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DESIGN AND ANALYSIS OF AN X-BAND SYNTHETIC APERTURE RADAR FOR A JOINT MISSION WITH NASA'S SHUTTLE IMAGING RADAR

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ABSTRACT

This paper describes the conceptual layout of a Shuttle borne X-band Synthetic Aperture Radar (SAR). In a joint mission this German/Italian radar experiment shall complement the Shuttle Imaging Radar (SIR-C) of NASA operating in L- and C-band. The main objectives are simultaneous measurements in L, C and X-band. In future this will increase the viability of radar image interpretation and hence enlarge the role of radar remote sensing in the global Earth scientific research programme concerning oceonography, meteorology, geology, hydrology, vegetation and other land applications.

The results presented in this paper are derived from a design study being performed in 1984/85 by DORNIER SYSTEM (Germany) and Selenia Spazio (Italy) on behalf of their Ministries of Research and Technology.

I. INTRODUCTION

The Shuttle X-SAR continues the development line of the German microwave remote sensing programme having been started with the Microwave Remote Sensing Experiment "MRSE" that unfortunately failed during its first flight before SAR measurements could be made due to a High Power Amplifier Problem.

The first Shuttle X-SAR/SIR-C mission is envisaged in 1988 and will perform multifrequency and multipolarization measurements making maximum use of its high variety of radar parameters as there are the off-nadir angle (15°-60°), the radar pulse length (66 μs or 105 μs), the receiver bandwidth (13 MHz or 20 MHz), the echo quantization (I/Q = 3/3, 4/4, 5/5 or 6/6 bit), the receiver gain (20 steps of 2 dB), and the SAR antenna gain (37 or 41 dB).

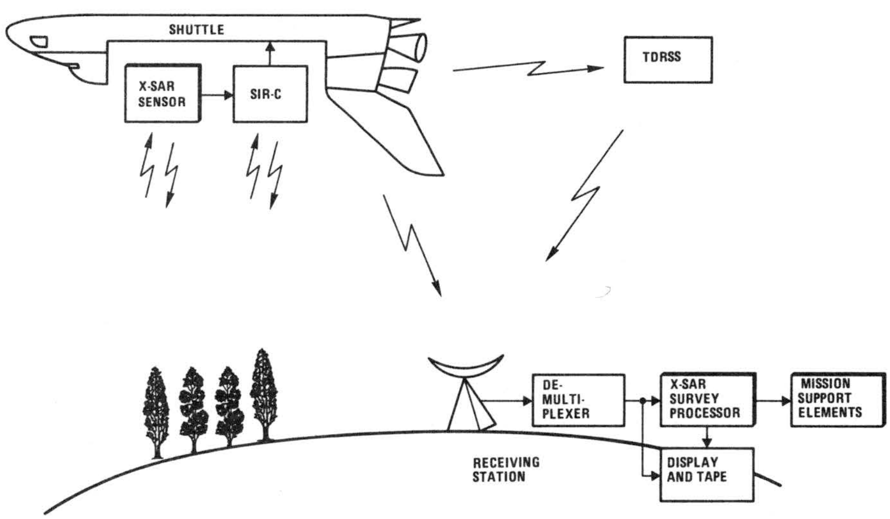

Fig. 1: The X-SAR System uses SIR-C/Shuttle Data Transmission Services

This SAR system was conceptually laid out by employing a computer aided system synthesis procedure followed by the design of the onboard instrument and the ground based SAR processor. A final overall analysis pointed out the SAR system performance for several possible parameter constellations.

II. THE X-SAR SYSTEM

The major two elements of the X-SAR system are the onboard X-SAR sensor or instrument and the ground based survey processor (see Figure 1). A SAR Data Transmission Service is provided by SIR-C and Shuttle, and possibly a SAR Data Recording Service by SIR-C. Low rate Telemetry data and commands are transmitted via Shuttle TM/TC service lines. After transmission to ground the unprocessed X-SAR sensor raw data are stored on tape and partly processed by the X-SAR Survey Processor.

A. BASIC MEASUREMENT PRINCIPLE

The X-SAR will produce images of the Earth's surface by virtue of the differing local normalized radar cross section (reflectivity) of the targets. As the instrument has its own source to illuminate the target it can be operated independently of diurnal and weather-influenced solar illumination. Microwave signals in X-band (9.6 GHz) can even penetrate heavy rain and hence have an advantage over optical sensors.

