

SPACEBORNE SYNTHETIC APERTURE RADAR

FOR IMAGING SEA ICE

by

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ABSTRACT

The preliminary design of a Synthetic Aperture Radar (SAR) for imaging sea ice has been completed in response to functional requirements established by the Ice and Climate Experiment (ICEX) Science and Applications Working Group. The radar is required to produce high quality imagery in near-real time of both polar regions above 60 degrees latitude, with a two-day repeat cycle of complete coverage. Ice type, extent, morphology, and dynamics are the primary geophysical parameters to be derived from the images.

The SAR operates at X-band (about 3 cm wavelength) and provides a 360 km-wide continuous image swath from a 700 km orbit. The imagery has a 23 dB dynamic range, pixels of 100 x 100 m, and good geometric and radiometric accuracy. A high resolution mode provides imagery with 25 x 25 m pixels over a 90 km swath.

The design details of the dual planar array antenna and the sensor on the spacecraft, the near real-time digital ground processor, and the expected performance of the system are described.

INTRODUCTION

Synthetic Aperture Radars (SARs) carried over the Arctic during the last several years by aircraft and the Seasat spacecraft have demonstrated [1,2] that high-resolution, all-weather, day-or-night, high-quality imagery of sea ice can be acquired on a synoptic scale. The analysis of such data has shown that SAR, in fact, is a unique tool for studying sea ice extent, morphology and dynamics at various space and time scales, and to a lesser extent for determining ice age. Thus, when NASA initiated the ICEX (Ice and Climate Experiment) study in 1979, a high performance SAR system was included by the Science and Applications Working Group (SAWG) in the baseline instrument complement [3] for the proposed experimental spacecraft. In response to preliminary functional requirements established by the SAWG, personnel of the Jet Propulsion Laboratory carried out a short feasibility study for a SAR capable of meeting these requirements. This paper summarizes the requirements, presents the design details of the end-to-end radar system, and describes its expected performance characteristics.

FUNCTIONAL REQUIREMENTS

The purpose of the radar system is to provide continuous imaging of the North and South polar regions above 60 degrees latitude, with a two-day repeat cycle of complete coverage. To allow derivation from the imagery of the geophysical parameters of interest, in particular ice age, the system has to operate at X-band (about 3 cm wavelength or 10 GHz frequency), has to provide imagery with 100 m pixels, and has to have a 23 dB dynamic range. In addition, the images have to have high quality and good geometric and radiometric (amplitude) accuracy. A high resolution mode yielding imagery with 25 m pixels over selected areas is also desired. The complete set of requirements together with key derived parameters, are listed in Table I.

Of note is the parameter of swath width, computed to be 345 Km for complete coverage in 2 days, from the required 700 Km satellite altitude. To allow for edge effects and to facilitate mosaicking of individual swath pieces, this was increased to 360 Km, and was specified to be obtained in a single continuous piece. This requirement is a major driver of the system design, and to denote its importance, the system was dubbed the Wide Swath Imaging Radar, or WSIR.

SYSTEM DESIGN

The WSIR is an X-band imaging radar using synthetic aperture techniques to obtain high resolution and operating at 9.6 GHz. It is designed to obtain continuous imagery with a 360 Km swath and 100 m pixel spacing from a 700 Km, near polar, orbit. A simplified block diagram is shown in Figure 1.

The radar system consists of a dual antenna subsystem and a sensor subsystem which are flown on the satellite. A digital correlator to generate image data from the raw radar data and a pixel processor are on the ground at a central location. An on-board high-density tape recorder together with a high-rate communication channel using the Tracking and Data Relay Satellite (TDRS) are used to link the spacecraft portion of the radar system with the ground station portion.

Each of the two antennas consists of a pair of 19 x 0.6 m planar arrays oriented parallel to the spacecraft velocity vector, with their normal axes boresighted at an angle of 28.6 and 37.9 deg respectively with respect to local nadir as shown in Figure 2. One of the antenna pairs is oriented to the right of the spacecraft and is used to image one of the polar regions, the other pair is oriented to the left of the spacecraft and is used to image the other pole. Each individual antenna array has a field-of-view of about 9.25 deg, and the two arrays of each pair are time-shared to generate two contiguous 180 Km wide subswaths of radar image. The pixel processor on the ground merges the two image strips into a single continuous swath. A detailed description on how the time-sharing is to achieve the required swath is given in Appendix A.

