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Studies Directed toward the Achievement of Wide Swathwidths in Synthetic Aperture Radar

Louis J. Cutrona

February 28, 1979

JPL Contract No. 955019

FINAL REPORT

UNIVERSITY OF CALIFORNIA, SAN DIEGO
Applied Physics and Information Science Department

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology and sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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Abstract of Report

This report describes studies to achieve wide swath widths in Synthetic Aperture Radar. The use of multiple beams in range and/or azimuth is considered. Radar system parameters for a number of cases are computed.

TABLE OF CONTENTS

Summary

This report considers techniques available for achieving wide swath widths in synthetic aperture radars.

Antenna dimensions and area strongly affect the area per second which can be mapped without ambiguity by radar systems.

The limitation is in effect a channel capacity phenomenon. For this reason multiple channels are needed to achieve greater area coverage rates.

The multiple channels can be arranged in either the along track or range directions.

Computations for antenna dimensions and area are made for systems with swath width of 10^2, 2×10^2, 5×10^2 and 10^3 km.

More complete computations are made for an eight range channel system covering 5×10^2 km swath and a two range channel system covering 3.5×10^2 km swath. For these cases the average power needed per beam and for the system are also computed using the J.P.L. model for ocean reflectivity.

An eclipsing problem occurs which makes the wide band systems require some duplication of equipment in each channel rather than sharing of common equipment among all channels. In all cases the antenna area is common to all beams, although multiple beams with multiple output ports are required.

1.0 Introduction

This report summarizes the results of a study under J.P.L. Contract 955019 carried out at the University of California at San Diego.

The purpose of the contract was to support a study to determine means to achieve wide swaths in satellite borne synthetic aperture radars.

Antenna dimensions play a major role in determining the swath width and the area rate (area mapped per unit time) for a single beam radar.

The Seasat Radar, a single beam radar, for example, had antenna dimensions of 10.7m by 2.7m. This permitted a swath width of 100 km and an area rate of about $7.6 \times 10^8 m^2$/sec (Using $V = 7.6 \times 10^3$m/sec).

At the start of the contract it was felt to be desirable to determine the system parameters needed to achieve swath widths greater than 100 km for synthetic aperture radars at the same height and speed as the Seasat.

Since the limitation on area rate can be considered to be the result of reaching channel capacity on a single radar beam, one noted that the use of multiple beams or channels was a necessary part of the solution.

Multiple channels could be arranged to cover a number of range intervals, or multiple channels could be used to cover adjacent lateral (along track) intervals while covering the same range interval. Of course one can also arrange a combination of the above, namely: beams covering intervals extending in both the range and along track directions.

Since the combination of beams along both the range and along track direction is the more general case, that case was studied.

Radar parameter values were obtained for a number of systems having swath widths of 100 km, 200 km, 500 km and 1000 km.

The radar parameters were obtained by first considering the satellite geometry and then requiring that the desired resolution and swath width be achieved while avoiding ambiguities.

For each swath width, the antenna area required was found to be esentially constant, the value of the constant increasing with desired swath width.

For a given swath width, computations were made for radar parameters for the case that the desired swath width was covered by 1, 2, 3 ... range intervals.

It was found when the desired swath width was covered by a single beam that one needed the largest horizontal dimension and the smallest vertical aperture. As the number of range channels was increased, the dimension of the needed horizontal aperture decreased while that of the vertical aperture increased. In each case the area for a given swath width remained essentially constant.

Eventually for each swath width there is a number of range intervals for which the horizontal and vertical antenna apertures needed become essentially equal. For a larger number of range intervals the vertical aperture needed then becomes larger than the horizontal aperture.

Essentially square antenna apertures seemed desirable, hence the computations were continued until this crossover occurred for each of the swath widths selected.

The detailed computations and results are given in Section 2.1.

Discussion of the above results with the technical monitors of the contrast indicated the desirability of putting greater emphasis on those radar systems designed to cover a 500 km swath width.

Since nearly square antenna apertures also seemed desirable the systems studied were those covering a swath width of 500 km with 8-9 beams in range.

It is important to point out, since antenna considerations dominate system design, that all of the multiple beam radar systems considered share the same antenna aperture. Thus if a number of beams are required in different directions, the antenna must form the required number of beams and present the output of each beam at a set of output terminals. A separate receiver is associated with each output antenna port.

For the case of 500 km swath width and nearly square antenna additional radar parameters were computed. The geometry of the multi-range case was computed as were also tentative values for unambiguous range, R_u; pulse repetition frequency, etc. Moreover, using the JPL model for ocean reflectivity the average power per elevation beam and the total average power to cover the 500 km swath were computed. These results are given in Section 2.2.

The parameter values obtained seemed reasonable. At this stage, however, it became evident that there was an eclipsing problem (i.e., the need to transmit at times when it is also necessary to receive).

When means to overcome the eclipsing problem were studied, it became evident that the multiple channels were becomming more nearly separate radar systems rather than a radar with a multibeam antenna and separate receiver channels but sharing most of the other components.

Discussion of this problem with the technical monitors of the program led to a decision to determine what could be done using two elevation channels with a goal of 350 km for the swath width.

This configuration was the final one to be computed. These results are given in Section 2.3.

The results of all these computations and of the considerations pertinent to them are described in Section 2.0.

2.0 Technical Discussion

As is indicated in Section 1.0 three sets of computations have been made. These are described in this section.

The first set of computations concerns itself with the geometry and antenna related parameters for radar systems having swath widths of 10^5 m, 2×10^5 m, 5×10^5 m and 10^6 m with m = 1, 2, 3 ... elevation channels. These computations are described in Section 2.1.

The second set of computations were performed to investigate the properties of radar systems having a swath width of 500 km and an approximately square antenna. These computations and the results are given in Section 2.2.

The final set of computations were those for a two elevation channel radar spanning 350 km. These results are given in section 2.3.

2.1 In this section computations and the considerations pertinent to them are described for radar systems having multiple beams in elevation and spanning a set of swath widths.

In making the computations, use is made of the geometry and various constraints such as achieving the desired swath width and resolution with a selected number of beams. One also prescribes that the radar system be free of ambiguities in both range and azimuth.

The manner in which these constraints are used and the sequence of selection of parameter values is described below.

The initial step is that of computing the geometry. One starts by computing the parameters associated with minimum and maximum range.

The geometry for minimum range is computed given values for h, R_0, and γ_0, the altitude, earth radius, and angle from nadir respectively. From these one computes ψ_0, θ_0, and r_0, the glancing angle at minimum range, the angle subtended at earth center, and the value of minimum range respectively using the equations

$$\left.\begin{aligned}\psi_0 &= \cos^{-1}\left[\frac{R_0 + h}{R_0}\sin\gamma_0\right]\\ \theta_0' &= 90 - \gamma_0 - \psi_0\\ \text{and}\qquad r_0 &= R_0\,\frac{\sin\theta_0}{\sin\psi_0}\end{aligned}\right\} \tag{1}$$

A swath width, W is desired. Values of W of 10^5 m, 2×10^5 m, 5×10^5 m and 10^6 m were used in the computations.

Given W and the parameters at minimum range, the geometry at maximum range can be computed. This is done using the equations

$$\left.\begin{aligned}\theta_M &= \theta_0 + \frac{W}{R_0}\left(\frac{180}{\pi}\right)\\ r_M &= \sqrt{R_0^{\,2} + (R_0 + h)^2 - 2R_0(R_0 + h)\cos\theta_M}\\ \psi_M &= \cos^{-1}\left[\frac{R_0 + h}{r_M}\sin\theta_M\right]\\ \gamma_M &= 90 - \psi_M - \theta_M\end{aligned}\right\} \tag{2}$$

The geometry associated with minimum and maximum range is shown in Figure 1.

