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# A SEASAT-A SYNTHETIC APERTURE IMAGING RADAR SYSTEM

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The Seasat-A Synthetic Aperture Imaging Radar System is the first radar system of its kind designed for the study of ocean wave patterns from orbit. The basic requirement of this system is to generate continuous radar imagery with a 100-km swath with 25m resolution from an orbital altitude of 800 km. These requirements impose unique system design problems and their solutions will be stated. The end to end data system will be described including interactions of the spacecraft, antenna, sensor, telemetry link, and data processor. The synthetic aperture radar system generates a large quantity of data (110 megabits per second) requiring the use of a dedicated data link. The data link selected for use with this synthetic aperture radar is an analog link with stable local oscillator encoding. The problems associated in telemetering the radar information with sufficient fidelity to synthesize an image on the ground will be described as well as the selected solutions to the problems. The interactions between the antenna, attitude control system, rotation of the Earth and the data processor will be described as well as proposed solutions, both optical and digital, to generate final imagery with the required 25m resolution.

## I. Introduction

Sidelooking radar systems have been used as a remote sensing instrument to generate radar images of solid surfaces for almost two decades. A radar image is a pictorial representation of the microwave reflection properties of the surface. During the early 1970's, radar images of coastal regions generated by the JPL L-band synthetic aperture radar showed that ocean wave patterns could also be imaged and were of interest to members of the oceanographic community. This interest led to the incorporation of an imaging radar system in the complement of remote sensors aboard the SEASAT-A satellite for ocean surveillance.

The objective of the SEASAT-A Synthetic Aperture Radar (SAR) system is to image ocean waves with a 25m resolution at a 100-km-wide swath in a continuous strip of length up to 4000 km. A synthetic aperture technique must be used to obtain the desired 25m resolution from orbital altitudes as the antenna real aperture along-track becomes prohibitively long. To realize an along-track resolution  $p_x$ , which is much finer than the resultant resolution of the range to the surface times the angular beam width of the physical radar antenna, the synthetic aperture radar system employs a coherent radar along with appropriate data storage and processing. A coherent radar derives its transmitted pulse from a phase-stable local oscillator and the returns are then phase-referenced to the same stable local oscillator (Figure 1). The radar returns from consecutive pulses, as the radar moves along a linear trajectory, are then stored and subsequently processed to synthesize an antenna aperture of length equal to the length illuminated on the surface as illustrated in Figure 2. The resultant along-track resolution  $p_x$  is:

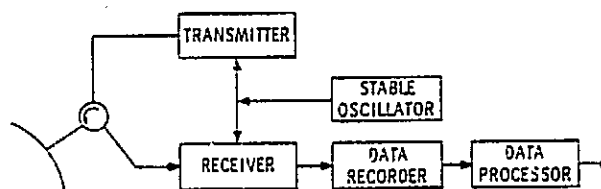


Fig. 1. Conceptual diagram from the SEASAT-A SAR system.

$$p_x = \frac{\lambda}{2\beta} = \frac{L}{2}$$

Fine resolution across track is obtained by using a short pulse technique and effectively time-gating the returns. In order to realize a practical system for use in a satellite, a pulse compression technique is used in order to minimize the peak transmitted power required to get an adequate signal to noise ratio.

## II. System Constraints

The synthetic aperture radar system is perhaps unique in the degree of design interaction among its subsystems, and the data rate and power requirements levied on the spacecraft. It is the purpose of this section to provide a clear insight into the way in which the various user requirements affect both the radar and spacecraft systems. For convenience, we have split the various constraints into four categories as follows: first, the mission requirements placed on the radar systems by teams who will be the ultimate data users; second, various miscellaneous requirements such as Earth rotation and frequency allocation; third, the derived constraints for the radar system design; and finally, the set of constraints levied on the spacecraft and mission operations systems so that the overall radar sensor can do its job. These constraints and their interactions are illustrated in Table 1. Details regarding the

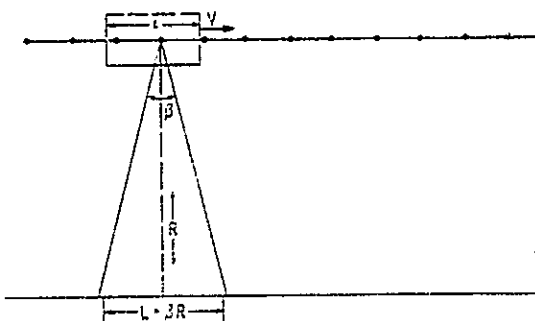
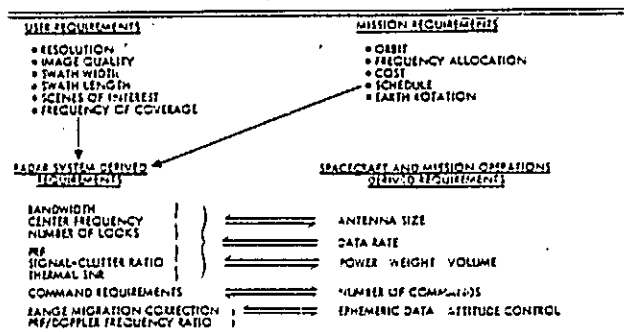


Fig. 2. Synthetic aperture radar geometry.

