

# ADDENDUM

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### 1978

## SYNTHETIC APERTURE RADAR

## TECHNOLOGY CONFERENCE

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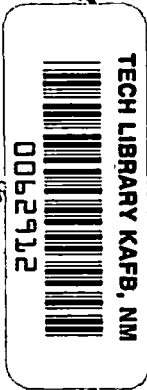
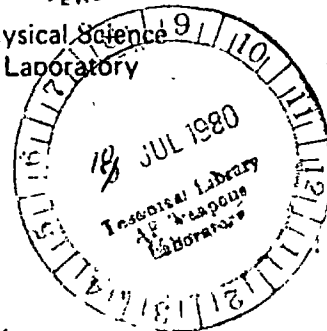
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This addendum to the March, 1978 Synthetic Aperture Radar Conference Proceedings consists of five papers that were presented along with a transcript of the Summary Session.. These papers, which were received too late to meet the original printer's deadline, are a significant addition to the original Proceedings.

K. R. Carver  
Technical Committee Chairman  
August 15, 1978

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## A PERSPECTIVE OF SYNTHETIC APERTURE RADAR FOR REMOTE SENSING

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SUMMARY

Because of its unique capability for providing good resolution in the cross-range, as well as the range dimension, synthetic aperture radar has proven to be of considerable interest for remote-sensing applications over both the land and the sea. In this tutorial report the characteristics and capabilities of synthetic aperture radar will be discussed so as to identify those features particularly unique to SAR. Brief comparison is made between SAR and optical images. SAR is an example of radar that provides more information about a target than simply its location. It is the spatial resolution and imaging capability of SAR that has made its application of interest, especially from spaceborne platforms. However, for maximum utility to remote sensing, it has been proposed that other information be extracted from SAR data, such as the cross section and the variation of cross section with frequency and polarization. Several of the special problem areas that might possibly limit the utility of SAR are mentioned, such as complexity, swath and resolution, image interpretation, need for calibration, EMC, as well as the handling of the large amounts of data generated from remote sensing applications.

1.0 INTRODUCTION

The synthetic aperture radar (SAR) has the unique capability of providing good resolution in the along-track, or cross-range, dimension as well as in the range dimension. This ability to provide an image-like high-resolution

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\*This report is an extended version of the keynote paper presented at the Synthetic Aperture Radar Technology Conference, March 8-10, 1978, Las Cruces, NM, sponsored by the NASA Johnson Space Flight Center and the New Mexico State University Physical Science Laboratory.

display has caused the SAR to be of considerable interest for remote sensing of the sea and land. This paper reviews some of the background of synthetic aperture radar as it relates to remote sensing, and discusses some of the issues involved in its application. The intention is to provide an introduction to the Technology Conference. The point of view is that of a radar systems engineer interested in the application of SAR technology, and is not that of a specialist involved in the daily pursuit of improved SAR technology. Thus, the comments presented here can be considered as the impressions of an interested observer viewing a dynamic and important radar field that has attracted much interest for its potential applications.

The SAR offers promise for remote sensing because of its unique characteristics that have already been demonstrated, as well as its as yet undemonstrated potential for extracting further information about an object, to supplement that already provided by the spatial resolution.

In this report a brief description will be given of the synthetic aperture radar concept and its special characteristics that make it of interest for remote sensing. This will be followed by a listing of some of the major applications of SAR and its proposed use in remote sensing. The emphasis is on the application from satellites. Several of the special problems involved in the use of SAR will then be discussed. The tone of the report is part tutorial and part "editorial," in that it is both a technical review and a means for expressing the writer's opinions and impressions of SAR as a radar tool for remote sensing.

The SAR concept is indeed a significant radar accomplishment. One version of where it fits within the major accomplishments in radar during the last 40 years might be as follows:

- 1930's - Early development of the basic concept of radar.
- 1940's - Microwave radar development.
- 1950's - Practical utilization of coherent (doppler) radar as in synthetic aperture radar, MTI and cw.
- 1960's - Digital processing, and HF OTH radar.

1970's - Extraction of information, other than "blob information" from radar signals.

Thus SAR ranks high in the inventory of radar accomplishments. The development of digital processing in the late 60's has enhanced the practical utility of SAR. Also, the SAR has contributed significantly in the 70's to the increased extraction of information from the radar signal.

## 2.0 THE SAR CONCEPT

The SAR may be considered from one of two viewpoints depending on whether the frame of reference is at the target or at the radar. These are:

- 1) as a sequentially synthesized array antenna of large effective aperture
- or 2) as the use of the doppler-frequency domain to spatially resolve different parts of objects having different doppler-frequency shifts because of different relative velocities with respect to the radar.

Both points of view have been successfully utilized in the analysis and development of SAR. It is not uncommon in SAR analysis to switch from one model to another, depending on which is the more convenient for describing some particular property of the system. Although SAR is usually thought of in terms of a synthesized antenna, it was the doppler viewpoint that first guided the original experimenters in this area. When viewed as the use of the doppler domain to achieve the equivalent of angle resolution, it can be seen that SAR is related to the scatterometer that uses a broad fan beam with doppler filters to achieve resolution in elevation. The use of doppler by the radar astronomer to image the planets (also called range doppler imaging or inverse synthetic aperture) is also based on the same physical principle as SAR.

The real-aperture antenna of a synthetic aperture radar is generally directed perpendicular to the flight path of the vehicle. In this configuration it is a sidelooking radar that produces a strip-map image of the terrain. The real-aperture antenna may also be directed forward or aft of the perpendicular. This is called the squint mode and also produces a strip map. Synthetic aperture processing can also be employed with a circular-

scanning antenna to provide enhanced resolution on a PFI, except in a sector centered about the forward or aft direction of the vehicle trajectory. This is called the doppler beam - sharpening mode. A positionable antenna can be made to dwell on a particular area to achieve a longer observation time, and thus provide better resolution than a fixed aperture. This is called the spotlight mode. It is also possible to obtain multiple looks of a particular scene with a fixed real-aperture antenna by trading resolution for a number of independent observations. The noncoherent superposition of these multiple looks of lower resolution produces a less speckled image than does a single observation of higher resolution. SAR has also been employed to obtain stereoscopic images of terrain.

The development of SAR began in the early 50's and took almost a decade to reach significant levels of application. The development of SAR and its original application were sponsored by the military, primarily for all-weather battlefield surveillance and as a reconnaissance sensor. Although it has seen important application for the military, it has been more of a complement to other military sensor rather than as a supplement.

Compared to other radars, SAR has the unique capability of obtaining resolution in the cross-range, or along-track, dimension comparable to the resolution obtained in range. With other radars the resolution in cross-range is determined by the antenna beamwidth and is usually considerably greater than the range resolution. The SAR is able to image a scene and obtain information about the scene by the spatial relationships and contrasts provided by the high resolution. The imaging and mapping qualities of SAR allow terrain features and man-made objects to be recognized, and their spatial relationships identified and utilized. In this regard its output is somewhat like an optical photograph, but with some important differences. The search for additional information that can be extracted from the received signal in both SAR and conventional radar continues. In the area of remote sensing it is especially important to extract other information about the objects being viewed. The resolution provided by SAR allows the isolation of the various objects of interest from those that might contaminate the measurement.

A cursory examination of a SAR image and an optical or IR image of the same scene, especially from long range, might give the impression that the active radar and the passive optical and IR images are similar and thus competitive. Actually, there are significant differences between these sensors. These may be described as:

- a) The almost  $10^5$  difference in wavelength between radar and optical (visual) frequencies means that the two sensors will respond to different size scatterers, as well as require significantly different equipment technology. Scattering occurs from those scale-sizes that are comparable to the incident wavelength. Thus SAR will detect scattering from those scatterers with dimensions of the order of centimeters. Optical imaging sensors are responsive to scatterers of the order of microns. Thus "radar eyes" are different than "optical eyes." The information provided is different, and different criteria are required in the interpretation of the images obtained by SAR than the usual techniques of photographic interpretation.
- b) Another major difference between the two classes of sensors is that the radar responds to its own illumination. Visual imaging sensors (and some IR sensors) require ambient illumination, as from the sun, and are thus limited to daylight and by the location of the sun relative to the sensor. IR imaging sensors depend on differences in the temperature and emissivity of the various objects of the scene. Areas near the poles with visibility and sunlight conditions poorly suited for photography can be readily imaged by SAR since it does not depend on sun angle. The usual viewing angles of radar can result in shadows produced by high relief such as hills and mountains, which can be used to obtain information regarding the three-dimensional character of the terrain. These shadows are generally not evident in optical photographs.
- c) Since optical and IR passive sensors view objects with incoherent ambient illumination or incoherent radiation from the objects



themselves, the result as an image to which the eye is accustomed. The image produced by a coherent SAR, however, is of a speckled nature, not unlike that seen by an object with laser light. The speckled nature of the scene can make its interpretation difficult, and can cause confusion to an interpreter not familiar with this effect. To minimize the effect of speckle, SAR radars sometimes superimpose multiple independent images of the same scene taken with different frequencies and viewing angles.

- d) The resolution of a "focused" SAR is independent of range, whereas that of passive imaging systems is worse with increasing distance. This makes SAR of interest from spacecraft where the ranges are large.
  
- e) Radar has the advantage of being able to operate any time of the day or night and under weather conditions that make IR or optical sensors inoperative. This advantage, in the writer's view, is not necessarily a major reason for using radar in remote sensing. Most remote sensors do not require "timely" data. If it is raining on one pass it might not be on the next pass. If an optical sensor capable of operating only in the day, passes over an important area at night, consideration can be given to using a second satellite to insure at least one pass in daylight during a specified time. Radar can be all-weather when used for imaging the spatial relations of the elements of a scene. But if other specific information is needed such as for soil moisture measurement or crop identification, the effect of rain might degrade the ability of SAR to provide reliable data.

### 3.0 APPLICATIONS OF SAR, ESPECIALLY FOR REMOTE SENSING

Although SAR does a different job than any other radar, and has unique capabilities, it has not enjoyed the wide application experienced by the more classical radar. The "bread and butter" application that would sustain a major segment of the electronics manufacturing industry has yet to appear.

Nevertheless, its continual development is pursued and there continues to be significant interest in its application.

In short range remote sensing from aircraft, the classical noncoherent high-resolution radar that obtains cross-range resolution with a physically large antenna with narrow beamwidth has proven competitive to coherent SAR. When its resolution is adequate, the lower cost, absence of sophisticated processing, and an image relatively free from speckle make it the preferred approach in many applications. However, at long range, as from a satellite, the resolution of a conventional antenna is inadequate for most purposes and synthetic aperture must be used to achieve resolution. The increased integration time (or effective aperture length) of the SAR with increased range helps compensate in part for the lower echo signals at longer ranges.

The specific applications of SAR from spaceborne platforms will not be discussed here since that is the subject of another paper in this Conference ("Applications of Space-Borne SAR Data," by Fawwaz I. Ulaby) The general application areas that are contemplated or proposed may be described as follows:

a) Measurement of sea state and sea spectrum

This is the objective of the NASA SEASAT-A. The resolution of the SEASAT imaging radar is coarser than might be desired, but it is a first attempt to demonstrate the utility of SAR for remote sensing from space. Other radars and other sensors can obtain a measure of sea state, but SAR is the only all-weather remote sensor (other than HF OTH radar) with the potential for obtaining the two dimensional sea spectrum. This SAR capability was first demonstrated by the Soviets using conventional imaging radar from aircraft.

b) Geological and mineral exploration

This is the prime objective of the NASA SIR-A (Shuttle Imaging Radar) experiment. Conventional noncoherent imaging radar on aircraft have been widely accepted as a tool for petroleum exploration. Imaging radar has also been used for mapping and mineral exploration of inaccessible areas by several South American

countries, presumably with success.

c) Agricultural Measurements

The chief measurements desired in this area are soil moisture and crop classification. This is the objective of SIR-B. These are difficult measurements to make with radar. There has been much preliminary work in this area, but it is not as far advanced as the other two application areas mentioned above since it is a more difficult task. Determination of soil moisture, as now proposed, requires an accurate, absolute measurement of the radar cross-section as well as a priori information about the nature and roughness of the scattering objects. It has been proposed that crop identification can be performed using multiple frequency and/or multiple polarization observations. The degree of success of these two measurements of soil moisture and crop identification have yet to be determined.

d) Other Remote Sensing Applications

SAR also has been demonstrated or suggested to be used for mapping of watersheds and flooded regions, ice mapping and identification, oil-spill detection, measurements of snow water-content, observation of precipitation, urban land-use monitoring, among others. It has also been used, of course, for military purposes.

Of the above, SEASAT is planned for launch in 1978, SIR-A has been approved as a NASA program and is planned for July 1979 launch. The above applications of SAR are not without competition by other sensors. Almost all of these measurements might be obtained by other means, even though such a competitor as optical and IR imaging are not all-weather, and microwave radiometry, another serious competitor, is not capable of the same resolution as SAR.

#### 4.0 ATTRIBUTES OF SAR

The features of the SAR that make it of interest for remote sensing include the following:

- a) Good resolution in the along-track, or cross-range coordinate as well as the range coordinate. This provides a map-like presentation which permits the identification of objects by their spatial

relationships, size, and shape.

- b) Resolution cell size independent of range.
- c) Ability to produce images from satellite ranges.
- d) All weather.
- e) Potential ability to extract information regarding roughness, symmetry, and dielectric properties of scattering media within the resolution cell
- f) Additional information possible with multiple frequency, dual polarization, and spatial diversity observations.
- g) Real-time processing and display either on board the sensor platform or by remote transmission of radar output.
- h) Information can be obtained from scattering objects not possible with optical or IR sensors, because of the use of microwaves. (A good example is that of geological prospecting where information on lineaments is found with microwaves not found with optical photographs.)
- i) The technology of SAR is well developed and there has been considerable experience with its application as an imaging device so that its current limitations are understood.
- j) The SAR technology is applicable over a wide range of frequencies, from VHF to millimeter wavelengths.

## 5.0 ISSUES AND CONCERNS IN THE POTENTIAL APPLICATION OF SAR

As with any device, SAR cannot do everything that may be desired of it. In this section, some of the areas of concern in its use are briefly mentioned. (The listing below is in no special order.)

### a) Complexity and resolution

The SAR is more complex and expensive than ordinary radar, as might be expected. However, there have been continual improvements made in the hardware, especially in the signal processing.

The complexity of a SAR is related to the resolution desired. It seems conceivable that better resolution than is now utilized can be obtained, especially at the higher microwave frequencies. However, it has been found in some applications that the ultimate in resolu-

tion is not always needed or even desirable, even if expense and complexity are not deciding factors. That is, the optimum resolution for any particular application is not necessarily the smallest resolution cell that can be obtained. It might even occur that too much resolution is harmful to the type of information desired. Traditionally, in mapping radars the along-track resolution and the range resolution are made equal, or nearly so, in order to present conventional-looking images. Perhaps practice ought to be re-examined critically for remote-sensing applications. It is far easier to obtain high resolution in the range dimension than in the along-track dimension. If asymmetrical resolution can be tolerated, simpler radar will result.

The highest resolution obtainable with a SAR is with a focused system that corrects for the curvature of the wave front experienced when using imaging objects in the Fresnel region of the synthetic antenna. An unfocused SAR is not capable of as great a resolution as a focused system. Also the cross-range, or along-track, resolution of an unfocused SAR is not independent of range, but varies as the square root of the range. In spite of such limitations, the lesser complexity of the unfocused SAR might make it a contender for those applications for which the ultimate in resolution is not required.

b) Magnitude of Data Available from SAR

The high resolution of the SAR results in a high data rate and a large amount of information. The handling of large quantities of data as can be obtained with an SAR can saturate and overwhelm some users interested in the radar information. Careful planning is required in what information is to be obtained, and in its efficient analysis. Some users believe that the increased data rate from a SAR will result in more information than they can digest. This might indeed be true, but it should not be a reason for restricting the resolution to a lesser value than might be desired. As mentioned above, there is generally an optimum resolution for any particular application, determined by what is to be imaged and the

information desired. If the total amount of data that can be handled is limited for some reason, then the choice between a large quantity of images of poorer resolution, or a lesser quantity of images of optimum resolution, must be carefully considered. The proper handling of large amounts of data is an area requiring more attention.

c) Swath

There is a limit to the coverage, or swath width, obtainable with a SAR, the swath depends on the resolution. This is due to the ambiguities in both angle and range when a sampled (pulsed) radar system is used. A high prf is necessary to achieve high resolution images without ambiguities causing overlap and superposition of images. On the other hand, a low prf is necessary in order to image a large swath in the range coordinate without the range ambiguities causing image overlap. Thus, there is a trade between swath width  $S_w$  and resolution  $\delta_a$ , which is given by

$$\frac{S_w}{\delta_a} = \frac{c}{4v \cos\phi}$$

where  $v$  is the velocity of the vehicle,  $c$  the velocity of propagation and  $\phi$  is the grazing angle. This equation was derived assuming optical processing, a flat earth and a vertical beam shaped to illuminate only the swath  $S_w$ . It would have to be modified when the curvature of the earth cannot be neglected. For a spacecraft with a velocity of 7500 m/s, with  $\cos\phi = 1$ , a swath of approximately 100 km is theoretically possible with a resolution of 10 m.

In addition to the fundamental limit on swath and resolution set by the complexity of the available signal-processing technology and the limited ability of a user to handle large amounts of information.

Thus one of the severe limitations of a SAR for space application is the limited swath width, which might be no more than several hundred kilometers, or less. Although this might seem to be

adequate for many applications and is comparable to that achieved by optical and IR images on Landsat, it does not take full advantage of the coverage that can be viewed from a satellite, which can be in the vicinity of 1000 to 3000 km for low and medium orbit heights. The limited swath means that many satellites must be used to obtain world-wide daily coverage, or that only limited parts of the earth will be covered if a single satellite is used. This is another reason for using only the resolution needed for the particular application, and no more. (The paper by J. Eckerman and J. P. Claassen in this conference, entitled "A System Concept for Wide Swath Constant Incident Angle Coverage," proposes a multiple beam radar configuration for increasing the swath.)