Table I. ICEX WSIR REQUIREMENTS

Wavelength	3 cm (x-band)
Range of Angles of Incidence	25-45 deg
Output Image Pixel Size	100 x 100 m (low resolution) 25 x 25 m (high resolution)
Number of Looks	4 or more
Swathwidth*	360 Km (low resolution) 90 Km (high resolution)
Polarization	Horizontal transmit, Horizontal receive
Range of Surface Reflectivities	-23 dB to 0 dB
Dynamic Range	3 to 6 bits per sample (low resolution) 3 to 4 bits per sample (high resolution)
Contrast Ratio	10 dB or Better
Surface Coverage	Complete above 60 deg Lat. (North and South), in 2 days
Duty Cycle*	30% Per Orbit
Data Format	Continuous
Data Availability	24 hours or less
Data Products	Images on Film and on High Density Digital Tape
Output Image Quality	Geometrically Correct and Radiometrically Linear
Amplitude Accuracy	Best Possible
Location Accuracy	100 meters
Data Telemetry	On-Board Recorder/TDRSS
Data Processing	Central Ground Station
Spacecraft	Multimission Modular Spacecraft (MMS)
Mission Life	3 Years Minimum 5 Years Desired

* Derived parameter

The operation of the system is as follows. The sensor derives its phase reference from the reference generator and upon command from the controller, a conventional CHIRP (frequency-modulated) signal is generated by pulsing a Surface Acoustic Wave Device (SAW line). The system incorporates four separate SAW lines to provide the appropriate CHIRP signal for the correct subswath and for the resolution mode. The CHIRP signal is amplified and frequency translated to X-band, and then amplified to a 3.3 kW peak power level (100 W average) by a pulsed traveling wave tube amplifier. One amplifier is used for each array in an antenna pair to avoid switching in the high power lines; the two amplifiers are pulsed alternately as required to provide illumination of the 180 Km subswaths. Following the amplifier and the receiver protector-circulator, the "pole switch" allows the selection of either antenna pair on the two sides of the spacecraft to image the desired polar regions. Accounting for the losses of the switches, the radiated power is approximately 2.5 kW peak (70 W average).

In the receiver, the return echo is amplified and down-converted with spectrum inversion to the SAW line intermediate frequency. The signal is then passed through an identical SAW line to that used for transmission and thus is range compressed. Two receivers, one for each antenna, are used to avoid switching and to provide redundancy. The signals are then frequency translated to range-offset video, digitized, stored in a buffer, formatted, and transmitted to the on-board tape recorder of the spacecraft telemetry system, at a rate of 19.8 Mbps and 26.7 Mbps in the low and high resolution modes, respectively. Subsequently, the data are played back at high rate into the TDRS data system which beams it to a terminal at White Sands, New Mexico. At White Sands, the data are recorded on a high density digital recorder (HDDR) for playback into the data correlator.

The correlator reads raw data in blocks of approximately 75 pulses and generates a multi-look, 150 m resolution map of a 180 km wide subswath. The azimuth pixel spacing is approximately 100 meters. After generating a nominal amount of imagery from one subswath, the correlator returns to the initial data and generates imagery from the other subswath. The inner and outer subswath imagery is produced in such a manner that the range lines register in the azimuth direction. Correlator output data is recorded on HDDR tapes for transfer to the pixel processor.

The pixel processor reads the HDDR output tapes from the correlator, combines the two separate subswaths to produce the full 360-Km range lines, performs resampling in range to convert from slant range to ground range and to obtain 100 m pixels, and provides radiometric correction. The data is then stored on a high density tape and recorded on photographic film at a rate of 270 kilo-bytes per second with each byte corresponding to the reflectivity of a 100 x 100 m pixel element.

The system also provides a commandable functional option which allows the production of imagery with a pixel size of 25 x 25 m. This is accomplished by switching in a wider bandwidth CHIRP and by reconfiguring the data sampling and formatting subsystems, and by utilizing only one of the two antennas. The swathwidth achieved in this mode of operation is 90 Km (rather than 360 Km). The output data rate is increased but there are no additional complexities in the rest of the system.

SUBSYSTEM DESIGN

Antenna Subsystem. The WSIR antenna subsystem consists of four horizontally polarized 19.0 x 0.6 m planar waveguide arrays and appropriate feed networks mounted on a single aluminum supporting structure. The arrays are arranged in a "W" configuration as shown in Figures 2 and 3 to point the antenna beams at the proper cross track angles. In the launch configuration the complete assembly is folded once to reduce its length to slightly less than 10 m. It is then preloaded and latched against the spacecraft. After the spacecraft is released from the Space Shuttle cargo bay, the antenna is deployed and locked into position by the shuttle crew using built-in alignment pins and fixtures.