Table 1. System Constraints



parameters with a description of the manner in which they interact are discussed below. The first set of parameters, entitled mission requirements, are usually defined by a group of users or scientists who will use the data procured. User requirements will dictate the area to be imaged, content of interest, the resolution which must be achieved in order to yield meaningful information, the quality of the image that is necessary to provide good interpretability, and finally the time scale on which repeat coverage of scenes and events of interest should be accomplished. Of these, the resolution and swath width directly affect data rate, the antenna size, and the amount of spacecraft power that must be made available to the radar. Since the radar is a coherent imaging system, a problem exists in radar images called speckle. This problem is common to all coherent imaging systems and can only be reduced by some form of incoherent integration of the data, frequently referred to in radar terminology as the use of multilooks. Since incoherent integration by its nature destroys resolution as well as information, the maximum possible resolution of the radar system will be considerably in excess of the capability required to meet the user resolution requirements. In view of the complexity of on-board synthetic aperture radar data processing, the image quality criteria will also directly affect the data rate and the antenna size used on the spacecraft. Swath length is basically governed by the orbit chosen for the spacecraft and the time that the spacecraft will be in view of a ground station capable of receiving the data transmission. Since the data rates for most radars are very high, in the SEASAT case over 100 megabits per second, on-board storage of data is not presently practical. The coverage of scenes of interest is therefore restricted to areas covered by the spacecraft when it is in line of sight of the recording ground station. For this reason, precise orbit determination and the way in which it affects revisit time of a particular location on the ground is of more importance than with conventional systems, where on-board recording allows experimenters to define the targets of interest and opportunity after launch.

Finally, turning to the scenes of interest themselves, these influence the radar system design in several ways. Some targets of interest are from areas having very low backscatter cross sections, these adversely impact the amount of transmitted power required to form an adequate image. Other scenes are from areas with wide variations in backscatter cross section within the scene and thus impose constraints on both the dynamic range of the system and the effective data rate. It is worth noting here that due to the manner in which the

radar operates, a signal overload affects the image generated from the data differently from the manner in which most current visible and infrared mappers are affected. Since the radar is receiving signals from a relatively wide area on the ground simultaneously, the signal overload causes the phenomenon of weak signal suppression, so that over areas where this occurs those portions of the image with relatively low backscatter cross section will have no image content.

The second class of requirements originated in a number of different ways. While the frequency of the radar is grossly defined by the desires of the users, the specific allocation is determined by what is available in an already very crowded frequency spectrum. In a similar way, the orbit that is most preferable from a radar standpoint may not be consistent with the desires of the user teams and sensor designers for the other experiments to be flown on the spacecraft. The final orbital design will, therefore, usually be a compromise and as such will levy additional requirements on either the radar sensor or ground data processing equipment. Since the SAR relies on the doppler spectrum generated by the relative motion of the spacecraft from the earth, the fact that the earth rotates and, moreover, rotates at apparently different rates between pole and equator must be allowed for in both the sensor and ground data processor design. Finally, there are the constraints of cost and schedule. These affect the quantity of the equipment but also the decisions that are made in terms of where to accept risks. Both constraints will tend to push the system design so as to minimize the complexity of the equipment actually on the spacecraft thus tending to raise the complexity of the ground data processing equipment. In addition, a short schedule will reduce the degree to which new technology can be employed while cost may well affect the amount of data that can be processed into image form and the degree to which image enhancement can be employed subsequently.

Turning now to the derived requirements on the radar system, these consist of nine significant: center frequency, number of looks, bandwidth PRF, signal-to-clutter ratio, thermal-signal-to-noise ratio, command requirements, range migration correction, and the PRF to doppler frequency ratio. Of these, the first two interact with the spacecraft through the antenna size while the next four determine the power, weight, and volume required for the radar sensor. The conjunction of both these sets determines the necessary data rate which the spacecraft must be capable of handling and transmitting to the ground station.

Next the number of commands necessary to operate the radar sensor is primarily affected by the user requirements for image quality and observation of scenes of interest. The way in which these two user requirements affect the radar is through the need for a commandable gain control which will allow the sensor to maximize the available dynamic range for particular scenes. Image quality affects the number of commands through the need for sensitivity time control, and gating in the receiver. This time-dependent amplitude modulation of the receiver gain is used to compensate for the non-uniform beam shape of the antenna in the range dimension. A lack of this feature in practical systems would limit dynamic range and cause the image quality at the near and far edges of the range

swath to be degraded over the performance available in the center. In addition to these command requirements, which are radar specific, there are the normal requirements for power on and off, transmit on and off, etc.; that are common to all instruments flown on spacecraft.

