CHAPTER 5

Active Microwave Sensor Technology

Active Microwave Working Group

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INTRODUCTION

Radar technology is concerned with ways and means to provide information about a reflecting area. During the past two decades, major advancements have been made in this technology, and sophisticated techniques have been developed for locating the direction and range to a reflecting area. Furthermore, other characteristics of the reflection, such as amplitude, phase, Doppler frequency, and polarization, have been used to identify additional properties of the target area. The radar provides its own illumination, and there is no question that the target information contained in the echo is unique. The wavelength, bandwidth, polarization, and modulation of the illuminating signal are selectable by the experimenter, thus providing a wide choice of operational parameters over a frequency spectrum of approximately three decades (150 MHz to 150 GHz).

The amount of information concerning a target area contained in the echo (reflection) is enormous. For example, a comparison between a photographic picture element (pixel) (visible spectrum), which has a high information content, and an element of a radar image is shown in table 5–I.

The radar echo per unit areal element contains as much or more information than the photograph. Each representation of the target area contains unique information because the wavelength range is different, and the surface reflection represents the response to the respective illumination wavelengths.

TABLE 5–I.—*A Comparison of Photographic and Active Microwave Data Content*

Photographic pixel	Radar image
X-angle	X-angle
Y-angle	Y-angle
Frequency (color)	Frequency
Albedo	Amplitude
Polarization	Polarization
No comparables	Phase (absolute)
	Doppler
	Phase jitter

For example, a wheatfield can be observed on both an areal photograph and a radar image. The two output sensor images do not necessarily contain the same information because the image areas may be covered by a wide-wavelength separation, from 3×10^{-5} to 25 cm. Because each image has a different information content, the wheatfield may be "visible" to one sensor or the other, or both. The objectives are to determine the relationship between the surface property and the echo characteristic and to enhance the effects to reduce the measurement uncertainty. This area is a major endeavor for radar technology.

One purpose of this chapter is to provide a link between the recommendations of the science or application studies and the implementation aspects of the radar. Thus, the technology support group (TSG) has contributed comments on feasibility, suggested baseline functional descriptions of the various types of active microwave sensors, and submitted some examples of existing radar techniques and examples of the results. This chapter also includes an example of how the data are used to obtain scientific results. Data handling, particularly for high-rate information systems (i.e., imaging radar), is a major problem area. Hence, a special section has been devoted to the data-management aspects. The last section is concerned with future development and reflects the concern of technologists for obtaining factual information about the measurement process.

Science and Application Guidelines

The various science and applications measurement recommendations were compiled and summarized to determine how many different types of systems may be required and to ascertain the major categories of essential microwave sensor parameters. These summaries are intended to serve only as guidelines for instrument development, not as specifications.

A summary of active microwave sensor parameters (resolution, swath width, and surface coverage) is given in table 5–II. These parameters were inferred from the science and application objectives to measure spatial and time-varying phenomena with various physical dimensions.

Most of the science and application objectives are related to imaging radar techniques in that they are concerned with the location of physical phenomena in two directions and sometimes in three dimensions, with resolutions that vary from 3 m to 40 km in areal (x, y) locations and 1 to 2 km in elevation (z). For subvehicle track profile measurements that require altimeter or sounder experiments, the accuracies and resolutions are 2 to 10 cm in range for surface profiles and 5 cm to 50 m for subsurface profiles. For

TABLE 5–II.—*Summary of Active Microwave Sensor Parameter Guidelines*

Application	Resolution, m	Swath width, km	Surface coverage
Imaging radar			
Earth/land	3 to 15	>20	Selected areas
	10 to 30	>40	Global
	30 to 100	≥100	Global
Atmosphere	1000 to 2000	....	Hemisphere
	10 000	....	Hemisphere
Earth/ocean	10 to 30	10 to 100	Global
Scatterometry			
....	40 000	>100	Global
Altimetry			
....	1 to 3 (elevation)	10 (diameter)	Global

upper surface profiles (i.e., cloud water), accuracies of approximately 1 km would be useful. One other sounder, the surface pressure sensor, would be measuring the slope of the oxygen absorption line to within a fraction of 1 percent. The following are the most stringent requirements:

1. Amplitude: Generally within 15 percent.
2. Dynamic range: 50 dB.
3. Polarization: Within 1°.
4. Range (time delay): 2 to 10 cm (10^{-10} sec) (correction for variations in index of refraction not expressed).
5. Frequency: Within 10 percent.
6. Phase: Within 5°.
7. Doppler frequency: Within 1 percent.

A large majority of the ocean and Earth/land science and application objectives could be realized with a single imaging radar system operating perhaps in various modes (in incident angle, swath width, or resolution). There are some special-purpose radar systems required for geoid measurements and surface-wind determination.

The atmospheric science and applications objectives have, in general, a different class of radar design criteria. The discussion of these criteria is contained in chapter 4.

The surface-sounding radar requirements are, in a sense, an extension of the altimeter radar design and may be restricted to aircraft programs for the next several years.

General System Considerations

The design of imaging radar systems for spacecraft leads to a set of system parameters that are interrelated. A change in one parameter implies changes in most of the others. This section will delineate some of the tradeoffs required for an acceptable system.