One next selects M, the number of elevation beams to be used. Given r_M and r_0, the maximum and minimum ranges corresponding to each W, one forms m elevation beams defined by a range difference

$$\Delta = \frac{1}{M}(r_M - r_0) \tag{3}$$

The unambiguous range R_u must be not less than Δ for each of the m elevation beams. If one selects a value $\beta =$ ($\beta \geqq 1$) then one can compute R_u from equation

$$R_u = \frac{1}{\beta}\Delta \tag{4}$$

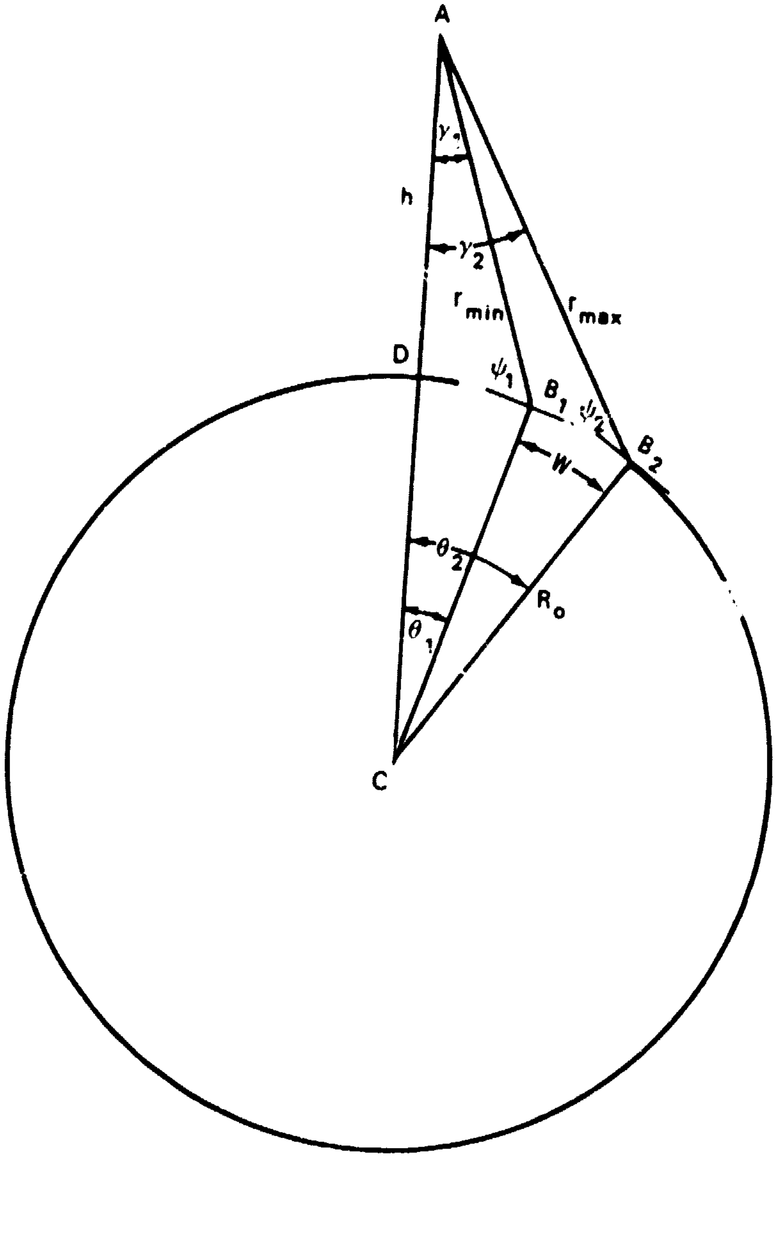


Figure 1. Geometry for Satellite Borne Radar.

The radar pulse repetition frequency, prf, and the interpulse period, T, are now determined.

$$prf = \frac{1}{T} = \frac{c}{2R_u} = \frac{c\beta}{2\Delta} \tag{5}$$

The number of pulses, p, underway simultaneously is given by

$$p = \frac{r_M}{R_u} \tag{6}$$

One needs next to choose the horizontal antenna aperture, D. This is done by noting that the doppler frequency shift, f, at the 3db point of an antenna of horizontal aperture D moving at velocity V parallel to its aperture is

$$f = \frac{V}{D} \tag{7}$$

To avoid frequency ambiguity one needs the sampling rate (prf) to be at least twice the value of f_d. Hence

$$\left.\begin{aligned} prf &= 2\gamma \frac{V}{D} \\ \gamma &\geqq 1 \end{aligned}\right\} \tag{8}$$

From equation (8) one gets for D

$$D = \frac{2\gamma V}{prf} = \frac{\gamma}{\beta} 4 \frac{V}{c} \Delta$$

$$D = \frac{\gamma}{\beta} 4 \frac{V}{c} \; \frac{r_2 - r_1}{m} \tag{9}$$

The number of azimuth beams needed is given by

$$n = \left[\frac{D}{2\alpha\delta_a}\right]_{GE} \tag{10}$$

In equation (10), the notation $[x]_{GE}$ means the smallest integer greater than or equal to x.

One needs next to compute the vertical antenna aperture, H. To do this one must first solve the geometry by subdividing the range intervals between minimum range and maximum range. The geometry is solved as follows:

$$r_q = r_0 + q\Delta$$

$$q = 2, 3, \ldots M$$

with

$$r_0 = r_{min}$$

$$r_M = r_{max} \tag{11}$$

One then uses

$$\theta_q = \cos^{-1}\left[\frac{R_0^{\,2} + (R_0 + h)^2 - r_q^{\,2}}{2R_0(R_0 + h)}\right]$$

$$\psi_q = \cos^{-1}\left[\frac{R_0 + h}{r_q} \sin\theta_q\right]$$

$$\gamma_q = \sin^{-1}\left[\frac{R_0}{r_q} \sin\theta_q\right] \tag{12}$$

Given this geometry, the swath width W_q is given by

$$W_q = \frac{180}{\pi} R_0(\theta_{q+1} - \theta_q)$$

$$q = 1, 2, \ldots m \tag{13}$$

The elevation beamwidth θ_{Eq} is given by

$$\theta_{Eq} = \gamma_{q+1} - \gamma_q \tag{14}$$

and the vertical antenna aperture is given by

$$H_q = \frac{180}{\pi}\left(\frac{\lambda}{\gamma_{q+1} - \gamma_q}\right) \tag{15}$$

The antenna area is given by

$$A_q \doteq H_q D \qquad (16)$$

In making the computations the values used were

$R_0 = 6.7321 \times 10^6$ m

$h = 8 \times 10^5$ m

$\gamma_1 = 20°$

$W = 10^5$ m, 2×10^3 m, 5×10^5 m, 10^6 m

$m = 1, 2, 3, \ldots$

$\beta = 0.75$

$\gamma = 1.5$

$\alpha = 0.8$

$\delta = 25$ m

Figures 2-6 were plotted from these computations.

Figures 2-5 show the values of H, D and A_{rec} as a function of m for each W.

It will be noted that as m increases the required value of D decreases, while the required value of H increases such that A_{req} while increasing slightly becomes nearly constant for a given value of W.

In plotting Figures 2-5, the largest value of H for all m at a give W is used since this is the driver in building a radar.