Basically, pulses emitted from the SAR antenna are reflected from a wide swath. All objects within the swath reflect signals with a strength according to their respective radar cross sections. The return of a pixel (a resolution element) is characterized by the four quantities of amplitude, phase shift, time of arrival and doppler shift, the last being caused by Shuttle motion and Earth rotation.

A pixel is illuminated by many pulses during a SAR overflight and consequently reflects these echoes, which are coherently summed up in the same range and doppler bin taking into consideration that the doppler shift of a pixel is changing from echo to echo.

B. SPACE SEGMENT

The space segment (X-SAR sensor) comprises only such functions of a Synthetic Aperture Radar, which are absolutely necessary to be performed in realtime onboard Shuttle. This limits the overall development effort concerning integration, test and qualification and reduces the criticality of the development schedule. These functions are:

- o Generation of the high power radar transmission pulse.
- o Illumination of a limited area on the Earth surface (swath).
- o Receiving of the echoes from the above mentioned swath.

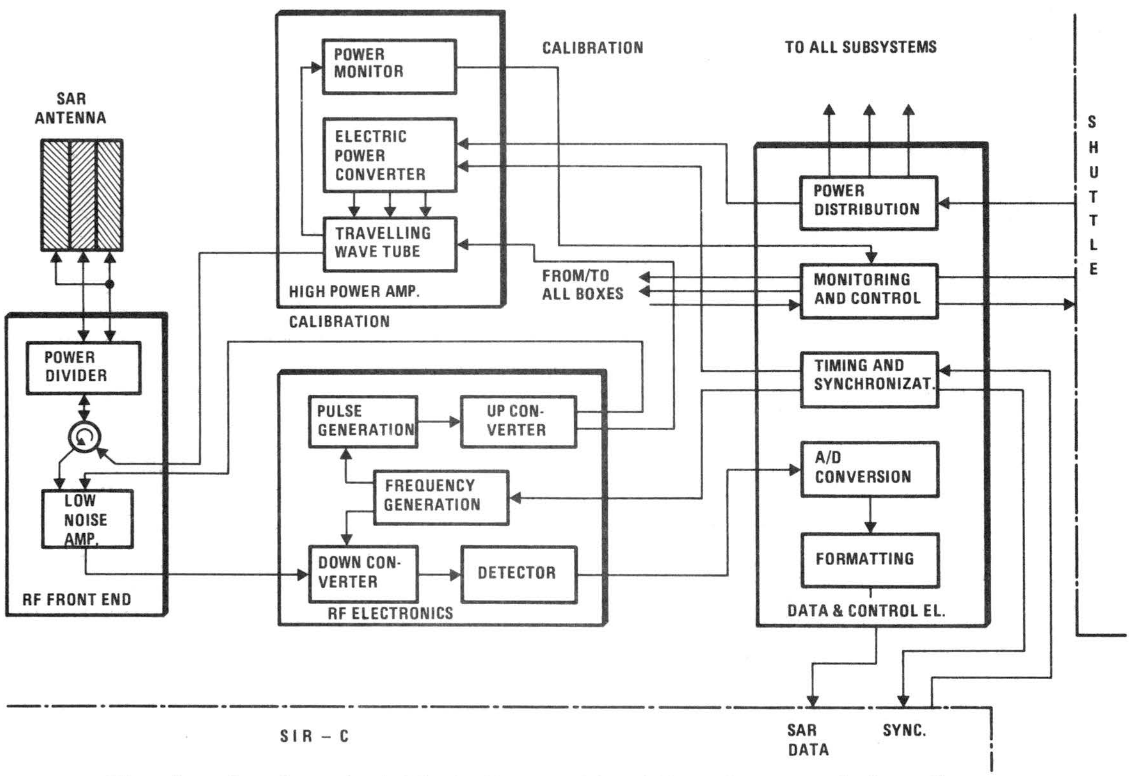

Fig. 2: The electrical block diagram identifies the general data flow

- o Coherent detection of the echoes.
- o Forming of a digital SAR data stream for transmission to ground.
- o Monitoring and Control of all units of the X-SAR sensor.
- o Provision of auxiliary and house keeping data being used on ground to operate the sensor, in order to maintain its performance and to calibrate the scientific SAR data.
- o Synchronization of X-SAR timing with SIR-C.
- o Transmission of a low power security pulse to SIR-C indicating the time of high power signal transmission of the X-SAR.

