THE SEASAT-A SYNTHETIC APERTURE RADAR DESIGN AND IMPLEMENTATION

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SUMMARY

The Seasat-A Synthetic Aperture Imaging Radar System is the first imaging radar system intended to be used as a scientific instrument designed for orbital use. The requirement of the radar system is to generate continuous radar imagery with a 100 kilometer swath with 25 meter resolution from an orbital altitude of 800 kilometers. These requirements impose unique system design problems and a description of the implementation will be given. The end-to-end data system will be described, including interactions of the spacecraft, antenna, sensor, telemetry link, recording subsystem, and data processor. Some of the factors leading to the selection of critical system parameters will be listed. The expected error sources leading to degradation of image quality will be described as well as estimates given of the expected performance from data obtained during ground testing of the completed subsystems.

1.0 SYSTEM DESCRIPTION

The design of the Seasat-A Synthetic Aperture Radar System was driven by the limitations imposed by the satellite system. In particular, the following constraints played a significant role in the system configuration determination.

1. No on-board data storage could be accommodated of the unprocessed radar signal.

2. The standard satellite system telemetry could not accommodate the large data volume generated by the SAR system.

3. Telemetry link bandwidth allocation was limited to 20 MHz.

4. The average raw power from the spacecraft for the SAR was limited to 500 watts.

With these factors in mind the system configuration evolved as that shown in
Figure 1. A tabulation of the principal system parameters is given in Table 1.

The radar antenna consists of a deployable 10.7 meter long by 2.16 meter wide
planar array. The antenna in its stowed configuration consists of eight
panels each 1.3 meters by 2.16 meters, these panels are folded into an accor-
dion configuration. Upon reaching orbit the antenna structure is folded up
from the spacecraft and the elements allowed to deploy into a long planar
configuration. Subsequent to deployment the antenna cannot be retracted.

The deployed antenna is configured to fly with the long dimension along the
spacecraft velocity vector. The antenna boresight is at an angle of 20°
from the nadir direction in elevation.

The antenna dimensions are dictated by the desire to limit range and
azimuth ambiguities to acceptably low levels. At a nominal 20° look
angle from nadir in order to illuminate 100 kilometers swath on the
Earth's surface from an 800 kilometer high orbit, a total beamwidth
elevation of 6.2° is required. Thus the antenna cross track dimension is
2.16 meters in order to limit the radiation to these sets of angles.

The antenna elements in elevation are weighted in illumination to limit
side lobes in the cross track direction. The resulting area illuminated
on the surface of the Earth is from 240 to 340 kilometers to the right of
the sub-satellites point. The arrival of radar echos from near and far
range prevents the radar transmitter pulses from being too close together
in order to prevent overlapping the returns, from near and far range, of
subsequent pulses. Thus, the pulse repetition rate is limited to a
maximum level by the antenna cross track dimensions.

The antenna along track dimensions is limited on the low end by a desire
to keep azimuth sample ambiguities at an acceptably low level. In order
to avoid sampling ambiguities of the radar data the antenna azimuth
beamwidth must be kept small enough so that the set of azimuth frequencies
do not exceed the sampling rate. However, if the azimuth beamwidth is
kept too small it is not possible to generate the synthetic aperture
large enough to attain the desired resolution for the four independent

TABLE 1

SEASAT-A SAR SYSTEM CHARACTERISTICS

Satellite altitude	800 km
Wavelength	0.235m
RF bandwidth	19 MHz
Transmit pulse length	33.4 μsec
Pulse repetition rate	1463 to 1640 pps
Time-bandwidth product	634
Radar transmitter peak power	1000W
Telemetry transmitter power	10W
Telemetry frequency	2265 MHz
Radar transmitter average power	55W
Sensitivity time control range	9 dB
Data recorder bit rate	110 megabits/sec
Data recording pass duration	10 min
Radar DC power	500W
Radar antenna dimensions	11 by 2.3m
Radar antenna gain	35 dB
Telemetry antenna	Quadrufilar Helix
Telemetry antenna gain	4 dB