The final interactions to be considered are those that affect the spacecraft attitude control system and the post facto knowledge of spacecraft attitude, and spacecraft ephemeris. These are related to the problems of range migration correction and ensuring that the knowledge is accurate enough to allow for effective data processing for all allowable positions of the real and synthetic beams of the Earth's surface.

To illustrate the magnitude of this latter problem, it is worth noting that the azimuth beam width of the SEASAT antenna is about 1 deg while the uncertainty in the attitude control system is about  $\pm 1$  deg with post facto knowledge of between 0.2 and 0.3 deg. The actual area on the ground illuminated by the antenna can, therefore, depart by as much as a full beam width from its nominal position. Since the doppler spectrum of the received signal is periodic at the PRF rate, one must know, a priori, the position of the doppler spectrum, or the centroid thereof, to be processed before a particular set of data can be processed effectively.

Since this wide variation in beam pointing will occur with all practical spacecraft systems, some form of doppler tracking must be incorporated into the ground data processing equipment. It is perhaps worth noting in passing that processing of the doppler spectrum of the received signal and an observation of its shape can, in fact, provide for an attitude determination for the spacecraft in the order of 0.05 deg once the initial conditions are known to sufficient accuracy to allow processor setup. The ephemeris data for the spacecraft is necessary for several reasons, a key one being the need to define exactly where a particular scene was observed. Location of particular scenes of interest is done through the conjoint use of both the spacecraft ephemeris data and the doppler data implicit in the return signal from the radar itself.

Now that the basic constraints operating on the overall system have been discussed, it is worthwhile noting those areas where tradeoffs between the radar and spacecraft systems are available. For the purposes of this discussion, the user and mission constraints will be considered to be fixed. This is a reasonable approach since the combination of user and mission constraints represents, in some sense, a definition of the job to be done by the radar and spacecraft systems. Tradeoffs will impact these requirements. One tradeoff area that is available is that between antenna size increases both the required power and the data rate in a manner proportional to the decrease in the azimuth length of the antenna. Another trade that can be made is to use range multilooks instead of azimuth multilooks. This requires an increase in the bandwidth on the transmitted chirp signal such that the effective range resolution element size is reduced below that necessary by the factor required to generate the multilook. If space on the spacecraft can be made available for a longer azimuth length antenna, savings can be made in the power required to operate the radar sensor.

The last area in which useful trades are available is between very accurate attitude control on the spacecraft and the complexity of the doppler tracking system necessary in the ground data processor. A way to achieve this, although at the expense of power and an increased degree of complexity on the spacecraft itself, would be to use the doppler signals from the radar to provide correction inputs to the spacecraft attitude control would be slaved to the radar and would track so that the zero doppler line of the radar would always lie at right angles to its line of flight.

The next section of this paper discusses the solution that was arrived at for the SEASAT-A mission. Prior to entering into the detailed discussion of this area, two points are perhaps worthy of mention. The first concerns the organizational framework within which the difficult and interactive problems were addressed and forced to solution; the second concerns the type of data transmission system which is being implemented for the SEASAT-A Project. To effectively control the technical and organizational interactions necessary to obtain viable solutions, a radar system design team was set up with responsibility and authority equivalent to that of the Spacecraft Design Team itself. This approach, which we feel will be necessary on future spacecraft radar systems, is quite different from the approach normally taken with most sensors flown to date. It was an organizational recognition of the unique nature of the synthetic aperture radar system and its demands upon both spacecraft and mission systems. The second point relates to the data transmission system. The transmission system selected is an analog single sideband link whose signal-to-noise ratio dynamic and bandwidth are roughly equivalent to those available from the radar sensor itself. The concept is thus to transfer the radar signal from the spacecraft to the ground without alteration and while maintaining coherence. This is a significant departure from the normal approach of using digital links that have been established on both Earth orbiting and planetary spacecraft over the last 10 years.

Two factors were instrumental in causing this specific selection. The first was the undefined effects of digitization on the radar system performance for the scenes of interest. Despite the fact that many airborne systems have flown over the past few years, no quantitative evaluation has been performed of the effect of quantization on the interpretability of images, particularly where fine low-level, low contrast detail is essential for image interpretation. The second factor was the fact that in an absolute sense, the communication efficiency with present digital lengths would have required link bandwidths in excess of 50 MHz to transmit the equivalent data rate of 120 megabits per second. This allocation at S-band was not, and is not, available, and thus the choice was between an analog system with its inherent imperfections and a digital length with less capacity than that required, together with on-board digital preprocessing of the raw signal data. In view of this, and considering that the problem of digitization and on-board data compression of the radar echo in the signal space is a relatively unknown field; the risk of attempting this on the first civilian SAR mission was felt to be too high.