Each antenna array is made of 8 sections approximately 2.4 m long by 0.6 m wide, uniformly fed by an 8-way corporate feed, and is composed of slotted half-height, thin-wall copper plated graphite epoxy waveguides. In the H-plane, amplitude and phase are controlled to yield a shaped beam which nearly compensates for the progressively increasing free space loss and decreasing surface reflectivity through the swath illuminated by the beam. This not only eliminates the need for a Sensitivity Time Control (STC) circuit in the receivers but allows lower average power to be transmitted.

The peak gain of each antenna, including all losses from the transmitter output port is estimated to be 45 dB; the overall stowed size is approximately 10 x 2.5 x 1.0 m, the deployed size 19 x 2.5 x 0.5 m, and the weight approximately 160 Kg.

It is felt that the antenna subsystem described here is at the leading edge of technology from several points of view, requiring additional study in at least the following areas:

- (a) The 0.6 m width for each array is the theoretical minimum required to perform a 2-harmonic approximation to the trapezoidal pattern shape desired and it may be necessary to increase this width to achieve performance.
- (b) The number of radiating slots that can be effectively fed needs to be determined to ascertain whether 8 or 16 panels are needed. If it is 16, the overall electrical and mechanical design is considerably more complex.
- (c) The mechanical structure has to be such that a 0.6 cm flatness is maintained over the 19 m long antenna after deployment and through its operating thermal environment. This might require the use of composite materials rather than aluminum in the panel support structure.
- (d) Alternate antenna configurations such as two 36 x 0.3 m (instead of four 19 x 0.6) arrays, reflector type systems, and frequency scanning arrays need to be examined for performance and cost effectiveness.
- (e) In-flight performance degradation needs to be modeled.

(f) Performance test approaches need to be developed or refined.

Sensor. The design of the sensor is based on military aircraft radar technology to the extent possible and incorporates the applicable lessons learned during the development of the successful Seasat SAR system. The configuration of the sensor is as shown in Figure 1; solid state design is used throughout except for the power amplifiers which are pulsed traveling wave tubes. The four amplifiers and their driver units are mounted on the back of the antenna structure to minimize RF losses. The transmitter system parameters are: volume 0.14 m³, weight 130 Kg, dc power 476 W and heat load 376 W. The rest of the sensor is mounted in the electronics bay of the spacecraft and has the following parameters: volume 0.16 m³, weight 62 kg, dc power 155 W and heat load 150 W.

(a) Transmitter. Of the four power amplifiers used, two are energized at one time during operation. During standby, only filament power is dissipated; high power dissipation occurs during transmission only. As described earlier, the two transmitters are pulsed alternately to develop the appropriate subswaths. A spare amplifier in each string can be switched in in case of failure. Additional amplifiers could be included in the system if required to meet the 3 to 5 year operational requirement of the spacecraft. Included in the transmitter module are receiver protector-circulators, and the "pole switch". Heat removal is by conduction to a base plate, and thence, by radiation to space.

(b) Electronics. The electronics assembly is comprised of the exciter, the receiver, the controller, the data formatter and the power supply modules, all of which are basically following Seasat SAR technology.

- (1) Exciter - A reference signal generator produces all low level RF signals for the radar, coherently with an ultra-stable crystal-controlled oscillator. Generation of the linear FM (CHIRP) pulses uses surface acoustics wave (SAW) devices. Redundant drivers are cross-strapped rather than switched to any of the four CHIRP generators (low and high resolution, near and far swath) and to all four power amplifiers for maximum reliability.
- (2) Receiver - Each receiver provides amplification of the radar echos, match-filtering (CHIRP compression), and conversion to baseband. Gain control is by ground command.
- (3) Controller - A microprocessor based controller generates all timing signals and sequences, provides mode controls, formats monitor and status signals for telemetry, accepts commands, and merges spacecraft parameters and time into the radar data stream.
- (4) Data Formatter/Buffer - Digitizes radar echos and converts them into a serial stream. Encodes spacecraft parameters, time and other pertinent data, and provides a buffering function with the data recorder.

- (5) Power Supply - Conditions the spacecraft bus power into various voltages as required by user circuits. The power converter provides isolation, regulation, and protection from bus transients and fluctuations. The power amplifiers have their own integral modulation and high voltage power supplies.