looks. These two requirements limit the antenna length along velocity vector to be between 10.5 and 14 meters in length. The antenna length of 10.74 meters was dictated by the available volume within the spacecraft shroud.
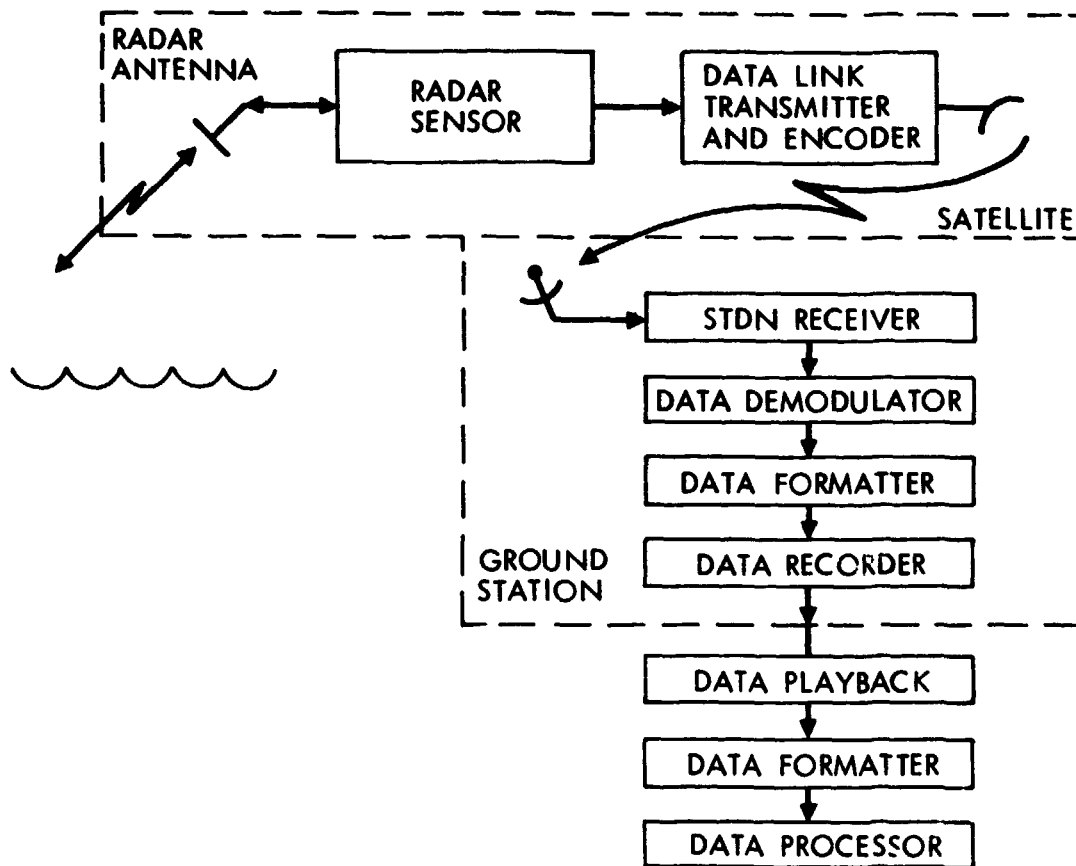
Figure 1. SEASAT-A SAR System Configuration Diagram.

The sensor electronics derives its signal from a surface acoustic wave line which generates a linear FM chirp signal with a bandwidth of 19 MHz and a duration of 33.4 microseconds. The signal is up converted to the L-band carrier frequency amplified to a power level of 1000 watts peak and transmitted to the ground. Upon reception the echo is amplified and up converted to an S-band carrier frequency for telemetering the data to the ground.

Prior to the data transmission a sample of the stable local oscillator is encoded into the S-band spectrum along with a dispersed version of the pulse repetition frequency event. The resultant spectrum of the data link is as shown in Figure 2.

Figure 2. Composite SAR Data Link S Band Transmitted Spectrum

The signal at this point has an analog form with a carrier at the S-band telemetry carrier spectrum. The telemetry signal is transmitted to the ground via a 5 watt solid state transmitter and a omni directional antenna. On the ground the data is received using a 9 meter dish of the STDN network. Upon reception of the composite spectrum by the STDN multifunctional receiver

and parametric amplifier the stable local oscilator pilot tone enables
phase-lock tracking of the signal spectrum and a 45.5 MHz signal is derived
from this pilot carrier. This signal is then utilized to generate a separate
11 MHz signal for performing the synchronous demodulation operation on the
entire carrier. The signal is also passed to the cross correlation device
which provides the retreval of the PRF pulse to a high level of time accuracy
required for reconstituting the signal on the spacecraft. Last, at the output
of the data link the signals are as follows:

1. A range offset video with a frequency spectrum of approximately
    2 to 21 MHz.

2. A PRF pulse which is coincident with the PRF pulse on the spacecraft
    except for the one way delay of the spacecraft to ground station.

3. A clock signal which is derived from the spacecraft stable local
    oscillator.

These signals are then passed on to a recording subsystem at the STDN network.
The recording subsystem consists of a analog to digital converter which is
controlled by the clock derived from the spacecraft stable local oscillator to
an accuracy of 5 bits per word. The data is next stored in a high speed
buffer for subsequent recording in a high density digital tape recorder.

A total of 302 microseconds of data is recorded which corresponds to a 104
kilometer swath width operation at the maximum pulse repetition rate of 1645
pulses per second. The resulting data rate into the high density digital
tape recorder is approximately 107 Megabits per second. The data recorder
has the capability to record a maximum of 15 minutes of data which corresponds
to one station pass. The high density digital tape is then used at the ground
data processor to convert the radar video signals in digital form to a radar
image.