### III. The SEASAT-A SAR System

The design of the SEASAT-A SAR system was driven by the limitations imposed by the satellite system. In particular, the following constraints played a significant factor:

- 1) No on-board data storage could be accommodated.
- 2) The standard satellite system telemetry could not accommodate the large data volume generated by the SAR system.
- 3) The telemetry link bandwidth allocation was limited to 20 MHz.
- 4) The average raw power from the spacecraft for the SAR was limited to about 500 watts.

The factor of no on-board data storage determined that the satellite system would have to telemeter to a ground station in real-time as the SAR gathered data. Data recording would be accomplished at the ground station. Since the data rate generated by the SAR system (110 megabits per second) greatly exceeds the rates which previously developed NASA data links could handle, a special dedicated data link would have to be developed for the SAR. An additional complication developed when a bandwidth allocation exceeding 20 MHz could not be obtained. Thus, the SAR system was restricted to use of an analog data link where the radar signal spectrum was translated up to S-band for transmission to the STDN ground station telemetry network. Finally, the average power limitations and available transmitter amplifiers determined that the radar frequency be in the L-band region.

A functional description of the SEASAT-A SAR system is shown in Figure 3. The operation of the system is as follows. The radar sensor generates a high-power linear FM (CHIRP) signal which is radiated to the ground by a planar array antenna. The received echo is amplified by the sensor and its frequency coherently translated up to S-band. The radar PRF pulse and stable local

oscillator are encoded into the same telemetry signal band and transmitted to the ground by a low-gain antenna. The S-band telemetry signal is then received by the 9 meter STDN antennas and amplified by the station receivers. The data demodulator then recovers the stable local oscillator and synchronously demodulates the signal to recover the coherent video. The radar video is then converted to a digital format by an analog-to-digital converter whose conversion rate is controlled by the radar stable local oscillator and recorded in a wideband high-density magnetic tape recorder. The output data tapes are then sent to a central ground data processor for conversion to radar images. A tabulation of the principal characteristics of the SEASAT-A SAR system is given in Table 2.

Table 2. SEASAT-A SAR System Characteristics

Satellite altitude	300 km
Wavelength	0.235m
RF bandwidth	19 MHz
Transmit pulse length	33.4 $\mu$ sec
Time-bandwidth product	634
Radar transmitter peak power	800W
Telemetry transmitter power	10W
Telemetry frequency	2265 MHz
Radar transmitter average power	44W
Radar AGC range	21 dB
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	Quadru filar Helix
Telemetry antenna gain	4 dB

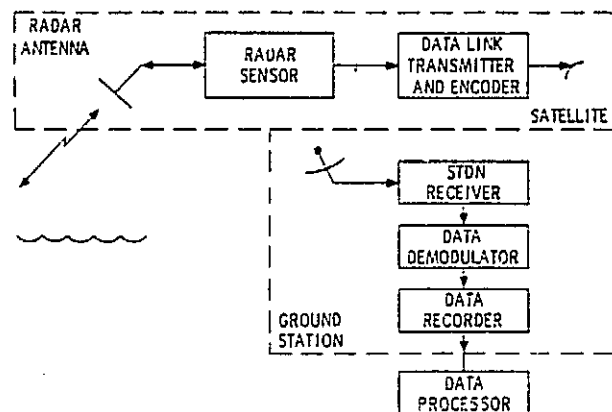


Fig. 3. SEASAT-A SAR system functional diagram.

A radar frequency at L-band was selected because 1) experience gained at this frequency band showed that ocean waves whose wavelengths

exceeded 50 meters could be observed, 2) the technology of high power solid state amplifiers did not, at this time, permit operation at significantly higher frequencies and 3) the average power requirements to image a constant swath becomes larger at higher frequencies for conventional synthetic aperture radar systems where very complex antenna systems are not considered.

#### A. Radar Antenna

The radar antenna consists of a deployable 10.74 meter long by 2.16 meter wide planar array. The antenna in its stowed configuration consists of 3 panels each 1.3 meters by 2.16 meters. These panels are folded into an accordion configuration. Upon reaching orbit, the antenna structure is folded out from the spacecraft and the elements allowed to deploy into a long planar configuration. A conceptual drawing of the antenna subsystem is shown in Figure 4. 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 deg from the nadir direction in elevation (cone and 90 deg from the nominal spacecraft velocity vector (clock). The antenna dimensions are dictated by a desire to limit range or doppler ambiguities to acceptably low levels. At a nominal 20 deg look angle from nadir, in order to illuminate a 100 km swath on the Earth's surface from an 800 km high orbit, a total beamwidth in elevation of 6.2 deg is required. Thus, the antenna cross-track dimension is 2.16m in order to limit the radiation to these sets of angles. The area illuminated on the surface of the Earth is from 240 to 340 km to the right of the sub-spacecraft point. The antenna elements in elevation are weighted in illumination to limit sidelobes in the cross track direction. The antenna along track dimensions is limited on the low end by a desire to keep azimuth sampling ambiguities to an acceptably low level and in the high end to illuminate a sufficiently large patch of terrain to allow processing the data to four looks. The radar transmitter pulses cannot be kept too close together in order to prevent overlapping the returns from near and far range. Thus, the pulse repetition rate is limited. 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 (doppler spectrum) do not exceed the sampling rate. However, if the azimuth beamwidth is kept too small, it is not possible to generate a synthetic aperture large enough to attain the desired resolution for the four independent looks. These two requirements limit the antenna length along the

velocity vector to be between 10.5 and 14m in length. The antenna length of 10.74 meters is dictated by available volume within the spacecraft shroud. The level of integrated ambiguities in azimuth lies between 13.0 dB and 19 dB depending on the pulse repetition rate frequency and processing bandwidth.

