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A SYSTEM CONCEPT FOR WIDE SWATH CONSTANT INCIDENT ANGLE COVERAGE

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SUMMARY

User requirements and inherent system constraints dictate that operational synthetic aperture (SAR) systems for observations at orbital heights should have the following characteristics:

1) Wide Swaths
2) Coverage at Nearly Constant Incident Angles
3) Programmable Incident Angles
4) Low Transmitter Power
5) Reasonable Antenna Size

Conventional designs fail to achieve these objectives.

A multiple beam radar is proposed as a solution meeting these requirements. The multiple beam approach readily overcomes the radar ambiguity constraints associated with orbital systems and therefore permits imagery over swaths much wider than 100 kilometers. Furthermore, the antenna technique permits imagery at nearly constant incident angles. When frequency scanning is employed, the center angle may be programmed. The redundant use of the antenna aperture during reception results in lower transmitted power and in shorter antenna lengths in comparison to conventional designs. Compatibility of the approach with passive imagery is also suggested.

The system concept is developed and illustrated by means of examples. One design example is thought to be suitable for hydrological monitoring while the other is thought to be suitable for monitoring vegetation resources.

1.0 INTRODUCTION

The role for the imaging radar as an orbital sensor for earth oriented ob-

observations has emerged in recent years. Efforts are underway to demonstrate radar's capability from space using conventional design approaches to minimize development costs and risks. Although conventional radar imaging systems should be flown aboard spacecraft on an interim basis to demonstrate their capability and utility, ultimately operational systems should be based on advanced radar concepts motivated by user requirements and by inherent system constraints. An examination of these requirements indicates that a calibrated operational system should, among other factors, have the following general characteristics:

1) Wide Swath Coverage
2) Nearly Constant Incident Angle
3) Programmable Incident Angle
4) Low Transmitter Power
5) Reasonable Antenna Length

In addition to these it is also desirable that the radar system be compatible with a radiometer system so as to permit active and passive imagery simultaneously.

Swath width is necessary for frequent and timely observations. In conventional systems wide coverage is limited by practical antenna lengths, by available transmitter power, and by other factors. Crosstrack oriented systems typically image over a large domain of incident angles. Quantitative interpretation of these returns will require removal of the incident angle behavior, particularly at the smaller incident angles. Broad beam systems which generate wide swaths typically require high peak transmit powers since the PRF rate must be reduced to meet range ambiguity constraints. In some cases this can shorten the transmitter's lifetime.

To overcome swath width limitations Moore, et al. [1] have suggested and investigated a scanning synthetic aperture radar. Another technique to improve swath width while imaging at nearly a constant incident angle is suggested by a multiple beam antenna concept advanced by Bucknam, et al. [2] for a different application. This antenna concept is examined here to demonstrate its applicability in a synthetic image formation system.

2.0 THE MULTI-BEAM SAR CONCEPT

2.1 REAL BEAMS

The multi-beam antenna in its mapping mode is illustrated in Figure 1. The antenna consists of two horizontal arrays of vertical elements. This planar composite array faces at an azimuthal angle ϕ_o between the uptrack and crosstrack directions. One array serves as the transmitting antenna and the other as the receiving antenna. The vertical elements in the arrays are identically phased to create in the elevation plane a narrow beam which points downward at an incident angle Θ_o. By using a frequency scanning technique the angle of incidence may be changed as illustrated in Figure 2. The width of transmit antenna is sufficiently small to illuminate a circular swath to the right of the ground track. The vertical elements in the receive array are the same height as the elements in the transmit array. The output signals from the receive elements are processed simultaneously to form N_B real beams. The real beams overlap to provide receive coverage over the entire illuminated area.

2.2 SYNTHETIC BEAMS

The translation of the real aperture together with range gating is employed to generate high resolution synthetic beams in each real receive beam. The intersection of these synthetic beams with the scene forms pixel elements as suggested by Figure 3. A mosiac of radar images may be created by appropriately combining the synthetic resolution elements in all receive beams.

It is advantageous to image in the uptrack sector defined by the azimuthal interval $0° < \phi < 45°$. More swath is generated per unit azimuthal beamwidth in the uptrack sector in comparison to the crosstrack sector ($45° < \phi \leq 90°$). Therefore, fewer receive beams per unit of swath length are required. In addition the multi-look strategies differ significantly between the two sectors. The choice of one sector, consequently, simplifies the SAR processing.