The antenna design is one of greatest importance because its proper selection is required to give an image with low ambiguous returns in either range or azimuth. The theoretical azimuthal resolution of a synthetic aperture radar (SAR) system is equal to one-half of the along-track length of the antenna. However, a small azimuthal beamwidth returns energy with a high Dop-

pler bandwidth. To unambiguously sample the data, according to the Nyquist criteria, a high pulse repetition frequency (PRF) must be used. Thus, to avoid successive pulse mixing, the radiation of the antenna must be confined to a narrow set of angles in the crosstrack dimension, which results in a large antenna dimension in the crosstrack dimension (fig. 5–1).
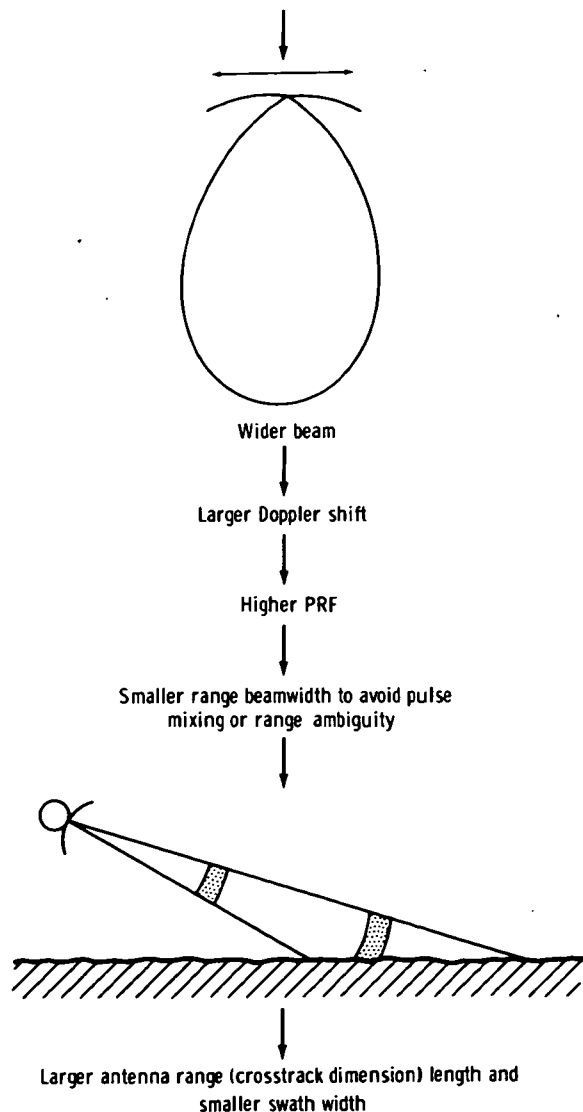

FIGURE 5–1.—Diagram showing that a decrease in one dimension of the antenna requires an increase in the other dimension to avoid ambiguities.

Given a required swath width or PRF, the antenna length in azimuth must be sufficiently large to limit radiation in the azimuth dimension to give low azimuthal ambiguities. These ambiguities are returns from areas other than the area being imaged, which, when sampled periodically and processed, map in identical locations as those of the desired surface returns. These ambiguities are reduced by sampling the data with several pulses (2 to 5) every time the spacecraft moves a distance equal to the antenna length. The illumination pattern of the antenna may be weighted to minimize the returns coming in through the antenna side lobes. In the range dimension, ambiguities can also result from successive pulse mixing, and these ambiguities are again reduced by limiting radiation by means of a large crosstrack antenna with illumination tapering. The implication of this antenna design, to keep ambiguities at a low level at orbital altitudes, results in a required minimum antenna area that follows a curve such as that shown in figure 5–2 for variations in spacecraft or aircraft altitudes. The antenna look angle also has a significant effect on the minimum area required for unambiguous illumination of the surface. As the antenna crosstrack length is increased from the nadir direction,
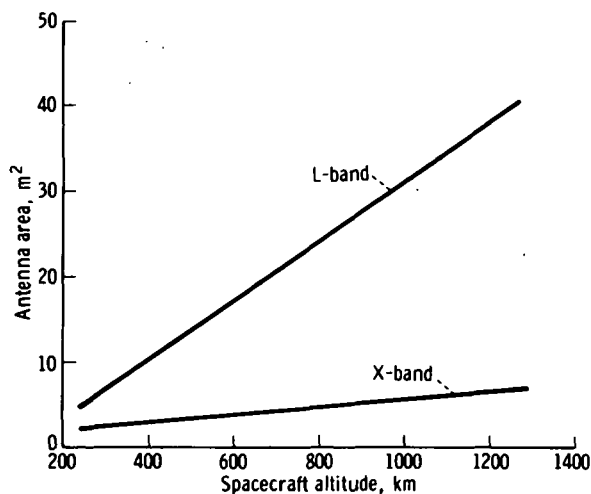
the resultant echo shape is increased in duration. Thus, for a given PRF, to avoid consecutive pulse mixing, the radiation must be confined to look-angle widths, which, in turn, implies longer antenna crosstrack dimensions. The required antenna area then varies with the look angle as shown in figure 5–3. Another factor that will be affected by raising the look angle for a given system bandwidth is the radar system range resolution (fig. 5–3).

The transmitter power required to yield an acceptable image is another parameter that needs careful consideration. The following information is required before these parameters may be determined:

1. The minimum detectable backscatter coefficient required of the radar.

2. The angle of incidence necessary for the measurement.

3. The necessary resolution.

4. The antenna characteristics.

The orbital characteristics presumably are known. For a given set of user conditions, the radiated power average required varies inversely with wavelength unless sophisticated multiple-feed antenna systems are used. Figure 5–4 shows a plot of the transmitter power required for a system with a 15° incident angle and is indicative of the dependence of power on wavelength. Thus, if wavelength is not a user requirement, a tradeoff between power and antenna area is involved in wavelength selection.