Space systems that view the earth's surface should have a large swath coverage in order to obtain timely information over a large part of the earth in an economical manner. Unfortunately, large swaths with SAR are obtained at the expense of poor resolution. If SAR is to provide full benefit in space applications, its swath should be larger than has generally been considered. At present, there do not appear to any simple solutions available.

d) Coverage and Revisit Time

A swath coverage of about one hundred kilometers typical of the experimental SARs proposed for remote sensing applications from space results in a long revisit time of the same area on the surface of the earth. This might be 10 to 15 days in some cases. Several of the proposed applications of SAR require more timely revisits. This means a larger and more complicated satellite radar with a large swath is required, or there must be more satellites. The need for proper coverage and revisit time might be of little concern for the exploratory phases of remote sensing on which NASA is now embarked, but it is an issue which cannot be neglected when operational systems are considered where cost-benefit is a criterion for the spending of funds. This is a fundamental issue that must be faced by the technologists.

e) Image Interpretation

An image produced by a SAR is similar to an optical photograph. However, there are significant differences between the two, so that someone trained to interpret optical photographs might not extract the proper information from a SAR image. Even with the same resolution there can be significant differences between the two because of the large difference in wavelengths of the two sensors and the speckle in the SAR image. Each sensor responds to those scattering objects with dimensions comparable to the wavelength. With SAR there will likely be greater variation in echo strength as a function of viewing angle than with optical imaging. Thus different passes over the same area with SAR can result in differences in the images. The coherent nature of microwave radiation results in a speckled image due to constructive and destructive interference. This does not occur with optical or IR imaging which depends on incoherent radiation. Speckle can be reduced in the SAR by observing the same scene with different frequencies and/or from different viewing aspects, and noncoherently superimposing the resultant images.

f) Signal and Data Processing

Past improvements in digital processing circuitry have resulted in improved real-time processing either on- or off-board the satellite. Developments in digital processing are continuing and further improvements for SAR can be expected.

g) Equipment

Unfortunately there do not now seem to be any significant developments in spaceborne radar transmitters that would lead to significantly smaller, more efficient packages for space application. If radar in space is to be a permanent tool for operational remote sensing, basic work in transmitters is indicated. The present conference includes a number of papers on antenna design, indicating an awareness of the importance of the antenna to a spaceborne SAR. Cost of equipment is an important consideration. The cost is not only in dollars, but in the space and weight that must be accommodated in a spacecraft. Radar is not small. If radar can perform



a desired function for remote sensing, then one should not be afraid of large systems and should strive to obtain what is needed, rather than what would be tolerated.

h) Information Extraction

Work has been underway to obtain information about the objects within a scene based on a measurement of the absolute value of the cross-section within a resolution cell, as well as by measuring cross section as a function of frequency, polarization, or both. The measurement of the absolute value of cross section per unit area, as has been suggested as needed for certain remote sensing applications, is a difficult measurement to make to the desired accuracy. If useful measurements are to be derived from other than the spatial relationships, some other measurement is needed. A method for extracting information, that seems as yet untapped, is the employment of pattern recognition or two-dimensional matched filtering comparison to classify one type of terrain from another on the basis of the spatial pattern of the return. For example, in a one square mile of terrain there are approximately 3800 resolvable cells when the radar has a resolution of 30 m, and about 34,000 cells with 10 m resolution. It would seem that there are distinctive elements that might be uncovered by proper processing.

i) Frequency and Space Diversity

Some proposed SARs for Earth Resources Survey are to view the same scene with more than one frequency and at more than one aspect. The purpose of these multiple images is to superimpose them so as to smooth out the speckle that appears with coherent radar and obtain a less grainy image more like that seen with incoherent light. The potential benefit from frequency diversity and spatial diversity and spatial diversity will make it likely that such SARs will be considered further, possibly along with polarization diversity. Such diversity likely would improve the ability of pattern recognition to recognize one type of scene from another.

j) Statistics of Land and Sea Echo

Several of the papers in this conference (Korwar and Lipes, Pierce,

and Korwar) assume the statistics of the echo within a pixel or resolution cell are described by the Rayleigh probability density function. This may be true of receiver noise and low-resolution radar, but it is generally not true of land and sea backscatter. It is well known that with high resolution, the probability density function for both sea and land echo have higher "tails" than that given by Rayleigh statistics. The log-normal pdf is sometimes used as a model for the extreme case of non-Rayleigh statistics, but the Weibull pdf, which lies between the Rayleigh and the log-normal, seems better able to model most examples of non-Rayleigh and the log-normal, seems better able to model most examples of non-Rayleigh clutter. Different constants (such as mean-to-median ratio, standard deviation, or Weibull coefficient) apply for different terrain and sea conditions and for different radar resolutions. It is not obvious what effect the non-Rayleigh pdf has on those analyses in which Rayleigh statistics are assumed, but it is a consideration that needs to be kept in mind. It is suggested that a Weibull or some other suitable non-Rayleigh pdf be used in analyses of SAR remote sensing.

The fact that different forms of terrain and sea conditions result in different Weibull coefficients might be used as a means for identifying one form of terrain from another. Measuring the parameters of the pdf of a patch of terrain might be one method for obtaining classification, but there might well be others,

k) Calibration, Accuracy, and Precision

The measurement of soil moisture as proposed for remote sensing from space with SAR requires the absolute measurement of the radar cross section per unit area  $\sigma^{\circ}$ . The scatterometer also requires an absolute measurement of  $\sigma^{\circ}$  for many of its proposed applications. Absolute measurements require good calibration and good stability of the radar. From past experience with attempts to measure the absolute value of radar cross section, it is unlikely that the measurement of  $\sigma^{\circ}$  can be consistently made to an accuracy better than  $\pm 3$  dB, or at best  $\pm 2$  dB. (The precision of measurement might

be better than this.) There is no fundamental reason why a more accurate measurement of  $\sigma^0$  cannot be made, but this seems to be a practical limit that has been hard to make better. A  $\pm 3$  dB accuracy is apparently not satisfactory for soil moisture measurement or for accurate measurement of wind with a scatterometer. Several of the papers in this conference treat the problem of radar calibration. It is an important problem that is one of the major limitations in several remote sensing applications.

Even if it were possible to calibrate the radar to any accuracy desired, there is still the problem of statistical variation of the measurement itself which can limit the ability to obtain average values with small variance. The  $\sigma^0$  of the terrain might not be uniform, and the speckle associated with coherent radar observations might require long-term averages to obtain meaningful measurements. It is not unusual for two passes over the same terrain to give as much as 10 dB difference in measured  $\sigma^0$ .

At the present time SAR is best used where absolute measurements of  $\sigma^0$  are not required. The chief attribute of SAR is to provide the resolution needed for imaging and for recognizing effects by the shape, position, and relative intensity of the scattering objects.

1) Millimeter Wavelengths (Frequencies greater than 40 GHz)

There has always been interest in the application of millimeter wavelengths for radar, above  $K_a$  band. One of the reasons millimeter wavelengths have not had application is the large attenuation through the earth's atmosphere, especially at low grazing angles. If higher grazing angles can be utilized, millimeter waves might be of interest since their scattering properties might be different than at lower frequencies. (There is no evidence at present that would suggest that millimeter waves will provide significant new information not attainable with lower frequencies, but the possibility that it does should not be overlooked.)

m) Synchronous Orbits

Synchronous satellites have the advantage of being able to observe continuously a large portion of the earth's surface. A synthetic aperture radar cannot be precisely synchronous since relative motion is required between the radar and the scene being viewed, hence the term near-synchronous SAR. (One approach is described by the paper by Tomiyasu.) A satellite in near synchronous orbit requires larger real antenna apertures and large powers in order to achieve the necessary signal-to-noise ratios from such large distances. It is not likely that near synchronous orbit SAR will be seriously considered (that is, large funds spent) before closer orbit satellites or aircraft SAR have proven the value of the measurements to be made.

n) Electromagnetic Compatibility (EMC)

The potential interference between a satellite radar and ground equipment can be quite serious. Not only is the mutual interference problem aggravated by the large ground area within the line-of-sight of a SAR in a satellite, but a SAR for remote sensing applications will be of high power and with a broad signal bandwidth. In some applications there is proposed multiple frequency operation, which further complicates the EMC problem.

If a conflict results between a spaceborne radar and ground electromagnetic services, the application with greater economic impact (or greater military or national need) will likely be the one given priority for the use of the electromagnetic spectrum. As the SAR proves its worth for remote sensing, the potential problems of EMC and spectral occupancy must be kept in mind. If SAR does create a serious interference problem to other services, its use will have to be justified. It is thus important to pay special attention to the needs of the potential users of SAR so as to maximize its economic potential.

o) Sustaining Applications and Competitors

There have been a whole host of applications proposed for the spaceborne SAR. There are many potential users of the information

derived from such a sensor. However, there seem to be few, if any, potential users of SAR who are serious enough to pay the large costs involved for a useful operational system, even assuming developmental costs are paid by someone else. There is insufficient knowledge available at present to allow a prudent investor to make that kind of decision. More information is needed regarding what such systems will eventually be able to do. If a sustaining "bread and butter" application is not found, interest in SAR for space application likely will wane. More effort is required in fereting out suitable applications for SAR. Mere "interest" by some user is not sufficient. Evidence is required to prove that SAR has the potential for performing an important function not capable of being fulfilled by some other sensor, or that it can perform a needed function more effectively or more cheaply than by any other method.

## 6.0 DISCUSSION

Synthetic Aperture Radar certainly offers potential for unique capabilities for remote sensing from space. Current SAR technology can provide more information than will be obtained with SEASAT-A or SIR-A. There exists an available hardware base from which to draw, as well as new technology developments as evidenced from this meeting and the continued developments under NASA sponsorship. Theoretical analysis, ground experiments, aircraft experiments, as well as the interests of potential users, all support the need for further efforts. However, the current base of knowledge is still inadequate to march confidently into the future with a definitive plan that will lead to operational spaceborne SAR systems performing some needed function in an economical affordable manner. Conferences such as this one are important if that goal is to be reached. There are certainly unresolved problems with SAR for remote sensing. If there were none, then there would be no need for R&D. Problems are a natural consequence of pioneering efforts.

SAR must provide something other than is provided by IR and optical images, or by microwave radiometers. With its use of microwave wavelengths, its

own controlled source of illumination, ability to use many octaves of the spectrum, control of polarization, its potential wide swath and adequate resolution, SAR offers some significant differences over the other sensors. These differences should be exploited for remote sensing applications. It must also be shown that operational satellite-borne SAR offer a competitive cost-benefit advantage over aircraft-mounted SAR.

One thing this paper has not done, since it is not within the capability of the writer to do so, is to describe what SAR needs that it does not now have, that would allow it to be a major sensor for remote sensing from space. Before it will be widely used it must be verified that SAR from space can achieve an important remote sensing capability better and/or cheaper than any other means, and that this capability is something of economical or societal value.

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## AN UNCONVENTIONAL APPROACH TO IMAGING RADAR CALIBRATION

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SUMMARY

Absolute calibration of radar return signals has been a goal of radar system engineers almost since radar was invented. A large degree of success has been obtained in the development of calibration techniques for instrumentation and fire control radar systems.

However, calibration of imaging radar systems has proven more difficult. Most past attempts to provide calibration to such systems have consisted of sampling the transmitted signal, and re-inserting this signal into the receiver in known quantities. This approach has had limited success, and does not address the question of end-to-end calibration.

This paper will present an unconventional approach in that it considers the entire system, including the imaging processing as a measurement instrument to be calibrated. The technique makes use of a calibrated aircraft scatterometer as a secondary standard to measure the backscatter ( $\sigma_0$ ) of large units of constant roughness. These measured roughness units when viewed by an imaging radar system can be used to provide gray-scale level corresponding to known degrees of roughness.

To obtain a calibrated aircraft scatterometer, a homogeneous smooth surface was measured by both the aircraft scatterometer and a sphere calibrated ground system. This provided a measure of the precision and accuracy of the aircraft system. The aircraft system was then used to measure large roughness units in the Death Valley, California area. Transfer of the measured roughness units to radar imagery was demonstrated.



Absolute calibration of radar return signals has been a goal of radar system engineers almost since radar was invented. A large degree of success has been achieved in the development of calibration techniques for instrumentation and fire control radar systems.

However, calibration of imaging radar systems has proven more difficult. Most past attempts to provide calibration to such systems have consisted of sampling the transmitted signal, and re-inserting this signal into the receiver in known quantities.

One such use and evaluation of this technique was reported by the Environmental Research Institute of Michigan (ERIM) in 1973<sup>[1]</sup>. This approach has had limited success, and does not address the question of end-to-end calibration.

Imaging radar was originally developed to provide information for mapping and target recognition.

In the mid-1960's, the Department of Defense (DOD) developed techniques and ranges for evaluation of imaging radar systems. A summary of the DOD effort was presented by Marden in 1967<sup>[2]</sup>. The DOD effort was related to detection of cultural targets in various types of backgrounds and evaluation of geometric fidelity.

In the late 1960's and early 1970's as investigators started using radar imagery in Earth Resources investigation, the lack of end-to-end system calibration quickly became apparent. Most early imaging radar systems used optical recording and correlation techniques. Procedures and techniques for control of image quality during recording and correlation have been developed. Control of image processing will provide a uniform image output, but in no way addresses the end-to-end calibration problem. Variations in imaging radar systems performance, unknowns about the antenna characteristics, and atmospheric effects all must be accounted for to ensure end-to-end calibration.

At the Johnson Space Center, studies of the potential use of imaging radar in Earth Resources investigations were begun in the late 1960's. The results of one of these early studies by Stafford<sup>[3]</sup> outlined a concept of a large radar target range with varying degrees of known roughness. This target would be overflowed frequently to give a means of relatively known image roughness to unknown image roughness.

The need for end-to-end calibration of imaging radar systems for Earth Resources investigations was not clearly established until the mid-1970's when investigators working in the fields of water resources and soil moisture areas began to realize the importance of radar backscatter data in their investigations. The inadequate performance of imaging radar systems with regard to end-to-end calibration have hindered meaningful investigations in these two important areas of Earth Resources.

## 2.0 END-TO-END RADAR CALIBRATION CONCEPT

Traditional approaches to imaging radar calibration generally involve the independent measurement of subsystem parameters, the calculation of total system transfer function and prediction of error bounds. Unfortunately, the error bounds associated with this approach may range as high as  $\pm 3\text{db}$ <sup>[1]</sup> which is excessive for a number of applications investigations using extended scene radar signatures. In addition to the difficulty of obtaining absolute calibration with reasonable error bounds, the problem of determination of the precision of the measurement exists.

In 1976, Johnson Space Center (JSC) initiated a program to establish the precision and accuracy of 1.6 GHz and 13.3 GHz scatterometers flown on the Airborne Instrumentation Research Program (AIRP) C-130 aircraft. This program as initially conceived involved the following:<sup>[4]</sup>

- (1) Creation of a known sigma zero ( $\sigma_0$ ) scene by performing in situ measurements over a smooth homogeneous surface using a sphere calibrated ground scatterometer system operating at 1.6 GHz and 13.3 GHz.

(2) Overflight of this scene with the aircraft 1.6 GHz and 13.3 GHz scatterometers.

(3) Determination of the aircraft systems precision and accuracy by analysis of the data gathered on the flights over the known sigma zero scene (calibration site).

In the course of determining how to evaluate the precision and accuracy of the aircraft scatterometer systems, the question of how pure roughness and its effect on sigma zero could also be evaluated, was addressed. A paper by Schaber, Berlin, and Brown in 1976<sup>[5]</sup> presented data indicating that sufficient studies and ground truthing of the roughness units in the Death Valley Area of California had been performed to allow it to be used for evaluation of roughness. However, gathering of ground scatterometers data for sigma zero verification would be extremely difficult.

A comparison of the terrain features and soil characteristics of the site chosen for the precision and accuracy evaluation (Northrop Strip, White Sands Missile Range, New Mexico) and the Badwater Basin region of Death Valley indicated many similar characteristics. This led to the concept of extending calibration from a known and tested ground site to a training site, via aircraft scatterometer systems. The training site would contain roughness units varying in roughness from smooth to extremely rough.

A concept of end-to-end radar calibration as shown in Figure 1 was derived. This concept would function as follows:

Step #1: The calibration site sigma zero curves for a smooth homogeneous surface would be derived by performing measurements with a calibrated ground scatterometer system.

Step #2: This site would then be overflown with the airborne scatterometers and the precision and accuracy of the aircraft systems established.

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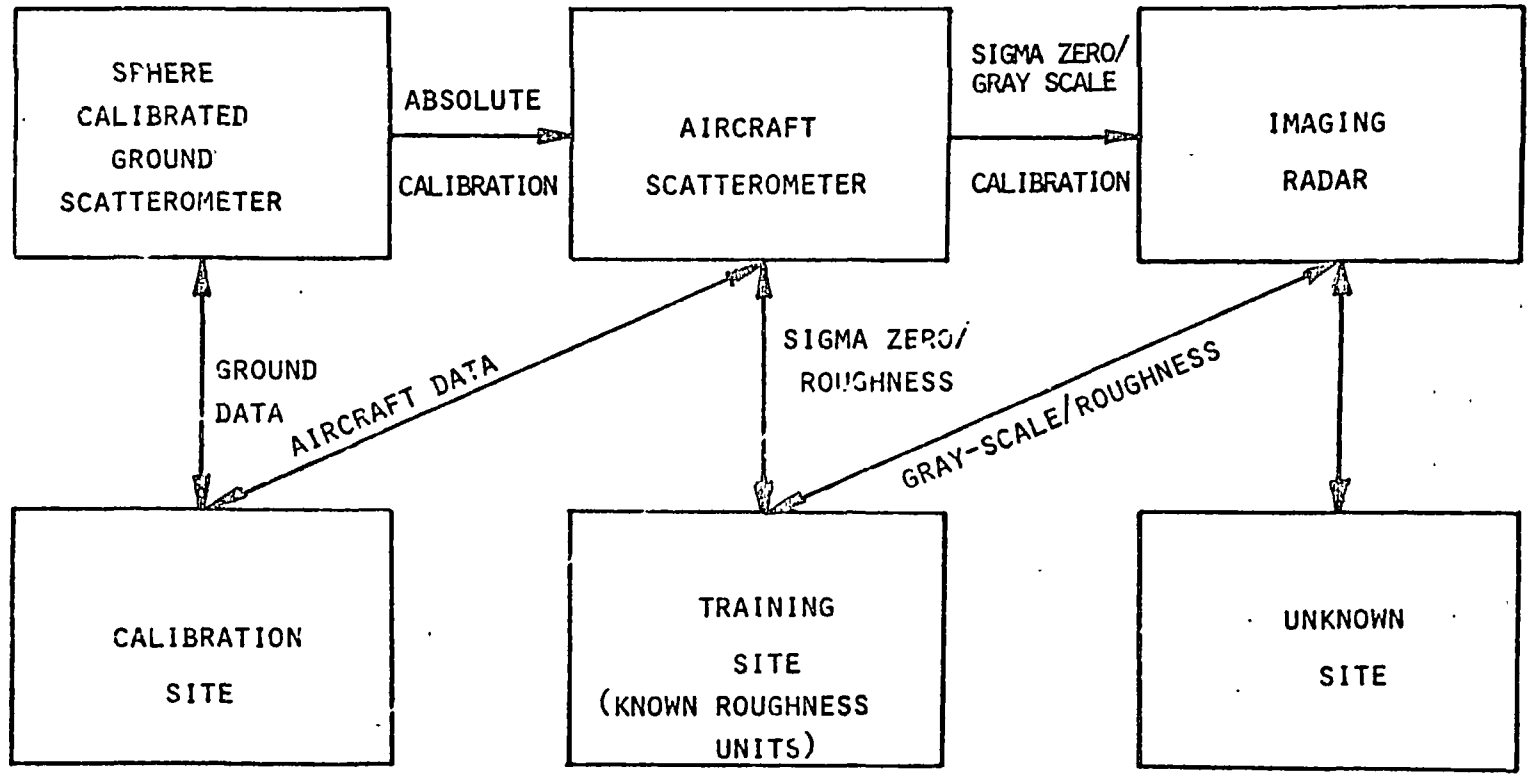


FIGURE 1

END-TO-END RADAR CALIBRATION CONCEPT

Step #3: The training site would be overflown with the aircraft scatterometer systems and sigma zero curves for the pure roughness units in the test site derived.

Step #4: The sigma zero curves derived for the test site would be used to relate gray-scale levels to roughness in imagery taken over the test site.

Step #5: The gray scale to roughness relation derived from imagery taken over the test site would be used to evaluate the amount of roughness and/or variations and deviations in roughness in radar imagery taken over unknown sites. Knowledge of the gray scale to roughness relation is an important piece of information in evaluating radar imagery.

Certain criteria must be applied to the sites selected for calibration and training sites. Each must be devoid of vegetation and have surface characteristics that are stable with time. Once measured, they must be controlled to ensure that manmade changes such as construction do not alter their characteristics.

On the calibration site, the surface must appear smooth at the highest frequency that data will be gathered at. The site must be accessible for ground scatterometer testing.