The function of the data processor is to convert the radar video signals
stored in the high-density digital tape format into the radar image in a
format equivalent to a map coordinate system. The task of converting the
radar signal into a radar image from the orbiting spacecraft to the Earth is
a significant one. One must take into account the effect of the Earth
rotating beneath a satellite which is stationary with respect to inertial
space. As the spacecraft orbits the Earth, the antenna will, in practice,

not point in a direction exactly normal to the velocity vector of the spacecraft in inertial space or normal to the velocity of the spacecraft relative to the points being imaged. Consequently, during the generation of a synthetic aperture which has a 15 km nominal length, any one point in the area that is being imaged will undergo an effect termed range migration.

This effect causes a point on the surface to either approach or recede from the spacecraft by as many as 70 resolution elements. The exact amount of range migration that any one point will undergo is a function of the range of that point to the spacecraft, as well as the direction that the antenna is pointing in respect to the true zero doppler direction from the spacecraft.

In practice the knowledge of the location of the antenna bore sight is not good enough to compute the range migration characteristics of each e of the 8000 resolution elements in the cross track directions that are imaged. Thus, spectrum analysis of the radar signal must first be accomplished in order to determine the range migration characteristics. Once the range migration characteristics are known and compensated for, then both the range and azimuth compression operations can take place.

The processing of the Synthetic Aperture Radar Data for Seasat A will be done in an optical correlator. The information from the high-density digital tape format is first converted into a two-dimensional photographic signal film as shown in Figure 3. This signal film is then illuminated with a coherent beam of light. A two-dimensional transform of the signal film is then accomplished by observing the light intensity after the transmitted light beam goes through a spherical lens. The light then passes through a set of lenses which deflect the light beams in proportion to the azimuth spatial frequency and thus perform a range migration correction. The inverse transform is then accomplished by passing the light through another spherical lens.
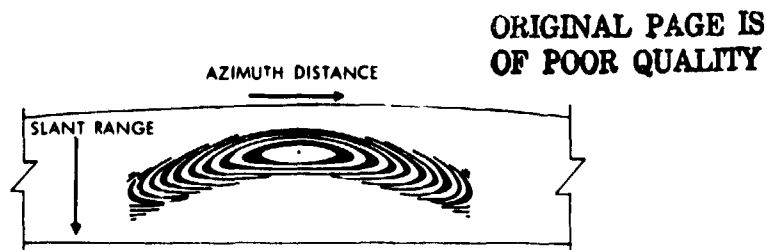
Fig. 3. Signal Film Showing Point Target Phase History

A set of cylindrical lenses then allow the light conversion from targets of all ranges to come into focus at the output plane.

An examination of the characteristics of the radar parameters yields that the resolution equal to approximately 4 times better than the 25 meter resolution required is possible along-track or that the synthetic aperture length required to obtain the 25 meter resolution is 1/4 of that length that the real aperture antenna illuminates the ground. It is therefore, possible to generate a total of 4 separate radar images of the surface and consequently the concept of multiple looks becomes possible when trying to image the surface of the Earth at the 25 meter resolution with the antenna selected. A radar image, because it is generated by observing the surface with a monochromatic source of light has a speckly nature to it. This speckle gives an inability for the data user to accurately estimate the strength of the return. In order to give a better estimate of the return from each individual resolvable element, the image is observed a number of times and the results of each of these measurements is averaged. Thus, the standard deviation of the measurement is reduced. The result to the radar image is that as the number of independent looks is increased, the texture of the radar image becomes a smooth one or a more pleasing one to the eye.

The SEASAT SAR is capable of processing data up to a maximum of 4 independent looks, consequently the radar data processor must be capable of processing the data 4 times, generating 4 separate images and registering the images to a sufficient accuracy so that the resultant image has a low standard deviation for a uniform target field and not have a loss of resolution due to misregistration.

2.0 SPACECRAFT PECULIAR SOURCES OF ERROR

Operations of the synthetic aperture radar in orbit gives rise to some errors or peculiarities that are not found in conventional aircraft borne synthetic aperture radars. A spacecraft, because it operates in inertial space and the Earth rotates beneath the sensor, results in a geometry that is peculiar to imaging radars. First the effects of imaging from an orbiting platform will be described and then the effects of imaging from an orbiting platform discussed.

If the Earth were not rotating and the antenna was pointed exactly normal to
the spacecraft velocity vector the return spectrum would be the spectrum of
the transmitted waveform convolved with the effects of the pulse repetition
frequency and effects of the antenna along track beamwidth. The centroid of
the doppler spectrum would be along zero doppler. If either an antenna point-
ing error is introduced or the Earth rotates, the spectrum would no longer be
centered above zero doppler but would shift to some other frequency deter-
mined by the doppler effect. Since range migration correction is dependent
upon the knowledge of the doppler spectrum, the direction in which the antenna
is pointed must be known to within an angle:

$$\Delta\theta \leq 1/2 \ \sin^{-1} \ \{\frac{\lambda(PRF)}{2V}\}$$

where $\Delta\theta$ is the antenna pointing angle uncertainty, λ is the radar wavelength
and V is the velocity of the spacecraft.