The accuracy (relative or absolute) of the measurement is one parameter having a great impact on the capability of an imaging radar system to measure a given phenomenon. The side-looking coherent imaging radar system provides the user a measure of the radar-backscatter coefficient of each resolution element on the surface being imaged. Because of numerous factors, this measurement will have an uncertainty in its absolute value. However, through careful design and implementation, this uncertainty can be reduced to arbitrarily low values at the expense of complexity, power, weight, etc.

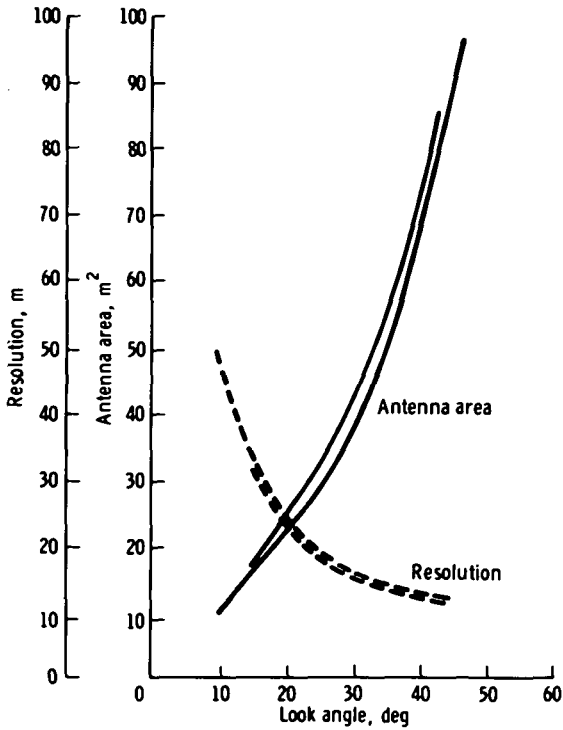A given resolution element, when illumi-

FIGURE 5–2.—Minimum antenna area required for X- and L-band radar systems with a 30° look angle from nadir.

FIGURE 5-3.—Required antenna area and resolution as a function of incident angle.
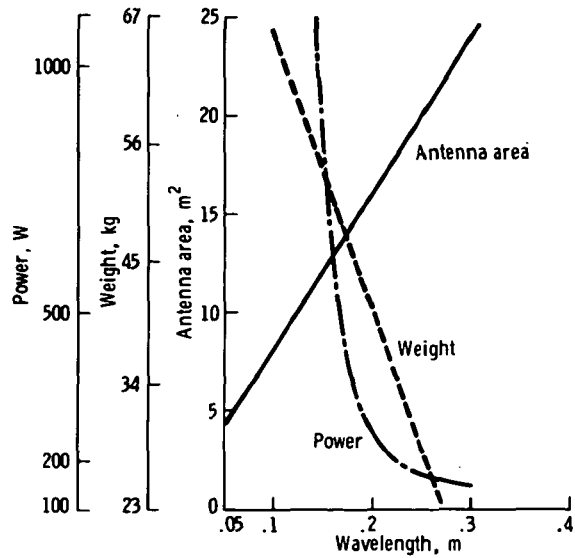

FIGURE 5-4.—Antenna area, radar power, and weight as a function of wavelength for a single feed antenna system at an altitude of 1000 km, with a 70-km swath width, 33- by 33-m resolution, and 15° look angle.

nated by a coherent source of electromagnetic energy, will exhibit a variation in its measured backscatter value as the antenna moves in location. This effect is known as target scintillation or "speckle." This variation is also observed when a large number of returns are added coherently to improve system resolution, which is done with a synthetic aperture system. To reduce the error in the estimated value of the backscatter coefficient of the resolution element being observed, the measurement process can be made repeatedly, and the measured values can be added noncoherently. Coherent addition implies that both quadrature elements of the measurement are added vectorially; whereas, in noncoherent addition, only the magnitude of the resultant vector is added. This concept of separate or independent measurements taken and summed is also known as multiple-look processing or noncoherent averaging in an SAR system. Thus, as a prime consideration early in the study of a potential imaging

radar system, it is necessary to know the degree of precision to which a measurement at each resolution element must be made so that the user is able to accomplish his required task. The implementation implications of multiple-look processing are many. The major impact lies in the data-reduction process and, to some extent, in radiated power.

If the data-reduction process is accomplished on board a spacecraft, then each separate or independent look requires a separate digital processor. If the looks are accomplished in azimuth, then a large two-dimensional buffer is required to combine the separate looks that are gathered at slightly different delays. If the data-reduction process is accomplished on the ground, then a large data telemetry system or data storage device is required.

The data rate that the radar system will generate is similar to that of a photographic system and depends on the swath width, resolution, and vehicle velocity. If multiple-look processing is involved, this factor will also affect the data rate, if the data are

recorded or telemetered to Earth unprocessed. The data rate DR_r out of the radar system is given approximately as

$$DR_r = \frac{2N_{r1}N_L v S_r}{r_r r_a} \qquad (5\text{--}1)$$

where N_{r1} is number of bits per data sample, N_L is number of looks, v is vehicle velocity, S_r is swath width, r_r is range resolution, and r_a is azimuth resolution. The data rate DR_r out of the digital processor is given by the following equation:

$$DR_r = \frac{N_{r2} v S_r}{r_r r_a} \qquad (5\text{--}2)$$

where N_{r2} is the number of processor bits per data sample. These two equations differ by the ratio

$$\frac{2N_{r1}N_L}{N_{r2}} \qquad (5\text{--}3)$$

In general, N_{r1} will always be smaller than N_{r2}. However, the data rate out of the processor will be somewhat smaller than the radar system output, particularly if multiple looks are involved. The complexity of an onboard processor must be considered in any decision for its inclusion.