To generate multiple looks in the uptrack sector processed returns are sampled in azimuth at identical cross-track distances at all range intervals as illustrated in Figure 3. The detected samples at identical

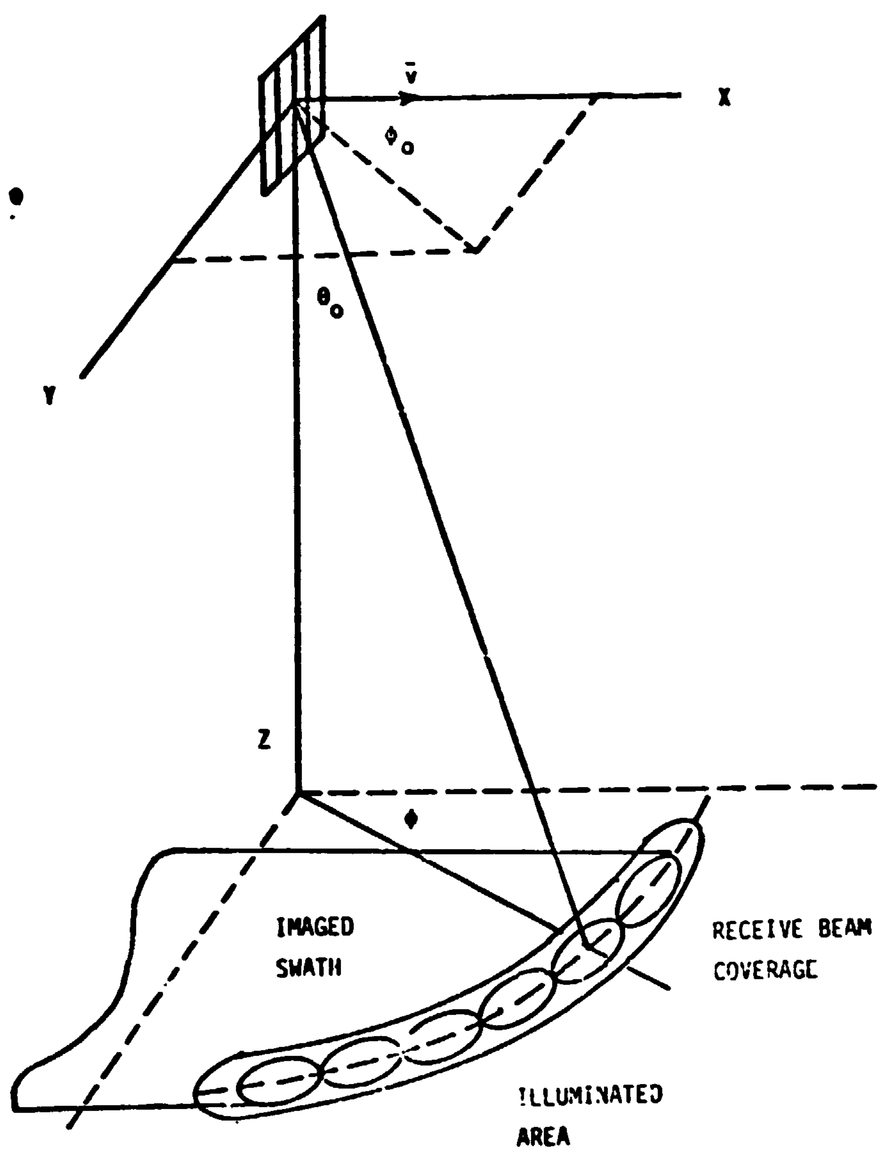

FIGURE 1. THE GEOMETRY OF THE MULTIPLE BEAM SAR

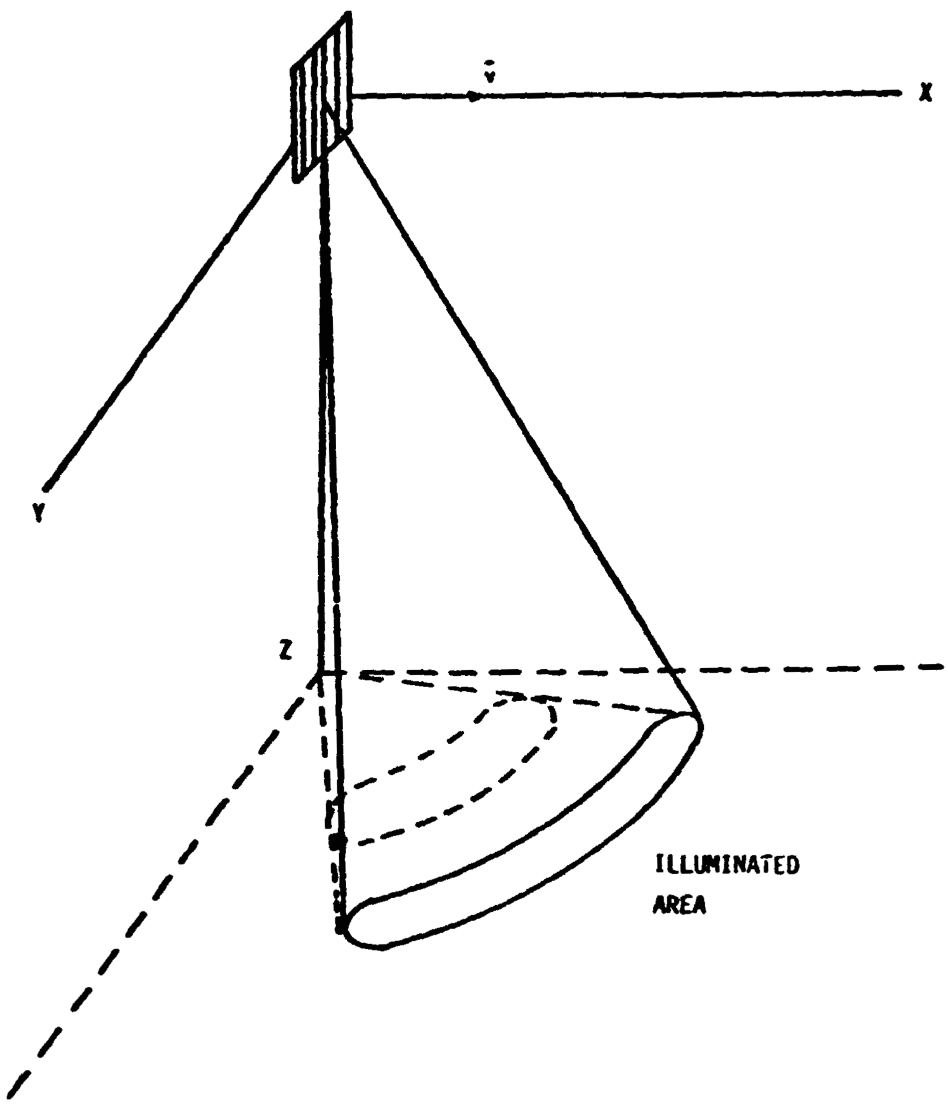

FIGURE 2. THE EFFECT OF A PROGRAMMABLE INCIDENT ANGLE