The training site must contain roughness units varying from a smoothness approaching the calibration site and increasing in roughness graduations to the largest degree of roughness available. These units must be large enough to provide sufficient independent samples for precise measurements. The sites chosen for the calibration and training sites meet all of these criteria.

### 3.0 CALIBRATION SITE

The site chosen for the calibration site is the Northrop Strip located on the White Sands Missile Range in New Mexico. Northrop Strip is a 10,000-foot long by 300-foot wide emergency landing strip built on a dry lake bed. The

TABLE I

MEAN VALUE OF MEASURED DIELECTRIC CONSTANT

NORTHROP STRIP, WSMR

	1968 (10.0 GHz)	June 1977 (13.3 GHz)	Nov. 1977 (13.3 GHz)
Real	4.12	4.76	5.31
Imaginary	3.01	2.37	1.63

surface is packed gypsum sand with a high alkaline content. This site was chosen for a number of reasons as follows:

- (1) The entire area is naturally smooth with the runway surface graded and packed.
- (2) The site is located in an arid area, devoid of vegetation and not subject to seasonal variations in surface moisture.
- (3) The high alkaline content of the soil will tend to make it a highly reflective surface at the frequencies of interest.
- (4) Radar reflectivity and soil dielectric constant data had previously been gathered on the site as part of the Apollo Lunar Reflectivity Program in 1968.<sup>[6]</sup>
- (5) The runway is well marked with visual aids for repeatability of aircraft flight lines.

Ground truth data acquisition at the site was initiated in June of 1977 by taking a series of soil samples and measuring the dielectric constant in the same manner as reported by Dickerson.<sup>[6]</sup> Additional samples were taken in November 1977. Table I shows the average results of these samples. This data shows that there are no long-term (yearly) or short-term (seasonal) variations in the surface properties of the soil at the site.

To ground truth the site, a ground scatterometer utilizing the FM/CW approach reported by Bush and Ulaby in 1973<sup>[7]</sup> was constructed. Initial plans were to ground truth the site in June of 1977 coincident with the aircraft overflight, but mechanical difficulties with the antenna system prevented the ground measurements from being made until November of 1977.

#### 4.0 TRAINING SITE

The use of known terrain scattering properties to provide a convenient method of calibrating airborne radar systems was first suggested in 1960 by Cosgriff et al<sup>[8]</sup>. Recent work by Schaber (1976) has delineated the characteristics of geologic units on radar images of Death Valley. The unique combination

of large pure roughness units, unchanging electrical surface properties, and time constant roughness units makes Death Valley an ideal training site for imaging radar calibration. The well-documented characteristics of the region, the absence of rainfall and vegetation ensure the temporal stability of the backscatter coefficient obtained. For these reasons Death Valley was chosen as a potential training site.

A series of scatterometer flights were flown over Death Valley in June of 1977. Flight lines were chosen such that sufficiently large areas of constant roughness were overflown to ensure adequate sampling.

## 5.0 PROGRESS TO DATE

As stated previously, aircraft scatterometer data was gathered over the Northrop Strip, WSMR calibration site and the Death Valley, California test site in June of 1977. The calibration site ground scatterometer data was gathered in November of 1977.

Analysis of this data has progressed slowly because of difficulty in processing of the aircraft data. To date, only the precision or repeatabilities of the data sets has been addressed. Attempts to arrive at an accuracy estimate by comparison of ground and aircraft data sets has not proved completely successful.

Some of the differences between scatterometer data sets and the ground scatterometer data sets may be due to problems in the data reduction methods for the two systems. Analysis of the data reduction techniques is presently underway to resolve the differences.

The following paragraphs will discuss the results of the data analyzed to date:

### 5.1 DATA ACQUISITION

Ground scatterometer calibration site data was acquired for two frequencies (1.6 GHz and 13.3 GHz) at six locations spaced 500 feet apart along the Northrop Strip runway center line. This provided a 2500 foot long sample



area. Azimuth rotation of the antenna systems provided multiple samples at each location. Incident angle data was acquired at 10, 20, 30, 40, 50, and 60 degrees.

The aircraft scatterometer data was acquired by multiple flights over the same sample area as used by the ground scatterometer. A total of 16 data runs were made on two successive days with four morning and four afternoon runs each day. Five data runs were made over the Death Valley training site to establish the relative magnitude of the radar reflectivity data from the wide range of surface roughness conditions available.

The aircraft flew at a 1500-foot altitude and a ground speed of 150 knots. The radar antenna footprints at this altitude were 225 feet and 75 feet for the 1.6 and 13.3 systems, respectively.

In order to gather 13.3 scatterometer samples only over the Northrop Strip runway, the aircraft flight had to satisfy the conditions of either being exactly over the runway centerline with a combined roll and drift of less than three degrees or be less than 100 feet off the centerline with no roll or drift. Photography obtained during the data runs was used to establish aircraft flight path relative to runway centerline. The LTN-51 inertial navigation system was used to determine aircraft roll and drift. For the 16 runs flown, these conditions were satisfied on ten runs thus defining the data set that was used for analysis.

## 5.2 DATA PROCESSING

Ground scatterometer data was reduced as it was gathered by the use of a Hewlett-Packard 9820 programmable calculator operating in conjunction with the scatterometer systems.

The aircraft scatterometer data is recorded on FM analog recorders and returned to JSC for playback, analog to digital conversion and digital processing. The data processing is accomplished on a PDP-11/70 minicomputer using the algorithms developed by Krishen. [9]

The program output is in the form of time correlated sigma zeros at angles of 5, 10, 15, 20, 30, 40, 50, and 60 degrees off nadir. The sampling times used were 0.42 seconds and 0.1 seconds for the 1.6 and 13.3 systems respectively.

### 5.3 DATA ANALYSIS RESULTS

#### 5.3.1 Northrop Strip

##### 5.3.1.1 Ground Scatterometer

Figures Two and Three are plots of mean and standard deviations of the data gathered by the ground system. Mean standard deviation for the 1.6 GHz data is 0.77 db. Mean standard deviation for the 13.3 GHz data is 1.0 db. This is a limited data set since the sigma zero values for angles of 10° and 20° represent a small number of statistically independent samples.

##### 5.3.1.2 Aircraft Scatterometers

Curves of relative mean radar reflectivity versus incidence angle have been developed to illustrate the precision of measurement obtained. Figures 4 and 5 represent mean values for 1.6 GHz VV and HH data acquired on four runs over two successive days. Figure 6 represents mean values for 13.3 GHz data acquired on ten runs over two successive days. The day-to-day repeatability of the aircraft systems is excellent as indicated by the less than 1 db standard deviation of all data acquired.

The data standard deviations within a run and between runs on the same day provided in Table II are lower than those obtained when considering data acquired on different days. This should be expected since the conditions under which the data was gathered could not be rigidly controlled from day to day, hence the mean values of the data sets are different.

#### 5.3.2 Death Valley

Data acquired over the Death Valley site has not yet been processed, however, analog time histories provide information on the dynamic range available at this site. Figures 7 and 8 are radar reflectivity time histories illustrating the changes present at the transition from the roughest geological