The following criteria must be satisfied to make a proposed application attractive in an overall sense:

1. The application or mission must have a degree of national importance or benefit that justifies the cost.

2. The technology either must be available or must be attainable with an acceptable level of risk.

3. The radar signature base and the proposed data-analysis techniques either must be available or must be attainable with high probability.

The judgment and applications pertaining to the first and second criteria are probably outside the scope of this workshop. However, the TSG believes that current technology and understanding of signature bases and analysis techniques are sufficiently advanced so that several of the proposed applications

appear highly attractive in terms of the second and third criteria. These applications have relatively low technical risks and therefore will offer a high possibility of success from a purely technological viewpoint. If any of these same applications also happen to be cost-effective from a national viewpoint, then they lead to excellent candidate missions upon which to base a long-term program. Of course, none of the proposed applications are totally without problems, and each requires some level of further study and technique development, which will need to be planned and implemented.

Applications that appear to be low risk from a technological viewpoint include the following:

1. Use of an imaging radar for a variety of ice surveillance roles, including determination of the ice lead and polynya structure at high latitudes, iceberg detection in shipping lanes, monitoring drift and decay of icebergs off Antarctica, and lake-ice reconnaissance in the Great Lakes and St. Lawrence River shipping lanes.

2. Use of a radar profilometer for generating profiles of the ocean surface on a global scale, building upon the experience achieved in the Skylab S193 experiment and other experiments.

3. Use of a radar scatterometer for windspeed estimation for inputs to global weather models.

4. Use of an imaging radar for the observation of geologic structure and lithology.

5. Use of an imaging radar for a variety of applications that stem from the ability to observe land/water boundaries. (These applications include observations of lake levels and stream overflow, the analysis of watershed runoff, and the study of coastal and shoreline features.)

6. Use of an imaging radar for observations of ocean-surface patterns on a global basis.

7. Use of an imaging radar for gross land-use classification.

8. Use of a suitable multiband imaging radar with sophisticated analysis techniques

for estimation of crop acreage in agricultural contexts characterized by a small number of possible crops and moderate to large fields.

This list is not meant to be exhaustive. It reflects, in large part, the experience and comprehension of TSG members.

PART A

FUNCTIONAL DESCRIPTIONS OF SELECTED ACTIVE MICROWAVE SYSTEMS

In chapters 2, 3, and 4 of this document, the Earth/land panel, oceans panel, and atmosphere panel, respectively, have established requirements for several active microwave measurements. Although certain common features are present in these measurements, several basic types of measurements can be distinguished, and a class of sensors can be associated with each type.

MAJOR CLASSES OF CANDIDATE SYSTEMS

The following four classes of active microwave measuring systems appear to offer the greatest utility to the three user panels:

1. Scatterometers designed to measure electromagnetic scattering properties of surfaces (without emphasis on spatial resolution).

2. Altimeters designed to accurately measure the vertical distance between the sensor and the scattering surface directly beneath it or to profile the surface beneath it.

3. Sounders designed to penetrate the uppermost boundary of the medium beneath the sensor and to observe the vertical structure of this medium by means of a delicate balance between reflection due to vertical gradients and transmission through these gradients.

4. Imaging systems designed to measure the scattering properties of surfaces, usually with lateral spatial resolution finer than that required in any of the preceding classes.

Other useful radar-measuring configurations (e.g., a Doppler radar designed to observe the radial velocities of scatterers) can be treated in an analogous manner, but these configurations will be omitted in this report because they are less critical to the stated needs of the user panels.

For the purpose of this document, the term "functional description" will be a description of an active microwave system that answers the following fundamental questions:

1. What physical attribute of the scatterer does the system measure?

2. How does the system perform the measurement?

3. What are the principal parameters that characterize the output of the system?

4. In what form is the output provided to the user?

5. What are the principal sources of measuring system error, and how do they affect performance?

Questions 1 to 5 relate to figure 5–5. The answer to question 1 describes the input in terms meaningful to the sensor. Question 2 applies to the "transfer characteristic" of the measuring system, whereas question 3 describes the output in terms consistent with questions 1 and 2. Question 4, strictly a format question, may be critical to proper
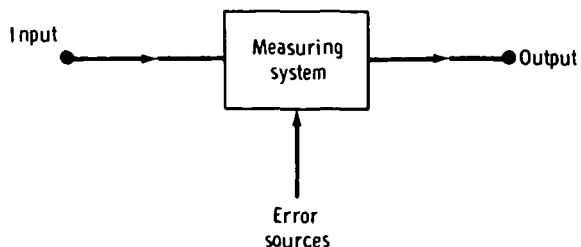

FIGURE 5–5.—Diagram of the basic measurement process.

data management. Question 5 is self-explanatory.

The topics of parameter interplays and system design tradeoffs sometimes are included in a functional description of a system. In general terms, a functional description provides a mathematical model on which to base a design exercise, whereas the parameter tradeoff question relates to the question of optimizing a design for a specific mission. However, a discussion of tradeoffs does provide useful insights and is included for some of the sensors.

Finally, two additional questions may arise in a functional description:

6. What level of performance does current technology permit, and how may this performance level be extrapolated into the future?