#### B. Radar Sensor

The function of the radar sensor is to provide the antenna with the coherent high power signal to illuminate the surface and a receiver to amplify the weak return echos captured by the antenna. The sensor also incorporates the master oscillator where all timing and phase stable signals are generated.

The radar sensor consists of a quartz stable local oscillator, a linear FM signal generator, a high-power transmitter-amplifier, a radar receiver, and a logic and control system. In order to get an adequate signal-to-noise ratio from a system whose range resolution is 25m on the surface and utilizes a solid-state transmitting device, it is necessary to use a long transmitted pulse and pulse compression techniques to reduce the peak power requirements. The SEASAT-A SAR sensor uses a linearly swept FM pulse with a 634-to-1 pulse compression ratio. This linearly swept FM pulse of 19 MHz bandwidth and 34  $\mu$ sec duration is generated by pulsing a surface acoustic wave device with a short sample of the stable local oscillator, mixed with a appropriate coherent signal to bring the frequency to 1275 MHz and amplified to a nominal 800W level. The receiver consists of a low noise RF amplifier which incorporates an automatic gain control. Because the waveform from the nominal sea surface with a uniform illumination antenna is expected to vary in intensity in proportion to the variation of antenna gain with angle, a sensitivity time control (STC) is incorporated into the system. The STC results in a near-uniform expected signal return for a uniform scattering field, and thus the dynamic range required to send the data back to Earth is minimized. The STC waveform linearly drops the gain of the receiver a total of 9 dB for the first half of the expected echo waveform, and during the second half, the receiver gain returns back to normal again linearly. The sensor logic and control provides the required timing functions to the sensor.

#### C. Data Link

The sensor data spectrum is in the 19 MHz bandwidth around the center frequency of 1275 MHz. In order to telemeter the information bandwidth to Earth, the sensor signal spectrum is coherently translated up to 2265 MHz by mixing the sensor signal return at 1275 MHz with 990 MHz derived from the sensor stable local oscillator. Since the system requires that a synchronous demodulation operation be accomplished on the ground, the stable local oscillator is encoded in the signal spectrum as well as the PRF pulse in a PN-coded form. These operations are accomplished as follows. The signals upon translation to S-band frequency are amplified linearly to a power level of 10W at the maximum signal input level. The stable local oscillator (stalo) from the sensor is translated to S-band and added as a pure tone to the signal spectrum at a low level, and the PRF pulse phase codes this pure tone with a PN

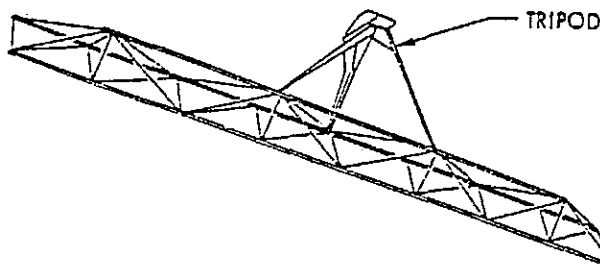


Fig. 4. SEASAT-A SAR antenna.

sequence for later retrieval on the ground. This composite S-band signal is then transmitted to ground via an essentially omnidirectional antenna and received on the ground using a 9m dish of the STDN network. Upon reception of the composite spectrum by the STDN multifunctions receiver, the stable 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 a synchronous demodulation operation on the entire carrier. The signal is also passed through a cross-correlation device which provides the retrieval of the PRF pulse to a high level of time accuracy required for reconstituting the signal on the spacecraft. The resultant signals are then 1) a range of set 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 from spacecraft to ground station and 3) a clock signal which is derived from the spacecraft stable local oscillator. These signals are then passed on to the recording subsystem at the STDN network.

#### D. Data Recording

The signal is first converted to digital format at a rate that is controlled by the clock derived from the spacecraft stable local oscillator to an accuracy of 5 bits per word, and the data is stored in a high-speed buffer for subsequent recording in a high-density digital tape recorder. The total of 288  $\mu$ sec of data is recorded, which corresponds to a 100 km swath with operation at the maximum pulse repetition rate of the system at 1645 pulses/sec. The resulting data rate into the high density digital tape recorder is approximately 107 megabits/sec. The data recorder has a capability to record a maximum of 15 min. of data, which corresponds to one station pass. The high-density digital tape is then used at the ground central data processor to convert the radar video signals in digital form to a radar image.