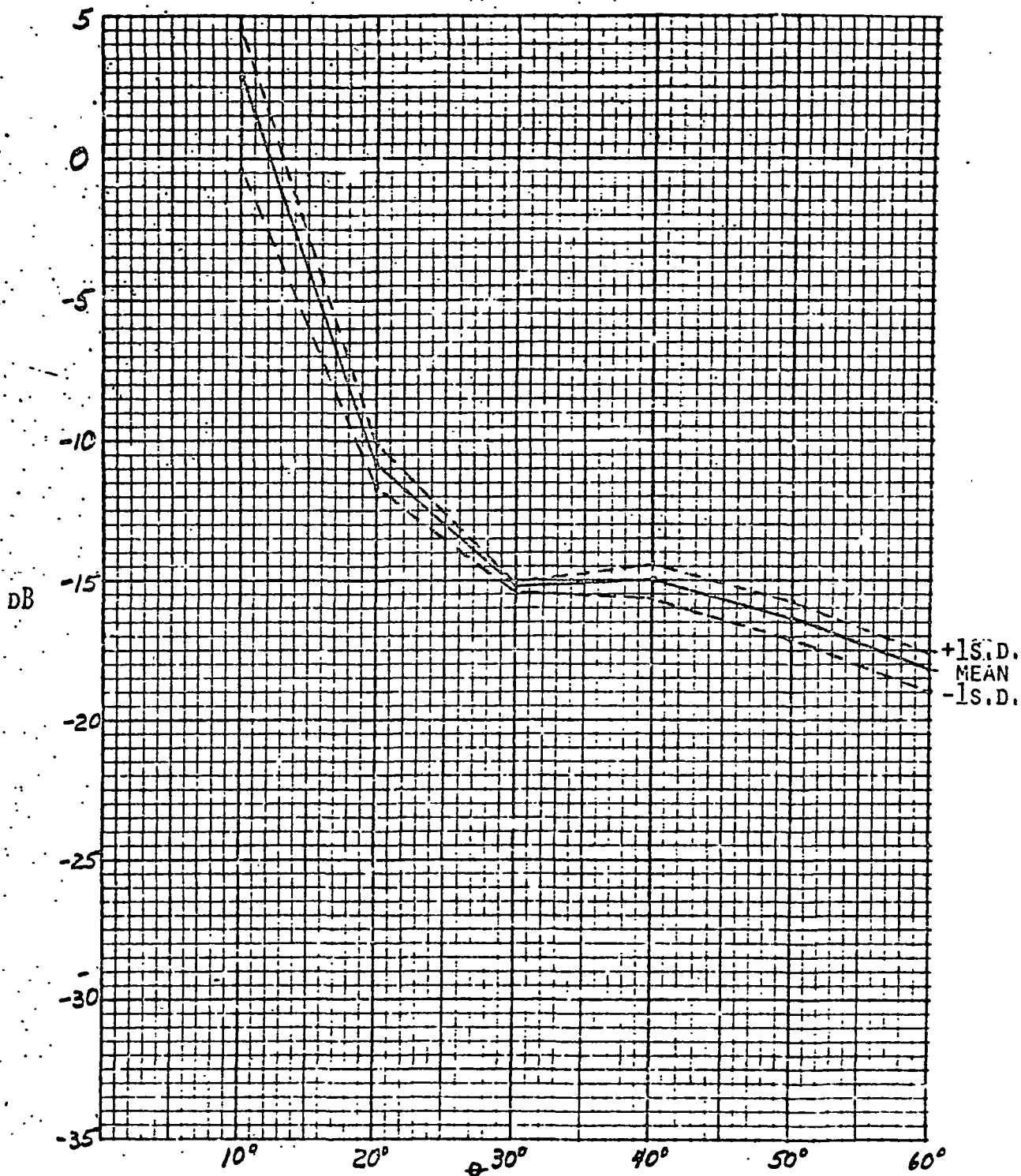


FIGURE 2. RELATIVE MEAN RADAR REFLECTIVITY  
- GROUND 1.6 GHZ VV - WHITE SANDS

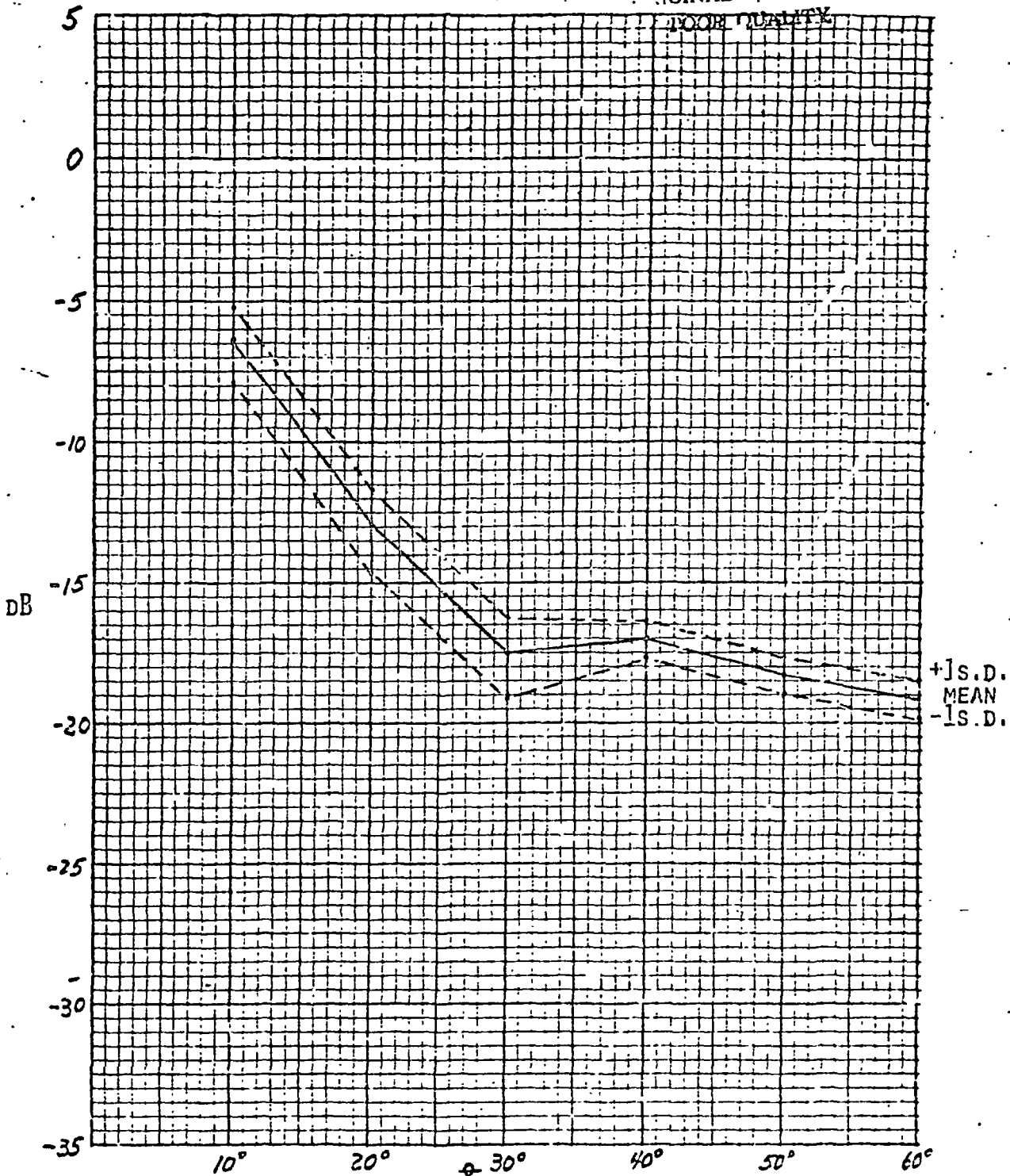


FIGURE 3. RELATIVE MEAN RADAR REFLECTIVITY  
- GROUND 13.3 GHZ VV - WHITE SANDS

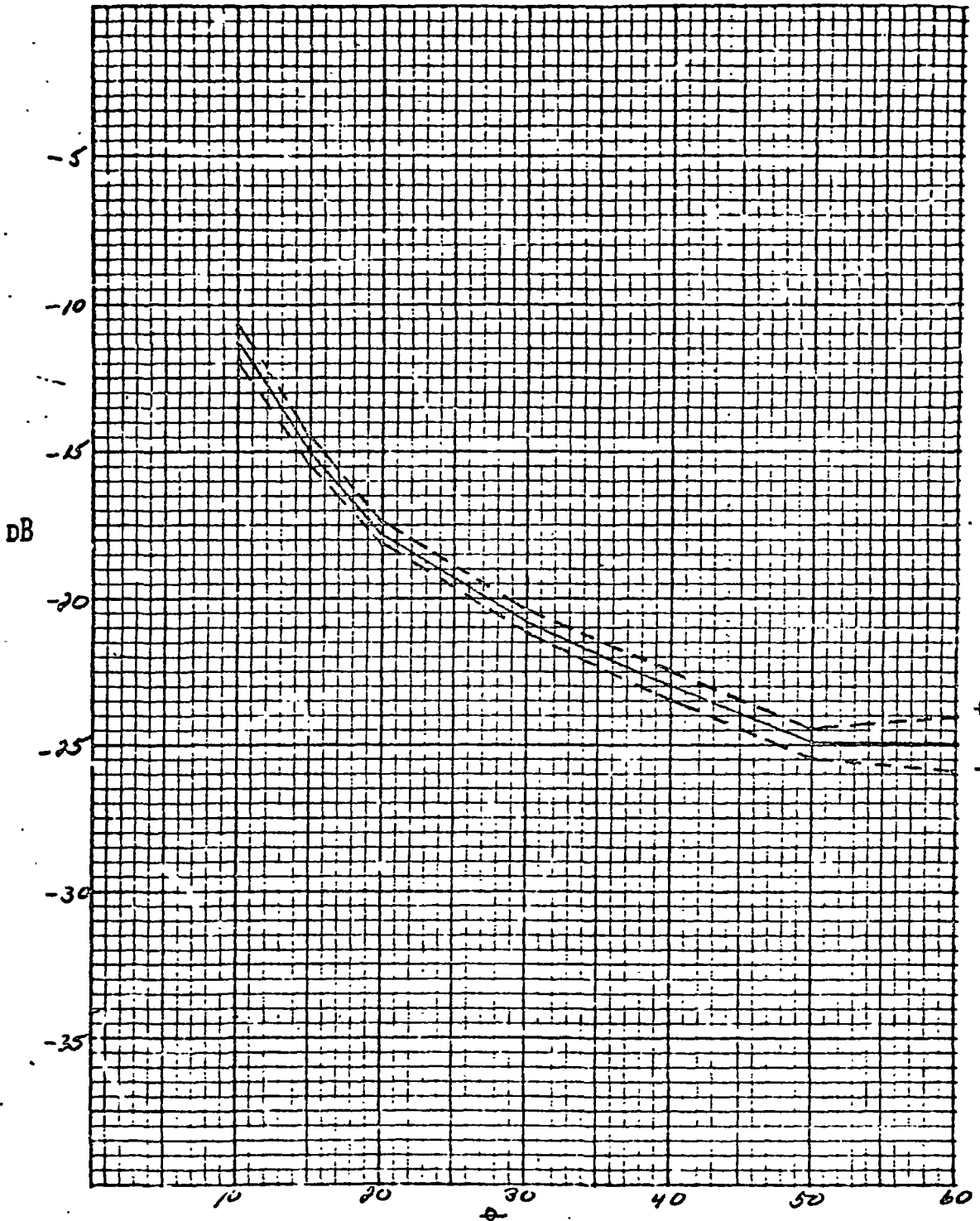


FIGURE 4. RELATIVE MEAN RADAR REFLECTIVITY  
 - A/C 1.6 GHz VV - WHITE SANDS

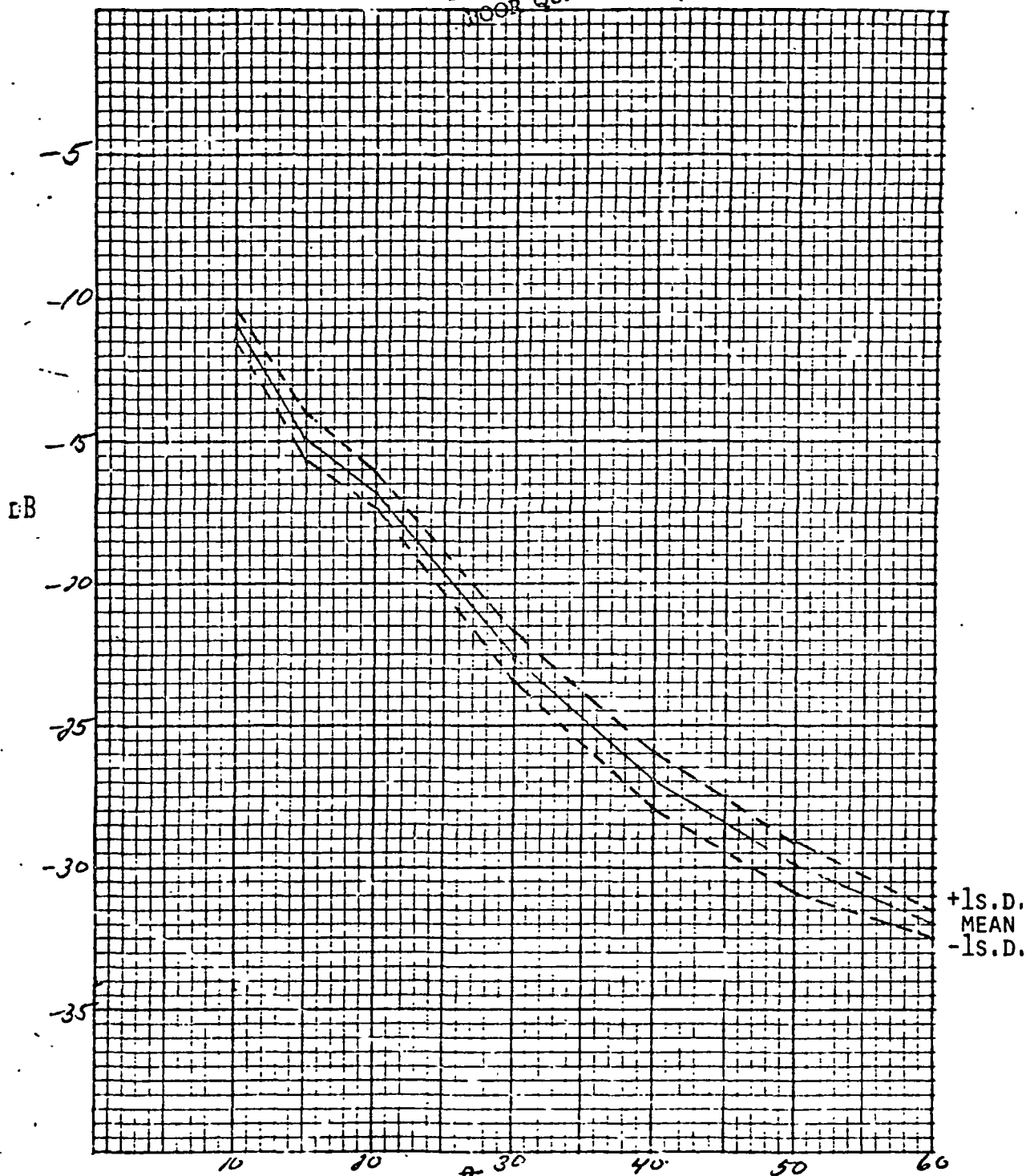


FIGURE 5. RELATIVE MEAN RADAR REFLECTIVITY  
- A/C 1.6 GHz HH - WHITE SANDS

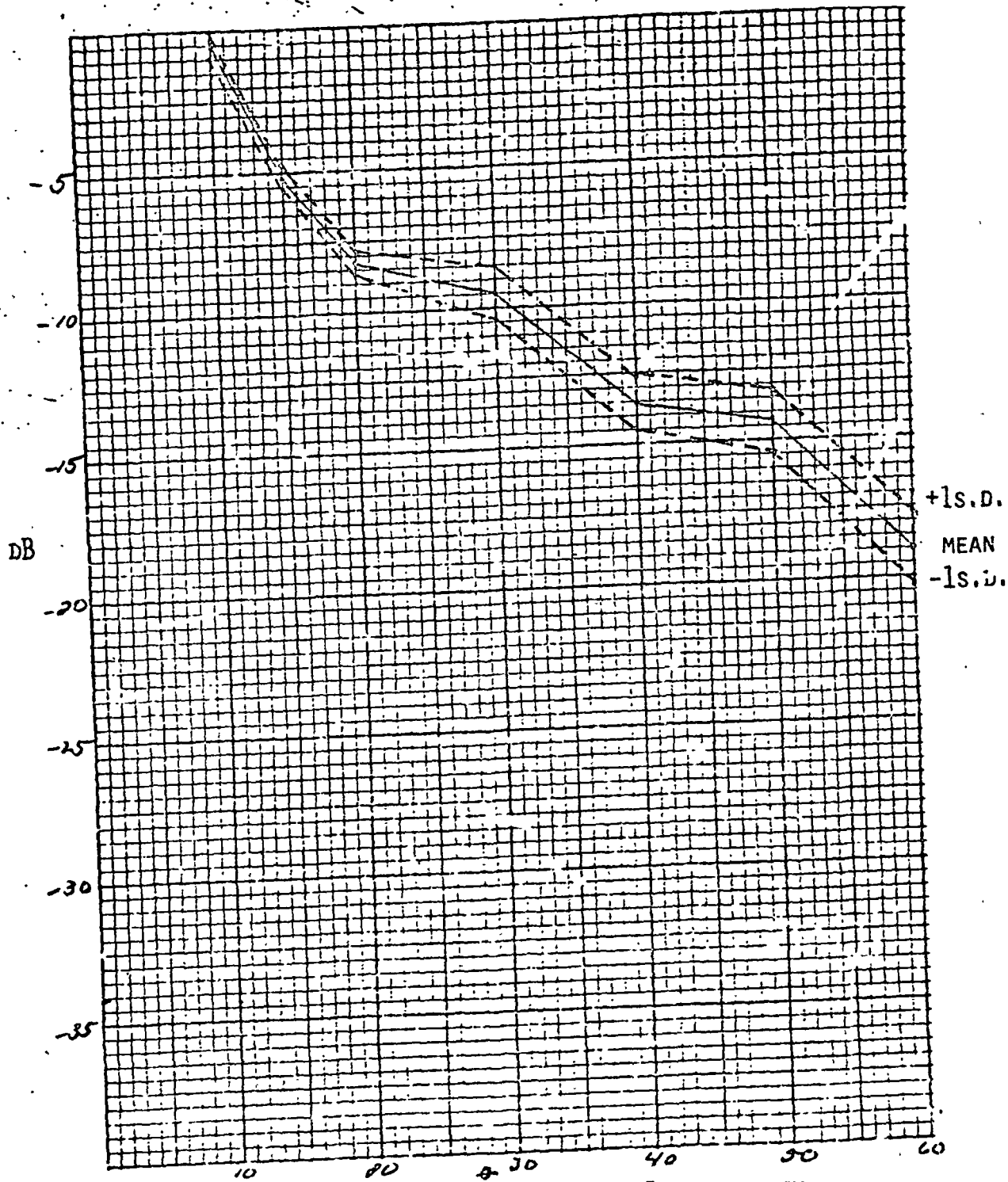


FIGURE 6. RELATIVE MEAN RADAR REFLECTIVITY  
 - A/C 13.3 GHz VV - WHITE SANDS

TABLE II

## STANDARD DEVIATION OF A/C DATA

			10°	20°	30°	40°	50°
1.6 GHz	VV	WITHIN RUN	0.4	0.5	0.5	0.5	0.5
1.6 GHz	VV	RUN-TO-RUN SOME FLIGHT	0.6	0.5	0.7	0.8	0.7
- 1.6 GHz	VV	DAY-TO-DAY	0.8	0.9	1.0	0.7	0.8
1.6 GHz	HH	WITHIN RUN	0.3	0.3	0.4	0.5	0.5
1.6 GHz	HH	RUN-TO-RUN SOME FLIGHT	0.5	0.5	0.6	0.6	0.7
- 1.6 GHz	HH	DAY-TO-DAY	0.7	0.7	0.7	0.6	0.8
13.3 GHz	VV	WITHIN RUN	0.3	0.4	0.5	0.5	0.6
13.3 GHz	VV	RUN-TO-RUN SOME FLIGHT	0.4	0.4	0.7	0.7	0.9
- 13.3 GHz	VV	DAY-TO-DAY	0.5	0.5	1.0	1.0	1.1



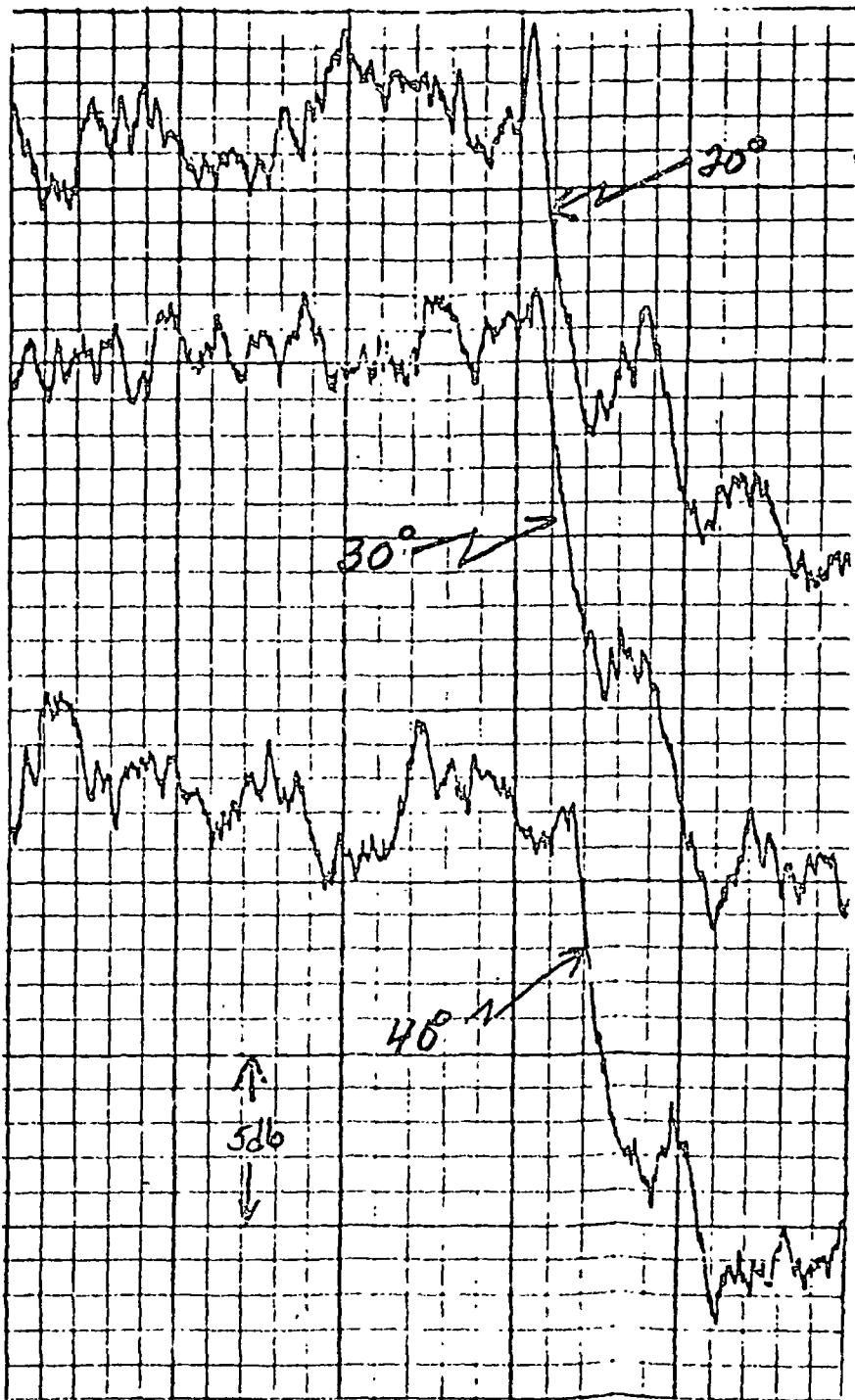


FIGURE 7. RADAR REFLECTIVITY TIME HISTORIES - 1.6 GHz VV - DEATH VALLEY

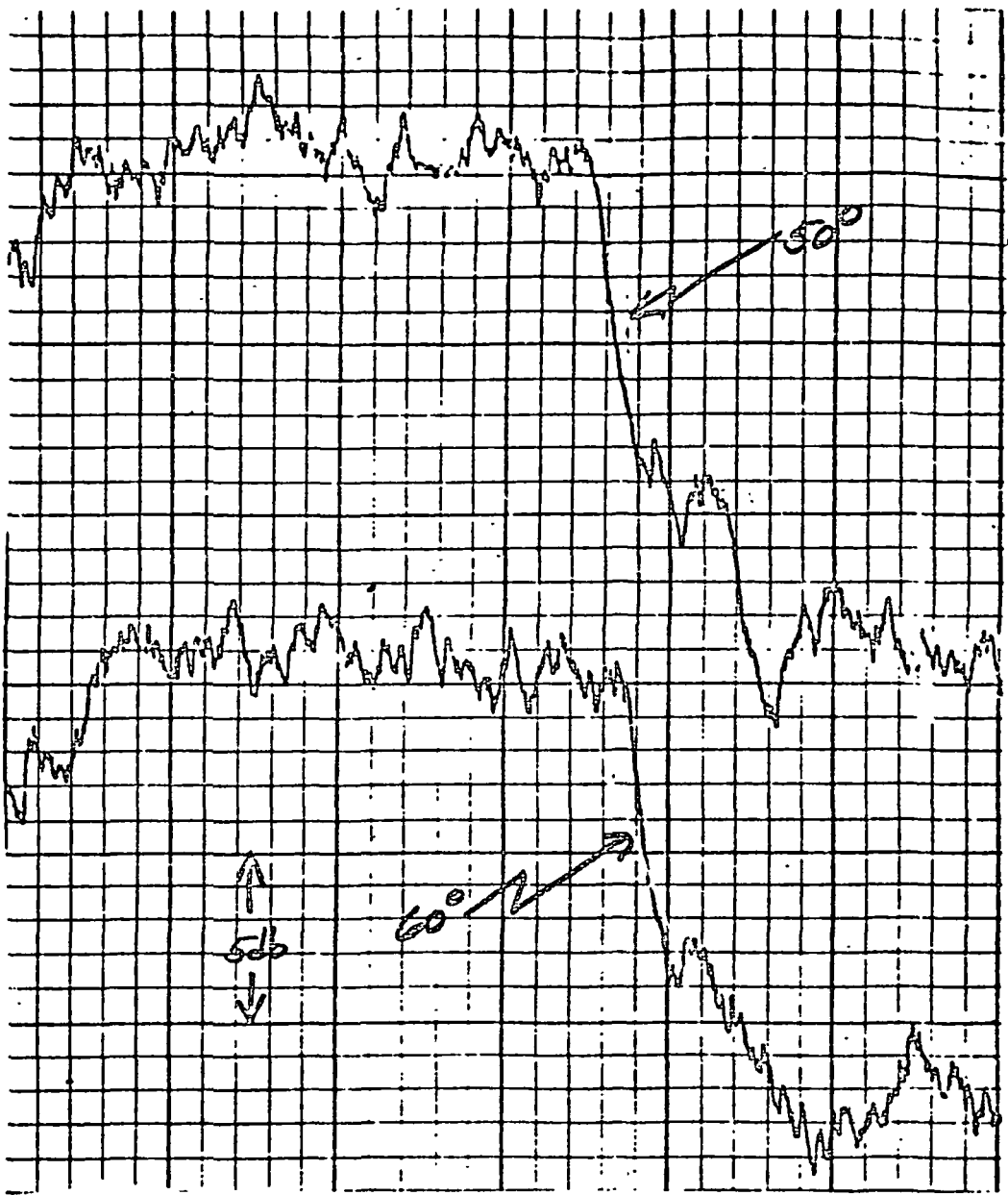


FIGURE 8. RADAR REFLECTIVITY TIME HISTORIES - 1.6 GHZ W - DEATH VALLEY

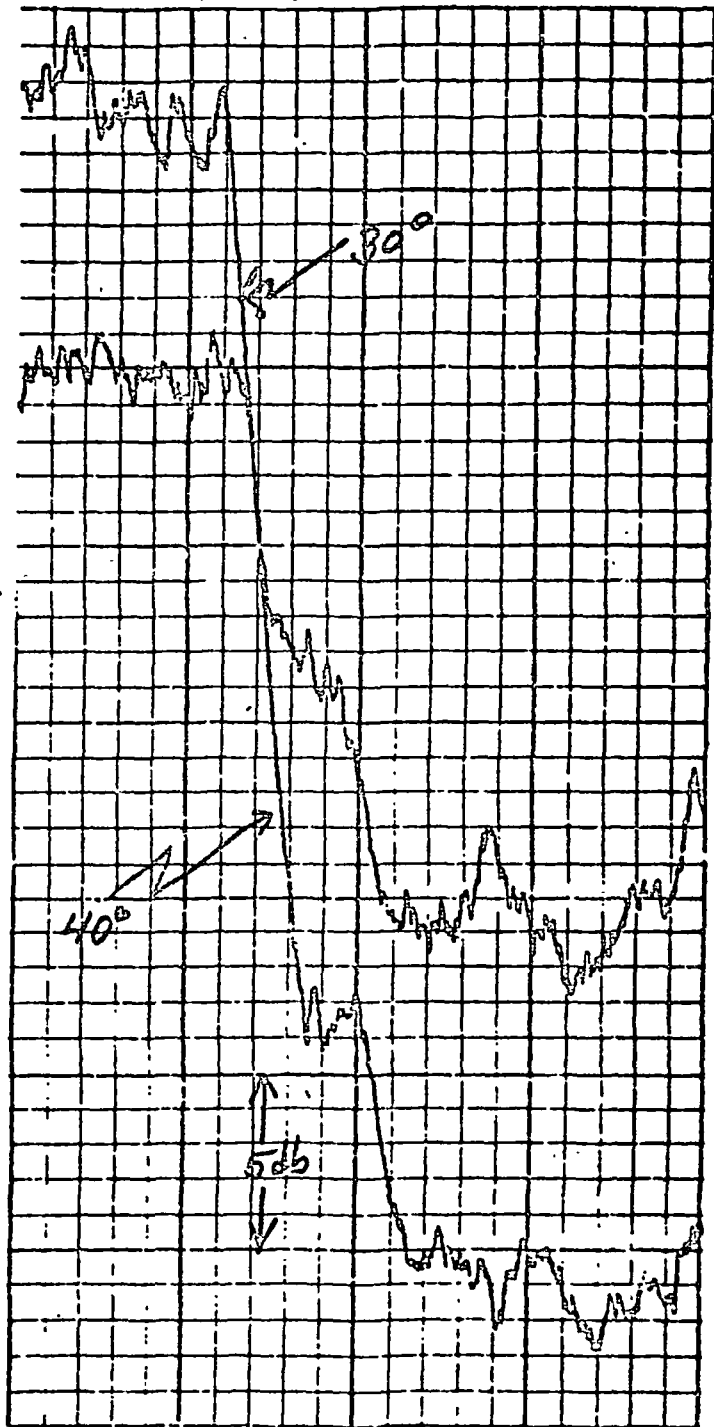


FIGURE 9. RADAR REFLECTIVITY TIME HISTORIES - 1.6 GHZ VH - DEATH VALLEY .