1. Electrical Layout of the Instrument

The X-SAR sensor primarily consists of 5 subsystems (see Fig. 2):

- o The RF Electronics, generating the radar pulse in the video band on low level and upconverting it to 9.6 GHz. This subsystem finally downconverts the received and pre-amplified radar echoes and performs the I/Q detection.
- o The High Power Amplifier, amplifying the RF radar pulse up to about 3 kW peak power by use of a Travelling Wave Tube and monitoring its RF output power.
- o The RF Front End, isolating its low noise amplifier in the receiving channel from the high power signal being fed to the antenna and selecting the required antenna gain mode by switching between two antenna feed systems.
- o The SAR Antenna, transmitting and receiving the radar signals. It is fed in two different ways, one using the full aperture in elevation to provide high gain and narrow beamwidth (narrow beam mode) and the other using only one third of the aperture to increase the beamwidth, inherently decreasing the antenna gain (wide beam mode).
- o The Data Control Electronics, converting the analog SAR data into a continuous digital data stream having auxiliary information included. Additionally, it monitors and controls the instrument, provides the required DC-power and the timing for all of the above subsystems, and allows to synchronize the X-SAR with SIR-C.

In addition special functions are foreseen to allow calibration of the system. The output of the High Power Amplifier Power Monitor is transfered to the Data Control Electronics and transmitted to ground for analysis. The radar chirp after up conversion is fed into the Low Noise Amplifier and further treated as a normal input signal, down converted, detected and transmitted to ground. This allows analysis of the actual chirp signal.

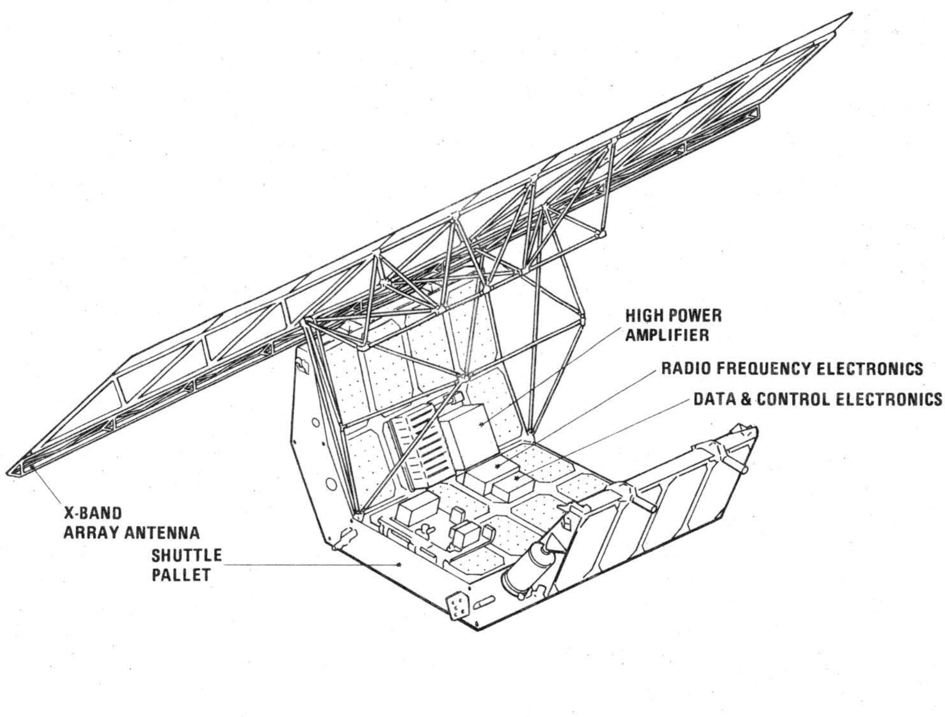

Fig. 3: The X-SAR is mounted on a Shuttle pallet close to SIR-C

2. Mechanical Configuration

The hardware units are directly related to the electrical subsystems. Borne on a Shuttle Pallet the RF Electronics and the Data Control Electronics are located on one cold plate at the bottom of the pallet (see Fig. 3). The High Power Amplifier uses another cold plate at the pallet side close to the RF Electronics. The X-SAR Antenna is mounted on a stiffening truss being attached to the truss of the SIR-C antennas. Very close to the microwave input of the antenna feed system the RF Front End is mounted on the rear side of the antenna truss to avoid lengthy and flexible waveguides or rotary joints between SAR and the Low Noise Amplifier within the RF Front End. The pointing of the antenna is provided by the truss structure.