Ground Processor. The digital ground processor consists of two subsystems: the correlator and the pixel processor. The input to the system is by high density digital tape. The primary output product is a catalogued archival quality data set on high-density magnetic tape (HDDT). These data can also be transmitted subsequently or in parallel over high speed data lines to operational users, or they can be recorded on film by a laser beam recorder for subsequent photoprocessing and product distribution. The system is sized to process 8 hours of radar data in an 8-hour work shift which leaves two additional 8-hour shifts per day for maintenance and repair.

(a) Digital SAR Correlator. The digital SAR data correlator accepts raw data on high density tapes and transforms these data to digital images covering a 360 Km swath. The output data are recorded on high density tapes in fixed block format for later transfer to the pixel processing subsystem, or are fed directly to the pixel processor. The correlator consists of a minicomputer, standard peripheral equipment, and a custom designed high-speed time-domain correlator unit. It incorporates self-test and display capability to facilitate performance monitoring and maintenance.

(b) Pixel Processor. The input to the pixel processor subsystem is fixed block-formatted files from the digital correlator subsystem which contain image pixels arranged in full swathwidth range lines along with the data required to determine the sensor location, orientation, and time. The pixel processor is capable of processing at least 270,000 pixels per second to support 8-hour per day radar operation. It performs the following operations on the pixel data:

- (1) radiometric correlations for range, antenna pattern and incidence angle
- (2) image enhancement
- (3) slant range to ground range conversion
- (4) range resampling
- (5) scaling and formatting
- (6) annotation (time and location)

In addition the following tasks are performed:

- (1) data record production
- (2) archival record production and retrieval
- (3) image production
- (4) limited interactive image production (volatile display and hardcopy on request)
- (5) data record transmission

The implementation of the processor utilizes a large scale mini-computer which serves as the host CPU, and array processors for the pixel processing computations. For technical (redundancy) and economic reasons, this computer is expected to be identical to the one used in the correlation portions of the system. The host CPU handles all executive functions, annotations, part of the image enhancement computations, and the interactive display of the image data being processed.

SYSTEM PERFORMANCE

The system performance is characterized by the range of surface reflectivities (σ_0) that the SAR system will image linearly, and the degree of image degradation that will be suffered due to system imperfections. The range of reflectivities that the WSIR system will image linearly is shown in Figure 4 for the low resolution mode. The derivation of the performance curves is accomplished by computing the overall system gains and losses at varying look angles. As seen in the figures, the difference between the system sensitivity requirement as indicated by the curve labeled "ice model", and nominal system noise-equivalent σ_0 is of the order of 5.0 dB for the 180 Km subswath nearest the nadir and 0 dB for the other subswath in the low resolution mode. In the high resolution mode, the system performance margin is approximately 3 dB over the near subswath and -5dB for the far subswath, indicating that this mode can only be used over areas where the ice reflectivity is substantially higher than indicated by the model at the larger angles of incidence. Based on the SEASAT SAR experience, system imperfections should decrease the above performance estimates only slightly.

CONCLUSION

The WSIR system design presented here represents the results of the first iteration of a complex and lengthy design optimization process both at the overall system and the subsystems level. These results show that the functional requirements levied by the ICES Science and Applications Working Group can fundamentally be implemented, albeit with a complex, heavy, high power, and costly system. In particular, the antenna subsystem, the transmitter power amplifiers, and the ground digital data processor represent substantial technological challenges at the frontiers of the present state-of-the-art. Undoubtedly, however, such a system will be designed and implemented in the not too distant future since it can obtain imagery of unique value not only over ice, but land and the oceans as well.

APPENDIX A
WIDE SWATHWIDTH IMAGING RADAR OPERATION

The operation of the dual beam synthetic aperture radar system is as follows. The system consists of two antennas which are identical and are boresighted at an angle of 28.6 deg and 37.9 deg from local nadir. Each antenna illuminates a different portion of the 360 km swath and the radar system uses first one antenna to get the first portion of the swath, gathers enough data to obtain imagery of the region illuminated, and then switches to the second antenna to get the remainder of the swath.