7. What are order-of-magnitude estimates of weight, power, volume, cost, expected lifetime, and other variables that are potentially important in experiment selection and planning?

The answers to these last two questions must come from design exercises that begin with a set of proposed mission objectives and design constraints and that are then optimized over all variables.

FUNCTIONAL DESCRIPTIONS BY CLASS

In this section, functional descriptions of the four principal classes of active microwave sensors are provided.

Radar Scatterometer

The radar scatterometer is a special-purpose instrument that measures the relative value of the radar-backscatter coefficient at a range of angles. Because no spatial resolution is required other than the area illuminated by the antenna, this system is less complex than other systems that require a high degree of spatial resolution. The data rate generated by a scatterometer is also much lower than imaging systems because the coarser resolution does not require close spatial sampling of the surface. Measurements of the relative radar-backscatter coefficient of the surface at various angles, polarizations, and wavelengths are used to infer characteristics regarding the surface (such as wind velocity and direction for the ocean and surface roughness for the land).

The scatterometer measures the microwave backscatter cross section of a surface for various angles of incidence. During flight over an area of interest, radar backscatter as a function of incident angle is generated from which some physical attributes of the surface can be inferred. These measurements may be taken at different polarizations or wavelengths to enhance interpretation of the surface characteristics. These measurements are taken by illuminating the surface with microwave energy and measuring the portion of this energy that is reflected back to the transmitting/receiving antenna. The output of the scatterometer system is a set of data points corresponding to radar-backscatter measurements as a function of angle and spacecraft position. These data are presented to the user as a plot of radar backscatter as a function of angle for each data cell on the surface.

System noise is the primary source of error in the measurement of radar backscatter. Radar scatterometers have been built that measure a minimum backscatter coefficient of -30 dB. However, this does not in any way mean that more sensitive microwave scatterometers cannot be built. Most observed phenomena have backscatter coefficients exceeding this value. Because of the simplicity of the radar scatterometer, its weight, excluding the antenna system, is usually in the tens of kilograms and power consumption is in tens of watts. Thus, the scatterometer is suitable for spacecraft use.

The scatterometer consists of (1) a microwave transmitter, (2) an antenna, (3) a microwave receiver, and (4) a detector and data integrator. Variation of these four basic components results in the two basic scatterometer types: the beamwidth-limited scatterometer and the pulse-width-limited scatterometer.

The beamwidth-limited scatterometer consists of a long-pulse-width transmitter, a pencil-beam antenna, a microwave receiver and down-converter, and a detector with an integrator. The transmitter pulse is sufficiently long to simultaneously illuminate the area of the antenna footprint. The return energy from the illuminated area is down-converted, amplified, narrow-bandpass-filtered, then square-law-detected and integrated as shown in figure 5–6. Because all the energy entering the antenna illuminates the surface, the sensitivity of backscatter coefficient varies as the square of the range to the surface. To obtain a backscatter function from which to infer surface characteristics, the pencil-beam antenna will be scanned in elevation while measurements are taken. In addition, the antenna may radiate and receive energy at different polarizations as an aid in inferring surface characteristics.

The pulse-width-limited scatterometer dif-

fers from the beamwidth-limited scatterometer in that a shorter pulse is transmitted to the surface by a fan-shaped antenna beam. The return echo is then time-gated to obtain elevation angle resolution. The received energy processing is the same as that for the beamwidth-limited scatterometer, except that a number of channels are required for the measurements. Each of these channels is time-gated for a slightly different delay from the transmitted pulse, and, consequently, each of these channels processes energy corresponding to a different range of elevation angles from the spacecraft. Scanning of the antenna angle in elevation is not needed to generate a backscatter function. As with the beamwidth-limited scatterometer, different polarizations can be used as an aid to data interpretation.

Radar Altimeter

The radar altimeter has played an important role in navigational and landing systems for aircraft and spacecraft. Remote-sensing applications of radar altimeters impose requirements for high measurement accuracy that depend not only on the altimeter but also on the control or monitoring of the motion of the platform on which the system is mounted.

To gain a proper perspective of the use of an altimeter as a remote-sensing instrument, the basic operating principles of a simple altimeter system will be considered. Figure 5–7 shows a block diagram of a radar altimeter that could represent several actual implementations.

On command from the timing system, the transmitter generates a modulated radio-frequency (rf) waveform that is directed by the duplexer to the antenna port. The antenna directs the radiated energy toward the target surface and subsequently collects that portion of the energy reflected or scattered back in the direction of the antenna. Once collected by the antenna, the returned signal is directed by the duplexer to the receiver input. The receiver processes the returned signal and provides an output from which
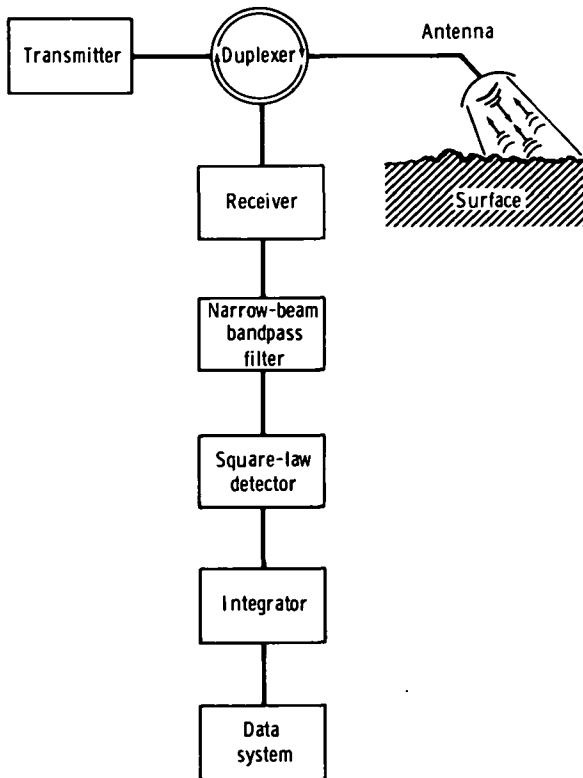