C. GROUND SEGMENT

As shown in Fig. 1, the X-SAR Survey Processor and some Mission Support Elements (computer programms to support the operation of the X-SAR) are related to the X-SAR only.

Fig. 4 shows the functions of the Survey Processor. A main control unit controls the overall processing, while the three sections range processing, azimuth processing and post processing are separately controlled. The image processing is performed in the processing pipeline starting with the range compression followed by the correction of the range migration. After that, the echo data are subdivided into two subswaths to allow processing in parallel in order to save processing time. In either subswath path the data are dechirped with the respective azimuth reference chirp, the orientation of the data is changed from range to azimuth within the corner turn memory and the synthetic aperture is built up by appropriate filtering applying a Fast Fourier Transform (FFT). The output at this stage is a single look SAR image. Images of several looks of the same area are summed up to multilook images followed by some image corrections and formatting the swath. Mean doppler estimation and autofocus are support functions to the azimuth processing to correct for Shuttle pointing errors.

III. OPERATIONS

A. INSTRUMENT MODES

The onboard sensor can be operated in the following modes:

- o Autonomous Operation:
  X-SAR measurements only
- o Synchronized Operation:
  Simultaneous operation of SIR-C and X-SAR with synchronized pulse repetition and master clock
- o Coarse Range Resolution
  (low range compression/bandwidth)
- o Fine Range Resolution
  (high range compression/bandwidth)