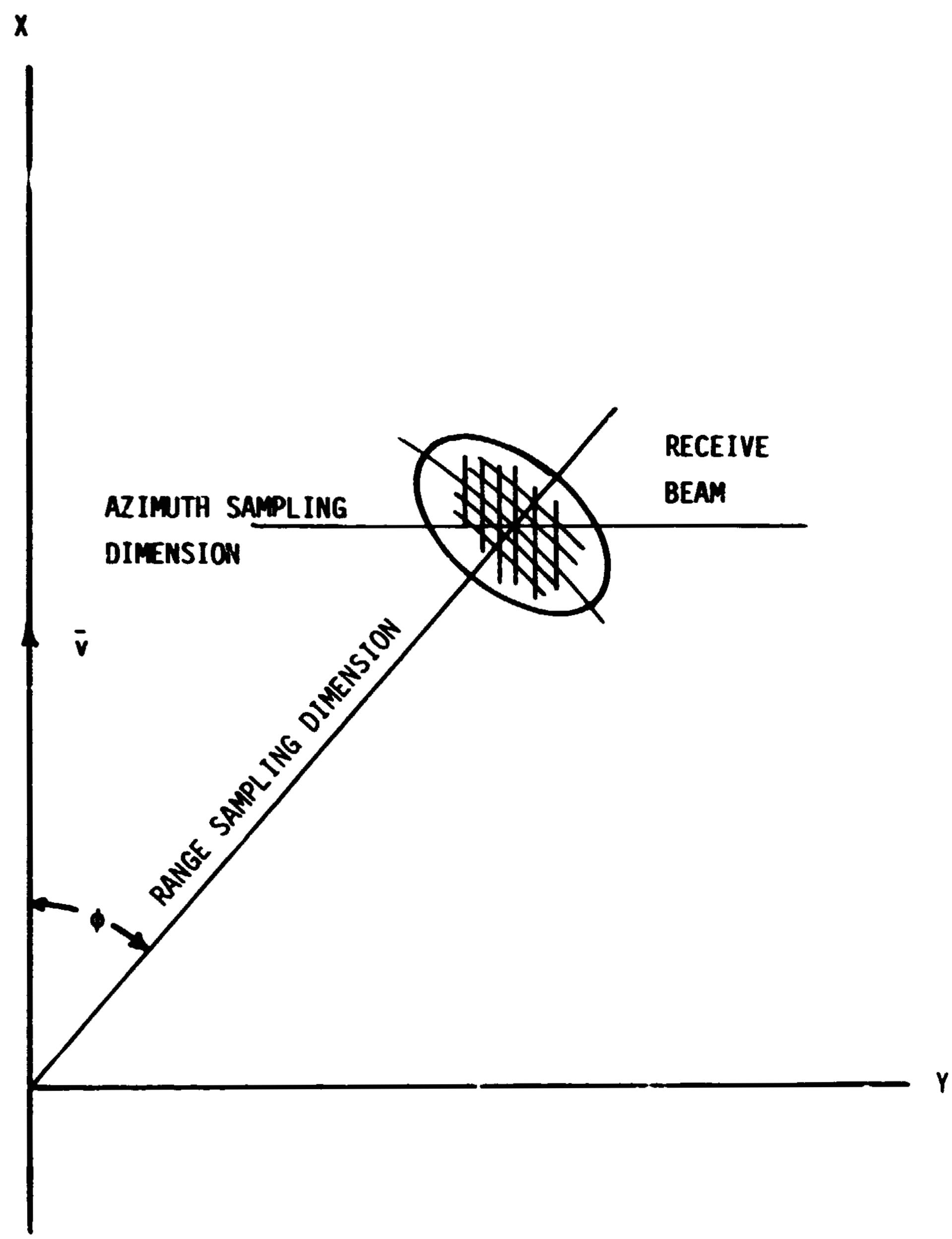

FIGURE 3. AZIMUTHAL SAMPLING STRATAGEM FOR GENERATING MULTIPLE LOOKS

crosstrack distances are then summed on the same cell but from different range bins as made possible by the translation of the aperture. Therefore multiple looks are created "in elevation" rather than "in azimuth" as is the case with systems looking crosstrack.