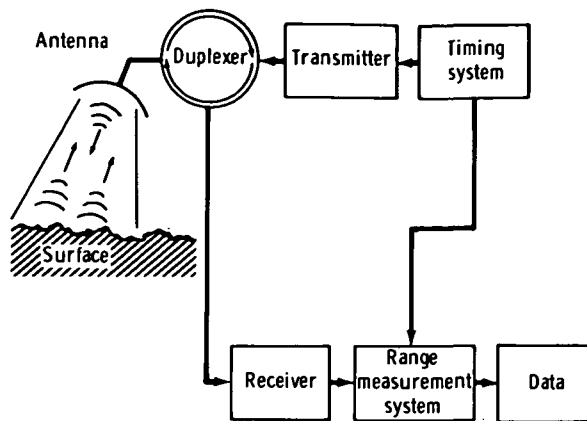FIGURE 5–6.—Block diagram of scatterometer.

FIGURE 5–7.—Block diagram of simplified radar altimeter.

the two-way propagation delay can be determined. Because the velocity of propagation is known, the range to the target may be computed directly from the time-delay measurement.

To fully address the question of accuracy in terms of limiting factors, a particular implementation must be specified (e.g., frequency-modulated continuous wave, pulse, interrupted continuous wave (ICW), etc.), which, in many cases, is dictated by the given application. An in-depth discussion of the various radar altimeter implementations is beyond the scope of this report; instead, a comment on those aspects of system accuracy that relate primarily to a given application and that are common to all altimeter systems is provided.

For the applications that require the true range between the vehicle and the surface, some means of correcting for vehicle attitude and altitude changes must be provided. In addition, the timing system must have high long-term stability to insure that measurements made over a long period of time are repeatable.

If profiling is the desired measurement (i.e., measurement of the variation in surface height over a confined area), the long-term stability of the timing system needs to be good only for the desired measurement period, but measurement-to-measurement

stability must be extremely high. Again, fluctuation in the system platform attitude and altitude can introduce serious errors unless steps are taken to correct for such variations.

Measurement of surface roughness may not require attitude or altitude correction, but measurement-to-measurement stability is still required.

In general, the achievable accuracy of a radar altimeter system depends on the measurement type and frequency and on the particular system implementation. Typical range measurements with present-day altimeter systems can be made with an accuracy of ±30 m, whereas profiling measurements can be made with an accuracy of ±60 cm.

Radio Subsurface Sounders

The radio subsurface sounder is a device to measure subsurface layers and boundaries. Radio subsurface sounders operate on the following principles:

1. That low frequencies can penetrate the surface of the Earth for some particular ground situations.

2. That the power reflected back to the sounder can be detected.

3. That adequate resolution in range can be realized.

This technique is only applicable to aircraft operations because of the large reflection from the air-surface boundary. Because the aircraft is at a given altitude above the surface, this strong reflection can be removed by range gating and can be minimized by viewing the surface at an incident angle other than normal. The special situations in which ground losses are small enough to enable the radio subsurface sounder to be useful include the polar ice and the inland ice in Greenland and Antarctica. An experiment application for a radio subsurface sounder is described in a subsequent section.

Image-Forming Radars

Of the various active microwave sensors, the imaging radar is most in demand. Radar

imagery is unique because it enables the scientific investigators to view the Earth at microwave frequencies in a manner exactly analogous to viewing the Earth with their eyes.

Several analogies can be drawn between a radar-imaging system and the more familiar photographic system, and they may be of value in understanding the basic principles of the imaging radar. A radar image is a record of the intensity of microwave energy reflected from each resolution cell within the radar field of view, just as a photograph is a record of the intensity of light reflected from each resolution cell within the camera field of view.

The radar system may be designed for a single-frequency or multiple-frequency operation with single- or multiple-polarization capability, which is analogous to monochromatic (black and white) or multispectral (color) photography with or without polarizing filters.

While the similarity between radar and photographic imagery is important, it is the inherent difference, both in measurement capability and information content, that makes the imaging radar an extremely valuable tool for Earth resources applications. In terms of measurement capability, imaging radar has the distinct advantage of providing its own illuminating source and is therefore not restricted to daytime operation. Within certain frequency bands, microwave signals are relatively unaffected by clouds, fog, and so forth, which results in an all-weather measurement capability.

Even more valuable than an all-weather day/night sensing capability is the ability to view the Earth in a band of frequencies outside the visible portion of the electromagnetic spectrum. The complex interaction between microwave energy and the Earth surface produces images that reveal striking contrast and subtleties in the structure and surface cover of the Earth, which are relatively unnoticed in even the most careful analysis of conventional photography.

Despite the similarity of output product, the image-forming process of an imaging radar is quite different from that of photography. The resolving power of a camera is determined by the lens and the granularity of the film. Angular resolution is accomplished by constructing a lens of a sufficient number of wavelengths in diameter to yield an image with the required quality of detail.