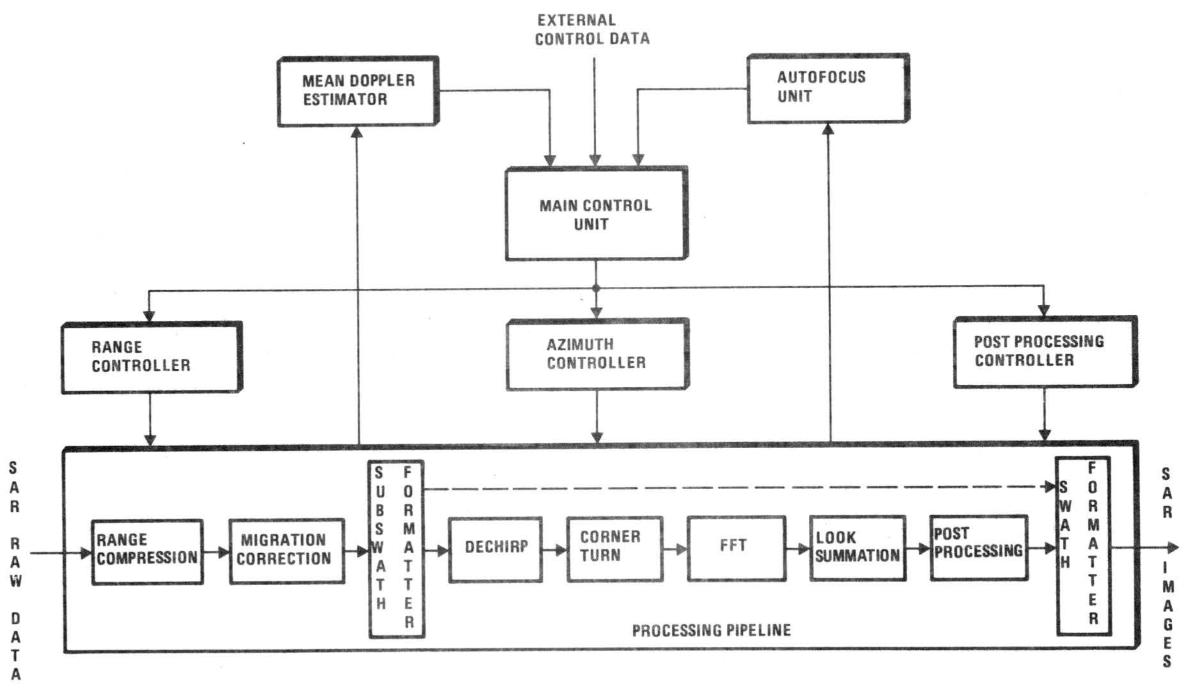

Fig. 4: The X-SAR Survey Processor provides real time SAR images

- o Wide Beam
  (wide swath/low antenna gain)
- o Narrow Beam
  (high measurement sensitivity/high range ambiguity suppression)
- o Calibration:
  The low power chirp after the up converter is attenuated and fed into the low noise amplifier and transmitted to ground similar to a normal echo. This is performed many times with different attenuation levels in order to cover the total dynamic range of the sensor. Additionally the output power of the High Power Amplifier is monitored.
- o Pause
- o Standby
- o Off

B. RANGE OF RADAR PARAMETERS

The Shuttle X-SAR is designed to be an instrument with a high variety of its parameters in order to allow optimizing the measurements over a wide range of different applications. The parameters to be selected by commands are:

- o Off-nadir angle:
  15-60 deg. (1 deg steps)
- o RF bandwidth: (spatial resolution)
  13 MHz/20 MHz
- o Antenna elevation aperture width:
  (incl. changes of Antenna peak gain and beamwidth)
  4 waveguides/12 waveguides
- o Echo quantization (I + Q):
  6/8/10/12 bit
- o Pulse repetition frequency:
  16 discrete values within 1.248-1.824 kHz
- o Echo window position and length:
  64 discrete values
  (submultiples of the pulse repetition interval)
- o Output data rate:
  45 Mbps/30 Mbps
- o Sigma nought window position:
  (gain setting)
  20 positions within 40 dB

C. PARAMETER SELECTION BY PERFORMANCE PREDICTION

The high variety of radar parameters has many advantages from a measurement performance point of view, but it creates severe problems for operation. During a Shuttle mission of one week the X-SAR has to operate in many modes with different parameter constellations. The user require the target areas to be covered and the SAR measurement performance. The X-SAR Operations Team has to convert these requests to optimum radar parameters taking the actual Shuttle orbit into consideration. This will be supported by a computer programme "Shuttle X-SAR Performance Estimator" that allows to optimize X-SAR modes and parameters in an interactive manner, providing a performance in accordance with the user requests.

IV. MEASUREMENT PERFORMANCE

A. PERFORMANCE AT REFERENCE POINTS

The measurement performance of this multiparameter system was analysed at four off-nadir angles (15°, 30°, 45°, 60°). At each of these angles a typical parameter configuration was choosen. Beside this nominal performance the sensitivity of the system was analysed concerning typical error conditions which are:

- o $\pm$ 1.5 km altitude prediction uncertainty and
- o $\pm$ 0.5 degrees pointing error in roll, pitch and yaw.

The analysis used the following fixed values for those parameters which can be changed during operation:

- o Doppler bandwidth per look: 250 Hz
- o Quantization 5 bit I and 5 bit Q
- o Output data rate: 45 Mbps.

The echo window in each case was chosen to maximize the swath width taking into consideration that the required image quality should be met all over the swath under nominal operational conditions. Nominal operational conditions neglected errors due to the Shuttle (pointing, altitude, etc.). Concerning the pointing error it should be noted that the errors in pitch and yaw are compensated by the ground processor (autofocus, zero doppler tracker). Hence only the roll error and the error of the compensation processing remained for analysis.

The following table shows the main instrument and nominal performance parameters of the X-SAR in comparison with SIR-C.

	X-SAR	SIR-C
Altitude/km	255	255
Orbit Incl./deg.	57	57
Frequency/GHz	9.6	1.28/5.3
Polarization	VV	VV HH HV VH
Off-Nadir Angle/deg.	15-60	15- 60
Swathwidth/km	29-56	20-100
(Quantization)	(10 bit)	(6-12 bit)
Azimuth Resolution/m	<30	25
Range Resolution/m	10-60	17- 58
Peak Power/kW	3	1/2.5 (L/C)
RF Bandwidt/MHz	13/20	12
Radiometric Resol./dB	2.5 (3*)	
σ^{o}_{min}/dB	(-26)-(-18)	
Azimuth Ambigu./dB	<-20 (-19*)	<-24 (-9*)
Range Ambiguities/dB	<-20	

* at 60 deg. off-nadir angle

This table indicates a certain range of performance values per parameter due to the fact, that these inherently depend on the actual angle of incidence within the swath. Figure 5 shows this dependency for the range resolution.