2.3 TRANSMITTER CONFIGURATION

The transmitter architecture is illustrated in the block diagram of Figure 4. A bank of frequency synthesizers provide the frequency scanning capability. The output of a frequency source is modulated, amplified and directed to the transmit antenna. A small portion of the transmitter power is sampled for internal calibration of the system.

2.4 RECEIVER CONFIGURATION

A receiver block diagram representing a processing approach for the multi-beam SAR is illustrated in Figure 5. Amplified signals from the elements of the receive antenna are combined with appropriate phase shifts to produce return signals within each real beam. The output of each beam is then coherently demodulated to zero IF using quadrature local oscillators Range compression is performed on the I and Q channels. The range sampling is performed in such a manner to track the range walk in each beam. The samples are then stored in a corner turning memory. Two such memory banks are provided to store samples from overlapping synthetic apertures.

As one memory bank fills, the samples in the other undergo azimuthal compression. Signals generated by the azimuthal processor are appropriately sampled in accord with the multi-look strategem described above. Detected samples are stored in the post processor memory. The processor registers and overlays the multiple looks. From the post processor memory the pixel elements are directed into the telemetry link.

3.0 CONCEPT VERIFICATION

3.1 INTRODUCTION

A design approach for the multi-beam SAR is presented in this section to confirm the acceptability of the concept. In the approach it is assumed that the radar wavelength λ, the elevation beamwidth β_H, the incident angle θ_o, the swath width S_w and spatial resolution ρ are specified by