To define the ambiguity a priori, the implication for SEASAT is that at some
point the antenna angle must be known to within 0.65° in order to be able to
correctly process the data. If not, the images will be blurred as the data
will be processed about an ambiguity. Since the spacecraft operates with
reference to inertial space, and the earth rotates beneath the sensor orbit,
the effect of th earth's rotation crosses a predictable shift in the azimuth
doppler spectrum, and consequently, the range of the target migrates in the
signal domain. In the absense of any antenna pointing errors if the target
latitude is known, it is easy to correct for the azimuth shift caused by the
earth's rotation because the earth's rotation is very well known.

Imperfect spacecraft attitude control also effects the data because of changes
in the ground area, which is illuminated by the antenna. The effects of the
doppler spectrum by yaw pitch and roll error is shown in Figure 4. Since there
there is a one to one relationship between the doppler frequency and range
migration once the doppler spectrum is known, the range migration correction
can be completed exactly. The quadrangled bracket by (b) represents the doppler
frequency versus ground range spectrum in the absence of any errors for an
equatorial crossing. In this case, the doppler spectrum is not centered around
the zero doppler because of the earth's rotation. The doppler frequency band-
width occurs between -650 Hz an .800 Hz for the near range targets. In far

range, the frequency will go from -1100 Hz to -2000 Hz. In presence of a yaw error of +0.5° the spectrum will shift up to (a). If the yaw and pitch errors are negative, the doppler frequencies will increase in the negative direction as shown by (c). The main effect is that the spectrum is shifting when the antenna is yawing, pitching, or rol ing. There is a skew because the antenna ground pattern is pointed normal to the spacecraft velocity while the iso doppler lines are oriented perpendicular to the relative velocity composed of the spacecraft velocity and the earth's rotation. The predicted doppler centroid versus latitude is shown in Figure 5. The lines bracketed indicate
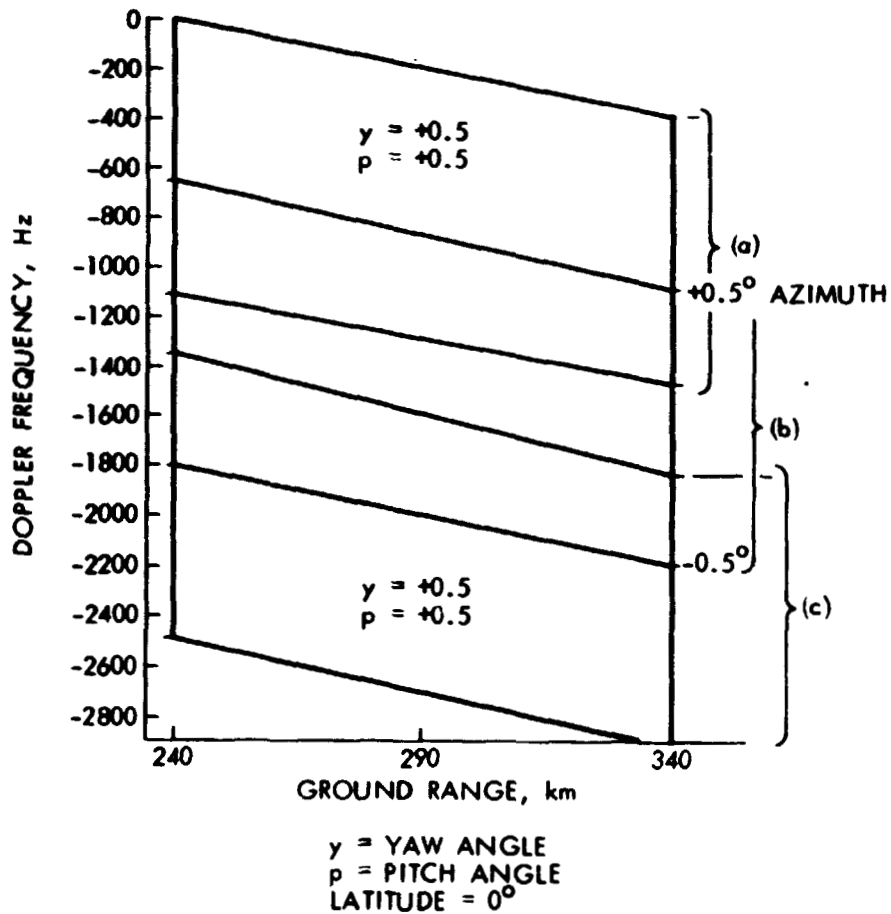
Figure 4. Effect of Pitch and Yaw Errors on Doppler Spectrum.