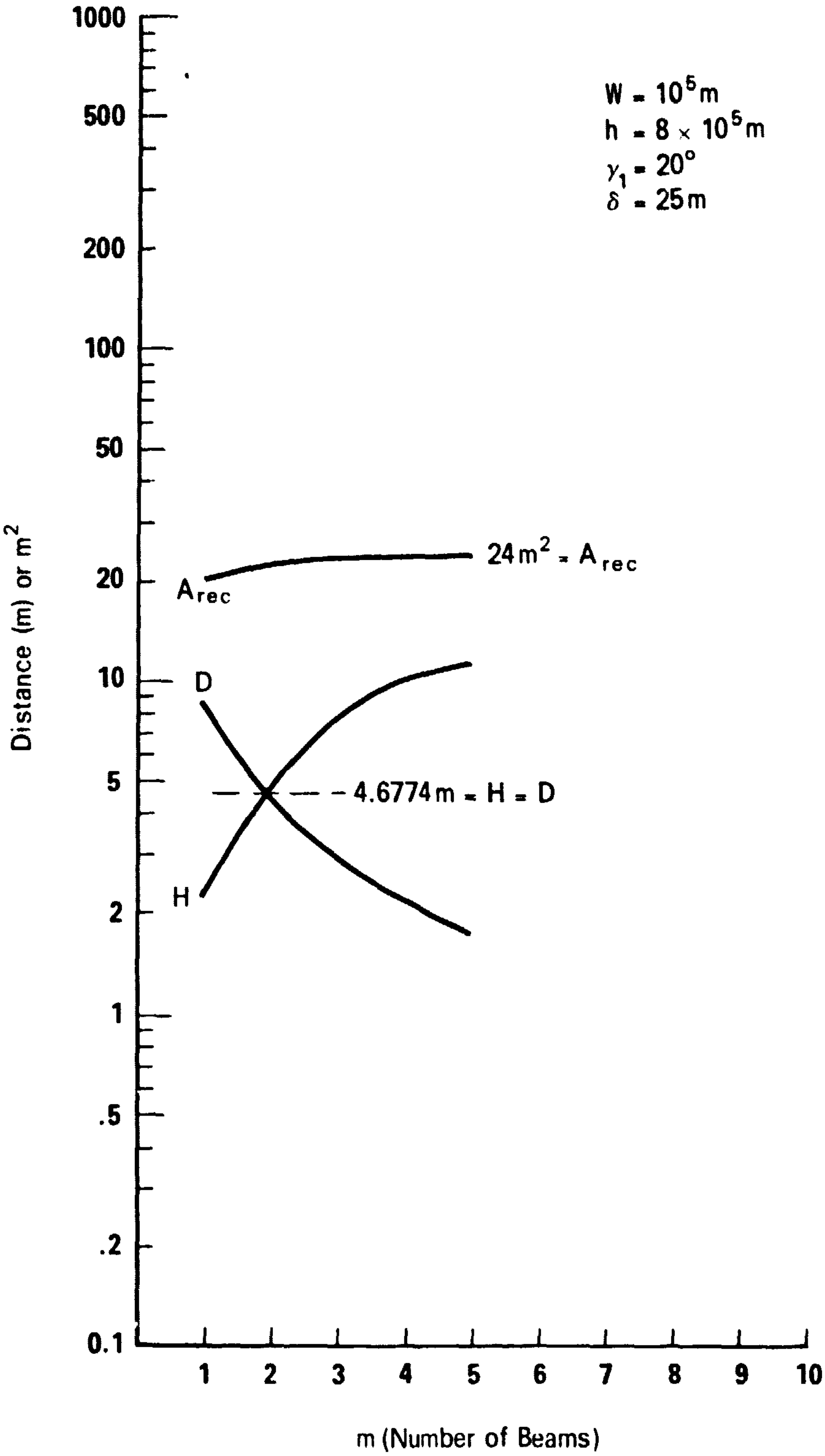
In Figure 6 the values of A_{rec}, as a function of W is plotted.

In Figures 2-5 it will be noted that for each value of W there is a crossover at which

$$H = D$$

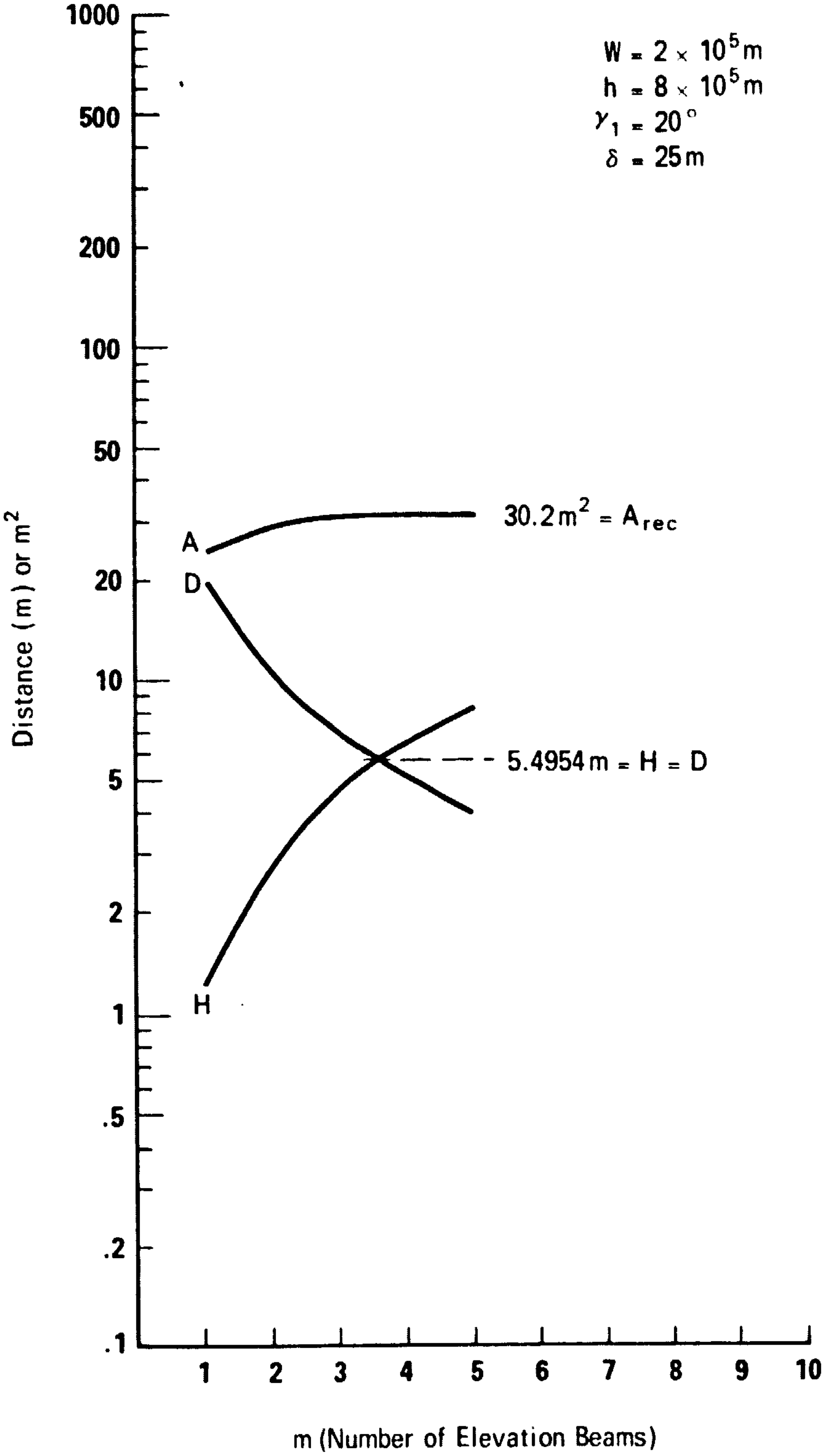
This crossover value is also plotted as a function of W in Figure 6.

The value of m at which equality of H and D occurs as a function of W is another quantity plotted in Figure 6.



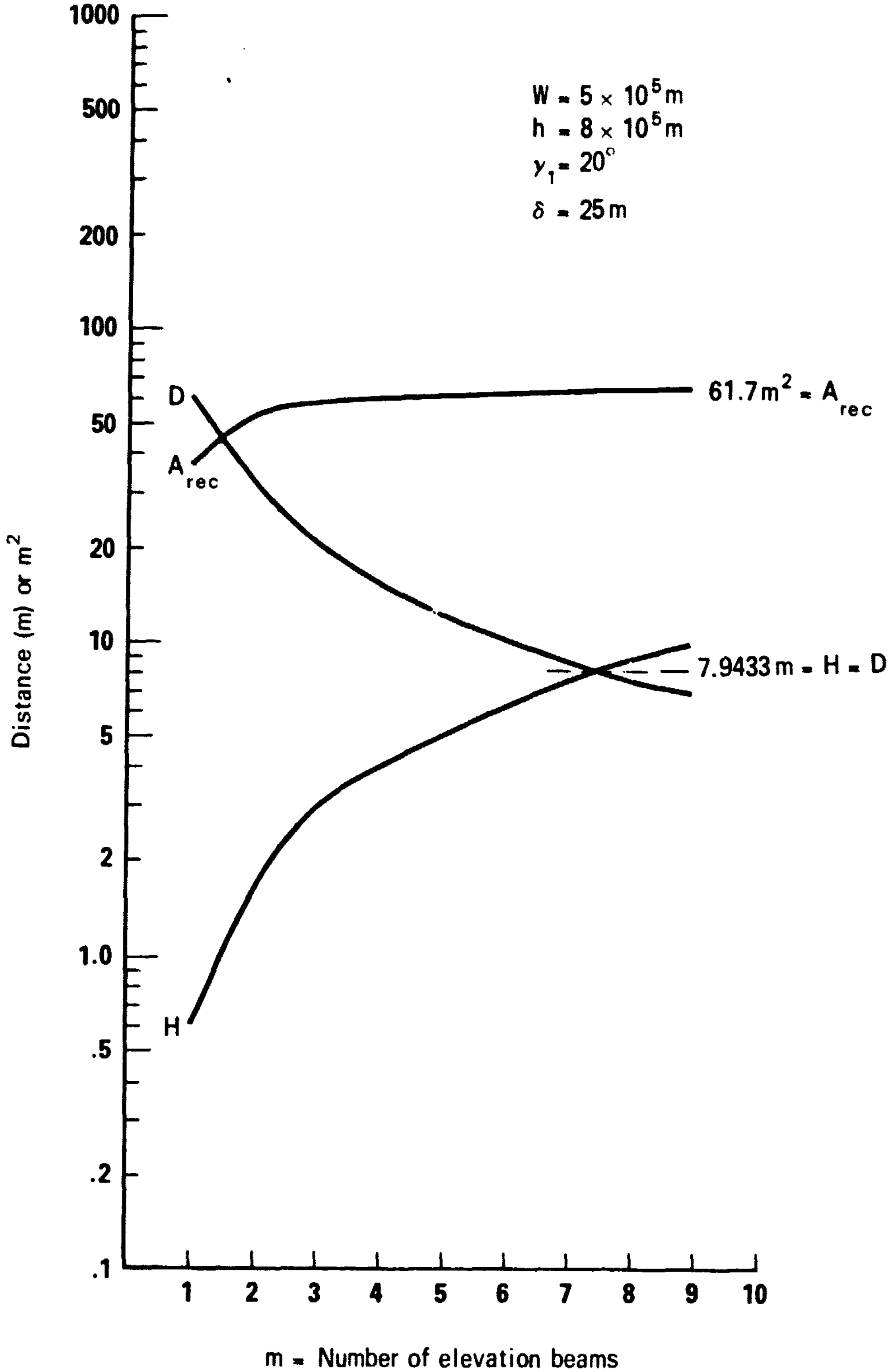
W = 10^5 m
h = 8 × 10^5 m
γ1 = 20°
δ = 25 m
1000
500
200
100
50
20
10
5
2
1
.5
.2
0.1
Distance (m) or m^2
Arec
24m^2 = Arec
D
H
4.6774m = H = D
1
2
3
4
5
6
7
8
9
10
m (Number of Beams)