The process of generating the continuous imagery is described next. Initially, the radar system is connected to antenna A and a total of 75 pulses are transmitted at a pulse repetition rate which results in low range and azimuth ambiguities. As shown in Figure A-1, the antenna illuminates during the first pulse the region along track between 0 and 3X. As the satellite moves, the antenna aperture illumination moves towards increasing values of X until, approximately 75 pulses later and after a time interval T, the aperture illumination along track is between X and 4X. Thus, any point which lies between X and 3X (the cross-hatched area) from the reference is fully covered for an interval of T seconds. At this point, the transmitter and receiver switch to Antenna B where a similar process gathers data, and the system obtains complete illumination over T seconds for terrain between 2X and 4X from the reference point. At time 2T, the transmitter and receiver are switched back to Antenna A and the previously mentioned process gathers data between 3X and 5X from the reference point. Thus, complete coverage is obtained for both swaths. Allowances have to be made for the round trip delay between the antenna and the surface but nevertheless complete coverage is obtained. For WSIR, the time interval T (or switching interval) is 0.075 seconds. The distance illuminated by the antenna is 1.7 Km with 1150 m imaged per image cycle. The synthetic aperture length is approximately 570 m resulting in a single look resolution of 27 m. Thus a total of 5.6 looks may be obtained at a 150 m radar resolution corresponding to a final image pixel size of 100 m.

The correlator makes the imagery of the cross-hatched area available to the pixel processor and the pixel processor corrects for any intensity variation in each swath frame and generates continuous corrected imagery.