the center of the spectrum in the absence of any spacecraft added to the
errors. As the latitude increases when the spacecraft travels north from
the equator, the effect of the earth's rotation gets smaller and smaller until
the spacecraft reaches 72° north latitude. At that point, the spacecraft is
at the top of the orbit and the earth's rotation is exactly parallel to the
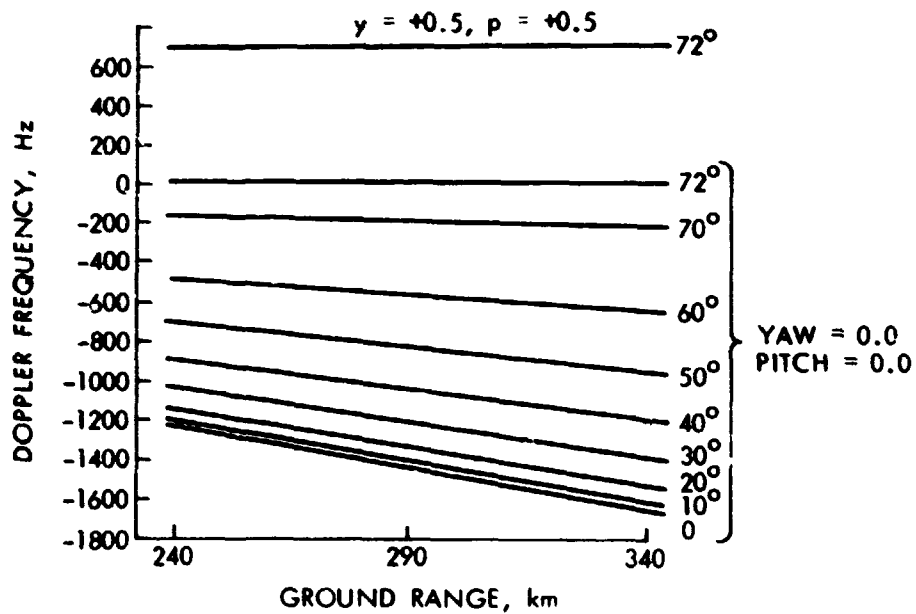flight path. Consequently, there is no doppler centroid shift at this point
again in absence of any pointing errors.

Figure 5. Predicted Doppler Centroid Versus Latitude.

3.0 EXPECTED RADAR PERFORMANCE

The synthetic aperture radar system gives a pictorial representation of the radar backscatter of the Earth surface in a maplike representation. The radar backscatter is defined as the ratio of reflected power per unit area to that which is incident on the terrain that is being illuminated. The ability of the radar system to give an adequate representation of the radar backscatter will be limited on the lower end by the sensitivity of the radar system and on the upper end by the dynamic range of the components comprising the radar system. Furthermore, the sensitivity of the radar system will depend on the location of the area beam map with respect to the assigned swath width of the radar system. The predominant element which determines the radar sensitivity as a function of the swath is the radar antenna. The radar antenna has a gain which will have a peak value at boresight, and as the angle changes from boresight, the antenna gain will drop with angle, and consequently the ability of the radar system to image the Earth's surface will vary with angular position.

The Seasat-A SAR system design is based on measuring the sea backscatter which has a model as shown in Figure 6 . This model is based on measurements taken with the JPL L-Band imaging radar as well as numerous other investigations. This model is based on average sea conditions and as the sea state becomes rougher, higher values of radar backscatter are to be expected and as the sea becomes smoother, lower values in radar backscatter will be observed.

The overall radar system designed allows nominal operation with a surface whose backscatter model follows this curve along the nominal gain of the overall radar system. This radar sensitivity curve is applicable for targets which are extended in nature. If on the surface there are target areas whose average backscatter differs substantially from the expected model, they will be imaged properly if the extent of this specular target is significantly smaller than 15 by 15 km in dimension. The reason for this increase is dynamic range of the system is that the radar signal which is transmitted is dispersed in time and also in azimuth because of the changing doppler frequency of each of the targets. The extent of the dynamic range and improvement which can be expected is a function of this dispersion and for the SEASAT-A SAR can reach values as high as 50 dB.
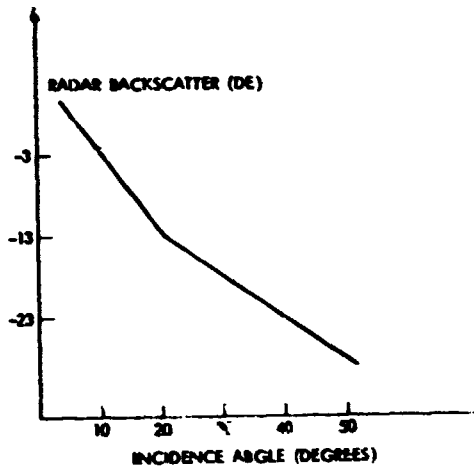
Figure 6. L-band Average Sea Backscatter Model.