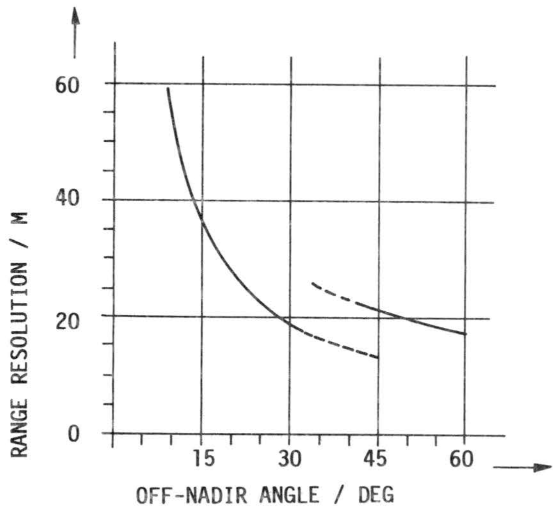

Fig. 5: Range Resolution

Two curves in this figure indicate that the instrument can operate in two resolution modes:

o Fine resolution mode

Length of compressed pulse:	66 ns
Compression ratio:	609
RF bandwidth:	20 MHz

This mode provides high spatial resolution, but entails high data rate transmission and hence limits swath width. This mode will preferably be used in swath regions with low off-nadir angles.

o Coarse resolution mode

Length of compressed pulse:	105 ns
Compression ratio:	380
RF bandwidth:	13 MHz

This mode has low spatial resolution with reduced data transmission rate and larger swath width. It should be prefered at high off-nadir angles where the range resolution is better due to measurement geometry.

The useful swath width (see Fig. 6) for the reference systems in nominal case is mostly well above 30 km. However, for 30 deg. in case of a typical error scenario it degrades to about 20 km, if the σ^{o}_{min} is kept better than -18 dB. This results (after antenna-aperture switching) from the narrow beam that limits the swath width in this case.

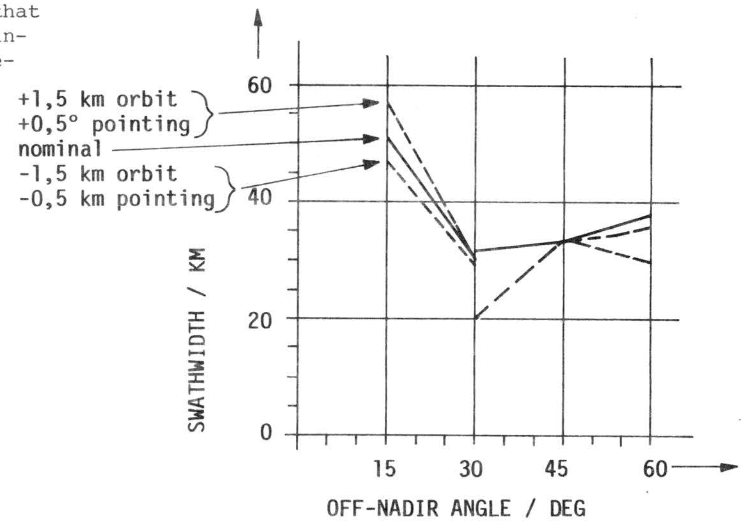

Fig. 6: Useful Swath Width

Another radar performance criterion is the ambiguity level that shows the ability of the radar to suppress ghost images. Figure 7 summarizes the ambiguity level in range of the X-SAR. The fat line shows that the nominal ambiguity level in worst case within the swath is below -20 dB over the total range of off-nadir angles. The consideration of a typical error scenario shows a good performance up to about 50 degrees off-nadir angle.