Figure 2



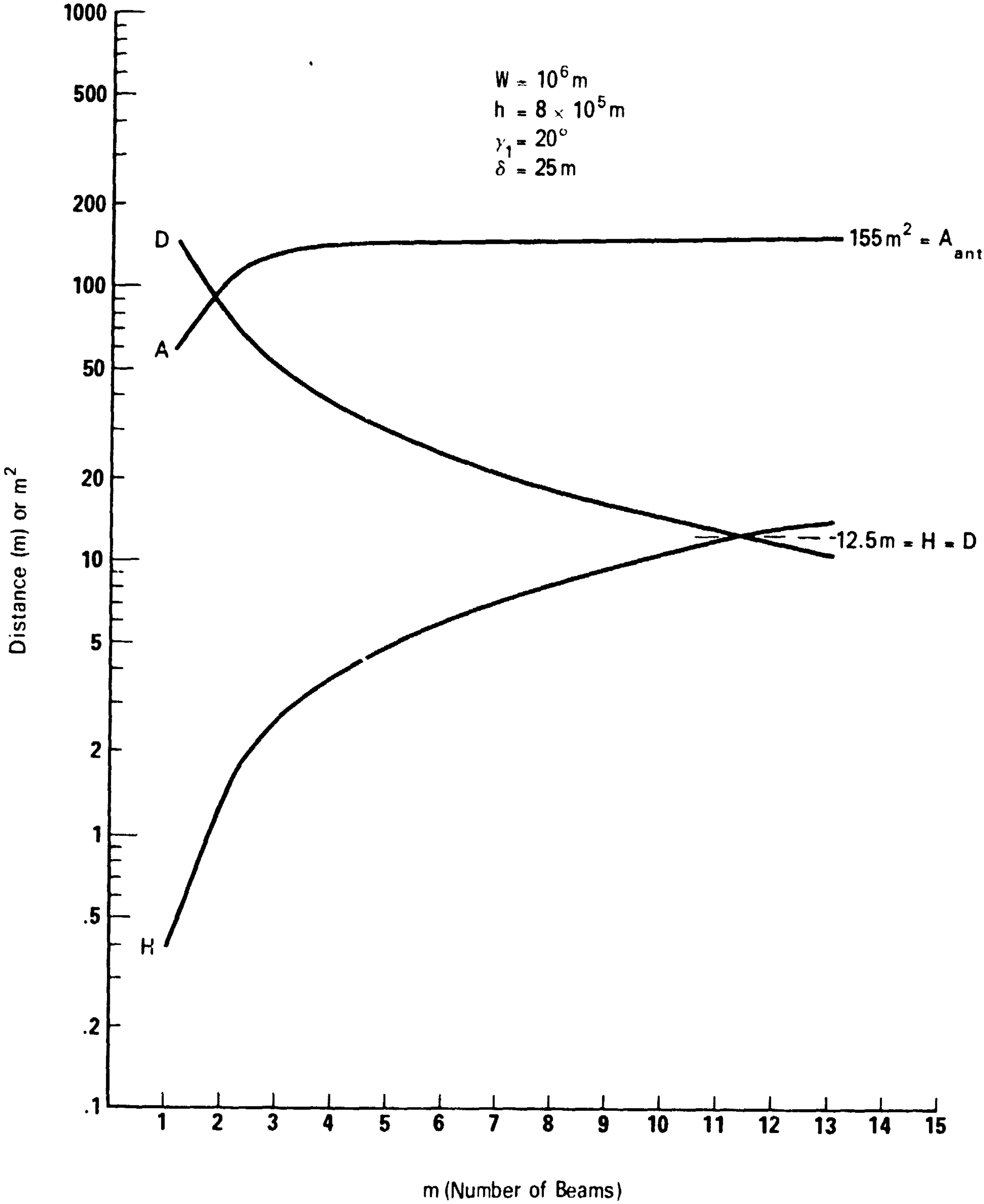
W = 2 × 10⁵m
h = 8 × 10⁵m
γ1 = 20°
δ = 25m
1000
500
200
100
50
20
10
5
2
1
.5
.2
.1
Distance (m) or m²
A
D
H
30.2m² = Arec
5.4954m = H = D
1
2
3
4
5
6
7
8
9
10
m (Number of Elevation Beams)

Figure 3



W = 5 × 10⁵m
h = 8 × 10⁵m
γ₁ = 20°
δ = 25 m
D
A rec
H
61.7m² = A rec
7.9433 m = H = D
Distance (m) or m²
1000
500
200
100
50
20
10
5
2
1.0
.5
.2
.1
1
2
3
4
5
6
7
8
9
10
m = Number of elevation beams

Figure 4



W = 10^6 m
h = 8 × 10^5 m
γ_1 = 20°
δ = 25 m
1000
500
200
100
50
20
10
5
2
1
.5
.2
.1
D
A
H
155 m^2 = A_{ant}
12.5 m = H = D
Distance (m) or m^2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
m (Number of Beams)