Whereas a camera lens is the functional equivalent of a microwave antenna, the longer wavelength of electromagnetic energy at microwave frequencies prohibits the construction of antennas large enough to have a resolving capability similar to that of a lens. To achieve acceptable resolution with antennas of limited size, it becomes necessary to use special signal-processing techniques. To achieve high resolution in the crosstrack dimension of the image, the radar return signal is processed so that it yields the magnitude of the reflected signal as a function of time. Because the time delay between transmission and reception of a signal is proportional to range (distance to the target), high resolution in the range measurement can be achieved by finely resolving the return signal in time. The bandwidth of the radar is therefore a limiting factor in achieving range or crosstrack resolution.

In the azimuth, or along-track dimension, high resolution can only be achieved by providing a large antenna aperture in that dimension. A real aperture radar (RAR) provides a large antenna aperture by means of the actual physical dimensions of the antenna. An SAR achieves a large antenna aperture by processing, storing, and adding vectorially (usually by optical means) the return from different positions within the beam. The positions within the beam are resolved by measuring the Doppler frequency shift of the return signal. The Doppler frequency shift and the scanning coverage in the along-track dimension are produced by the motion of the radar vehicle.

A typical real aperture system is shown in figure 5–8. Microwave pulses of the proper magnitude and duration are produced in the transmitter and radiated by the common
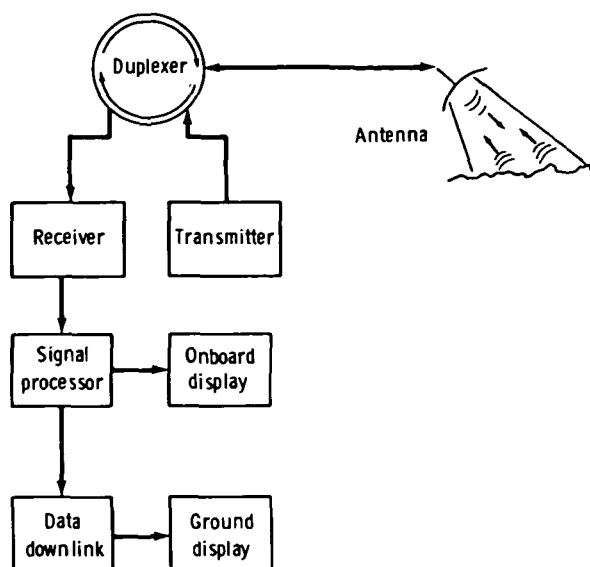
FIGURE 5–8.—Block diagram of a real aperture system.

FIGURE 5–9.—Block diagram of an SAR system.

transmit/receive antenna. The duplexer switches the antenna from transmit to receive at the appropriate times. The return echoes are amplified and transmitted to an Earth station where output data are prepared in the desired format. Onboard signal processing and near-real-time display of the image may be provided if required.

A block diagram of an SAR suitable for satellite application is shown in figure 5–9. A coherent pulsed microwave signal is generated in the master oscillator, amplified, and transmitted through the antenna. Echoes intercepted by the antenna are directed to the receiver by the duplexer. The amplified echoes are preprocessed in the satellite to reduce their bandwidth, stored if necessary, and sent to a ground facility by means of the data downlink.

The combination of satellite preprocessor and ground processor analyzes the microwave echoes for time of arrival (corresponding to crosstrack position of a resolution cell), Doppler frequency (corresponding to along-track position of a resolution cell), and amplitude (corresponding to intensity of the reflection from a resolution cell). The signal-processing task is discussed in part B of this chapter.
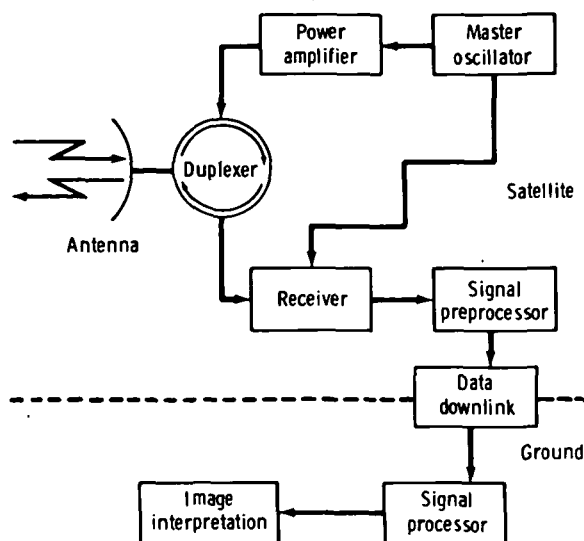
A result of the differences between photography and imaging radars is that there are different performance parameter tradeoffs, but no differences in output product to the user. In both cases, the product consists of photographic negatives, photographic prints, or videotape in black and white or false color (exactly as in the present Earth Resources Technology Satellite (ERTS) outputs).

The major performance parameters that affect radar cost and realizability are range resolution, azimuth resolution, coverage (swath width), dynamic range, antenna side-lobe levels, number of different frequencies, number of different polarizations, and accuracy of backscatter measurement. A detailed discussion of the interactions between these parameters is given in part B of this chapter. In summary, the tradeoffs are as follows:

1. Improved range resolution requires increased transmitter average power. For SAR, there is a small increase in processing complexity.

2. Improved azimuth resolution in RAR requires a longer antenna, which increases the weight and complexity of the satellite. However, the longer antenna provides higher gain, thus lowering the required transmitter power. For SAR, improved azimuth resolu-

tion has no effect on the antenna or transmitter power but greatly complicates the signal processor.