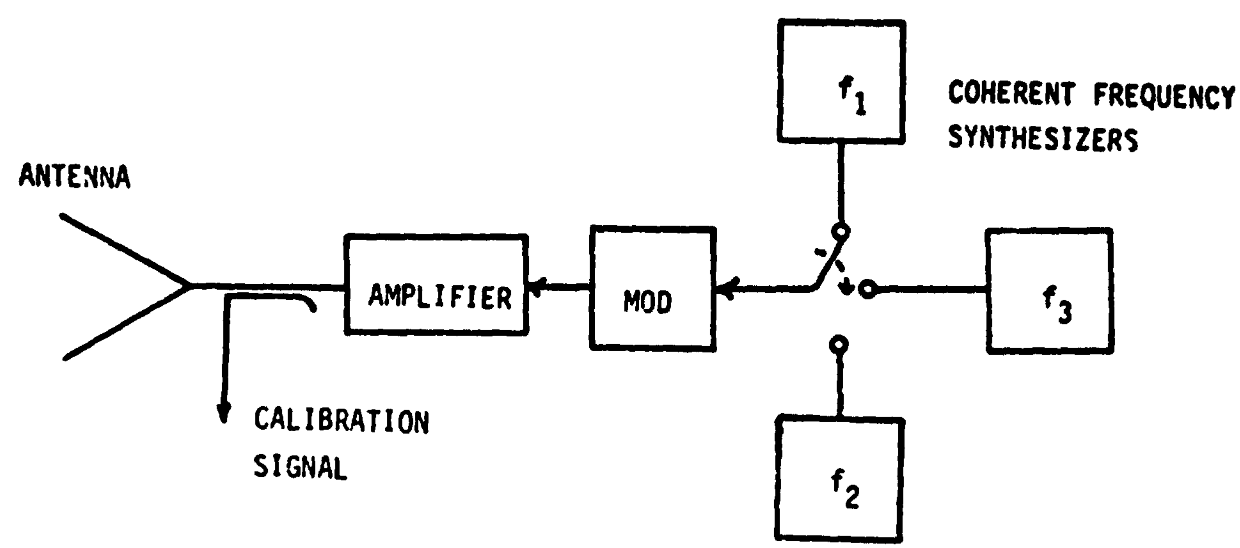

FIGURE 4. TRANSMITTER BLOCK DIAGRAM

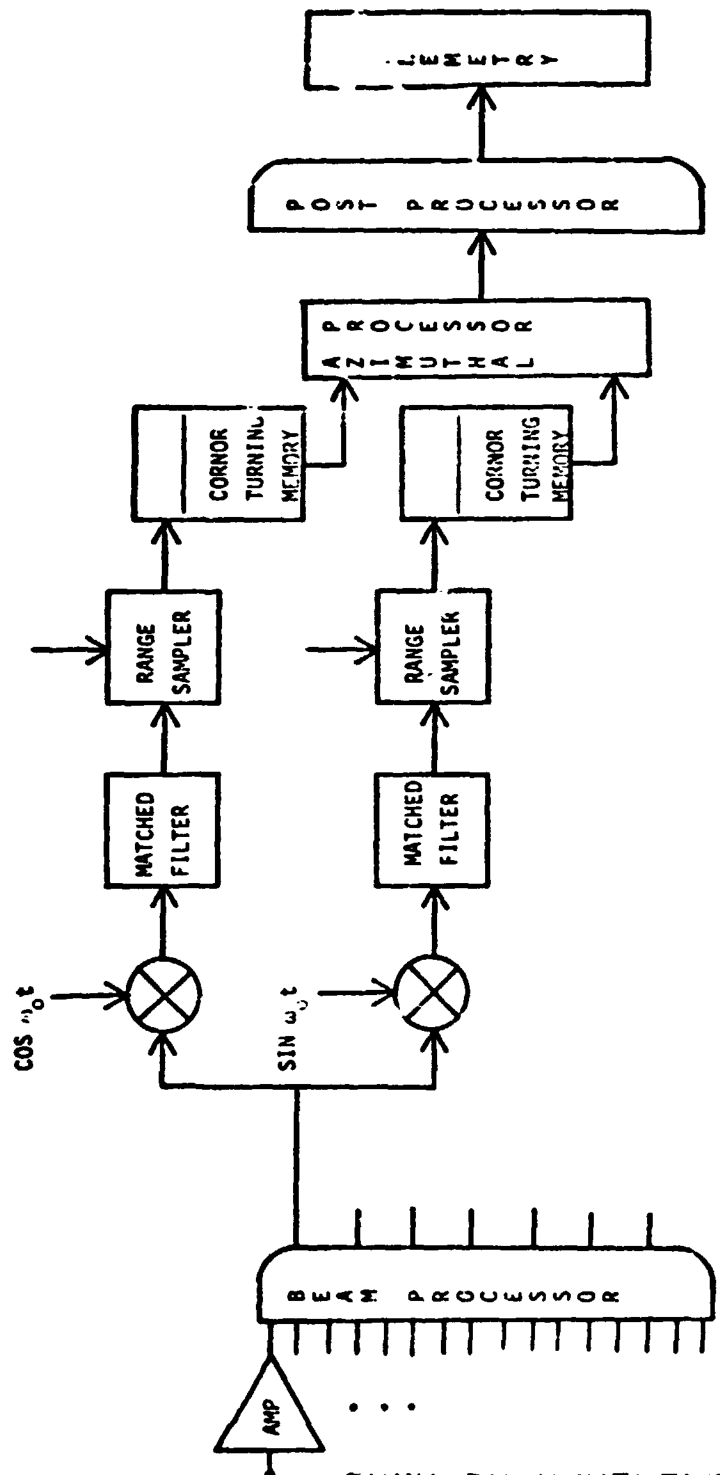

FIGURE 5. RECEIVER BLOCK DIAGRAM

the user application. Furthermore, it will be pragmatically assumed that the swath will be generated in the azimuthal sector between 10° and 45°. The antenna will, therefore, point at ϕ_o = 27.5°. Throughout the concept verification a planar earth will be used to simplify the analysis.

3.2 ORBITAL ALTITUDE

The orbital altitude z is dependent upon the swath width desired. The parametric dependence of the swath width on the altitude is illustrated as a function of incident angle in the graphs of Figure 6. At small incident angles it may be necessary to image on both sides of the ground track with separate systems to improve the swath width.

3.3 RADAR AMBIGUITIES

An important consideration in designing orbital SAR systems is providing sufficient ambiguity suppression. To achieve satisfactory suppression in this design verification a guard factor of 1.7 will be used in the range and azimuth sampling requirements. When these requirements are combined, the following restriction on the beam widths is derived:

$$\beta_L \beta_H \leq .088\lambda c/zv \tan^2 \theta_o \sin\phi \qquad (1)$$

where c is the speed of propagation and v is the ground track velocity. The above expression can be used to determine an acceptable azimuthal beam width β_L since β_H has been specified.

The suitability of such guard factors is dependent on reasonably low sidelobe levels. In view of the two-way characteristic in the range dimension, a 17.6 dB sidelobe level is chosen. The associated beam width is given by [3]

$$\beta_H = \frac{1.02\lambda}{H\sin\theta_o} \qquad (2)$$

where H is the antenna height. A sidelobe level of 40 dB is chosen in the azimuth dimension in view of the one-way characteristic there. The azimuthal beam width is given by [3]

$$\beta_L = \frac{1.66\lambda}{L\sin\theta_o \cos(\phi-\phi_o)} \qquad (3)$$

where L is the antenna length. To illuminate the entire 35^o sector, the width of the transmit antenna must be given by