#### E. Data Processing

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, as one must take into account the effect of the Earth rotating beneath a satellite which is stationary with respect to inertial space; and 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, and 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 boresight is

not good enough to compute the range migration characteristics of any one of the 8000 resolution elements in the cross track directions that are being 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 characteristics operations can take place.

There are two techniques which can be used to process the data to the required resolution: 1) optical and 2) digital. In optical processing, the information from the high-density digital tape format is first converted into a two-dimensional photographic signal film as shown in Figure 5. The 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.

A set of cylindrical lenses then allow the light conversion from targets of all ranges to come into focus at the output plane. A second technique for processing synthetic aperture radar data is utilizing a digital computer. The image generation of SAR data is accomplished as follows: the radar video after conversion into a digital format is first transferred into a linear array where range compression is accomplished. Range compression accomplishes the function of collapsing the signal from a single point target to a single resolution element and may be accomplished either through a linear correlation process or a matched filter operation. Subsequent to range compression, additional lines of data are brought into a two-dimensional array. Each of these lines corresponds to the returns from subsequent radar pulses. Upon reception of an adequate number of return echoes which, for the SEASAT case, number approximately 3000, a azimuth transform of selected lines is first accomplished in order to determine the center of the spectrum of the information. In effect, this is determining the exact attitude characteristics of the antenna while the data was being taken. This antenna pointing attitude determination information is then utilized to perform a range migration correction described earlier. After this determination of the range migration characteristics, data is removed from the two-dimensional array where an azimuth matched filter operation is performed. The readout process will occur

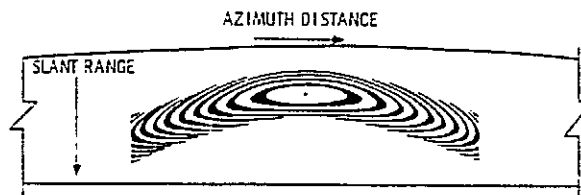


Fig. 5. Signal film showing point target phase history.

along lines where the characteristics of the range migration of an ideal point target are taken into account. A matched filter operation in azimuth or along-track is, like the range compression process, either a cross correlation operation or a matched filter process. This matched filter process may take place as a direct fourier transform followed by an array complex multiplication with a reference function stored in memory of the computer to be followed by an inverse fourier transform. Subsequent to the inverse fourier transform the complex data points will then be converted to real values. This process is simply one of obtaining the magnitude of the vector. Following the compression of a single line, the process is repeated for the remaining azimuth lines.

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 observed a number of times and the results of each of these measurements 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.

#### IV. Spacecraft Peculiar Sources of Errors

Operation of a synthetic aperture radar in orbiting spacecraft gives rise to some errors or peculiarities that are not found in conventional aircraft born synthetic aperture radars. A spacecraft, because it operates in inertial space and the Earth rotates beneath the sensor gives rise to a geometry that is peculiar to this class of imaging radars. This section will talk about two of the sources of errors; the first one is the effects of imaging from a platform that is rotating beneath the antenna and the second one is effects of antenna misalignment in presence of a rotating object.

##### A. Earth's Rotation

If the earth were not rotating and the antenna were pointed along the zero doppler line, the

return spectrum would be symmetrical about the N(PRF) line, and the centroid of the spectrum would be at zero doppler (Fig. 6). If either an antenna pointing error is introduced or the earth rotates, the spectrum will no longer be centered at zero doppler but would shift, and the centroid of the spectrum would also no longer be at zero doppler but at some other frequency.

Since range-migration correction is dependent upon the knowledge of doppler spectrum, the direction in which the antenna is pointed must be known to within

$$\phi \leq \frac{1}{2} \sin^{-1} \frac{\lambda(\text{PRF})}{2V}$$

to define the ambiguity a priori. The implication for SEASAT data is that, at some point, the antenna angle must be known to within 0.65 deg; otherwise, the image will be blurred.

Operation from a spacecraft also affects SAR data. The spacecraft operates with reference to inertial space. The earth rotates beneath the sensor. The effect of the earth's rotation causes a predictable shift in the azimuth doppler spectrum and thus in the range migration of the target in the signal domain. In the absence 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 affects the data because it changes the ground area illuminated by the antenna.

##### B. Antenna Misalignments

Yaw, pitch, and roll errors also affect the data. The cross-hatched curve shown in Fig. 7 describes the trajectory of the signal from a point target through the aperture. In the absence of any pointing error, the location of the data would be shown by the solid line. If a roll error is introduced, the aperture is shifted up, but the shape does not change at all. A roll effect simply shifts the location of the image on the ground.