3. Increased swath width requires increased transmitter power and, for SAR, requires an increase in the length of the antenna. Long antennas, in turn, decrease azimuth resolution capability and are more difficult and expensive to build and operate.

4. Improved resolution or increased coverage strongly impacts the data distribution problem and increases the data downlink bandwidth.

5. Improved dynamic range and lower side-lobe levels increase the data downlink bandwidth and, for SAR, increase the complexity of the ground-signal processor.

6. Multiple-frequency systems require duplication of the entire radar system: transmitter/receiver, antenna, data downlink bandwidth, and signal-processor capacity. However, if reduced coverage is acceptable, only the transmitter/receiver and antenna need to be duplicated.

7. Multiple polarizations require duplication of the entire radar system, except the transmitter.

8. For an RAR with fixed azimuth resolution requirements, the antenna size is inversely proportional to frequency. For this reason, designers use the highest operating frequency that also exhibits other acceptable characteristics such as low atmospheric attenuation.

9. Improved range resolution is normally provided by narrow transmitted pulse widths in a side-looking radar system. For SAR, chirp modulation is often used to improve range resolution and to lower peak power requirements.

10. Azimuth resolution of RAR is a function of the physical bandwidth. From the viewpoint of the radar system designer, very large antennas are preferred. Practical limitations on the maximum size depend on mechanical construction tolerance and the electrical accuracy required. For side-looking airborne radars, antenna dimensions of 150 to 300 wavelengths are common.

11. Accuracy of backscatter measurement depends on radar calibration. Calibration is a difficult process at best and becomes more so at broader bandwidths corresponding to better crosstrack resolution.

The ability of a camera to generate a true image of a scene depends on a lens that images the scene on film without geometric distortion and that images a point source into a small spot with minimum Airey rings. Furthermore, this ability depends on an emulsion and film process that provides a

TABLE 5–III.—*Present and Predicted Satellite Side-Looking Radar Performance*

Parameter	SAR		RAR	
	Present	5-year projection	Present	5-year projection
Resolution, m	10	3	1000 to 3000	500 to 1000
Range azimuth, m..............	<10	....	....	
Coverage:				
Along track, km.............	Continuous	Continuous	Continuous	Continuous
Across track, km............	50 to 100	100 to 200	241	322 to 805
Dynamic range (point targets), dB	60	80	....	
Dynamic range (distributed				
targets), dB	−20	−25	60	80
Peak side-lobe levels, dB........	−30	−40	−25	−25
Different frequencies, number.....	1 to 3	3+	4	4
	(L- to X-band)	(uhf to Ku-band)	....	
		2	....	
Different polarizations, number...	0 to 2	2	2	2
Absolute calibration accuracy, dB.	>4	≈3	>4	≈3
Relative calibration accuracy, dB..	≈0.5	≈0.3	≈0.3	<0.2

predictable relationship between the intensity of reflected light at a point and the image gray level. With radar imagery, there are corresponding effects. Geometric distortion can occur because of inaccuracies in the relationship between time delay and ground range in the crosstrack direction or, for SAR, between Doppler shift and ground range in the along-track dimension. Both of these distortions tend to be negligible when vehicle trajectory is well known (e.g., as with a satellite). Camera spot size corresponds to SAR resolution in both crosstrack and along-track dimensions; camera Airey-ring amplitude corresponds to SAR side-lobe levels. The relationship between brightness and

gray level in film corresponds to the dynamic range limitations in the radar receiver. The present and predicted performance parameters for RAR and SAR are summarized in table 5–III.

A typical SAR that would be suitable for the Space Shuttle and that has three frequencies, two polarizations, and other aforementioned parameters is described in a subsequent section. The satellite portion of such a radar will weigh approximately 500 kg and require 2 kW of prime power.

A general system description and tradeoff considerations for real aperture side-looking airborne radar (SLAR) are presented in part B.

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EXAMPLES OF CURRENT RADAR TECHNOLOGY AND APPLICATIONS

USE OF SLAR FOR EARTH RESOURCES MAPPING

The design and manufacture of SLAR evolved primarily from requirements established by military users. In recent years, emphasis has been directed toward improved moving-target detection and higher resolution fixed-target capabilities. Improvements in both these parameters are important for tactical applications; however, the applicability of state-of-the-art military systems to the general remote-sensing problem is not well established.

The potential of SLAR for Earth and ocean remote-sensing applications has begun to emerge only in the past decade. Earth scientists and engineers have found that the radar map is an extremely useful tool. To the casual observer, a radar map may appear very similar to high-resolution photographs and may seem to warrant similar interpretations. However, full use of the data available in radar imagery requires a general understanding of the operating principles of SLAR and the microwave reflectivity char-

acteristics of the terrain being mapped. The radar imagery will enhance certain features and suppress others.

This section briefly summarizes the basic principles and tradeoff considerations for SLAR. There are two fundamental types of SLAR sensors available to the remote-sensing user: real aperture and synthetic aperture. The primary difference between the two types is that a synthetic aperture system is capable of significant improvements in target resolution but requires equally significant added complexity and cost. The remote-sensing users must have a good understanding of the resolution required for each sensing mission.

The advantages of real aperture SLAR include long-range coverage, all-weather operation, in-flight processing and image viewing, and lower cost. The fundamental limitation of the real aperture approach is target resolution. However, the RAR is well suited for airborne missions that require real-time data with moderate resolution.

Synthetic aperture processing is the most practical approach for remote-sensing prob-