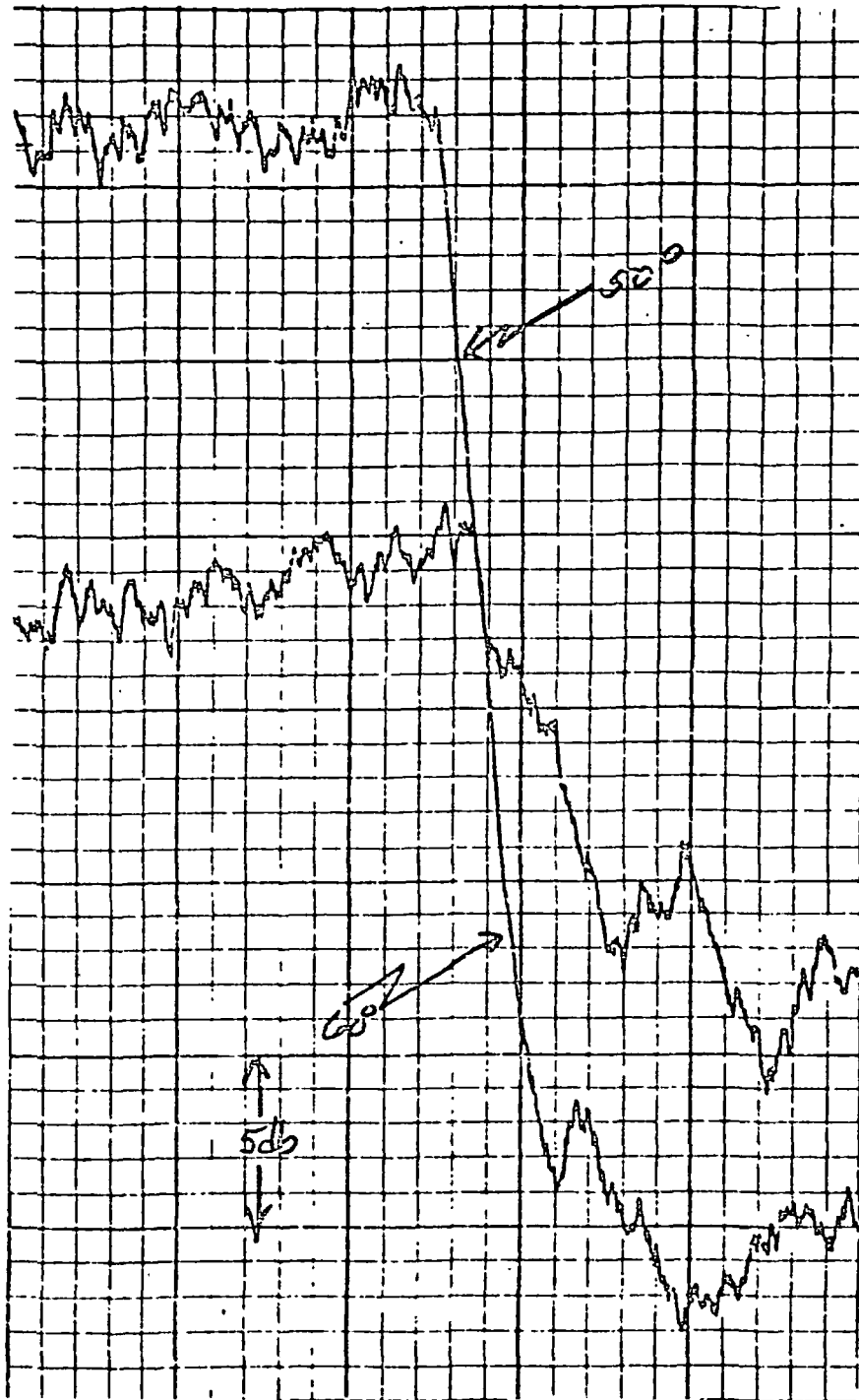


FIGURE 10. RADAR REFLECTIVITY TIME HISTORIES - 1.6 GHZ VII - DEATH VALLEY

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unit in Death Valley (Devil's Golf Course) to the smoothest (Badwater Basin). The linear polarized return changes by about 15 db at 50° incidence angle. An even more dramatic change, 25 db at 40°, is observed on the cross-polarized return as shown in Figures 9 and 10. The total system dynamic range indicated is in excess of 50 db.

It can be observed that no strong angular dependence is present for these extremes of random surface roughness.

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## WAVEGUIDE-EXCITED SLOT ARRAYS FOR SYNTHETIC ARRAY RADAR APPLICATIONS

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SUMMARY

The planar array antenna configuration offers many advantages compared with reflector antennas when microwave efficiency, precise control of the beam shape, and stowed and deployed volumes are important considerations. Of planar arrays, those with waveguide-excited slots provide better performance than arrays of printed-circuit radiators or dipole radiators because the dissipative losses associated with the waveguide feed system can be made to be very small. In this paper, the basic design considerations for waveguide slotted arrays are reviewed, with emphasis on those design requirements that are most significant to both airborne and spaceborne synthetic array radar (SAR) systems. As an illustration of both design procedures and performance capability of slotted waveguide planar arrays, an L-band planar array was designed, fabricated, and tested. This array has an aperture approximately one meter wide by two meters high and was designed to be a typical submodule of a larger antenna. Measurements of radiation patterns, gain, and VSWR were recorded and are presented, together with the performance characteristics predicted on the basis of theoretical analysis.

1.0 INTRODUCTION

The use of planar array antennas for large spaceborne SAR systems has many advantages compared with reflector types of antennas. These advantages include high aperture efficiency, precise control of the aperture distribution function, excellent packaging and stowage characteristics, freedom from non-uniform solar illumination due to feed shadowing, and reduced surface tolerances. The latter are permissible because the aperture acts as a generator or source of the microwave energy rather than as a reflector. The use of slotted waveguide and waveguide feed structures has the further

advantage of extremely low dissipative loss. In addition, there is a wealth of design data, computer programs, and experience available for slotted array design that generally assures achievement of predicted performance levels.

An example of an X-band array which was designed, fabricated, and space-qualified for a SAR application at the Hughes Aircraft Company some years ago is shown in Fig. 1. This antenna, which was roughly 7.27 meters (24 feet) long by 1.2 meters (4 feet) high, was found to have outstanding microwave performance characteristics most of which were directly attributable to the use of a waveguide feed and slotted waveguide radiating sections. The subject of the present paper is a feasibility demonstration model of a planar array with a similar design configuration but developed at L-band. It is shown that, at L-band as at X-band, the slotted waveguide type of planar array can provide superior performance.

## 2.0 GENERAL DESIGN CONSIDERATIONS

Typical SAR system requirements call for a radiation pattern with a fan beam shape, with the antenna oriented so that the broad section of the beam provides the desired swath coverage. The fan beam pattern requirement naturally leads to the use of a long narrow aperture of the type shown in Fig. 1. Typically in a planar array, the aperture is divided both electrically and mechanically into a number of modules or subarrays as shown in Fig. 2. The modules are electrically combined with a corporate feed structure as indicated. The subdivision of the aperture provides a useful frequency bandwidth, allows for thermal expansion joints to prevent aperture bowing, simplifies fabrication of the antenna, and facilitates folding if required for stowage during launch and retrieval.

In Fig. 3, it is possible to see most of the essential details of the construction of a single module of an array. In practice, the modules in a given array are usually identical, so that Fig. 3 actually characterizes a complete antenna system. As shown, the radiating elements of the module are formed from resonant slots cut in the broadwalls of a number of sections of waveguide. Each section of waveguide thus becomes an individual linear array. The module aperture is formed by joining these waveguide sections together in the manner illustrated. The individual linear array elements are slot coupled to a cross



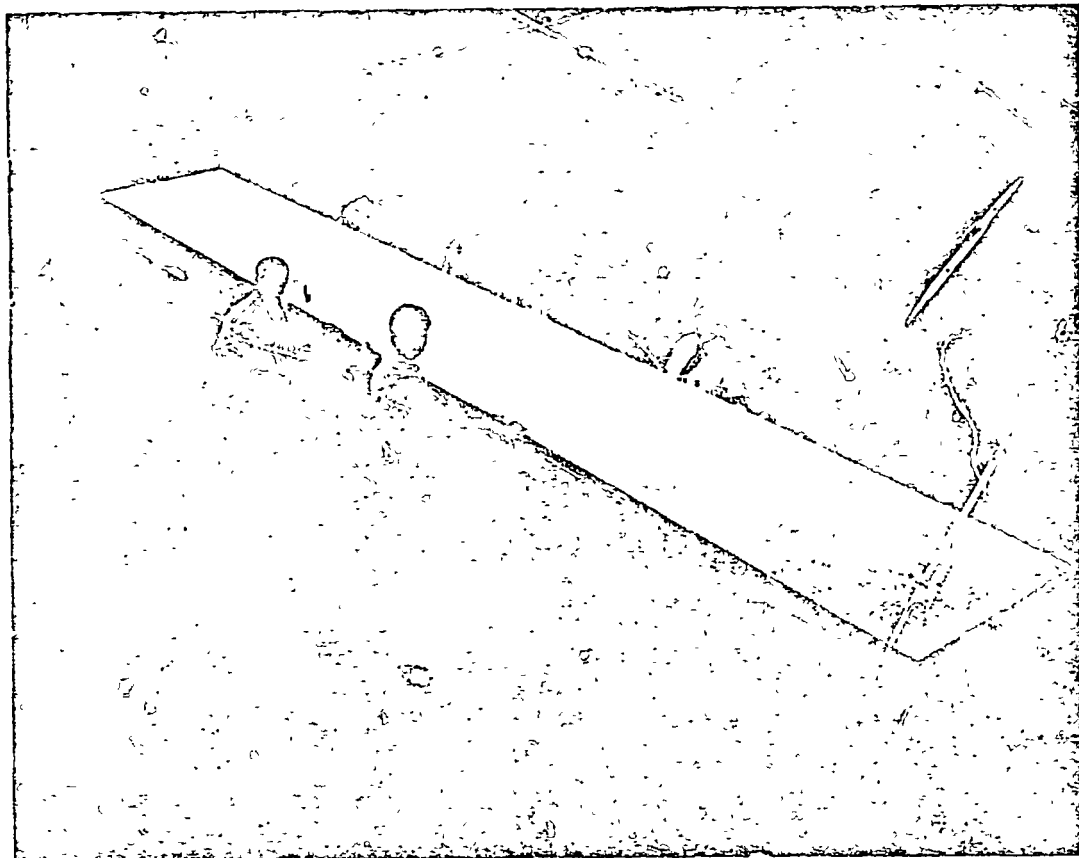


Figure 1. Space-qualified X-band array for SAR applications.

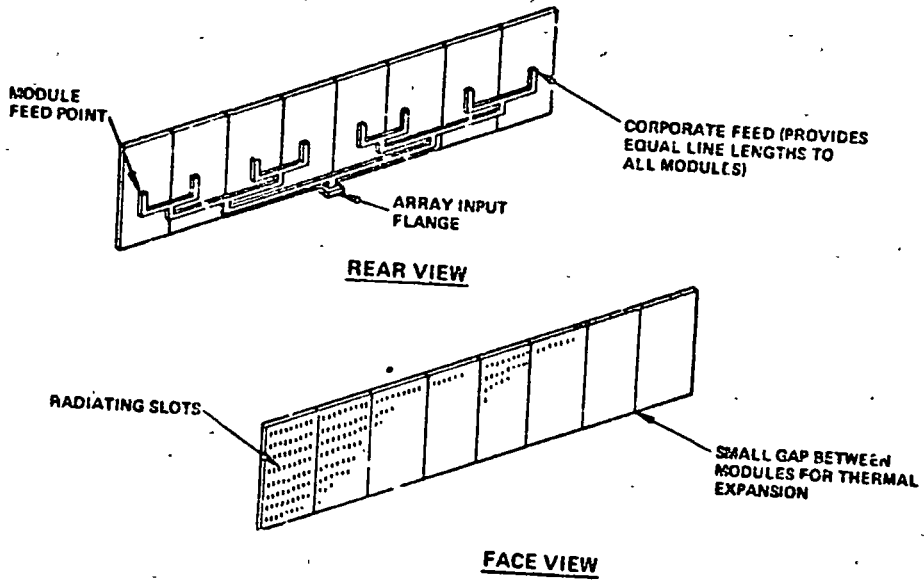


Figure 2. Subdivided aperture.

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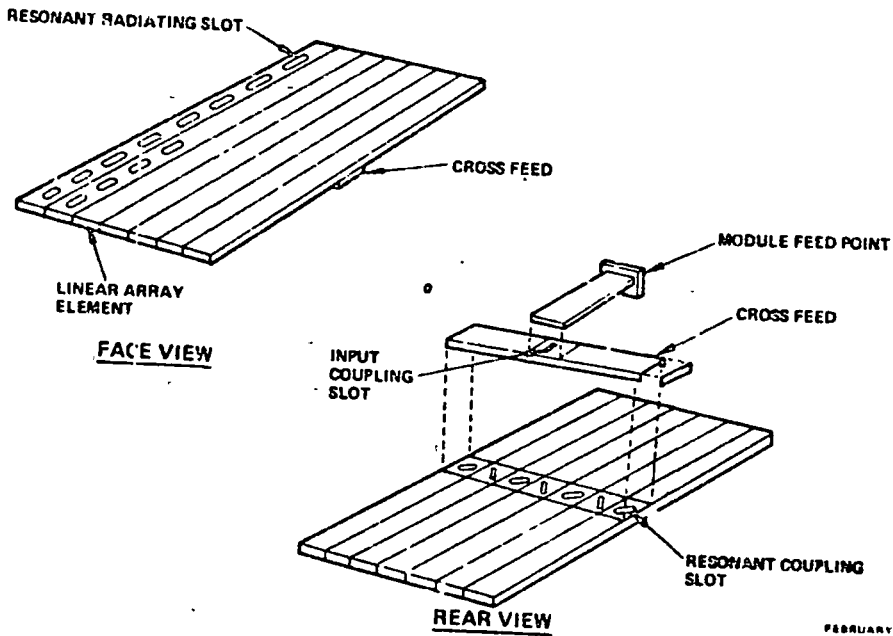


Figure 3. Typical module construction.

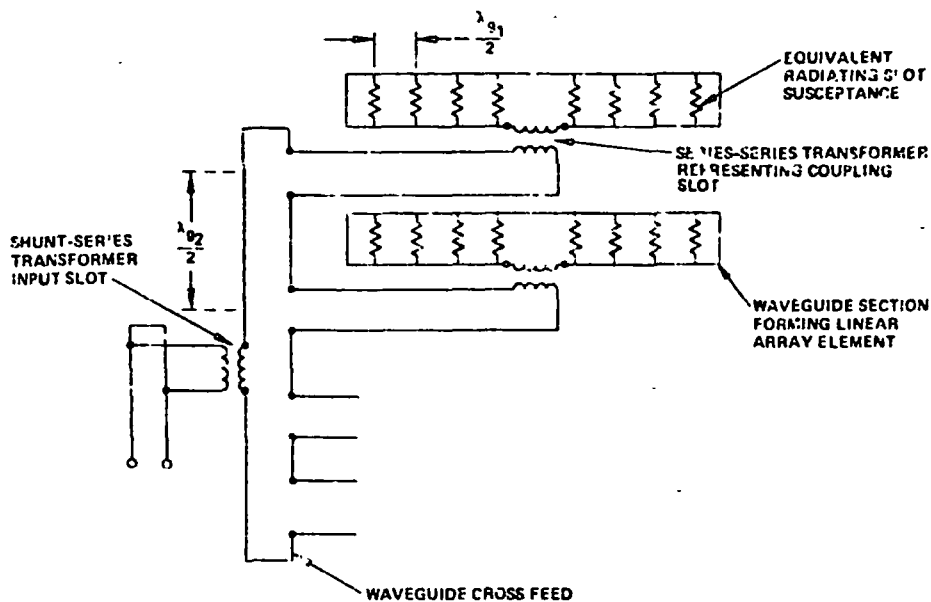
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feed guide that runs across the back of the module. The cross feed is in turn slot coupled to a flanged module feed guide section. This feed guide is the common feed point for all the slots in a given module.

In the module configuration of Fig. 3, it is generally most convenient to employ a resonant, or standing-wave design, for both the cross feed and the linear array element guide sections. For good pattern characteristics to be obtained over a wide frequency range with this type of design, the number of elements that appear in series in any given element must be limited. Typically, for example, it has been found that square arrays of 16 slots can provide useful bandwidths of about 10 percent.

The aperture distribution in the slot array can be tailored to provide precise control of the antenna beam shape. The mechanisms for such control are simple: the amount of power radiated by any individual slot is controlled by the amount the slot is offset from the centerline of the waveguide in which it appears, the power coupled from the cross feed to any individual linear array element is controlled by the angle at which the coupling slot is cut with respect to the guide axis, and the resonant frequencies of the slots are determined by the slot lengths. In the interest of mechanical simplicity, it is common to use separable aperture distribution functions in the E- and H-planes; this approach leads to a design in which all waveguide array elements have identical radiating slot patterns.

An indication of the degree of flexibility possible in the design of the module is provided by the equivalent circuit representation of Fig. 4. Each of the slot susceptances is individually controllable, as is the impedance transformation ratio of each of the coupling slots. Thus, various design configurations involving both different aperture distributions and different internal impedance levels can be easily realized. Because both radiating and coupling slot characteristics are well documented on both theoretical and experimental levels, design of a module for any desired set of pattern, bandwidth, gain, and impedance characteristics is a straightforward process. In general, the effects of such factors as mutual coupling between slots are accounted for during the design process by the use of the appropriate slot data.



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Figure 4. Equivalent circuit of module.

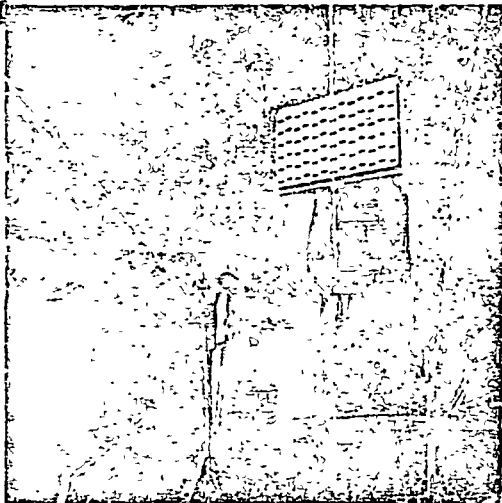
The design procedure for most cases can be summarized neatly:

- ① The antenna gain and pattern requirements determine the aperture size and shape.
- ② The radar signal bandwidth requirements then establish the maximum module size.
- ③ The radiating and coupling slots are then selected to generate the aperture distribution corresponding to the beamshape requirements.
- ④ The impedance levels and resonant frequencies of the slots are designed to provide a good input impedance match.

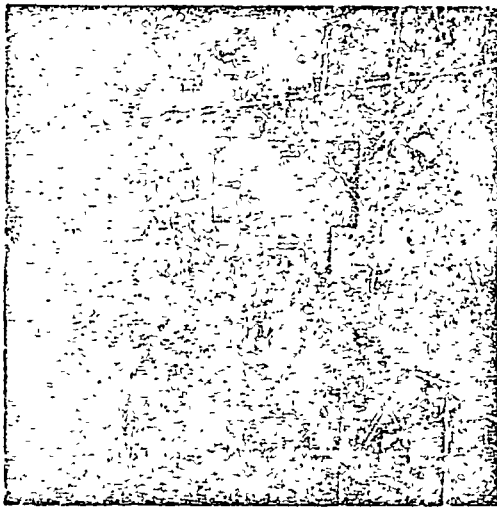
### 3.0 BRASSBOARD MODEL OF AN L-BAND ARRAY MODULE

Fig. 5 presents a photograph of an array module that was fabricated to demonstrate the performance capabilities of a slotted waveguide array at L-band frequencies. This module contains six waveguide linear array elements; each waveguide element has 13 radiating slots. The cross feed runs across the back of the aperture between the 6th and 7th rows of radiating slots. The input guide couples into the center of the cross feed. Half-height waveguide (4.6 cm or 1.6 inch high) was used throughout to minimize the thickness of the structure. The module was designed for use in an array of eight such modules. The various components of the module are easily identified by a comparison of Fig. 5 and Fig. 3.