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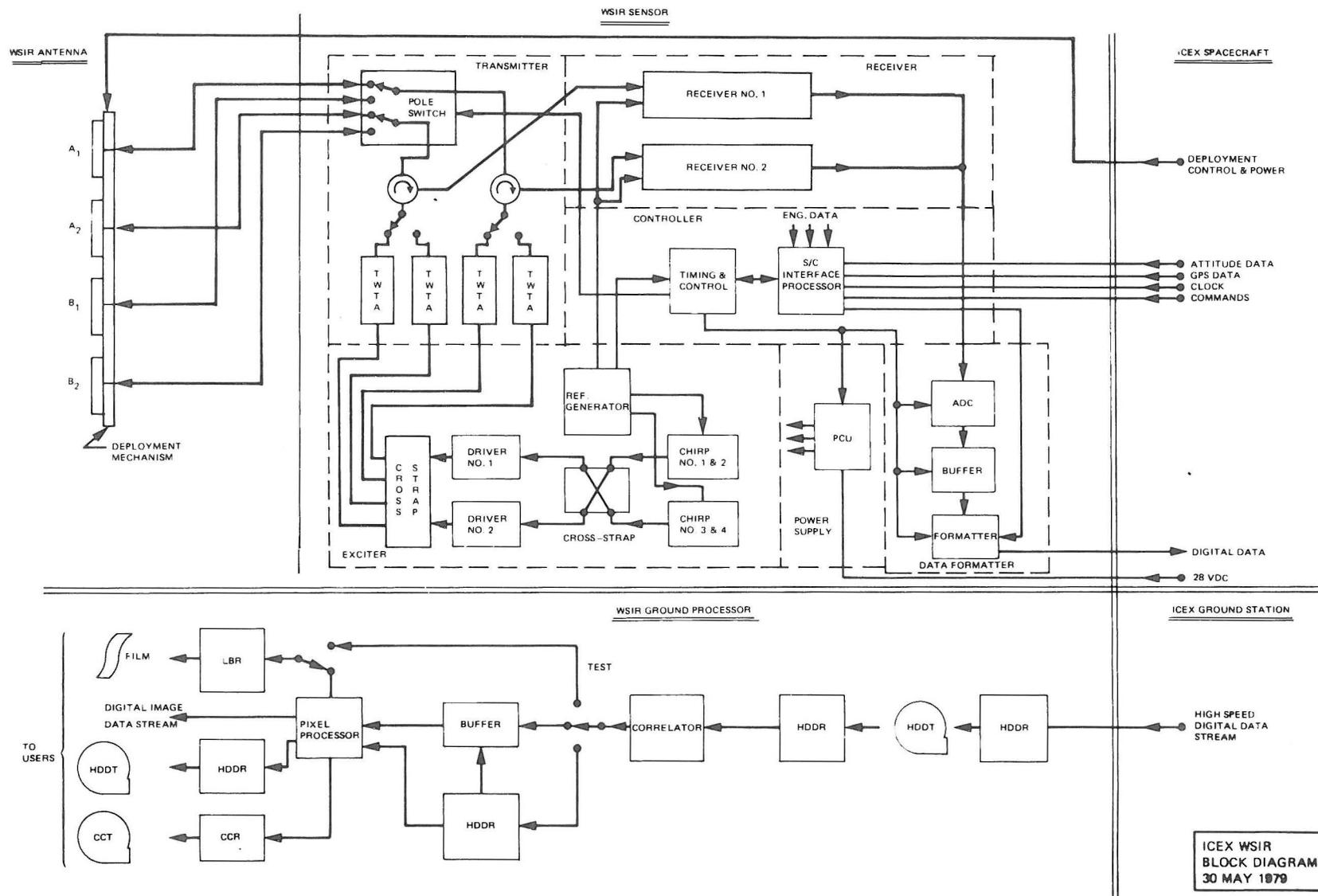
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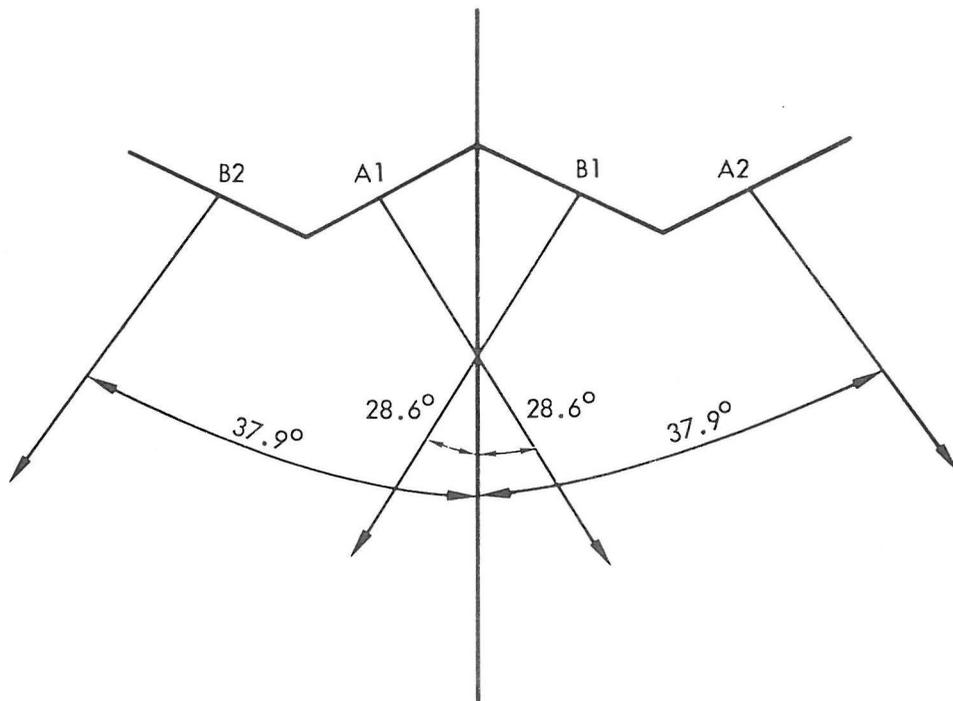