The effect of pitch is to move the aperture laterally so that the point target is no longer centered in the patch, but the range migration

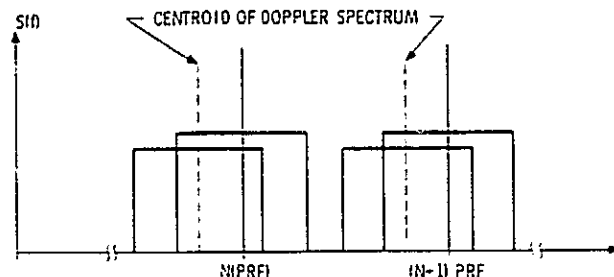


Fig. 6. Description of doppler (or azimuth) spectrum.



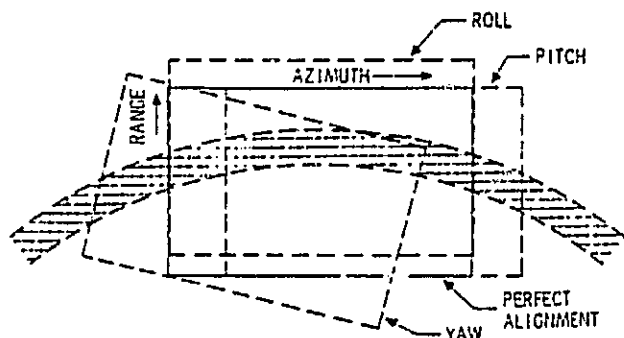


Fig. 7. Effect of antenna misalignment on data set in signal domain.

becomes greater on the right end than on the left. Yaw errors decenter and tilt the phase history with respect to the patch.

Figure 8 shows the effects of yaw, pitch, and roll on the doppler spectrum. Once the doppler spectrum is known, the range correction migration can be computed exactly. There is a one-to-one relationship between doppler frequency and range migration. The quadrangle bracketed 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 above zero doppler because of the earth's rotation. The doppler frequency bandwidth occurs between -650 Hz and -1800 Hz for the near range targets. In far range, the frequency will go from -1100 to -2000 Hz. If there were a yaw and pitch error of +0.5 deg, the spectrum would shift up to (a). If the yaw and pitch errors are negative, the doppler frequencies would increase in the negative direction as shown by (c). The main effect is that

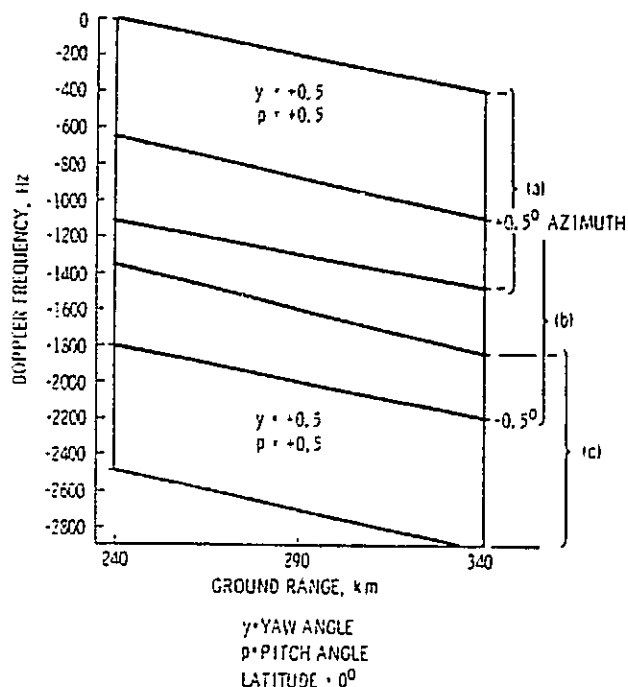


Fig. 8. Effect of pitch and yaw errors on doppler spectrum.

the spectrum is shifting when the antenna is yawing, pitching, or rolling. 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's velocity and the earth's rotation.

Figure 9 shows the predicted doppler centroid versus latitude. The lines bracketed indicate the center of the spectrum in the absence of any spacecraft attitude errors. As the latitude increases when the spacecraft travels north, the effect of the earth's rotation gets smaller and smaller until the spacecraft reaches 72°N lat. That point is 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 that point, if there are no pointing errors.

## V. 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 of 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 radar system incorporates the 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

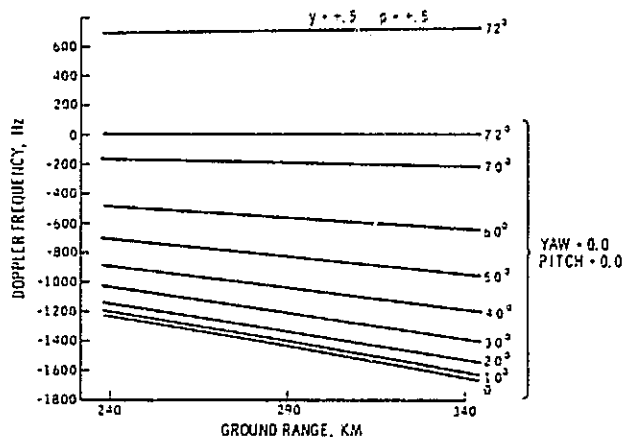


Fig. 9. Predicted doppler centroid versus latitude.