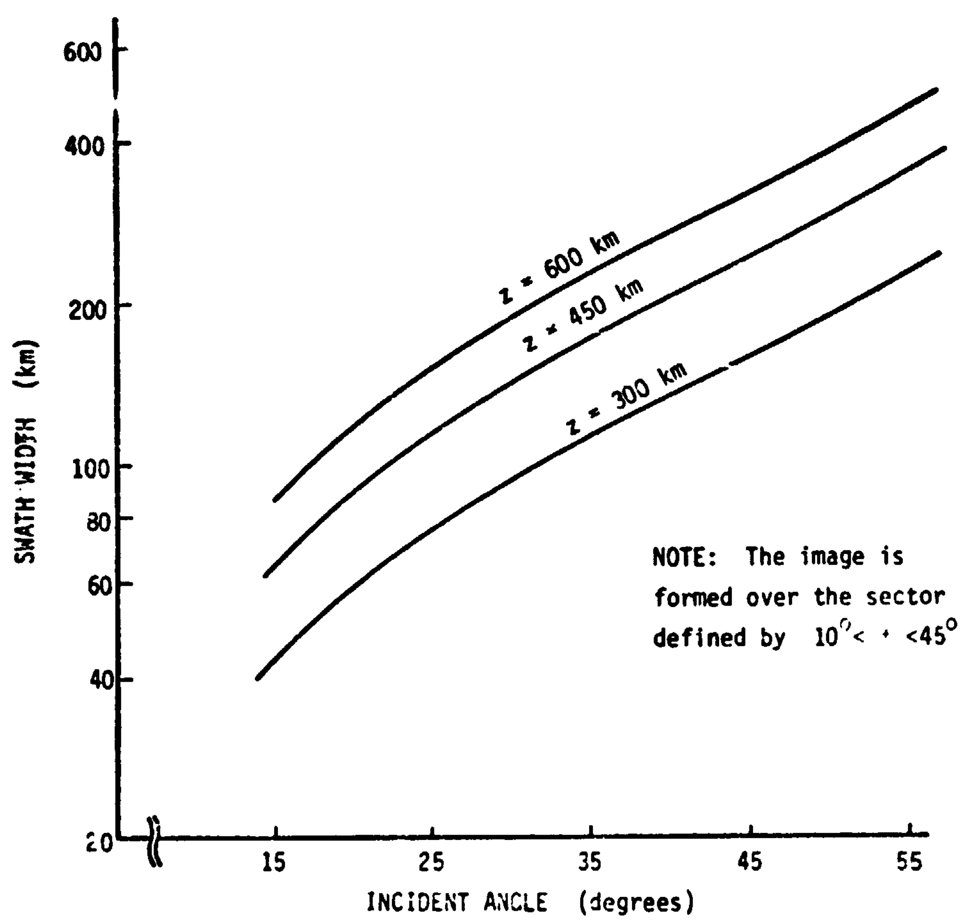

FIGURE 6. THE MULTI-BEAM SAR SWATH WIDTH CHARACTERISTIC

$$W = 1.7\lambda/\sin\theta_o \qquad (4)$$

The above relationshins specify the antenna dimensions.

From β_L the number of receive beams can be computed approximately as

$$N_B = 0.61/\beta_L(\phi=\phi_o) \qquad (5)$$

A PRF which includes the 1.7 guard factor is given by

$$PRF = 5.9\ v/L \qquad (6)$$

3.4 TRANSMITTER POWER

It is well known that the average transmitter power is given as

$$W_{ta} = \frac{4\pi\lambda^2 R^4 L_s FkT\ S/N}{T_a A_t A_r \eta_t \eta_r \sigma^o \rho^2} \qquad (7)$$

where

R = radar range

L_s = system loss factor

F = receiver noise figure

kT = noise power per unit bandwidth

S/N = signal to noise ratio

$A_t A_r = LWH^2 \sin^2\theta_o \cos(\phi-\phi_o)$ (8)

$\eta_t \eta_r$ = product of antenna efficiencies

σ^o = scattering coefficient

$T_a = 1.28\ \lambda R/2v(' \sin^2\theta_o \cos^2\phi)^{1/2}\rho$ (9)

The corresponding peak power is given by

$$W_{tr} = B_{rf} W_{ta}/PRF\ C_r \qquad (10)$$

where

C_r = range compression factor

$B_{rf} = 0.5c/\rho\sin\theta_o$ (11)

The range compression factor C_r cannot be increased indefinitely since the sum of the transmit and receive durations must be less than the PRF interval. When a guard space of four transmit pulse lengths is added to the interval to allow for receiver gate rise and fall times and for variations in altitude, a range compression constraint can be established

$$Cr \leq \frac{Brf}{6} \left[\frac{1}{PRF} - \frac{2\Delta R}{c}\right] \qquad (12)$$

where ΔR is the range interval over the illuminated area.

The above expressions are helpful in specifying the transmitter power requirements.

3.5 RANGE MIGRATION CONSIDERATIONS

Since the multi-beam SAR is a squinted system, the changing range to a resolution cell must be compensated. To keep a resolution cell within the same processing bin, the range gate must be advanced

$$t = \frac{2 \sin\theta_o \cos \phi v}{c \ PRF} \qquad (13)$$

every radar pulse. This will track the so-called range walk.