Figure 5

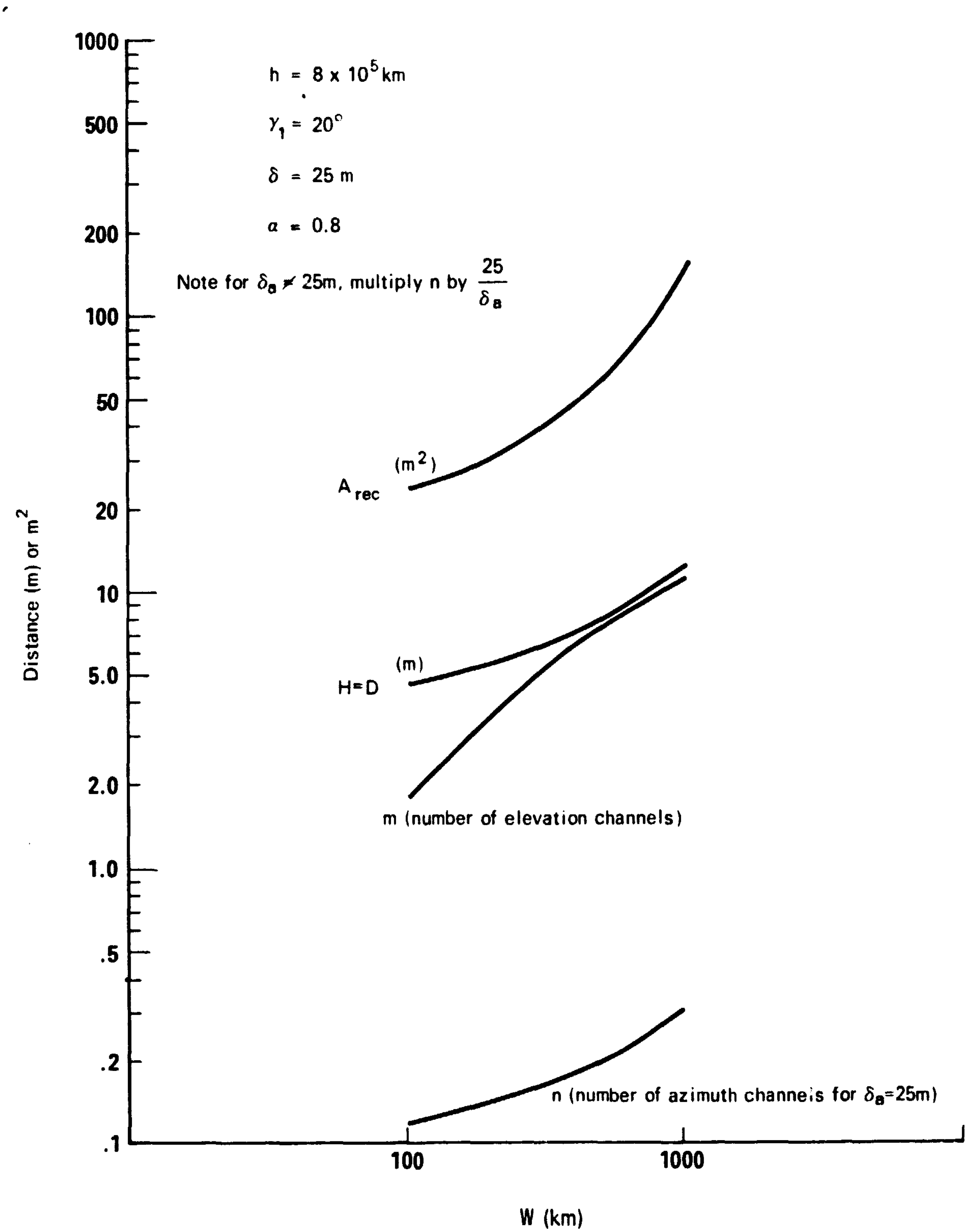

h = 8 x 10^5 km
γ1 = 20°
δ = 25 m
α = 0.8
Note for δa ≠ 25m, multiply n by 25/δa
A rec (m2)
H=D (m)
m (number of elevation channels)
n (number of azimuth channels for δa=25m)
Distance (m) or m2
1000
500
200
100
50
20
10
5.0
2.0
1.0
.5
.2
.1
100
1000
W (km)

Figure 6

The final quantity plotted is n, the number of azimuth beams required. The value of n is computed for $\delta_a = 25$ m. If one chooses another azimuth resolution one needs to multiply n by $25/\delta_a$.

Examination of Figures 2-6 indicate that reasonable antenna dimensions are predicted for systems having nearly square apertures. For this reason a system covering a swath of 5×10^5 m in width with nearly square antenna aperture was selected as a candidate for further study. These analyses are described in Section 2.2.

2.2

In discussions with the technical monitors of the contract it was decided to investigate more fully system parameters giving a total swath of 5×10^5 with the number of elevation beams chosen to achieve nearly square antenna. For this reason a radar system with a swath width of 5×10^5 m having 8 elevation beams was designed.

In making these computations, the geometric computations, and those leading to antenna dimensions were supplemented by those necessary to compute signal-to-noise ratio for signals reflected from the ocean surface.

In making these computations, the reflection coefficient model used was specified by J.P.L. This model is plotted as Figure 7.

The computation results are summarized in Table 1.0.

Figures 8 and 9 display some of the results of these computations.

Also shown in this figure are the swath width in each elevation beam, and the maximum range in each beam.

The angle parameters γ, ψ and θ for each elevation beam are plotted in Figure 9.

The angle of incidence for each elevation beam is also plotted in Figure 9. This value is used to compute target cross-section in computing average power.