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 behind the instantaneous dynamic range of the radar system, the radar receiver incorporates an automatic 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 10. 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 backscatter 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

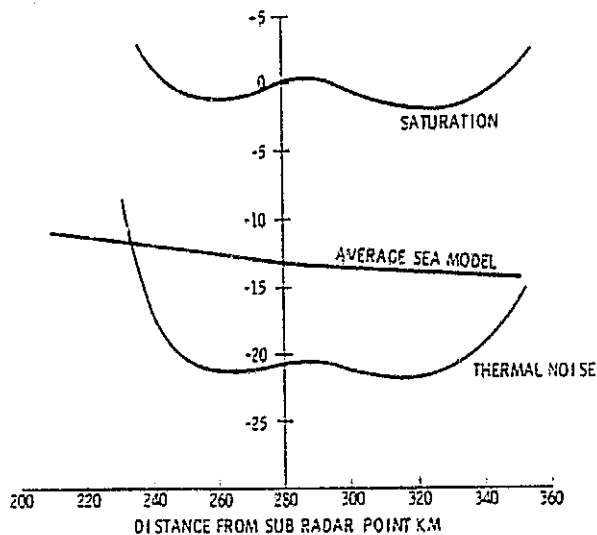


Figure 10. SEASAT-A SAR system  
 $G = 83$  dB.

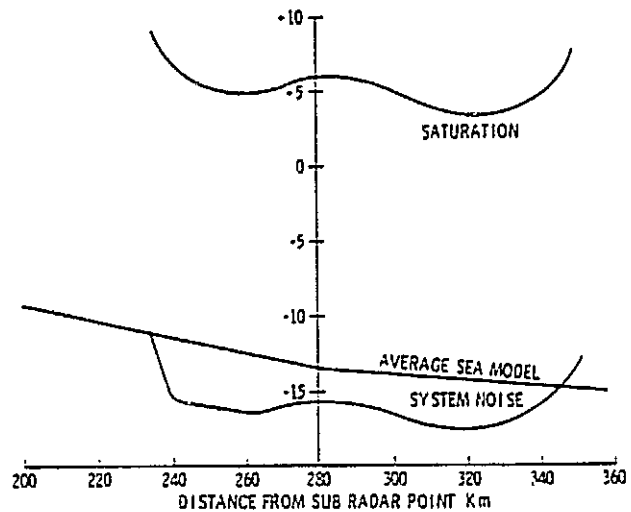


Fig. 11. SEASAT-A SAR system  
 $G = 77$  dB.

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 in its lowest gain state, as shown in Figure 11, 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 12. 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. Measurements taken

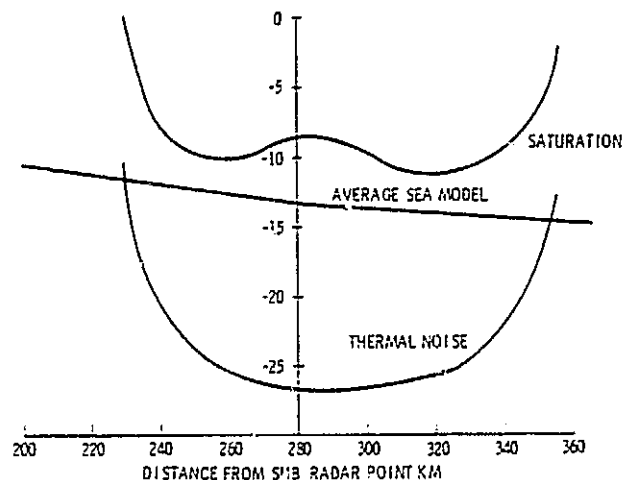


Fig. 12. SEASAT-A SAR system  
 $G = 92$  dB.

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with the JPL L-band imaging radar as well as numerous other investigations have shown that on the average the expected value of the radar backscatter from the average sea will follow the curve as shown in Figure 13. 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.

In summary, the performance of the SEASAT-A SAR system should allow adequate imaging of ocean surfaces from orbital altitudes and in time

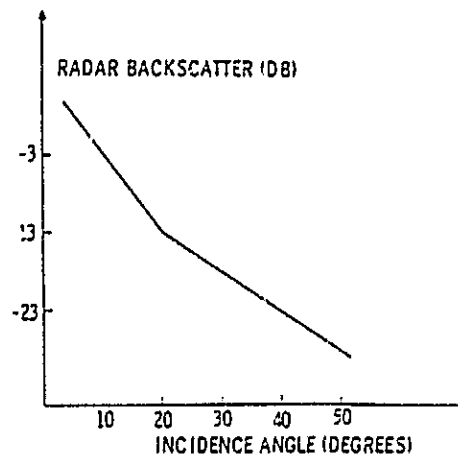


Fig. 13. L-band average sea backscatter model.

may prove to be a significant remote sensing instrument capable of measuring ocean swell wavelength and direction from orbit around the Earth.

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