar, Vol. GE-24, July 1986.

Jordan, R., "The SEASAT-A Synthetic Aperture Radar System", IEEE J. Oceanic Eng., Vol. OE-5, Apr. 1980.

Jordan, R. Il. Huneycutt, and M. Werner, "The SIR-C/XSAR Synthetic Aperture Radar System", Proc. IEEE, Vol. 79, no. 6, pp. 827-838, June, 1991.

Li, F. and R. Goldstein, "Studies of Multibaseline Spaceborne Interferometric Synthetic Aperture Radars", IEEE Trans. Geos. Remote Sensing, Vol. 28, no. 1, pp. 88-97, Jan. 1990.

National Aeronautics and Space Administration, "Earth Observing System Instrument Panel Report, Volume IF, SAR", 1988.

Special Section on Spaceborne Radars for Earth and Planetary Observations, Proc. IEEE, Vol. 79, no. 6, June 1991.

Tomiyasu, K., "Tutorial Review of Synthetic Aperture Radar (SAR) With Applications to Imaging of the Ocean Surface", Proc. IEEE, Vol. 66, pp. 563-583, 1978.

Topographic Science Working Group Report to the Land Processes Branch, Earth Science and Application Division, Lunar and Planetary Institute, NASA, Houston, TX, 1988, pp. 64.

Zebker, H. J. vanZyl, and P. Held, "Imaging Radar Polarimetry From Wave Synthesis", J. Geophy. Res., Vol. 92, pp. 683-701, Jan. 1987.

Table 1. Key parameters of Spaceborne SAR missions developed at JPL (XSAR is a joint Germany/Italy development to be flown in conjunction with SIR-C)

KEY MISSION PARAMETERS	SEASAT	SIR-A	SIR-B	SIR-C /XSAR
FREQUENCY (GHz)	1	1	1	1,5,10
POLARIZATION	HH	HH	HH	HH,HV,VH,VV
LAUNCH	'78	'81	'84	'93

TABLE 2 Key SIR-C System Characteristics

Parameter	L-band	C-band
Orbital Altitude		225 km
Wavelength	0.235 m	0.058 m
Resolution	30x 30 m on the surface	
Swath Width	15 to 90 km	15 to 90 km
Look Angle Range	20 to 55 degrees from nadir	
Pulse Repetition Rate	1395 to 1736 pulses per second	
Data Rate	90 Mb/s	90 Mb/s
Data Format	8.4 b/word and (8,4) BFPQ	8,4 b/word and (8,4) BFPQ

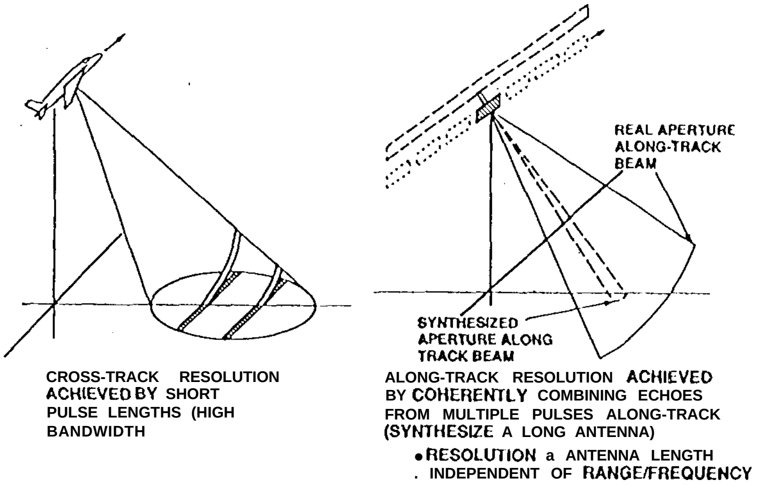

Figure 1, Overview of synthetic aperture radar design principle.

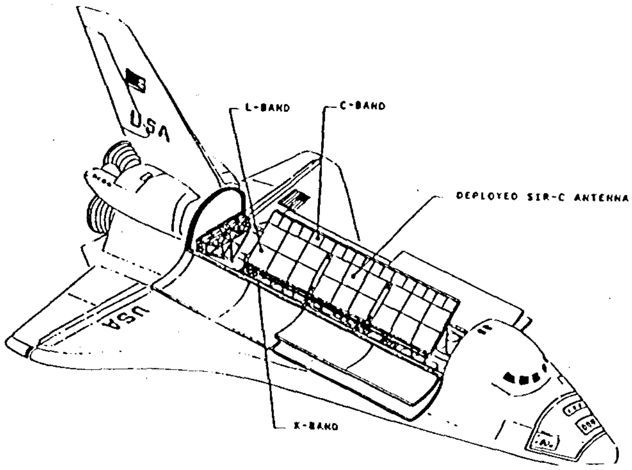

Figure 2. Artist's concept of deployed SIR-C/X-SAR antenna in the shuttle cargo bay. The three antenna sizes are: 12-m x 2.95-m (L-band), 12-m x 0.75-111 (C-band), and 12-m x 0.4-111 (X-band).

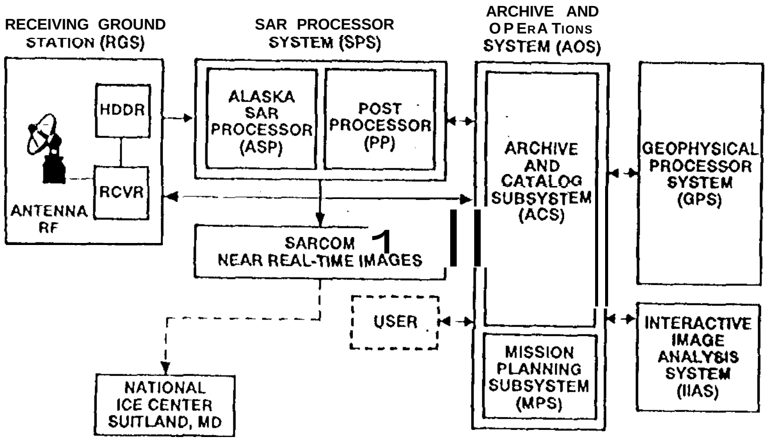

Figure 3. Schematic block diagram for the equipment in the Alaska SAR Facility. The key systems are: Receiving ground station, SAR processor, archive and operations system, and geophysical processor system. The SAR data from several international spaceborne SAR systems are tracked and captured by receiving ground stations and then processed by the SAR processor. The geophysical processor system extracts certain geophysical information from the SAR imagery (such as ice motion, ice type, etc.). The operation, data archive, and distribution is controlled by the archive and operations system.