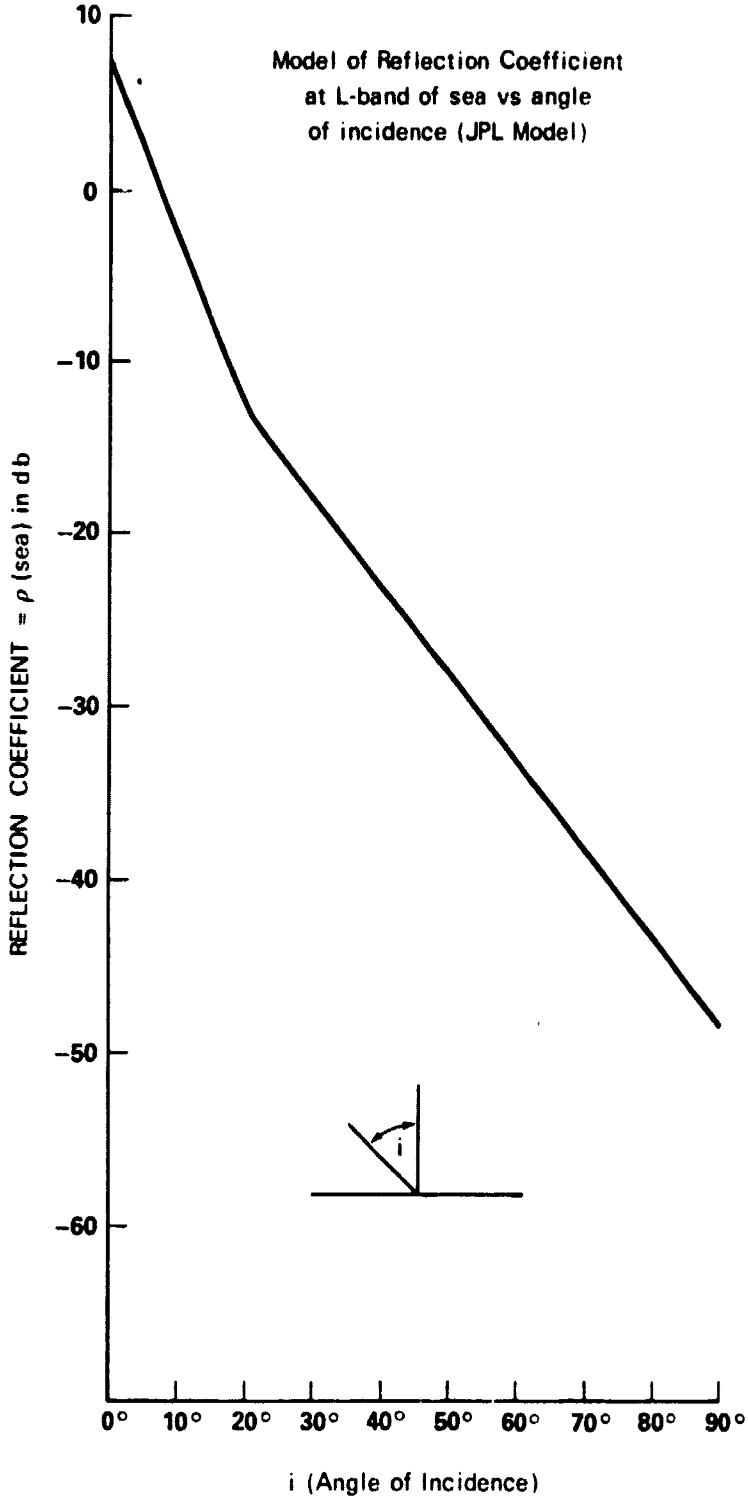
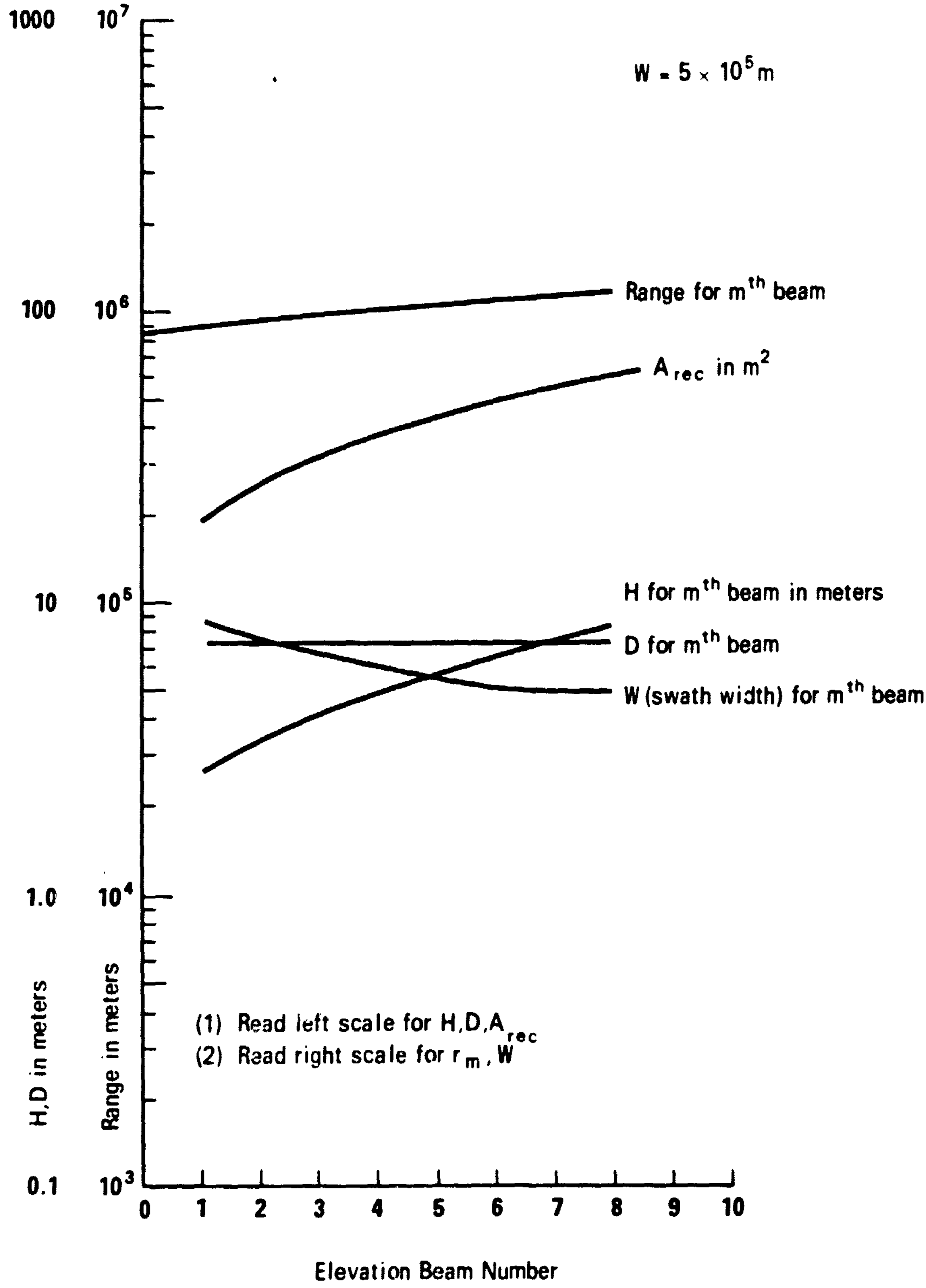
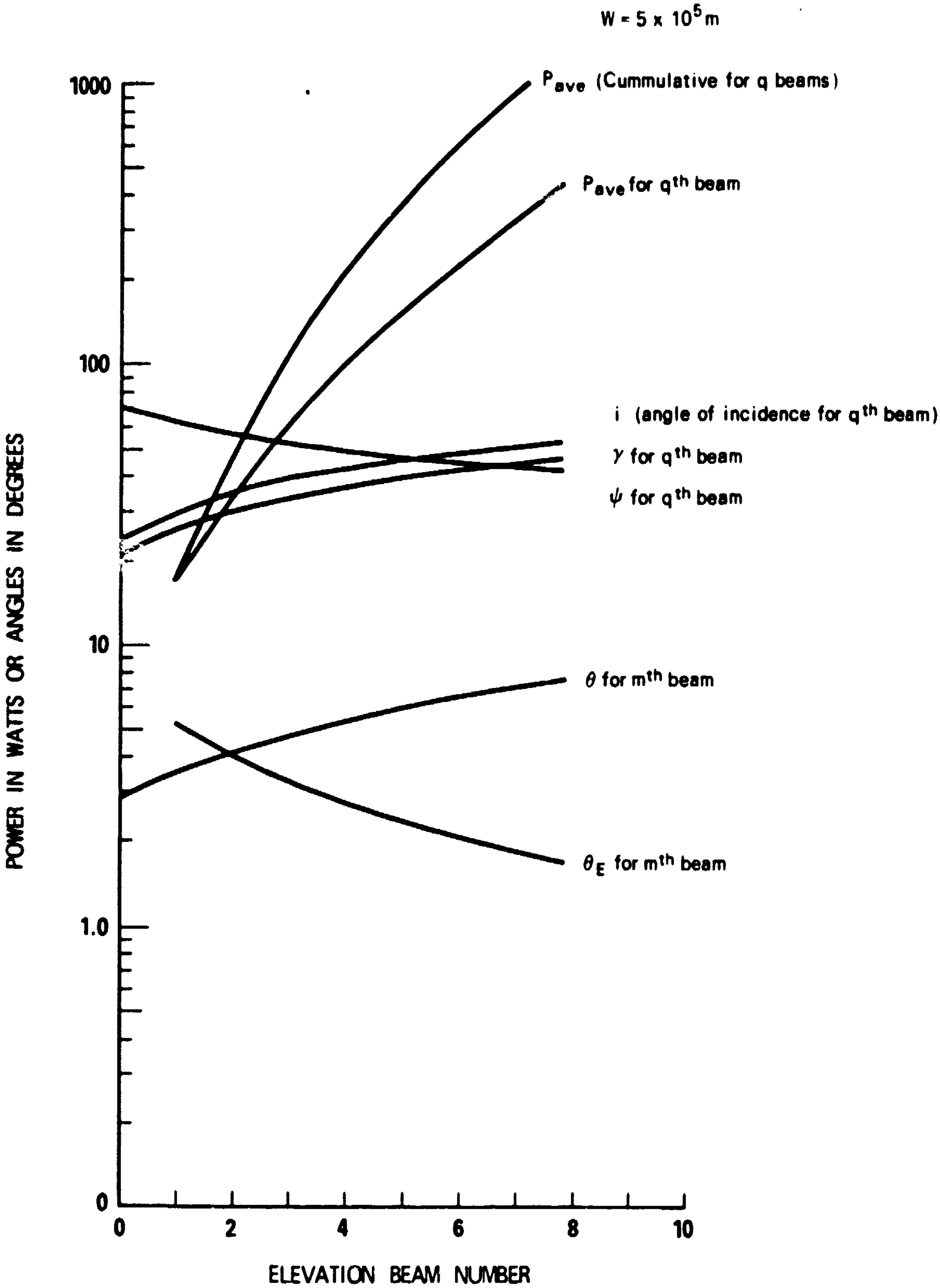

Model of Reflection Coefficient
at L-band of sea vs angle
of incidence (JPL Model)
10
0
-10
-20
-30
-40
-50
-60
REFLECTION COEFFICIENT = ρ (sea) in db
i
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
i (Angle of Incidence)

Figure 7



1000
100
10
1.0
0.1
10^7
10^6
10^5
10^4
10^3
W = 5 × 10^5m
Range for m^{th} beam
A_{rec} in m^2
H for m^{th} beam in meters
D for m^{th} beam
W (swath width) for m^{th} beam
(1) Read left scale for H,D,A_{rec}
(2) Read right scale for r_m, W
H,D in meters
Range in meters
0
1
2
3
4
5
6
7
8
9
10
Elevation Beam Number

Figure 8



W = 5 x 10^5 m
Pave (Cummulative for q beams)
Pave for qth beam
i (angle of incidence for qth beam)
γ for qth beam
ψ for qth beam
θ for mth beam
θE for mth beam
1000
100
10
1.0
0
POWER IN WATTS OR ANGLES IN DEGREES
0
2
4
6
8
10
ELEVATION BEAM NUMBER

Figure 9

Table 1. Data for Swath - 5 x 10^{5}m.