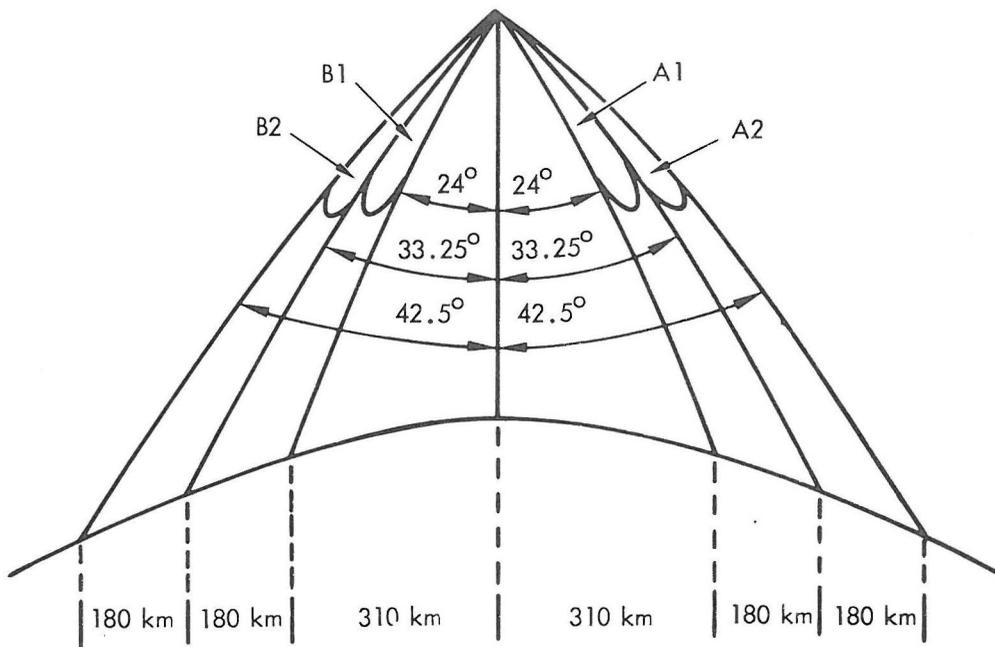
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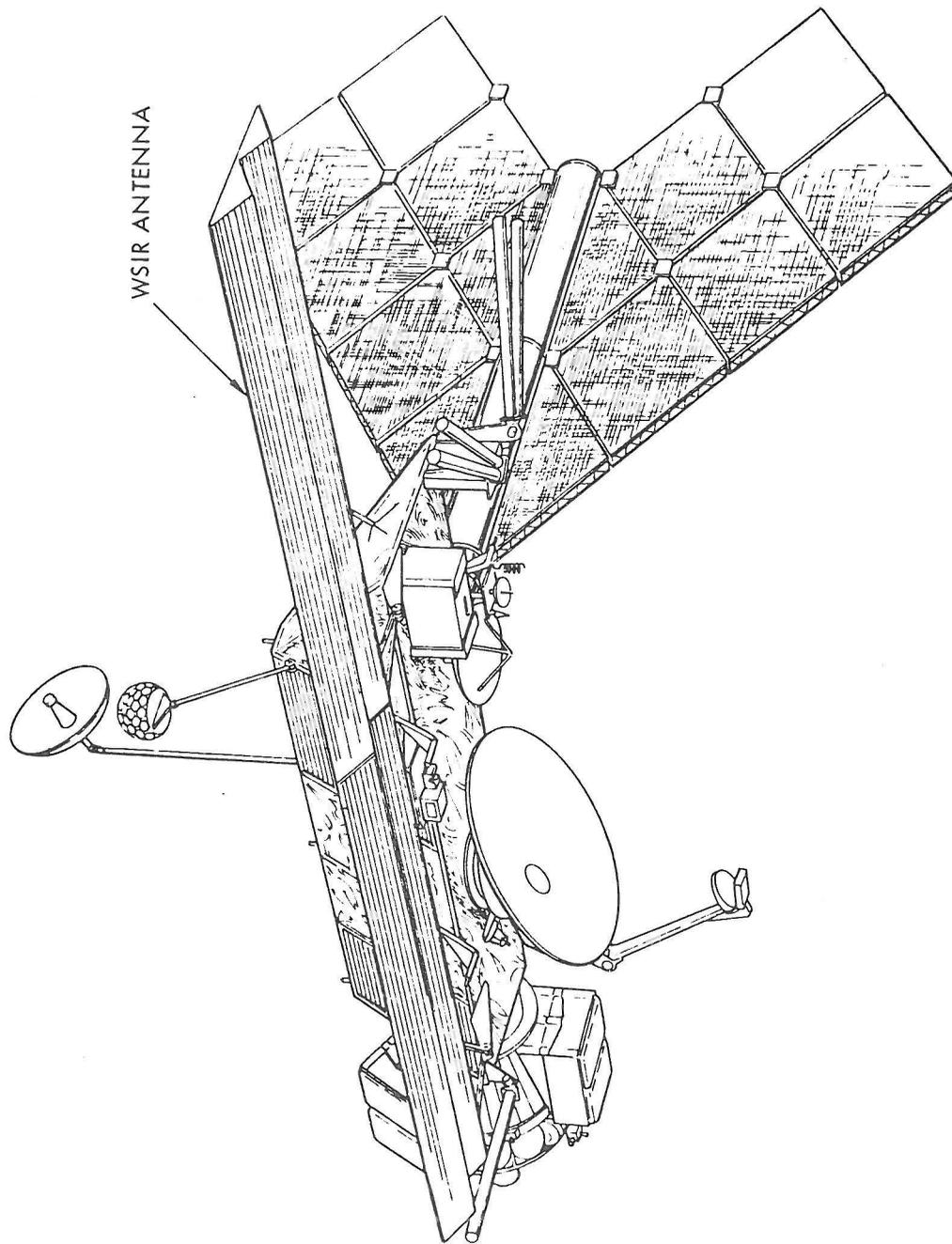
Captions for Figures