In addition, there is range curvature also induced by the advance of the spacecraft. The azimuthal coverage is restricted by this curvature as illustrated in Figure 7. To keep the azimuthal elements in focus throughout the beam the following inequality

$$\frac{z \beta_L}{\cos\theta_o} < \frac{3.1\rho^2 \sin \theta_o}{\lambda} \qquad (14)$$

must be satisfied. This restriction will impact the beam size or resolution if the processing is to be kept simple.

3.6 SAR PROCESSING REQUIREMENTS

To minimize the telemetry data rate on wide swath systems, it is important to perform the SAR processing on-board the spacecraft. The feasibility of such a processor is dependent on its adaptability, speed and memory requirements. Various processing techniques having sufficient speed and adaptability have been advanced [4]. The SAR processing memory size for the multi-beam SAR is nominally given by

$$M = 4.6 \ PRF \ v \ T_a^2 \ N_L \ N_B/\rho \qquad (15)$$

where N_L is the number of independent looks. This estimate is based on I and Q memories and two memory banks as described in Section 3.4.

3.7 TELEMETRY BIT RATE

If the processed data is logarithmically converted and if eight bits of

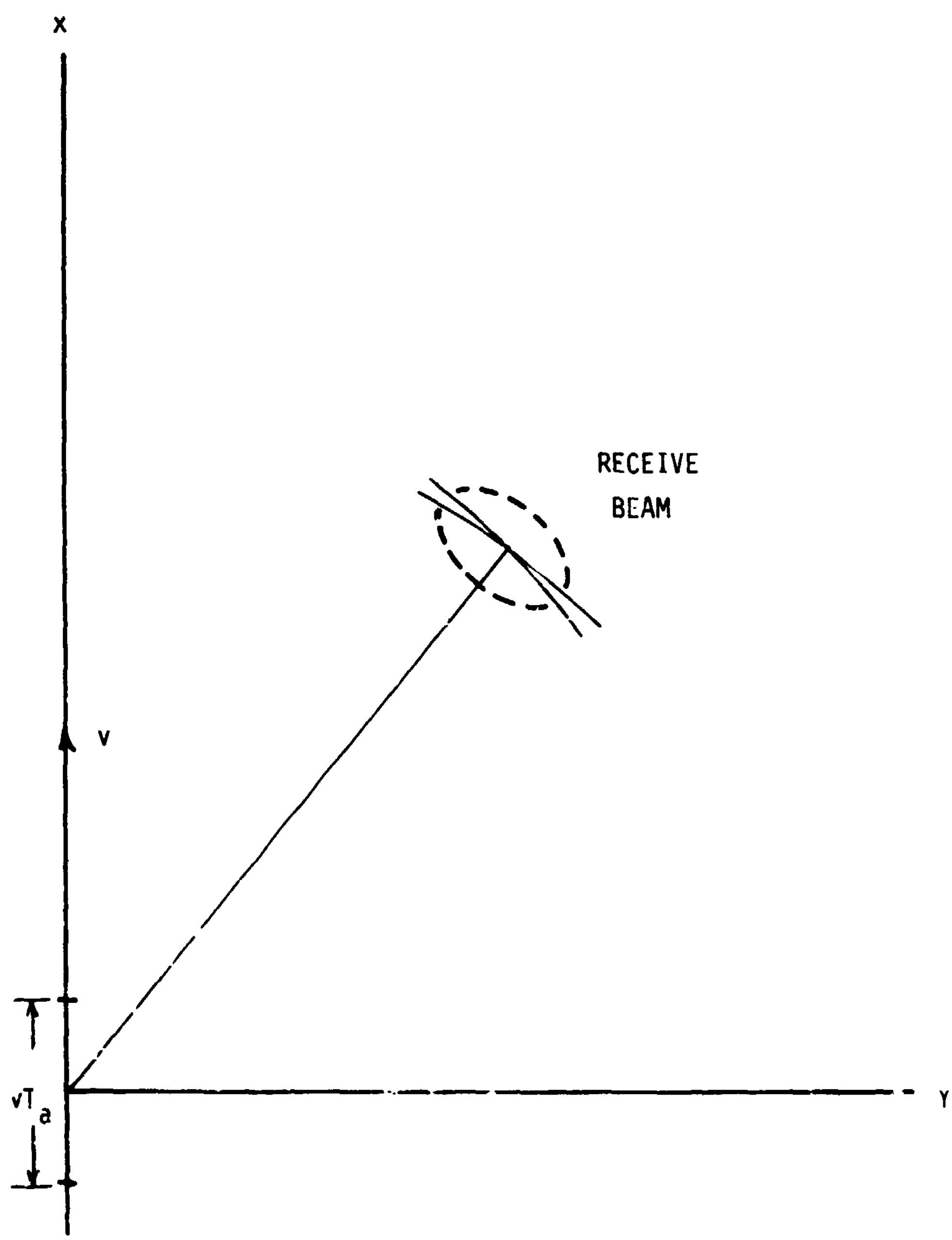

FIGURE 7. RANGE CURVATURE AS APPLIED TO A SQUINTED SYSTEM

dynamic range are employed, then the telemetry bit rate is given by

$$B_T = 5.5\ v\ z\ \tan\theta_o/\rho^2 \qquad (16)$$

This rate estimate does not include the bits required for housekeeping, synchronization, control, error recovery codes, etc. These will add slightly to the above estimate.