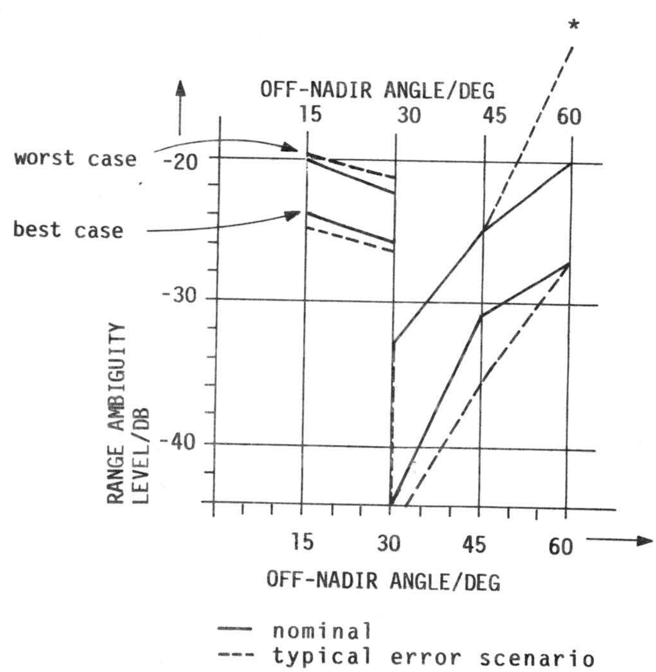

Fig. 7: Peak Ambiguity Level in Range

Then the level at the swath edges comes up to about -12 dB (see* in fig. 7) considering maximum possible swath width from a data rate point of view. This effect can be compensated by an additional antenna squint of about 1 degree in nadir direction (-1 deg. in the elevation coordinate system) and by reducing the swath width to about 30 km. This will allow to maintain -20 dB range ambiguity level in cases of a typical error scenario.

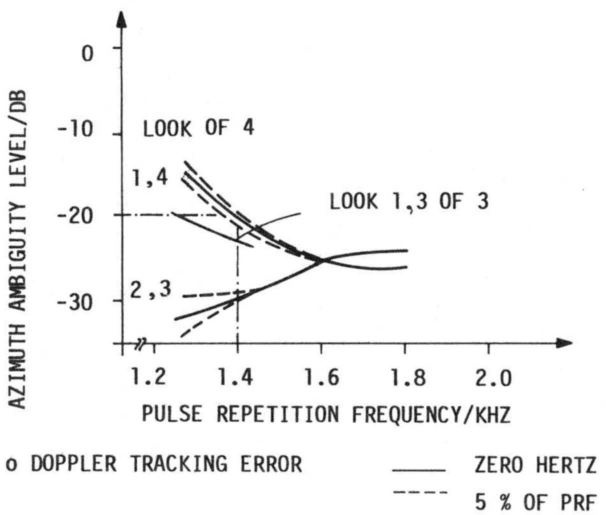

Fig. 8: Integrated Ambiguity Level in Azimuth

The results of the azimuth ambiguity analysis are shown in Fig. 8. The ambiguity level in azimuth is a function of pulse repetition frequency. The diagram indicates that look 2 and 3, the inner looks, are well below -20 dB for all pulse repetition frequencies. However, the ambiguity level of the outermost looks, look 1 and 4, increases with decreasing pulse repetition frequency and reaches -20 dB at about 1.4 kHz. For lower frequencies it is proposed to reduce the number of looks from 4 to 3, that degrades the radiometric resolution to 3 dB, or to overlap the looks, which does not significantly degrade the radiometric resolution, but needs more flexibility of the SAR ground processor.

The azimuth pointing error (pitch, yaw) has no influence in the SAR performance because of the pointing compensation by the ground processor. The accuracy of this compensation, so called doppler tracking errror, is taken into consideration by the dashed lines in figure 8.

B. PERFORMANCE AT 200 Km AND 300 Km ALTITUDE

The Shuttle X-SAR is designed to operate at any orbit between 200 km and 300 km altitude. A change in altitude mainly influences three performance parameters:

- o Swath width (Fig. 9)
- o Range Ambiguity Level (Fig. 10)
- o Minimum Sigma Nought (Fig. 11)

The nominal swath width for 200 km altitude is mostly beyond 30 km and degrades with an altitude increase. The nominal σ^{o}_{min} (worst case within maximum swath) for 200 km altitude is always better than -20 dB, however for 300 km it degrades partly up to about -17 dB. The nominal range ambiguity level (worst case within swath) is better than -20 dB for all off-nadir angles. A change in altitude of this size has no significant influence in the azimuth ambiguity level.