	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6	m = 7	m = 8
γ_{11}	20°							
ψ_1	67.358°							
θ_1	2.6410°							
r_1	8.5855×10^{5}							
θ_2	7.1381°							
r_2	1.1611×10^{6}m							
ψ_2	39.875°							
γ_2	42.987°							
Δ	3.7823×10^{4}							
δ	0.75°							
R_u	5.0431×10^{4}							
p	23.024							
prf	2.9744×10^{3}							
D	7.5041m							
n	$[1.876\times10^{-4}]=1$							
r_q	8.9637×10^{5}	9.3419×10^{5}m	9.7202×10^{5}m	1.0096×10^{6}m	1.0472×10^{6}m	1.0858×10^{6}m	1.1233×10^{6}m	$1.1611\ 10^{6}$m
θ_q	3.4278°	4.0900°	4.6812°	5.2255°	5.7364°	6.222°	6.6850°	7.1381°
ψ_q	61.423°	56.804°	52.980°	49.702°	46.830°	44.273°	41.970°	39.875°
γ_q	25.149°	29.106°	32.339°	35.072°	37.439°	39.505°	41.342°	42.987°
θ_E	5.1491°	3.9567°	3.2334°	2.7332°	2.3612°	2.0711°	1.8375°	1.6447°
λ	0.235m	0.235m	.235m	.235m	.235m	.235m	.235m	.235m
H_q	2.6149m	3.4030m	4.1643m	4.9262m	5.7025m	6.5011m	7.3278m	8.1868m
W	8.7418×10^{4}	7.3637×10^{4}m	6.5739×10^{4}m	6.0530×10^{4}m	5.6807×10^{4}m	5.4004×10^{4}m	5.1812×10^{4}m	5.0052×10^{4}m
A_{rec}	19.622m^2	25.536m^2	31.249m^2	36.967m^2	42.792m^2	48.785m^2	54.988m^2	61.434m
D	7.505m	7.505m	7.505m	7.505m	7.505m	7.505m	7.505m	7.505m
i	28.58°	33.20°	37.02°	40.30°	43.17°	45.73°	48.83°	50.13°
ρ	1.863×10^{-2}	1.094×10^{-2}	7.046×10^{-3}	4.831×10^{-3}	3.471×10^{-3}	2.586×10^{-3}	1.984×10^{-3}	1.559×10^{-3}
P_{ave}	16.20W	31.21W	54.61W	89.29W	138.8W	207.2W	299.4W	420.8W
P_{total}	16.20	47.41	102.02	191.31	330.11	537.31	836.71	1257.51

P_{total} = 1258W for 8 beams

The elevation beamwidth for each beam is also plotted in Figure 9. The vertical antenna aperture plotted in Figure 9 is that corresponding to the beam at maximum range, since this elevation beam width is the driver.

In the computations an analytic expression for sea reflection coefficient is used with the computed value of r.

From the data P_{ave} per beam, and P_{ave} cumulative can be computed. Both these quantities are plotted in Figure 9.

The average power required as a function of the number of elevation beams for $W = 10^5$ m and for $W = 5 \times 10^5$ m is plotted in Figure 10.

A block diagram of a possible mechanization is shown in Figure 11.

In making these computations, the average power per beam was calculated by requiring the signal-to-noise ratio to be 15 db and using a noise temperature of 1000°K. Other values used in the computations are

$$\lambda = 0.235 \text{ m}$$

$$\delta = 25 \text{ m}$$

$$V = 7.671 \times 16^3 \text{ m/sec.}$$

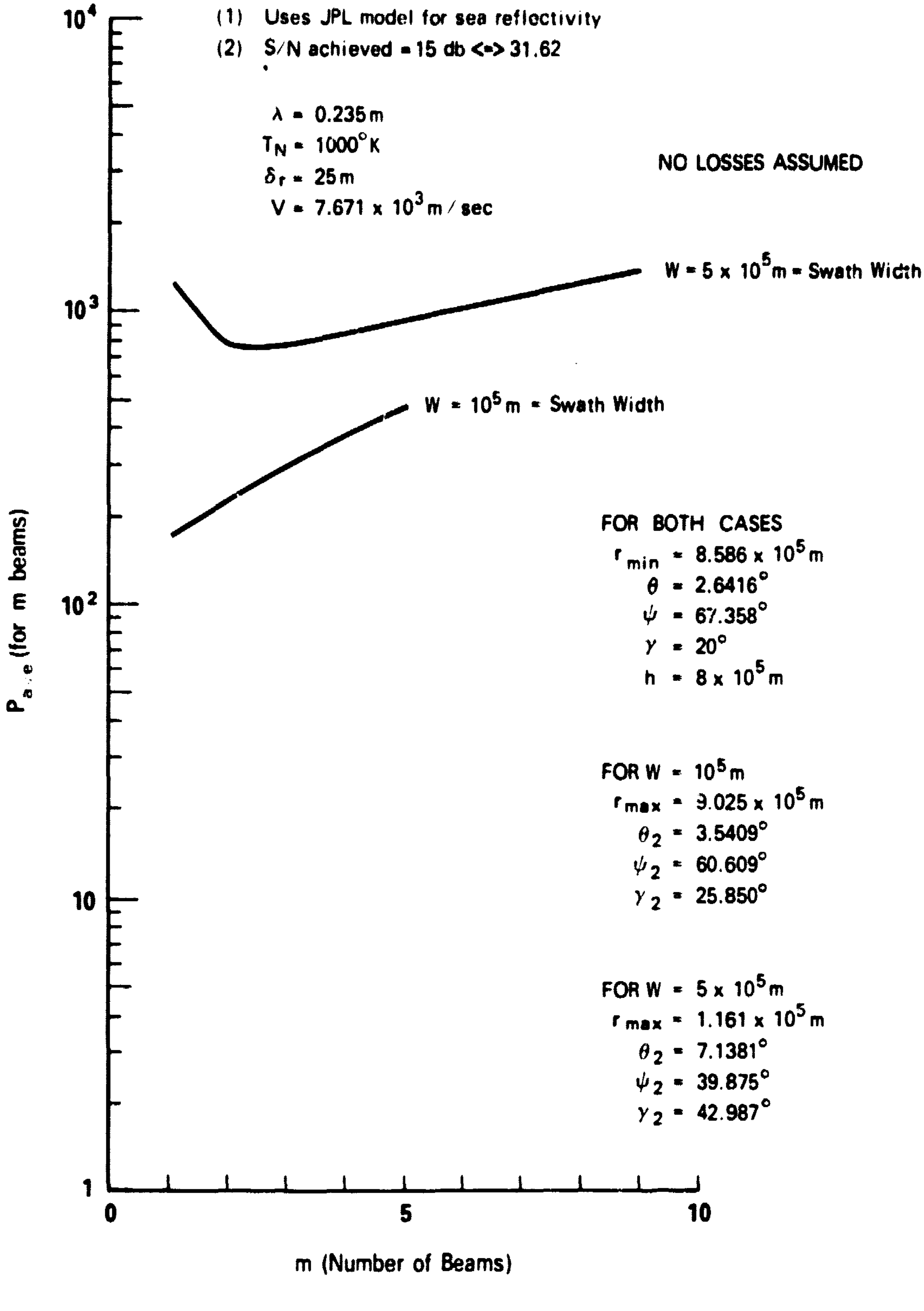
Consideration of the data in Table 1.0 and of the computations to this point indicated that reasonable system parameters were needed.

For this reason attention was directed toward deriving a system block diagram and a timing diagram for the system covering a 5×10^5 m swath with nearly equal horizontal and vertical antenna apertures. Such a block diagram is given as Figure 11.

It had been anticipated that a block diagram with the following characteristics would be adequate:

(1) A single transmitter illuminating the needed azimuth and range intervals would be satisfactory.

(2) The added complexity would come from the necessity to have a receiving antenna forming multiple beams with a separate receiver channel associated with



(1) Uses JPL model for sea reflectivity
(2) S/N achieved = 15 db <=> 31.62
λ = 0.235 m
T_N = 1000°K
δ_r = 25 m
V = 7.671 x 10^3 m / sec
NO LOSSES ASSUMED
W = 5 x 10^5 m = Swath Width
W = 10^5 m = Swath Width
FOR BOTH CASES
r_{min} = 8.586 x 10^5 m
θ = 2.6416°
ψ = 67.358°
γ = 20°
h = 8 x 10^5 m
FOR W = 10^5 m
r_{max} = 9.025 x 10^5 m
θ_2 = 3.5409°
ψ_2 = 60.609°
γ_2 = 25.850°
FOR W = 5 x 10^5 m
r_{max} = 1.161 x 10^5 m
θ_2 = 7.1381°
ψ_2 = 39.875°
γ_2 = 42.987°
P_{ave} (for m beams)
10^4
10^3
10^2
10
1
0
5
10
m (Number of Beams)

Figure 10

BLOCK DIAGRAM FOR MULTI-BEAM

Note (1) Pulse Compression Options at A, B and C

Note (2) This diagram assumes adequate sidelobe level control in receiving beam antennas.