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a. Front



b. Rear

Figure 5. Brassboard model of L-band module.

The radiation patterns in both E- and H-planes, gain, and VSWR of the brass-board module were measured. Results are illustrated and discussed below.

### 3.1 RADIATION PATTERNS

The measured principal plane radiation patterns of the brassboard model are shown in Fig. 6. The aperture distribution along the long dimension of the module was designed to give a first sidelobe level of 16.5 dB. The small crosses on the corresponding H-plane pattern (Fig. 6b) indicate the design or predicted levels and positions of the sidelobe peaks. As can be seen, the agreement between theory and measurement is excellent. Intercardinal plane patterns, which were also recorded, showed no indications of spurious lobes.

In the E-plane the array was designed for a uniformly weighted aperture along both the array and the module. This leads to an interesting dilemma peculiar to the design of the module as a demonstration piece of hardware: if the module is designed to generate a uniform distribution in the E-plane when it is part of a full array of eight modules, it will almost certainly have a nonuniform weighting when used separately. If, on the other hand, the module is designed to have a uniform E-plane distribution when used as a separate module, the array amplitude distribution will be nonuniform when a number of modules are joined together. The reason for this behavior is the strong E-plane mutual coupling that exists between the radiating slots. In a large antenna nearly all the slots see a common E-plane environment, and the mutual coupling is usually accounted for in the radiating slot data used in the design. In a small antenna, such as the module, if a uniform aperture excitation is required, the coupling slots in the cross feed are used to correct for the edge effects and compensate for the different behavior of the slots located close to the side of the array.

In the present design the module was designed and laid out as if it were part of a full array. As a result, the mutual coupling results in an effective amplitude taper in the module, and the sidelobe levels are considerably lower than the 13.3 dB normally to be expected. While it is quite feasible to calculate what the sidelobe levels should be, in the interest of economy this step is generally not done because the computation and the acquisition of the specific slot data required are relatively expensive. For these reasons, an

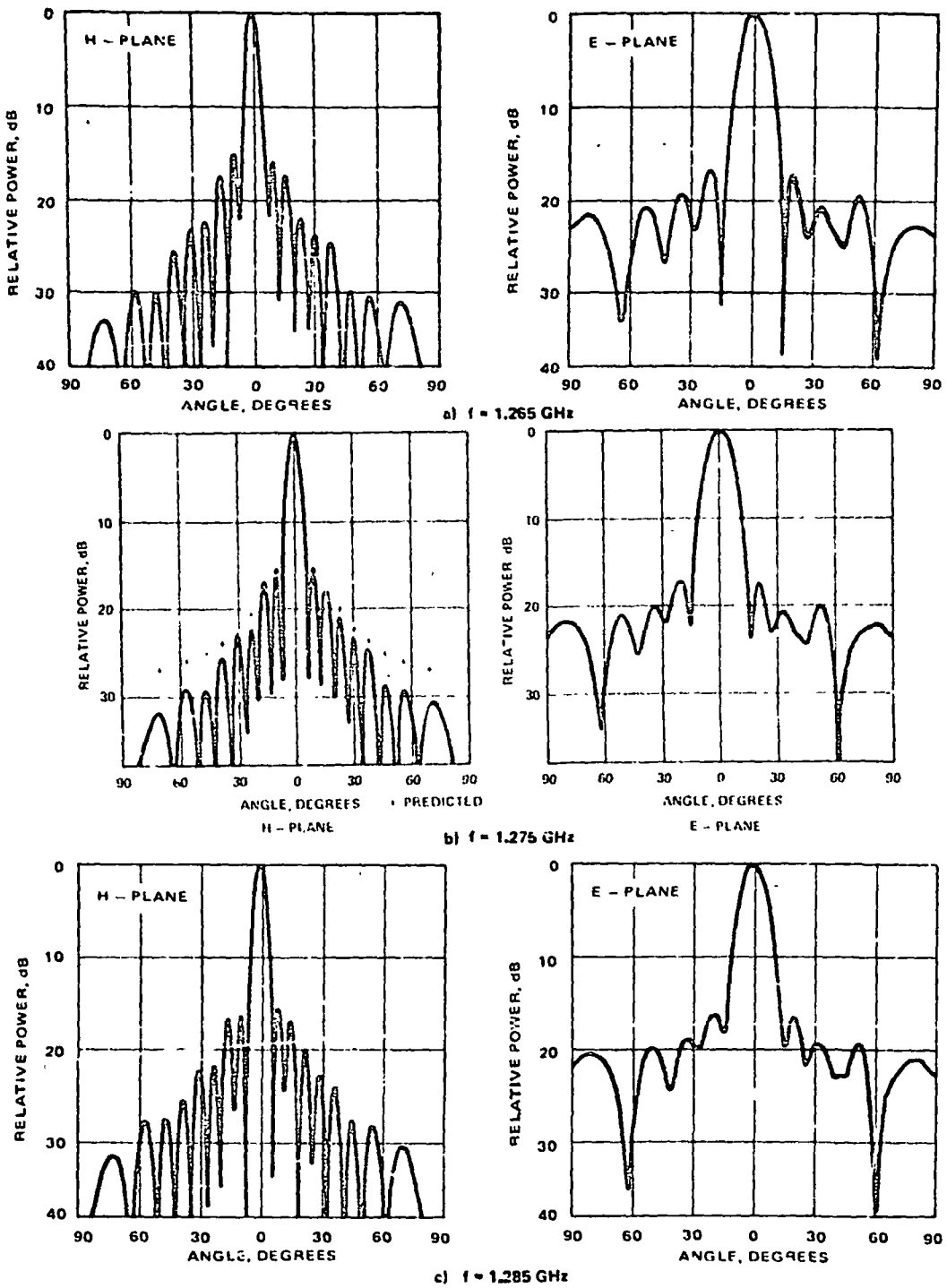


Figure 6. Measured E- and H-plane patterns of brassboard module.

estimate of the module E-plane sidelobe levels was not made. However, the E-plane sidelobes of the full, eight module array can confidently be predicted to be 13.3 dB.

Two particular aspects of both the E- and H-plane patterns that should be observed are the symmetry of the sidelobe levels and the deep clean nulls. These characteristics indicate good tolerance control of the module and small microwave and mechanical design and construction errors.

The measured performance of the module with respect to radiation pattern characteristics is summarized in Figs. 7 and 8 which show the first sidelobe level and 3-dB beamwidth as functions of frequency. The predicted curve for the 3-dB beamwidth of the H-plane pattern is also plotted in Fig. 8. The E-plane 3-dB beamwidth for the module was not predicted because the mutual coupling effects that lead to low sidelobes in this plane also produce a broader beamwidth than would otherwise be observed.

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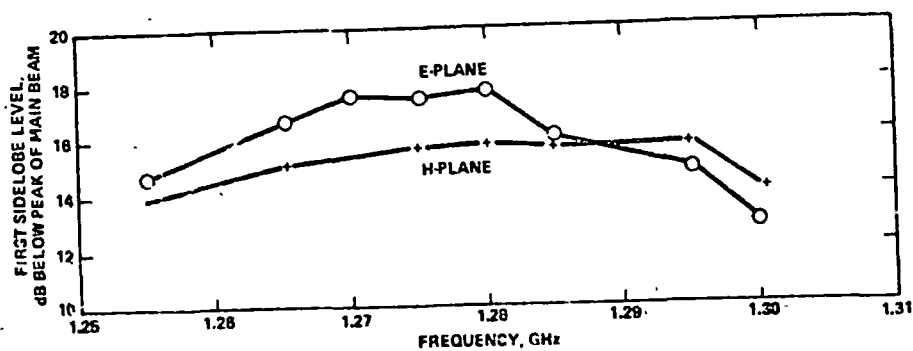
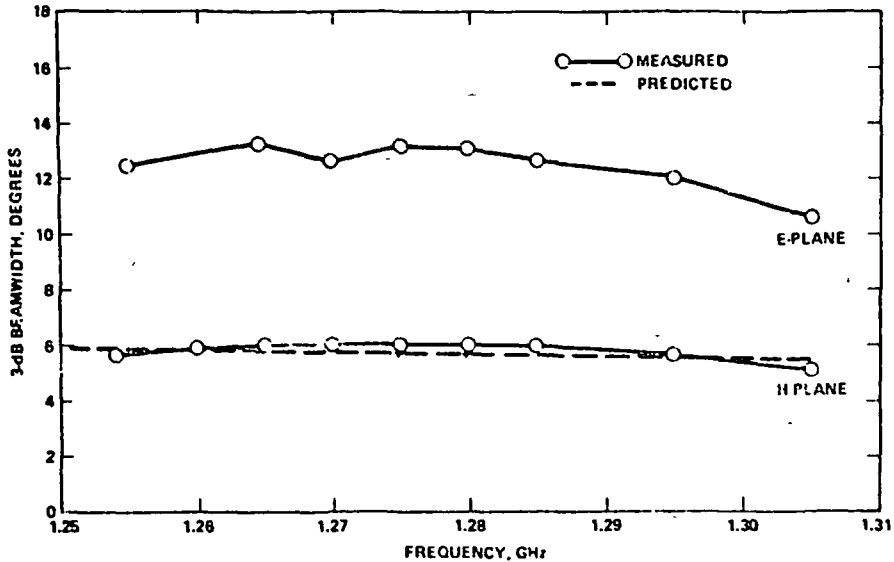


Figure 7. Measured sidelobe levels.





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Figure 8. Variation of 3-dB beamwidth with frequency.

### 3.2 GAIN

The maximum theoretical gain of a planar slot array is relatively simple to calculate with a high degree of precision. The procedure is to compute the so-called area gain from the well-known expression

$$G_0 = \frac{4\pi A}{\lambda^2}$$

where

A = aperture area

$\lambda$  = wavelength

and then subtract the losses associated with the aperture weighting function used for sidelobe level control and beam shaping.

A gain of 26.9 dB was calculated for the brassboard module for the design frequency of 1.270 GHz. A loss allowance of 0.10 dB, which included the calculated value for the H-plane weighting and an estimated value, based on experience, for the E-plane weighting, was made for the aperture weighting.

The measured gain of the module is plotted as a function of frequency in Fig. 9. For purposes of comparison, the maximum theoretical gain (G) achievable with an aperture of the module dimensions is also plotted on the same figure. The difference between the two curves at any frequency represents the losses due to random manufacturing errors, waveguide dissipative losses, design errors, and input mismatch.

The aperture efficiency is defined at Hughes as 100 times the ratio of the measured gain to the maximum theoretical gain of the aperture. When defined in this manner, the efficiency becomes a measure of the success of the antenna design in terms of achieving the theoretical pattern and gain characteristics. In the case of the L-band module, the aperture efficiency measured at 1.270 GHz is approximately 94 percent.

It should be noted that the gain data of Fig. 9 were measured through a stepped half-height to full-height transition and a coaxial-to-waveguide adapter. The gain was corrected for the gain reduction introduced by the waveguide transition and adapter dissipative losses. The input mismatch losses, however, were left in the data.

### 3.3 MODULE VSWR

The input voltage standing-wave ratio (VSWR) of the module, also measured through a stepped half-height to a full-height waveguide transition and a coaxial-to-waveguide adapter, is plotted in Fig. 10. As can be seen, the VSWR remained below 1.4:1 over most of the bandwidth. No matching or tuning devices were employed to obtain these results.

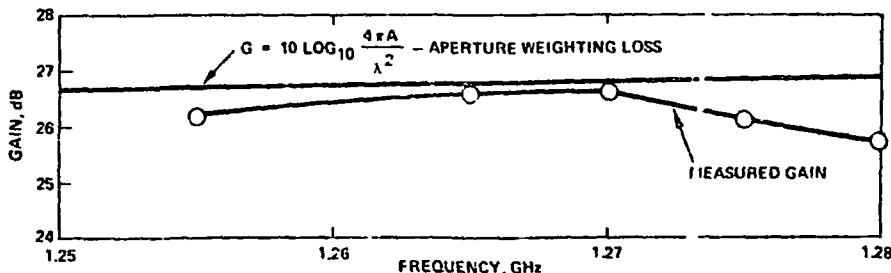


Figure 9. Measured gain of brassboard module over design bandwidth.

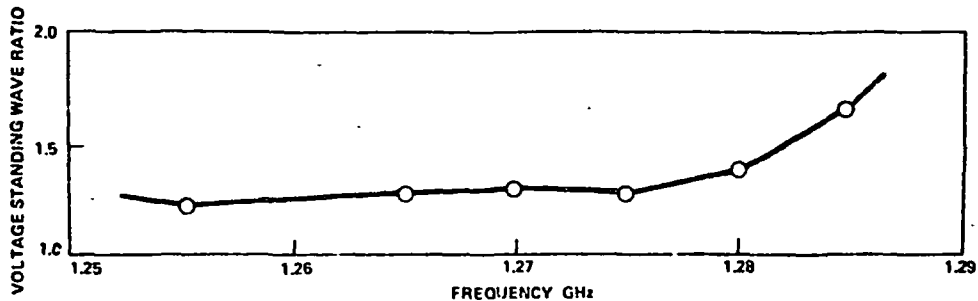


Figure 10. Measured voltage standing-wave ratio of module.

### 3.4 SUMMARY OF MODULE PERFORMANCE CHARACTERISTICS

The performance of the module, as characterized by the microwave measurements, is summarized in Table 1. The design objectives, which were based on theoretical values, are also tabulated for the purposes of comparison. Exact values of the cross polarization components of the radiation field are not given in the table because the measured values were so low that they implied that the module cross polarization was significantly better than that of the transmitting source used for the pattern measurements.

### 3.5 FULL SCALE ARRAY PERFORMANCE

As a final step, the measured module data were utilized as the basis for a prediction of the performance characteristics of a full-scale array of eight modules. These results are given in Table 2. It is believed that the numbers shown represent the full array performance with the same high degree of accuracy provided by the module data in Table 1.

The estimate of the array weight was based on the use of thin wall (51 mm or 0.020 inch) aluminum waveguide for the module panels and corporate feed and an aluminum honeycomb support structure. The physical design of array and support was predicted on the assumption of a structural resonant frequency requirement of 25 Hz. The mechanical design did not provide for aperture folding. Techniques for forming and maintaining the necessary waveguide cross sections with the thin wall aluminum waveguide have been developed and demonstrated at Hughes under both funded and company-sponsored research efforts.

TABLE 1. PERFORMANCE OF L-BAND BRASSBOARD MODULE

Parameter	Design Objective	Measured (at 1.270 GHz)
Gain, dB	26.87	26.60
Beamwidth, degrees H-plane	5.9	6.0
E-plane	NA	13.2
First sidelobe, dB H-plane	16.5	-15.8
E-plane	NA	-17.4
Input VSWR	<1.5:1	<1.3:1
Bandwidth (GHz)	1.265 to 1.285	1.255 to 1.285
Cross polarization, dB	<30	<30
Efficiency (relative to weighted aperture), percent	>90	94
Aperture dimensions	1.04 x 2.12 x 0.04 meters (41.1 x 83.28 x 1.6 inches)	1.04 x 2.12 x 0.04 meters (41.1 x 83.28 x 1.6 inches)

TABLE 2. PROJECTED PERFORMANCE FOR ARRAY OF EIGHT MODULES

Parameter	Performance
Aperture	2.12 x 8.33 meters (83.28 x 328 inches)
Gain (eight times module gain less corporate feed losses), dB	35.3
Bandwidth	1.255 GHz to 1.285 GHz
Beamwidth, degrees	
H-plane	6 0
E-plane	1.31
First sidelobe levels, dB	
H-plane	-15.8
E-plane	-13.3
Input VSWR	<1.5:1
Cross polarization, dB	<30
Weight (array panels, structural support, thermal control systems), pounds	220

#### 4.0 CONCLUSIONS

The measured performance characteristics of the L-band module described in this paper demonstrate the feasibility of slotted waveguide planar arrays for L-band SAR systems. In every respect the module exhibits a superior level of microwave performance, and it was established that excellent agreement between predicted and measured performance can be obtained by the use of simple, straightforward design procedures.

The relatively low microwave frequencies for which this module was designed represent the lower end of the range for which waveguide slotted arrays are most attractive. Below L-band the dissipative loss characteristics of

striplines and coaxial lines are sufficiently low as to warrant their consideration for use as the feed elements. As the frequency is increased, however, the loss advantages of the slotted waveguide configuration become increasingly great. At the same time, the waveguide dimensions decrease rapidly to the point at which the volume savings that can be obtained through the use of TEM line configurations have no particular significance.

## EFFECT OF WEIGHTING ON TIME SIDELobe SUPPRESSION\*

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SUMMARY

Weighting is a well known technique for shaping the compressed pulse waveform in radar processing. Usually, weighting is applied to the transfer function and has the effect of sacrificing the time mainlobe width (resolution) in exchange for decreasing the height of the neighboring sidelobes. This paper reports on simulations of weighting in the time domain, as used to shape the time-compressed pulse waveform. The digital input radar data is 32 bit I,Q, and simulates data from a point target as imaged by a Seasat-A type system. Weighting functions tested include stepped-amplitude distributions, (with 1 through 5 steps), and the cosine-squared plus pedestal distribution. Effects treated include mainlobe broadening, peak energy reduction, the integrated sidelobe ratio, signal to noise ratio, and nearest sidelobe suppression.

1.0 INTRODUCTION

Pulse compression in radar is commonly accomplished through matched filtering. A radar point target return  $s(t)$  is correlated against a  $\tau$ -shifted version of its conjugate  $s^*(t)$  over a time interval  $T$ , to yield an output at time  $\tau$ :

$$\bar{s}(\tau) = \int_{-T/2}^{T/2} s(t)s^*(t - \tau) dt. \quad (1)$$

\* This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

The estimate  $\tilde{s}(\tau)$  yields a prediction of the return from a target at the location specified by  $\tau$ . The function  $|\tilde{s}(\tau)|$  usually has multiple peaks, and thus creates detection ambiguities when there is large signal dynamic range. For example, if  $s(t)$  is a linear FM signal,  $\tilde{s}(\tau)$  approximates a sinc function with high (-13.2 db) sidelobes.

The relation (1) may also be expressed in the frequency domain. Set

$$s_r(t) = s^*(-t).$$

Then (1) becomes

$$\begin{aligned} \tilde{s}(\tau) &= \int_{-T/2}^{T/2} s(t) s_r(\tau - t) dt \\ &= s \otimes s_r(\tau). \end{aligned} \quad (2)$$

If capital letters denote fourier transforms, then (2) implies

$$\tilde{S}(w) = S(w) \cdot S_r(w). \quad (3)$$

The inverse transform of  $\tilde{S}(w)$  is of course  $\tilde{s}(\tau)$ . In (3) we can multiply  $S_r(w)$  by a weighting function  $W(w)$  to obtain a new output  $S_1$ :

$$S_1(w) = S(w) \cdot S_r(w) \cdot W(w). \quad (4)$$

The inverse transform,  $s_1(\tau)$ , is now only an approximation to  $\tilde{s}(\tau)$ . The goal of frequency domain weighting is to select a function  $W$  in (4) such that  $s_1(\tau)$  is a good local approximation to  $\tilde{s}(\tau)$ , but has lower sidelobes.