In order to compensate for the expected varying signal strength due to effects of the antenna pattern, the radar system incorporates a sensitivity time control as an attempt to maintain a constant sensitivity to a radar backscatter. This is possible because the returns from different angles arrive at different intervals of time. The price paid for this time dependent radar sensitivity is that the radar noise becomes time varying, and consequently the dynamic range that the overall radar system will have will again change with angular precision or swath that is being imaged. If the radar returns are too strong, because the radar backscatter is high, then the radar system will exhibit saturation, and consequently the dynamic range or the ability of the radar system to image over varying values of radar backscatter will be limited.

In the SEASAT-A synthetic aperture radar system, the predominant element which exhibits saturation is the analog data link. On the lower end the radar sensitivity for regions that correspond to the beginning and end of the radar swath, the radar system or radar receiver noise is predominant. At the center of the swath where the sensitivity time control puts a minimum gain, then the data link equivalent noise predominates. In order to accommodate radar signals that are beyond the instantaneous dynamic range of the radar system, the radar receiver incorporates a variable gain control system to accommodate varying values of radar backscatter. Since the radar system noise as seen by the data link is dependent on the gain state of the radar receiver, the overall system

sensitivity to measure radar backscatter becomes dependent on the receiver gain state.

For the nominal gain, the performance of the SEASAT-A SAR system is as shown in Figure 7. The upper curve represents the values of radar backscatter which would drive the overall radar system to saturation. As seen from this figure, this curve varies with position that is being imaged. As seen from the curve, for the beginning and end of the radar swath, the values of radar backs. .ter which will drive the system to saturation represent targets where radar backscatter is very high. The lower curve represents the threshold for the minimum values of radar backscatter, which would appear to have a level that is representative of the overall system noise. Again, the same curve has a higher value at the beginning and end of the area being imaged.

With the radar receiver a low gain state, as shown in Figure 8 it can be seen that the overall dynamic range of the system is quite high. However, the values of radar backscatter that result in a normal radar image correspond to surfaces having a high radar backscatter or reflectivity. This area will correspond primarily to strong reflectors, such as areas which are mountainous or forested. If the radar system gain is increased, the radar sensitivity curve is as shown in Figure 9 . In this case, it will be noted that the system dynamic range is quite limited since the radar gain is such that the radar noise is approaching the level required to saturate the data link. However, in the case, areas of radar backscatter which are quite weak will be detectable, and these areas are representative of rather quiet ocean wave conditions.