Note (3) Quadrative channel not shown.

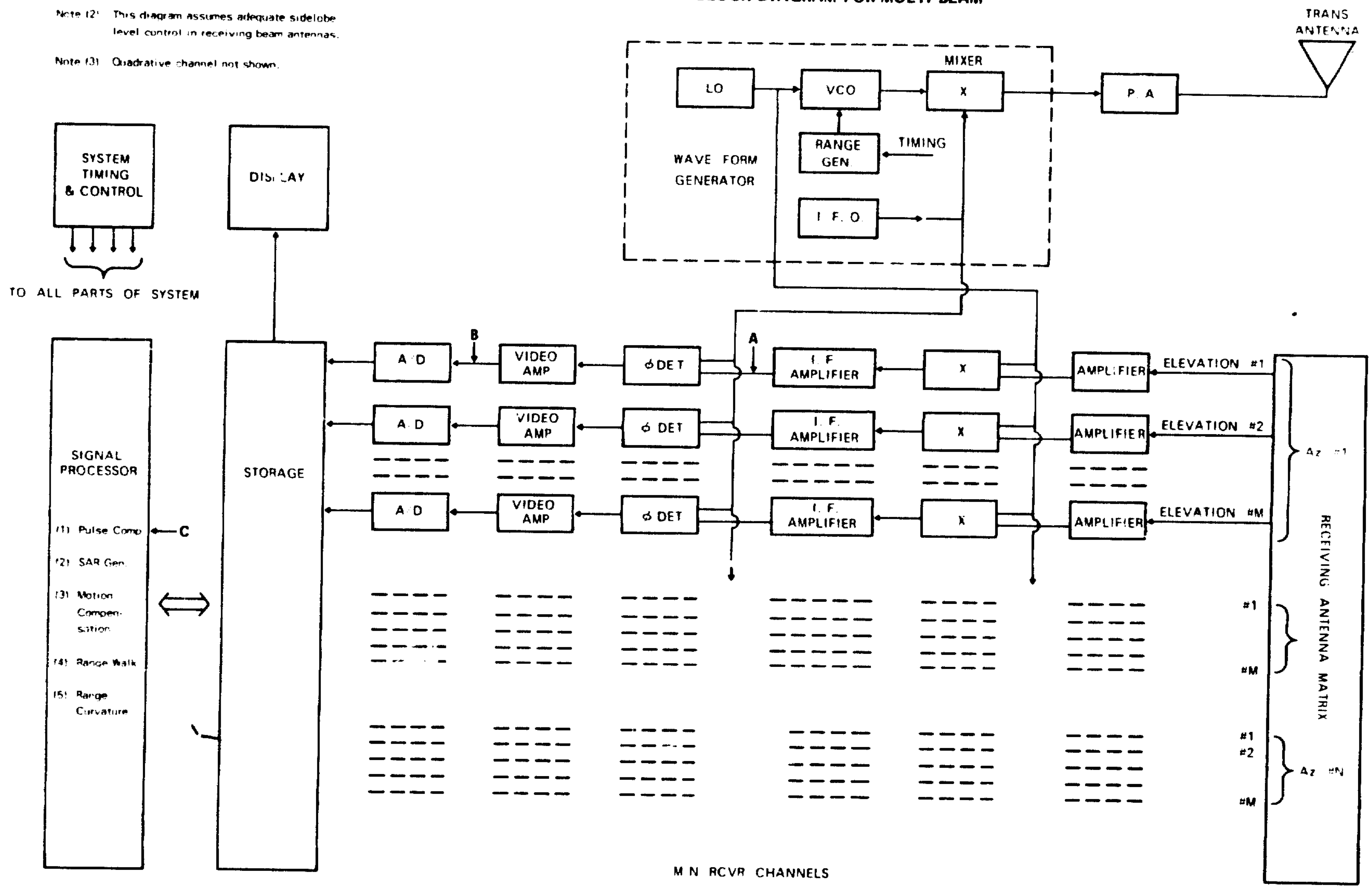


Figure 11

each beam.

(3) After putting signals into storage from each beam, the signal processor required would be essentially as would be required for a single channel system.

Unfortunately upon consideration of system timing it became apparent that an eclipsing problem existed--namely: the necessity to receive some signals at the same time that a transmission was taking place.

Means to overcome the eclipsing problem were sought. While such solutions exist, they tended to complicate the system block diagram by requiring beam forming for the transmitters as well as for the receivers, use of different frequencies on the separate elevation channels, use of different timing on the separate channels.

In essence the system to overcome eclipsing was becomming more like M separate radar systems than like a radar with a complex antenna and multiple receiver channels.

The increased system complexity mode it is desirable to consider reduced performance in order to achieve it with a less complex system.

Discussions along this line with the program monitors led to a decision to investigate a system having two channels and spanning a swath of 3.5×10^5 m. The results of that analysis are given in section 2.3.

2.3

In Section 2.2 the nature of the eclipsing problem was described, and it was indicated that the solution of that problem tends to require multiple transmitters at multiple frequencies, with different pulse repetition frequencies, along with beam forming for both transmitters and receivers, etc.

The effect of these considerations is to make more desirable systems having only a few elevation channels, even though this means providing antennas which are not square.

The final system computed has these characteristics—namely a radar system with two elevation channels, designed to span a swath width of 350 km.

The computation method used is identical to that described in Section 2.2.

The radar is assumed to be mounted in a satellite at an altitude of 800 km. The minimum range begins 20° from nadir and extends for 350 km beyond that point.

The geometry is solved for three triangles, one for minimum range, one for maximum range and one for the intermediate range.

The geometric parameters, the antenna dimensions, the values of unambiguous range, prfs, average power per beam and total power (for two beams) are given in Table 2.0.

Conclusions

The studies show how parameters for synthetic aperture radars may be chosen to achieve prescribed swath width.

One uses a number of constraints, especially those for ambiguity avoidance. These lead to antenna dimension specification and to an area rate limitation dependent primarily on horizontal antenna aperture.

Multiple channels are required when the area rate desired exceeds that set by antenna considerations. The multiple channels can be arranged either in range or in the along track direction.

Since large antennas result for many cases, multiple use of the antenna area to form multiple beams is used.

Procedures for establishing radar system parameters are described.

Detailed computations are given for an 8 beam (in range) system covering a swath width of 5×10^2 km and of a two beam (range) system covering a swath

Table 2. Data for Swath = 3.5×10^5m

	m = 1	m = 2
γ_0	20°	
ψ_0	67.50°	
θ_0	2.499	
r_0	8.582×10^5m	
θ_2	5.478°	
r_2	1.050×10^6m	
ψ_2	46.80°	
γ_2	37.723°	
Δ	9.607×10^4m	
β	0.75	
R_u	1.281×10^5m	
p	8.2	
prf	1.171×10^3	
P	10m	
n		
r_q	9.542×10^5m	1.050×10^6m
θ_q	4.186°	5.478°
ψ_q	54.817°	46.80°
γ_q	30.997°	37.723°
θ_E	11.00°	6.73°
λ	0.235m	0.235m
H_q	1.224m	2.00m
W	1.9822×10^5	1.5181×10^5
A_{rec}	20m^2	20m^2
D	10m	10m
i	35.18°	43.21°
ρ	6.31×10^{-3}	3.98×10^{-3}
P_{ave}	272.25 watts	575.6 watts
P_{total}		847.8 watts

width of 5 x 10^2 km and of a two beam (range) system covering a swath width of 3.5 x 10^2 km.

Multiple range channels present an eclipsing problem. The solution seems to be to duplicate items in each channel rather than use common equipment for all channels. This makes the system somewhat more complicated than was initially believed to be the case.

In most cases the parameter values required are reasonable for swath widths up to 5 x 10^2 km.

Recommendations for Further Study

The major problem illuminated by the studies is that of eclipsing, i.e., the necessity to transmit while wanting also to receive a signal from a previous transmission.

During this study, the means to avoid eclipsing considered were those of using different frequencies, and different prf's in each of the range channels. In addition antenna pattern control to reduce cross-talk between beams helps. These complicate system design.

There may be other means to combat eclipsing. Schemes to combat eclipsing which reduce system complexity should be studied before proceeding to a more serious consideration of wide swath systems.

New Technology

No new items of technology were developed during this contract.