4.0 DESIGN ILLUSTRATIONS

To illustrate the potential of the multi-beam SAR concept two designs are presented. One design is based on system parameters thought to be suitable for hydrological monitoring [5]. The second design is appropriate for monitoring vegetation resources [6]. The design guidelines are presented in Table 1. The resulting designs are presented in Table 2.

4.1 DISCUSSION OF THE DESIGN RESULTS

It is apparent from the power entries of Table 2 that the redundant use of the receiving aperture has reduced the average and peak transmitted powers considerably in comparison to conventional systems offering comparable swaths. The peak power requirement was further reduced by the high PRF permitted by the multi-beam approach. This low peak power will significantly increase the life of the transmitter.

As a point of reference a comparison of the SIR-B X band design [7] with the multi-beam X band design is presented in Table 3. It is clear from these entries that the multi-beam SAR can achieve identical resolution, more looks, larger swath, and a comparable S/N ratio with less transmitter power at much higher altitudes.

Also from the entries of Table 3 it is noted that the antenna length has been shortened considerably while achieving a larger swath with the multi-beam system. Had the SIR-B system obtained a similar swath its antenna length would have been 29 meters long. The area of the multi-beam antenna is considerably larger than conventional systems. This arises because the physical aperture is considerably larger than the projected aperture. This feature may become bothersome at the small incident angle and longer wavelengths. However, the aperture size for the C band design is within the capability of a free flying system; consequently, its size is not objectionable.

TABLE 1
DESIGN GUIDELINES

Parameter	Application		Units
	Hydrology	Vegetation	
λ	6	2.5	cm
θ_o	15	45	deg
β_H	2	0.5	deg
S_w	86	160	km
ρ	50	25	m

TABLE 2
NOMINAL DESIGN RESULTS

z	600	300	km
H	6.8	4.1	m
L	6.8	3.4	m
W	0.39	0.06	m
β_L	3.2	1.1	deg
PRF	4.5	9.3	KHz
B_{rf}	11.6	8.5	MHz
T_a	65.4	46.5	ms
S/N	10	10	dB
$\eta_t \eta_r$	-2.0	-2.0	dB
σ^o(min)	-10	-20	dB
L_s	6	3	dB
C_r(max)	390	150	-
W_{ta}	22	128	watts
C_r(design)	200	100	-
W_{tp}	280	450	watts
N_B	11	32	beams
N_L	10	10	looks
M_W	1.5×10^{6}	8.8×10^{6}	words
B_t	2.7×10^{6}	19.8×10^{6}	bits/sec

TABLE 3

COMPARISON OF MULTI-BEAM AND CONVENTIONAL ORBITAL SARS

Parameter	Multi-Beam	SIR-B	Units
λ	2.5	3.6	cm
z	600	185	km
W_{ta}	128	800	w
W_{tp}	.450	20	kw
L	3.4	12	m
H	4.1	.24	m
$\rho_{:}$	25	25	m
σ^{0}	-20	-23	dB
S/N	10	14	dB
S_w	160	68	km
N_L	10	8	
C_r	100	400	

It is encouraging to note that the memory sizes and telemetry bit rates are more than within the capabilities of current technology. The telemetry bit rates demonstrate the advantages of on-board processing. The reduction, among other factors, results from overlaying the multiple looks aboard the spacecraft.

5.0 CONCLUSIONS

A unique and novel approach to radar imaging has been identified. The results of the verification analysis have demonstrated that the multi-beam SAR exhibits sytem properties compatible with free flying satellites. The constant incident angle (particularly at the smaller angles) and the large swath are attractive features to experimenters and users requiring quantitative data over large areas.

The multi-beam approach allows flexibility in designing orbiting systems. The radar ambiguity constraints are more easily satisfied through the use of multiple beams on reception. The redundant use of the receiving aperture reduces the transmitter power by a sizeable factor. This allows the designer more choices in power amplifiers and assures him a more reliable transmitter section. It is also anticipated that real-time SAR processing within a multi-beam system will be easier to implement. The constant incident angle and narrow receive beams make clutter locking more effective and simplifies focusing of the processor associated with each beam. In particular, the depth of focus and range curvature are both easily managed within the confines of narrow beams.

The multiple beam approach is also compatible with a passive imaging system. A portion of the PRF interval not occupied by the transmission or the return can be used as a quiet listening time. The beam processor may be employed to form radiometer pixel elements. Concurrent passive and active imagery is a very attractive alternative, particularly when the radar images can be used to show the internal composition of the radiometer pixel element.

6.0 REFERENCES

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