It is known that weighting of the time domain signal can produce similar effects, particularly if the signal is linear FM. In time weighting the weighting function is multiplied with the return signal



$$s_1(t) = s(t) w(t)$$

or with the reference function  $s^*(t)$

$$s_1^*(t) = s^*(t) w(t),$$

prior to filtering.

This paper reports on simulations of time-weighting, performed on digital SAR data of the type expected from satellites such as SEASAT-A.

It is shown that use of a cosine-squared-plus-pedestal time-domain weighting scheme can result in sidelobe suppression down to -36 db, with mainlobe broadening of less than 30% for the simulated data.

Section 2 gives a brief description of the frequency domain weighting approach, which is then used to motivate the ideas on time weighting presented in section 3. Finally, section 3 contains the numerical results extrapolated from the simulations.

## 2.0 FREQUENCY DOMAIN WEIGHTING

Let the signal given by eq. (5) be received at the radar receiver at time  $t$ .

$$s(t) = \begin{cases} \exp \left\{ j \left( f_0 t + \frac{bt^2}{2} \right) \right\} & \text{for } -T \leq t \leq T \\ 0 & \text{elsewhere.} \end{cases} \quad (5)$$

The matched filter response at time  $\tau$  is

$$\hat{s}(\tau) = \int_{-T}^{T-\tau} e^{j \left( \frac{bt^2}{2} + f_0 t \right)} e^{-j \left( \frac{b}{2}(t+\tau)^2 + f_0 (t+\tau) \right)} dt. \quad (6)$$

By elementary calculation, we have

$$\tilde{s}(\tau) = 2Te^{-j f_0 \tau} \frac{\sin\left(bT\tau - \frac{b}{2}\tau^2\right)}{bT\tau} \quad (7)$$

Usually, the range of interest is such that  $\tau$  is small compared to  $T$ , so that the approximation

$$\tilde{s}(\tau) = 2Te^{-j f_0 \tau} \frac{\sin(bT\tau)}{bT\tau} \quad (8)$$

$$= 2T \operatorname{sinc}(bT\tau) \times (\text{phase factor})$$

is valid. Ignoring the phase factor, we see that  $\tilde{s}(\tau)$  peaks at  $\tau = 0$ . Thereafter, sidelobes 13.2 db below the peak intensity occur near  $\tau = \pm 3\pi/2bT$ .

These sidelobes can mask weaker peaks corresponding to neighboring targets, as shown in Figure 1.

By slightly mismatching the filter response, (and hence sacrificing signal to noise ratio and mainlobe width), the sidelobe levels of the filter output can be decreased. The process is most easily understood when mismatching is

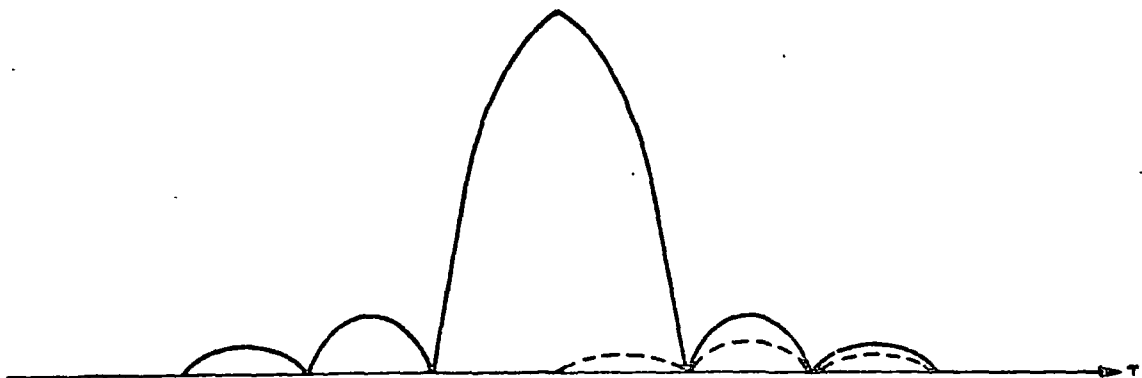


Fig. 1. Sidelobes Masking Weak Peaks

accomplished by weighting in the frequency domain [5]. Let  $s(t)$  represent the output of a matched filter. Its Fourier transform is given by

$$S(\omega) = \int_{-\infty}^{\infty} s(t) \exp \{-j2\pi\omega t\} dt. \quad (9)$$

(We assume  $S(\omega) = 0$  for  $|\omega| > B/2$ ). By the Fourier shift theorem the function

$$\tilde{S}_1(\omega) = S(\omega) \left[ 1 + a_n \cos \frac{2n\pi\omega}{B} \right] \quad (10)$$

has an inverse Fourier transform given by

$$s_1(t) = \frac{n}{\gamma} s\left(t + \frac{n}{B}\right) + s(t) + \frac{n}{\gamma} s\left(t - \frac{n}{B}\right). \quad (11)$$

(Here  $n$  is an integer and  $a_n$  is arbitrary).

Thus  $s_1(t)$  is the original matched filter output with paired echoes superimposed at a time offset of  $\pm n/B$ . The echoes are scaled by a factor of  $n/\gamma$ . In the case where  $s = \delta$ , the sine function in (8), then  $\tilde{S}(\omega)$  is a rectangle function (except for a shift factor due to the phase offset). Taking  $n = 1$ , we obtain from (3):

$$\tilde{S}_1(\omega) = \tilde{S}(\omega) \left[ 1 + a_1 \cos \frac{2\pi\omega}{B} \right] \quad (12)$$

and

$$\begin{aligned} s_1(t) &= \frac{a_1}{\gamma} \delta\left(t + \frac{1}{B}\right) + \delta(t) + \frac{a_1}{\gamma} \delta\left(t - \frac{1}{B}\right) \\ &= \frac{a_1}{\gamma} \operatorname{sinc}\left(B\tau\left(t + \frac{1}{B}\right)\right) \\ &\quad + \operatorname{sinc}(B\tau t) + \frac{a_1}{\gamma} \operatorname{sinc}\left(B\tau\left(t - \frac{1}{B}\right)\right). \end{aligned}$$

(Here  $B$  is proportional to  $T$ , by virtue of (8)). When the three sinc functions are added, a new "quasi-sinc" function results with lower sidelobes. (See figure 2).

Thus weighting by  $W(w) = [1 + a_1 \cos 2\pi w/B]$  can lower the time sidelobes. In the radar case, we would actually be confronted with a superposition of sinc functions at the unweighted filter output. Each sinc function would be centered on its own resolution element. However, by the linearity of the Fourier transform operation, one weighting function applied to the superposition spectrum serves to suppress the sidelobes of all sinc functions at once.

### 3.0 TIME DOMAIN WEIGHTING FOR TIME SIDELOBE SUPPRESSION

Time domain weighting is accomplished by multiplying the return signal or time reference function by a properly designed weighting function. Since the weights can easily be incorporated as part of the time domain reference function, the technique is a promising one for application to real-time spacecraft on board processors. The effect of time weighting on time output can often be easily determined [1].

For example, let the radar signal  $s(t)$  be the linear FM signal given in (5). Then, in a rough manner of speaking, there is a one-to-one correspondence between time and frequency. That is, each time interval  $\Delta t$  corresponds to a frequency interval  $\Delta w$  in the spectrum. Hence a time weighting function  $W(t)$  would have about the same effect as the frequency weighting function  $W(f = w)$ . Thus a first order estimate of the effects of time weighting by  $W(t)$  may be obtained through

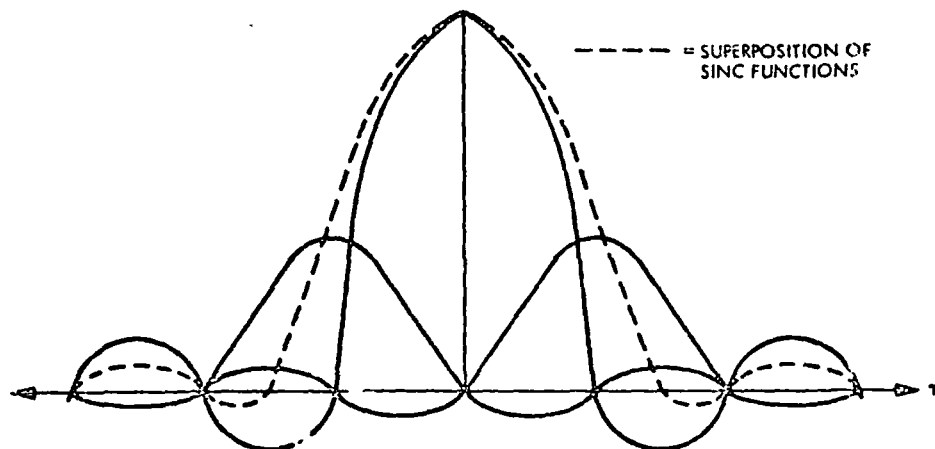


Fig. 2. Superposition of Sinc Function and Scaled Echo

frequency weighting with  $W(w)$ . More precisely, it is known that for the linear FM signal (5), the filter time output  $g(t)$  resulting from a time weighting  $w(t)$ , satisfies

$$|g(t)| = \sqrt{\frac{b}{2\pi}} \left| \int_{-T}^T w(\tau) \exp \{jbt\tau\} d\tau \right| \quad (13)$$

For further details, see [1] p. 187.

In SAR processing, the azimuth aperture is generated by a sensor moving linearly with constant velocity over the aperture length. Thus, to a reasonable approximation, the azimuth matched filter function is a linear FM chirp, and the above time weighting approximations (e.g. (13)) apply. However, the azimuth chirp is a sampled (discrete) function, and the results are somewhat different. Therefore, to discover the effects of weighting with discrete time functions, actual simulations were performed. The weightings were applied along the azimuth direction of simulated SEASAT-A SAR data. Each data input point was quantized to 4 bits, as was each reference and weighting coefficient. The ground spacing between adjacent data input points was around 4 meters. A total of 4096 input points was used to process a 4-look output data point. Thus each look required filtering of  $1024$  points, or  $1024$  separate weighting coefficients. The spacing between output data points was around 16 meters. The simulated input data was designed to represent the return from a point target so that the effects of weighting could be easily observed. The output image was 16 (range) by 512 (azimuth) points.

The weighting functions selected for simulation were the stepped amplitude distributions and the cosine - squared plus pedestal function [3], [4], [5].

The stepped amplitude distributions are given in table 1 for 1 through 5 steps. (See also figure 3). These distributions were chosen for their optimality in antenna pattern adjustment, and their ease of implementation [3]. Note that  $T$  is proportional to  $N = 1024$ , the number of weights.

TABLE 1  
 STEPPED AMPLITUDE TIME WEIGHTING FUNCTIONS

$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$b_1$	$b_2$	$b_3$	$b_4$	$b_5$
1	...	...	...	...	1	...	...	...	...
0.5	0.5	...	...	...	1	0.55	...	...	...
0.35	0.35	0.30	...	...	1	0.625	0.350	...	...
0.25	0.25	0.25	0.25	...	1	0.78	0.56	0.34	...
0.300	0.225	0.235	0.170	0.070	1	0.72	0.54	0.36	0.18

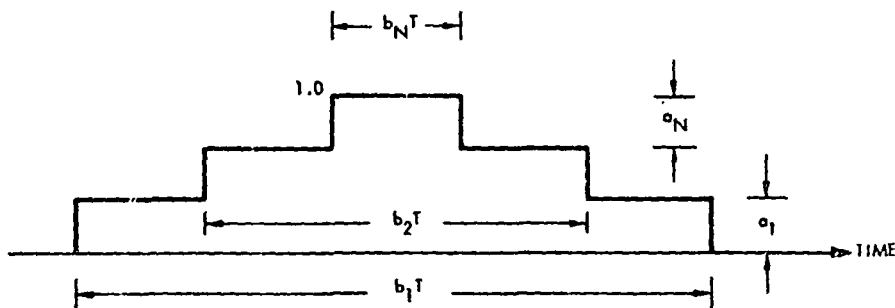


Fig. 3. Stepped Amplitude Time Weighting for Time Waveform Shaping

The cosine squared-plus-pedestal distribution [5] is, through a trigonometric identity, equivalent to the weighting given by the right-hand factor in eq. (10). It is defined by

$$W(t) = H + (1 - H) \cos^2 (\pi t/T) \tag{14}$$

where

$H = \text{pedestal height } (0 \leq H < 1)$

$T = \text{pulse timewidth.}$

For the simulation, we select  $H = 0.05$  to approximate Hamming weighting, which produces the lowest sidelobes attainable with this type weighting in the frequency domain [5]. The resulting weighting is similar to the Taylor approximation to the physically unrealizable optimum Dolph - Chebyshev weighting [2], [6], and represents a practical approach for digital processing.

Table 2 gives the total energy in decibels in the 3 center lines about the peak. (By "line" is meant a range line of 16 data points centered around the azimuth peak. See figure 4.)

TABLE 2  
PEAK ENERGY AND INTEGRATED SIDELOBE RATIO

Weighting Technique	Total Energy in 3 Center Lines	Peak Energy
Rectangular	103.109	100.067
2 step amplitude	103.458	99.667
3 step amplitude	103.514	99.415
4 step amplitude	103.549	99.359
5 step amplitude	103.552	99.362
$\cos^2$ + pedestal	103.478	98.748

Note: Total energy in 512 lines is 103.671 db for each type of weighting.

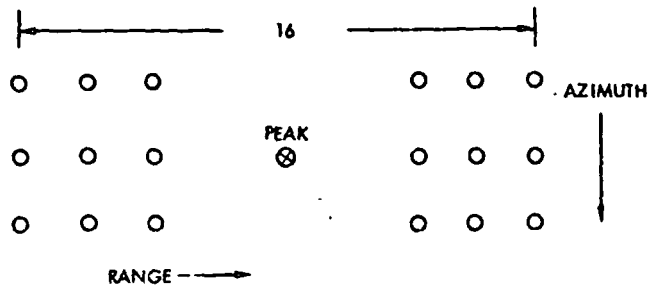


Fig. 4

Since the total energy in each 16 x 512 image was normalized to 103.671 db, the energy in the center lines reveals in a rough way how much energy is left over for sidelobe generation. This data can of course be used to compute the "integrated sidelobe ratio" in decibels, defined by

$$\text{Integrated Sidelobe Ratio} = 10 \log_{10} \left( \frac{\text{total energy outside mainlobe}}{\text{total energy in mainlobe (3 center lines)}} \right)$$

The results are summarized in table 3, for both 4 and 32 bit quantization, and give a fair estimate of the 2-dimensional integrated sidelobe ratio.

TABLE 3  
INTEGRATED SIDELOBE RATIO, DB FOR VARIOUS WEIGHTINGS

Weighting	Integrated Sidelobe Ratio	
	4 bits	32 bits
Rectangular (no weighting)	- 12.1 db	- 12.8 db
2 - step amplitude	- 13.3 db	- 14.3 db
3 - step amplitude	- 14.5 db	- 16.1 db
4 - step amplitude	- 15.6 db	- 17.8 db
5 - step amplitude	- 15.7 db	- 18.0 db
cos <sup>2</sup> + pedestal	- 17.3 db	- 21.7 db



Table 2 also gives an indication of loss in signal to noise ratio in terms of peak energy. Since each weighted output has the same total energy, the peak energy in the second column indicates the loss in SNR rather accurately. The greatest loss (1.319 db) relative to the unweighted case occurs with  $\cos^2 +$  pedestal weighting.

Table 4 is used to derive the mainlobe broadening resulting from weighting. As expected, the worst broadening is seen to occur with  $\cos^2 +$  ped weighting, with only a 3 db suppression 16 meters from the peak. In this case the 3 db resolution is degraded to 30 meters.

The values in Table 4 can be used to derive fairly precise values for the resolution achieved with each weighting scheme, in the following manner. The output filter function is modeled as a sine function which is closely tracked in the range of interest by a quadratic. Using Lagrange's interpolation polynomial, with the peak and 2 nearest neighbors as input points, the distance to the 3 db mainlobe threshold is calculated. The results are shown in table 5.

TABLE 4  
SUPPRESSION AT NEAREST NEIGHBOR, DB

Weighting Technique	Suppression, db	
	min	max
Rectangular	9	9
2 step amplitude	5	6
3 step amplitude	5	5
4 step amplitude	5	5
5 step amplitude	5	5
$\cos^2 +$ pedestal	3	3

TABLE 5  
RESOLUTION ACHIEVED WITH WEIGHTING

Weighting	Resolution
Rectangular	
(No weighting)	21 m
2 - step amplitude	27.2 m
3 - step amplitude	28.8 m
4 - step amplitude	28.8 m
5 - step amplitude	28.8 m
$\text{Cos}^2$ + pedestal	30.4 m

Finally, table 6 gives the sidelobe suppression actually achieved with each weighting scheme. Each technique generated 2 sidelobes of generally different heights; hence the min and max suppressions are both tabulated. The best suppression is achieved by  $\text{cos}^2$  + pedestal weighting, with a -36 db measurement at the highest sidelobe. (The sidelobe asymmetry results from the true peak occurring between two data output points).

TABLE 6  
NEAREST SIDELobe SUPPRESSION, DB

Weighting Technique	Sidelobe Suppression, db	
	min	max
Rectangular	20	-24
2 step amplitude	22	25
3 step amplitude	26	29
4 step amplitude	30	33
5 step amplitude	29	33
$\text{Cos}^2$ + pedestal	35	40

#### 4.0 CONCLUSION

Weighting in the time domain for time sidelobe suppression presents an attractive alternative to frequency domain weighting, especially if time-domain azimuth processing is to be accomplished. The simulations show that cos<sup>2</sup> + pedestal weighting achieves 36 db sidelobe suppression with a SNR loss of less than 1.5 db, and resolution loss of around 25%.

#### ACKNOWLEDGEMENTS

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MEANS TO ACHIEVE WIDE SWATH WIDTHS  
IN  
SYNTHETIC APERTURE SATELLITE BORNE RADARS

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SUMMARY

In deriving the characteristics of a synthetic aperture radar which is carried in a high speed vehicle there are a number of constraints as well as a number of degrees of freedom among the parameter values which may be selected for the radar system. It is the purpose of this paper to show how these constraints and the available degrees of freedom affect the swath width, resolution, area coverage rate, average power, system complexity, and system parameters of the radar.

The organization of this paper is as follows: The radar range equation including processing gains for pulse compression and synthetic aperture generation is the starting point. System geometry considerations are introduced. For simplicity flat earth geometry is used, although it is realized this is not a good model for satellite borne radars. Next the constraints are introduced. These include those needed to avoid ambiguities in both range and azimuth, those needed to achieve the desired resolution, and those needed to achieve the desired swath width.

It is found, if only a single channel radar system is used, that the number of degrees of freedom needed are not available. There are a variety of ways in which these added channels can be introduced. They may be multiple along track beams, or a combination of along track and along range beams.

The multiple along track channel case is analyzed in Section 1.0. It is referred to as Case I. The multiple along range case is analyzed in Section 2.0. It is referred to as Case II.

### 1.0 TECHNICAL DISCUSSION OF MULTIPLE ALONG-TRACK CHANNELS

Section 1.0 considers the case of a synthetic aperture radar in which multiple channels in the along track direction are introduced.

The corresponding analysis for multiple beams in the along track range direction is given in Section 2.0.