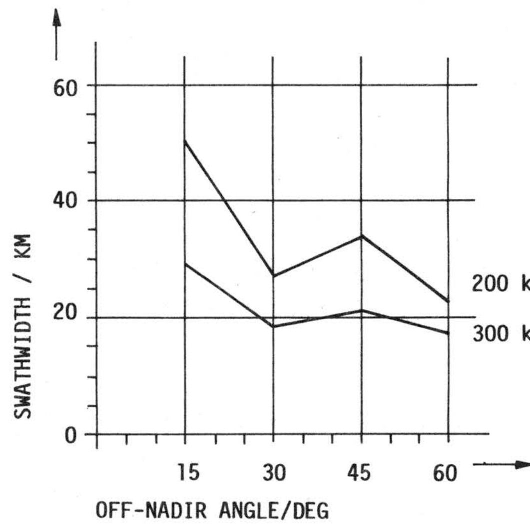

Fig. 9: Useful Swath Width

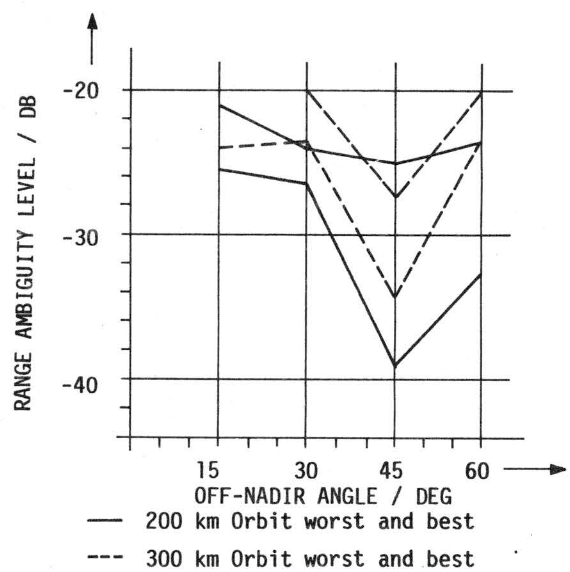

Fig. 10: Ambiguity Level in Range

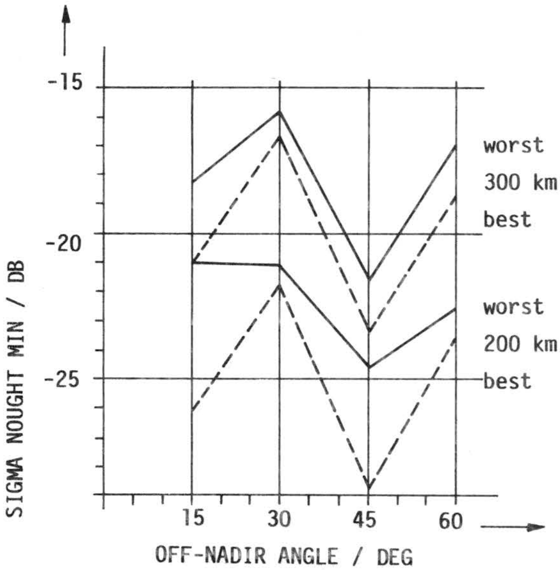

Fig. 11: Minimum detectable sigma nought for a radiometric resolution of 2.5 dB (3 dB at 60 deg.) in case of 200 km and 300 km altitude

VI. OUTLOOK

The design and the operation of the X-SAR in conjunction with SIR-C contribute to a significant advance in the field of science, research and technology. It may be assumed that a versatile instrument is being created that will play a central role in the national and international Earth resources programme and, therefore, will greatly influence other remote sensing projects, in particular those employing microwave sensors.

In general, one of the major aims of spaceborne remote sensing is the global monitoring of geological features. This requires in future that multispectral optical images are combined with multispectral radar images, polarization information is used and stereographic methods are applied. Auxiliary information must be used on a global base concerning weather, coastal ocean features and temperatures being derived by altimeters, scatterometers and radiometers etc. The work of several national centres of remote sensing during the last decade has fruitfully supported these ideas and has helped to understand strange features being detected in radar images. Nevertheless, an unambiguous detection of special geological features needs about one decade more of signature research, the development of complex sensors and extensive sensor calibration methods, and last but not least it needs operational remote sensing programmes providing many data of different sensor types to allow the scientists to play with.