In summary, the performance of the SEASAT-A SAR system should allow adequate imaging of ocean surfaces from orbital altitudes and in time may prove to be a significant remote sensing instrument capable of measuring ocean swell wavelength and direction from orbit around the Earth.
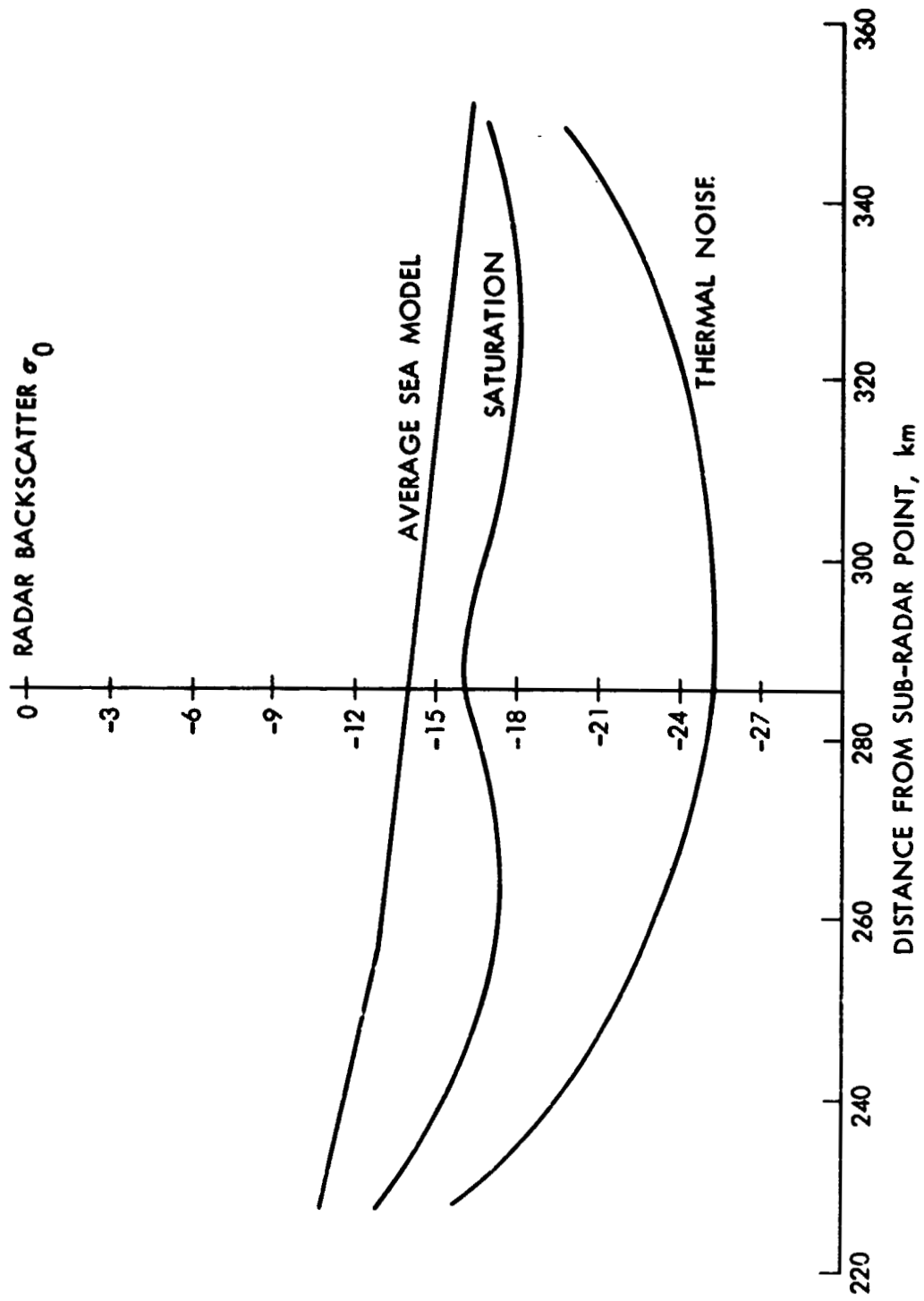
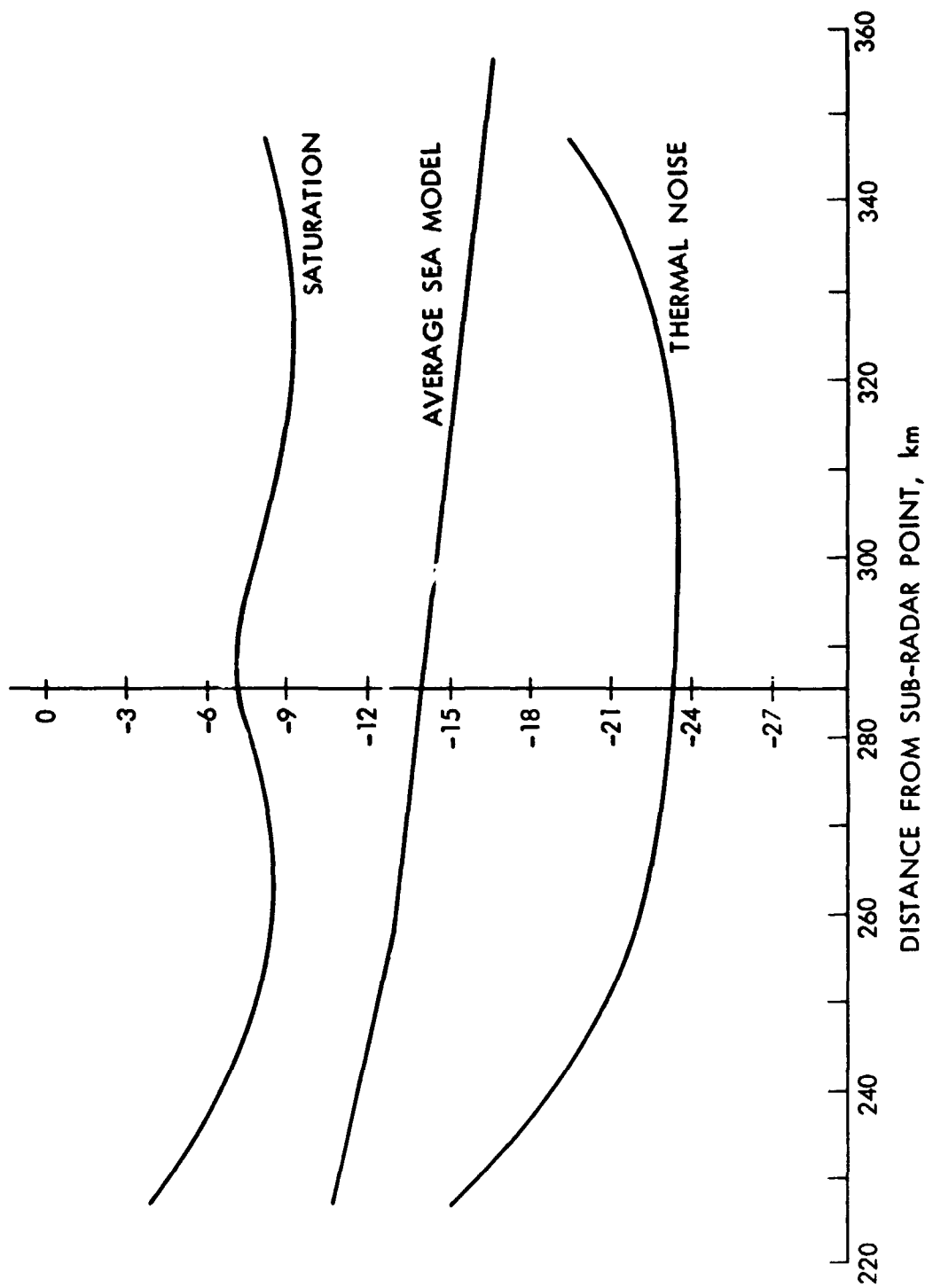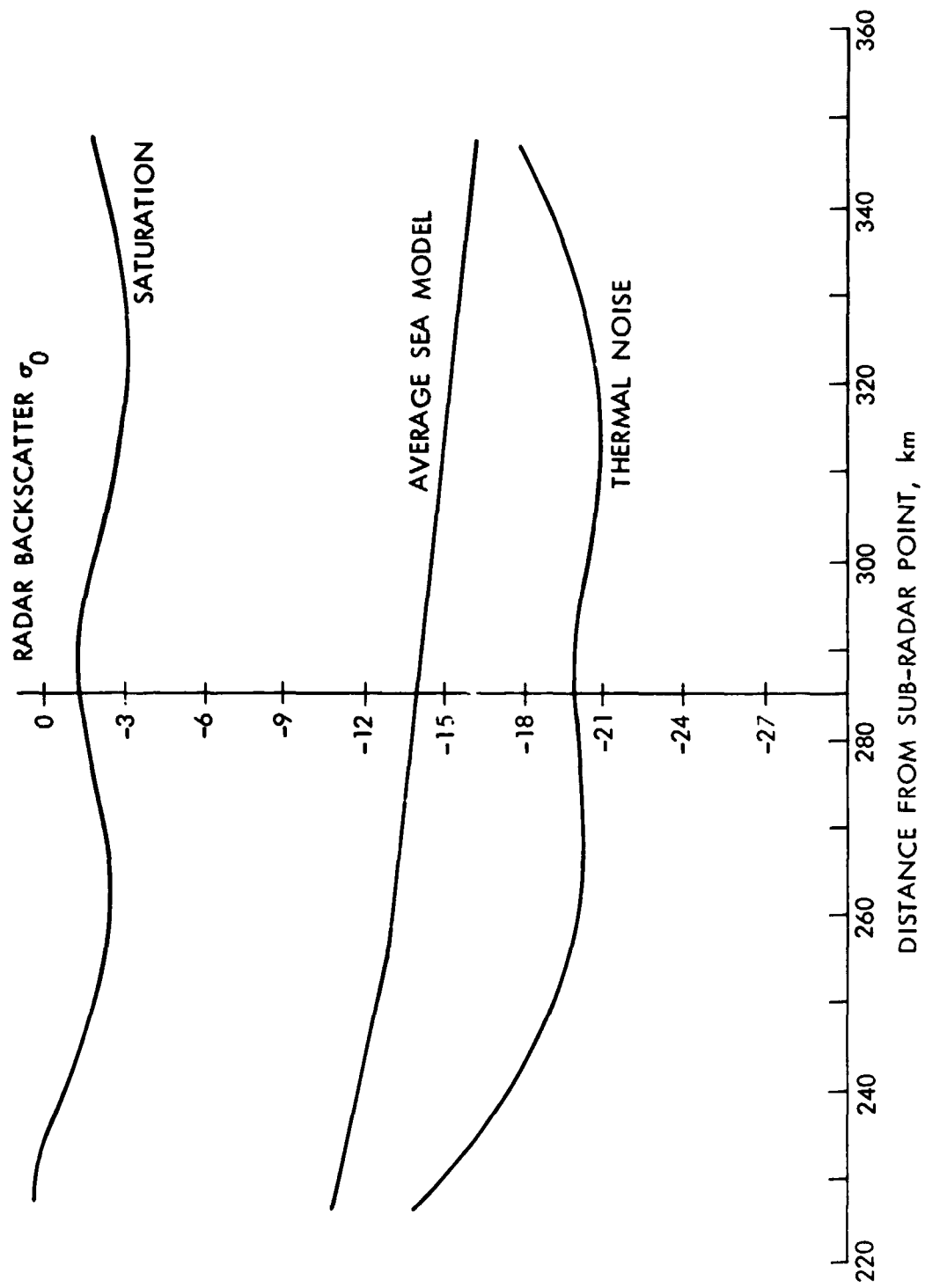Figure 9. SEASAT-A SAR System G = 95 db

Figure 7. SEASAT-A SAR System G = 86 db

Figure 8. SEASAT-A SAR System G = 80 db