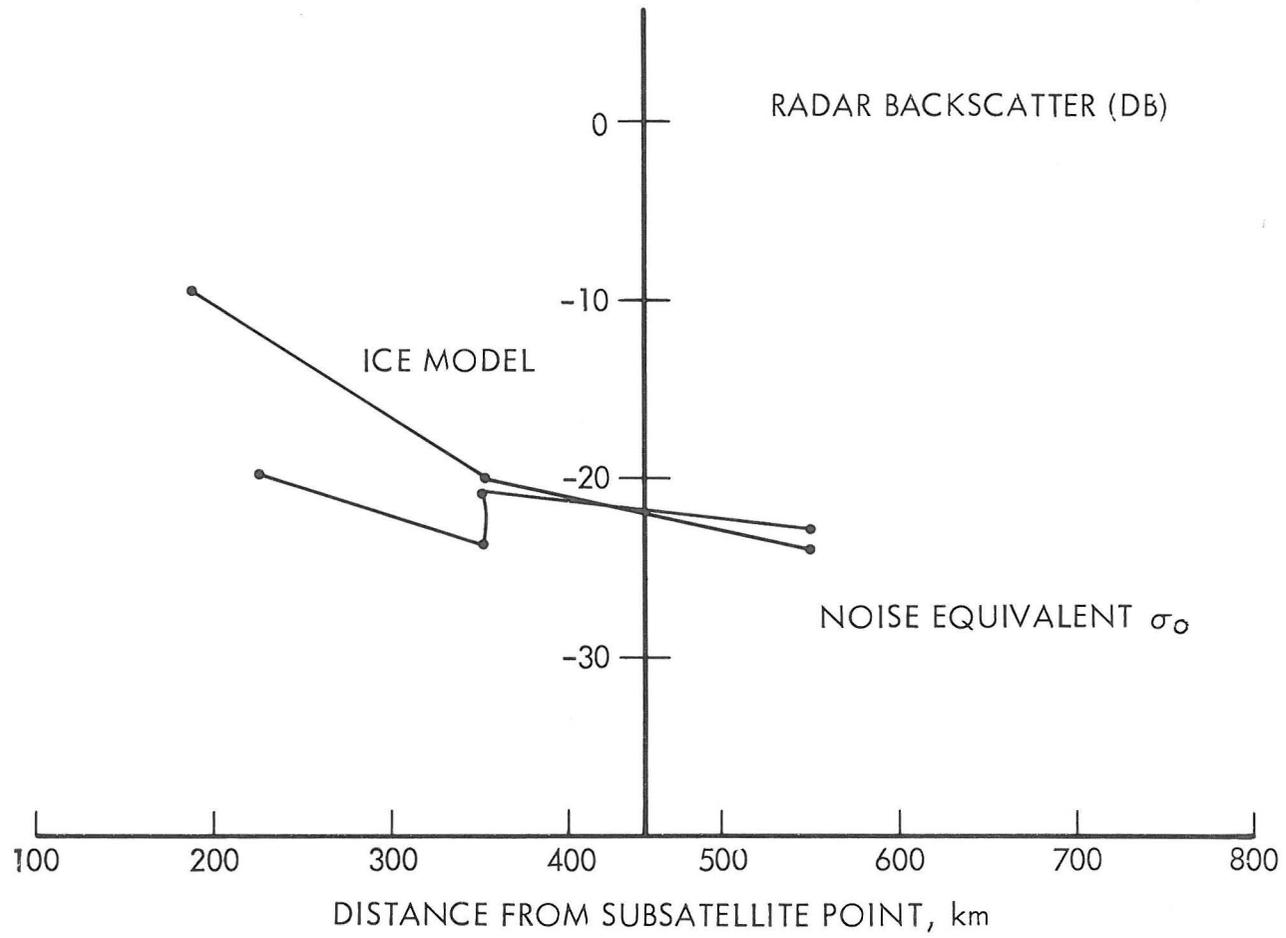
- Fig. 1: Wide Swath Imaging Radar (WSIR) simplified block diagram. The upper portion of the figure represents the spacecraft subsystems; the lower portion is the ground-based processor.
- Fig. 2: The upper portion of the diagram schematically shows the four WSIR antenna beams and the corresponding ground coverage. As the inclination of the orbit will be either 87° or 93° , the subsatellite track will pass approximately 300 Km from the poles. By using the appropriate set of beams, complete North and South polar coverage is obtained. The lower portion shows the geometry of the antenna phased array panels.
- Fig. 3: Artist's rendition of ICEX spacecraft, with the WSIR antenna shown in its operational configuration.
- Fig. 4: WSIR performance (Noise equivalent σ_0 vs. distance from subsatellite point) compared to a composite or "average ice" σ_0 characteristic.
- Fig. A1: ICEX WSIR Synthetic Aperture Operation.

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