Much of the analysis of Sections 1.1 to 1.7 is analogous to that used by the author in two papers analyzing the properties of synthetic aperture sonars.<sup>1,2</sup>

### 1.1 PRELIMINARY SIGNAL TO NOISE RATIO COMBINATIONS

The signal to noise ratio at the output of a single channel radar using both pulse compression and synthetic aperture generation is given as

$$\left(\frac{\hat{S}}{N}\right)_{\text{out}} = \left[ \frac{\hat{P}_T G_T \sigma A_{\text{rec}}}{(4\pi)^2 R^4 k T_N B} \right] \left[ \frac{\tau_1}{\tau_0} \right] \left[ \frac{\text{prf } R\lambda}{204 V} \right] \quad (1)$$

In equation (1), the first factor gives the usual radar range signal to noise ratio expression. The second factor gives the improvement in signal to noise ratio due to pulse compression, while the third factor gives the improvement in signal to noise ratio due to synthetic aperture generation.

It is useful to introduce the following relations into equation (1)

$$\left. \begin{aligned} G_T &= \frac{4\pi H L}{\lambda^2} \\ A_{\text{rec}} &= H D \\ P_{\text{ave}} &= P_T \tau_1 \text{ prf} \\ \theta_E &= \frac{\lambda}{H} ; \theta_B = \lambda/D \\ \beta \tau_0 &\approx 1 \end{aligned} \right\} \quad (2)$$

Combination of equations (1) and (2) gives

$$\frac{\hat{S}}{N} = \frac{P_{ave} D^2 \sigma \lambda}{8\pi R^3 kT_N \theta^2 \delta_a V} \quad (3)$$

At this point parameter values in equation (3) are unconstrained. The nature of the constraints is introduced in subsequent sections. When the constraints have been determined, they will be introduced into equation 3.

The definition of quantities used in all equations is given in a glossary of terms. Equations 1, 2, and 3 have been previously derived by the author in reference 3.

## 1.2 SYSTEM GEOMETRY

The geometry used is shown in Figure 1 for the flat earth case. This is done for simplicity only.

In Figure 1, the following relations apply. The quantities  $h$ ,  $\theta$ , and  $W$  are assumed to be the independent variables.

$$\begin{aligned} d &= h \cot \theta \\ R_{min} &= \sqrt{h^2 + d^2} \\ R_{max} &= \sqrt{h^2 + (d + w)^2} \\ \frac{\sin \theta_E}{W} &= \frac{\sin \theta}{R_{max}} = \frac{\sin E}{R_{min}} \\ \theta &= \theta_F + E \\ W &= (R_{max} - R_{min}) \frac{\cos \theta / 2}{\cos (\theta - E/2)} \end{aligned} \quad (4)$$

Figure 2 gives a plot of  $W/(R_{max} - R_{min})$ .

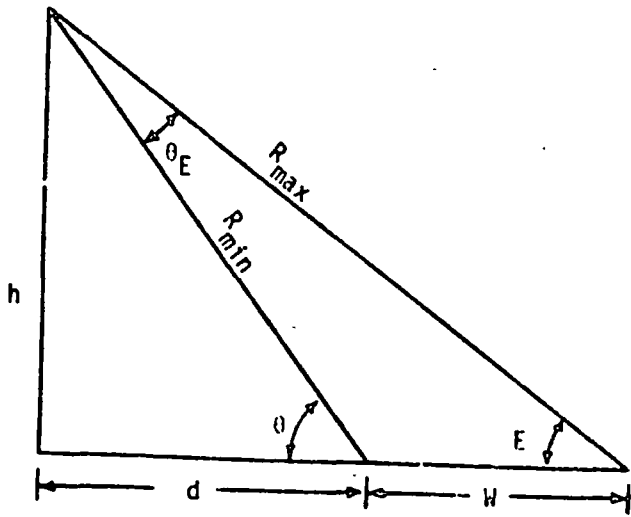


Figure 1. Geometry (flat earth approximation)

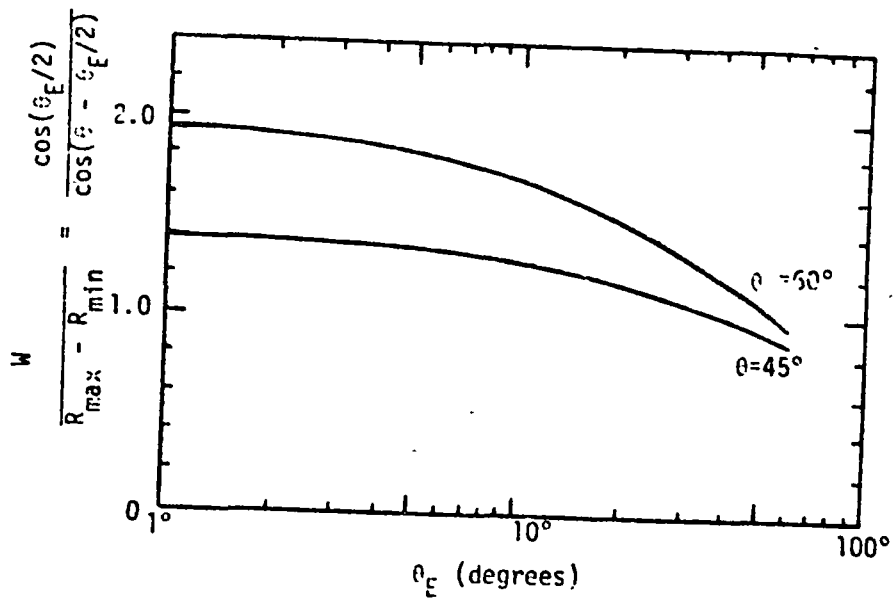


Figure 2. Plot of  $W/(R_{\max} - R_{\min})$  vs  $\theta_E$



### 1.3 RANGE SWATH SELECTION, RANGE AMBIGUITY AVOIDANCE, AND RANGE RESOLUTION

For the geometry of Figure 1, one first selects  $W$ , the desired swath width on the ground. Together with  $h$ , and  $\theta$ , this determines all the geometric parameters in Figure 1 using equations 4.

From the last of equations 4, the quantity  $W$  is related to  $(R_{\max} - R_{\min})$ .

The unambiguous range,  $R_u$ , may be chosen to have any value greater than  $R_{\max} - R_{\min}$ , i.e.,

$$\left. \begin{aligned} R_u &= (R_{\max} - R_{\min}) \\ \beta &\leq 1 \end{aligned} \right\} \quad (5)$$

To prevent eclipsing one needs also

$$\left. \begin{aligned} \frac{2}{c} R_{\max} &\leq M T \\ \frac{2}{c} R_{\min} &\geq (M - 1) T + \tau_f \end{aligned} \right\} \quad (6)$$

where  $M$  is an integer.

These relations are illustrated in Figure 3.

The quantities  $R_u$ ,  $T$ , and  $\text{prf}$  are related by the expressions

$$R_u = \frac{cT}{2} = \frac{c}{2 \text{prf}} \quad (7)$$

One additional requirement is necessary to avoid range ambiguities; namely: potentially ambiguous ranges must receive limited illumination by tailoring the elevation pattern of the beam so that  $\theta_E$  is given by the third of equations 4 and, hence,  $H$ , the vertical antenna aperture, is given by

$$H = \lambda/\theta_E \quad (8)$$

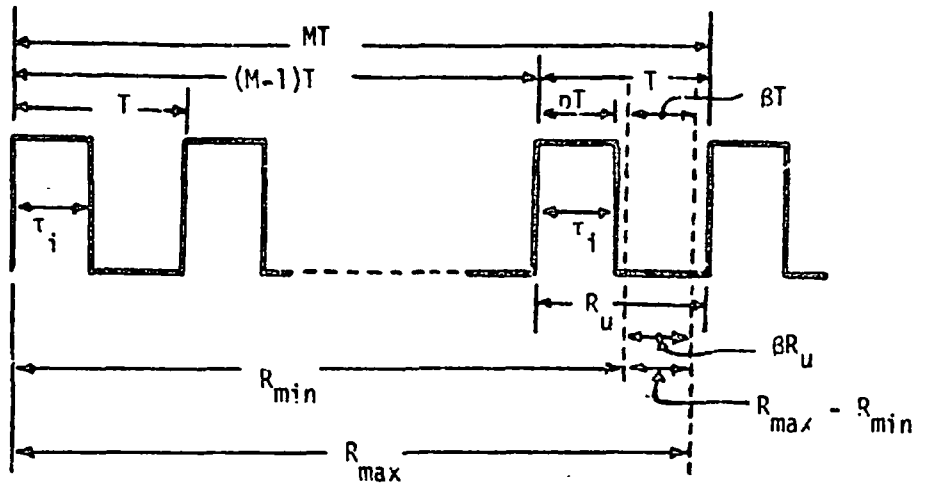


Figure 3. Relations among  $R_{max}$ ,  $R_{min}$ ,  $T$ , prf, and  $\tau_i$ .

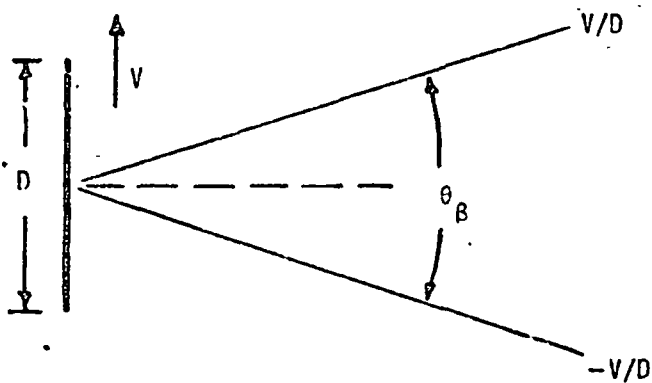


Figure 4. Doppler frequency shift for a moving antenna.

Having selected the values for  $W$ ,  $R_u$  and  $\lambda$ , the quantities  $R_u$ ,  $T$ ,  $\text{prf}$  and  $H$  are now determined.

Range resolution,  $\delta_r$ , of course depends on the radar bandwidth  $B$  in accordance with the relations

$$\delta_r = \frac{c}{2B} = \frac{c \tau_c}{2} \quad (9)$$

#### 1.4 AZIMUTH AMBIGUITY AVOIDANCE

It can be shown easily that given an antenna with horizontal aperture  $D$ , moving with velocity  $V$  in a direction parallel to  $D$  generates a Doppler frequency shift,  $f_d$ , given by

$$f_d = \pm V / D \quad (10)$$

at its three db beam width points. This is illustrated in Figure 4.

Since the radar systems of concern are sampled data systems, one needs to sample the signals in the antenna beam at a rate at least twice the value given by equation (10). Hence

$$\begin{aligned} \text{prf} &= 2\gamma \frac{V}{D} \\ \gamma &\geq 1 \end{aligned} \quad (11)$$

Recall however, that  $\text{prf}$  has been set by choice of  $R_u$ . Also  $V$  is a parameter whose value is set by primarily non-radar consideration. Thus equation (11) is really a constraint on the value of  $D$  - namely:

$$D = \frac{2\gamma V}{\text{prf}} = \frac{4\gamma V}{c} R_u \geq \frac{4V}{c} R_u \quad (12)$$

In writing the second form of equation (12), use was made of equation (7).

A useful relation is obtained by solving equation (12) for  $R_u V$ . This

quantity is the area rate mapped in the slant range plane. If  $\dot{A}$  represents this quantity, one has

$$\dot{A} = R_u V = \frac{c}{4\gamma} D \leq \frac{c}{4} D \quad (13)$$

Thus the area which can be mapped per second is determined only by  $D$  and  $\gamma$ .

Choice of the value of  $D$  according to equation (12) prevents azimuth ambiguities if the sidelobe levels of the antenna are properly kept below some acceptable level.

### 1.5 ACHIEVEMENT OF ALONG TRACK RESOLUTION

From equations 12 or 13 one notes that the value of  $D$  is set by the selection of swath width, or by the area rate desired. In some cases the value of  $D$  resulting from these considerations may be greater than  $2\delta_a$ , where  $\delta_a$  is desired along track resolution.

In such cases, the use of a single beam cannot achieve the desired resolution, because the width of the segment illuminated by the radar is too short.<sup>4</sup> However, there is no reason why one cannot use multiple beams. What one needs to do is illuminate a segment whose length is at least that needed to achieve the synthetic aperture length one needs.

The length of synthetic aperture needed (non-squint case) is given by

$$L_{SAR} = \frac{R\lambda}{2\delta_a} \quad (14)$$

Given an antenna aperture of horizontal aperture,  $D$ , one can form  $n$  beams using a technique such as that used in a Butler Matrix so that the same aperture is used to form the  $n$  beams. In this case the segment illuminated at range  $R$  is

$$L_I = \frac{n\lambda R}{D} \quad (15)$$

One needs to choose  $n$  so that

$$\left. \begin{aligned} L_{\text{SAR}} &= \alpha L_1 \\ \alpha &\leq 1 \end{aligned} \right\} \quad (16)$$

The multiple beam configuration is illustrated in Figure 5.

Combination of equations 14, 15, and 16 gives

$$n = \left[ \frac{D}{2\alpha\delta_a} \right]_{\text{GE}} \quad (17)$$

Equation (17) gives the number of beams necessary. In equation 17, the symbol  $[x]_{\text{GE}}$  is to be interpreted as the smallest integer greater than or equal to  $x$ .

The first of equations (6) with the equal sign chosen can be written as

$$R_{\text{max}} = M \frac{cT}{2} = M R_u \quad (18)$$

Thus  $M$  may be interpreted as the number of pulses simultaneously in transit during radar operation.

Use of equations 12 and 18 in equation 17 gives

$$n M = \frac{1}{\alpha} \left( \frac{V^2 R_{\text{max}}}{c \delta_a} \right) \quad (19)$$

Thus the product of the number of beams by number of pulses under way simultaneously is given by the right hand side of equation 19.

The quantity of  $R_{\text{max}}/c$  is the time required for a radar signal to traverse the path from radar to target and then back to the target. Multiplication of this time by  $V$  gives the distance traversed by the radar during this round-trip interval. This distance divided by  $\delta_a$  gives the product  $n M$  needed except for the factors  $\gamma$  and  $\alpha$  which relate to an oversampling.

factor and over illumination factor respectively.

### 1.6 SIGNAL TO NOISE RATIO WITH CONSTRAINTS

In writing the equations leading to equation (3) a single radiated beam was assumed so that  $P_{ave}$  in this equation is the average power in a single radiated beam. Since  $n$  beams are required, with  $n$  given by equation (17), the total average power,  $P_{Total}$ , is given by solving equation 3 for  $P_{ave}$ , and then multiplying this quantity by  $n$ . One has

$$P_{ave} = \left( \frac{\hat{S}}{N} \right) \left[ \frac{8\pi R^3 k T_N \theta_E^2 \delta_a V}{D^2 \sigma \lambda} \right] \quad (20)$$

and

$$P_{Total} = \left( \frac{\hat{S}}{N} \right) \left[ \frac{8\pi R^3 k T_N \theta_E^2 \delta_a V}{D^2 \sigma \lambda} \right] \left[ \frac{D}{2\alpha \delta_r} \right] \quad (21)$$

$$= \left( \frac{\hat{S}}{N} \right) \left[ \frac{4\pi R^3 k T_N \theta_E^2}{\alpha \sigma \lambda} \right] \left[ \frac{V}{D} \right]$$

From equations 13 and 18 several equivalent expressions for  $V/D$  may be obtained: namely

$$\frac{V}{D} = \frac{c}{4\gamma R_u} = \frac{c M}{4\gamma R_{max}} \quad (22)$$

Combination of equations 21 and 22 gives

$$P_{Total} = \left( \frac{\hat{S}}{N} \right) \left[ \frac{4\pi R^3 k T_N \theta_E^2}{\alpha \sigma \gamma} \right] \left[ \frac{c M}{4\gamma R_{max}} \right] \quad (23)$$

It will be noted that equation (23), evaluated at maximum range, predicts that the average power required varies as the square of maximum range.

### 1.7 ANTENNA CONSIDERATIONS

It has been shown in Section 1.2 that

$$\sin \theta_E = \frac{W \sin \theta}{R_{\max}} \quad (24)$$

and that

$$W = (R_{\max} - R_{\min}) \frac{\cos \theta_{E/2}}{\cos(\theta - \theta_{E/2})} \quad (25)$$

If it is assumed that  $\theta_E$  is sufficiently small so that

$$\sin \theta_E \approx \theta_E \quad (26)$$

then combination of equations 4, 8, and 26 gives

$$H = \frac{\lambda R_{\max}}{W \sin \theta} \quad (27)$$

One may rewrite equation 25 as follows:

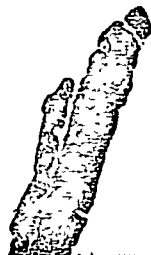
$$\frac{W}{R_u} = \frac{\beta W}{(R_{\max} - R_{\min})} = \frac{\beta \cos(\theta_{E/2})}{\cos(\theta - \theta_{E/2})} \quad (28)$$

Substitution of W from equation 28 into equation 27 gives

$$H = \left[ \frac{\lambda R_{\max}}{\sin \theta} \right] \left[ \frac{\cos(\theta - \theta_{E/2})}{R_u \beta \cos(\theta_{E/2})} \right] \quad (29)$$

The area, A, of the antenna can be obtained by multiplying equation 20 by equation 12. The result is

$$A = H \Gamma = \left[ \frac{\lambda R_{\max}}{\sin \theta} \right] \left[ \frac{\cos(\theta - \theta_{E/2})}{\cos(\theta_{E/2})} \right] \left[ \frac{4\gamma V}{c} \right] \quad (30)$$



Since  $\beta \leq 1$  and  $\gamma \leq 1$ , equation 30 shows that there is a minimum antenna area required.

One also recalls with respect to antenna requirements that  $D$  is given by equation 12 and that the number of beams required is given by equation 17.

## 2.0 THE MULTIPLE RANGE CHANNEL CASE

In section 3 the case in which the multiple channels are in the range coordinate is analyzed.

One starts by considering a single elevation channel with the value of  $\theta'_E$  at first unspecified. As the analysis proceeds, one will need to provide multiple elevation channels.

Quantities whose values differ in Case II from their values in Case I are designated by use of a prime on the appropriate symbol.

### 2.1 PRELIMINARY SIGNAL TO NOISE RATIO FOR CASE II

Equation (1) for the single beam case applies to the multiple range channel case. Equations (2) also apply. For this case one gets

$$\left(\frac{\hat{S}}{N}\right) = \left[ \frac{P_{ave} \sigma \lambda}{8\pi R^3 k T_N \delta_a V} \right] \left[ \frac{(H')^2 (D')^2}{\lambda^2} \right] \quad (31)$$

### 2.2 SYSTEM GEOMETRY

The system geometry in Figure 1 applies also for Case II as do also equations (4) except that the elevation angle,  $\theta'_E$ , will eventually be divided into a number of elevation channels which will span different range intervals. (See Figure 6).

One assumes for this case that  $h$ , and  $R_{max}$ , are independent variables. The third quantity to solve the geometry is specified later.



### 2.3 ACHIEVEMENT OF ALONG TRACK RESOLUTION

Given a desired resolution,  $\delta_a$ , the required value for D is given<sup>4</sup> by

$$D' = 2 \alpha \delta_a$$

$$\alpha \leq 1$$

(32)

### 2.4 AVOIDANCE OF ALONG TRACK AMBIGUITIES AND ACHIEVEMENT OF DESIRED SWATH WIDTH

Equation 11 applies to Case II. However, in this case, D has been specified by equation 32 so that equation 11 becomes a specification on prf. This, of course, also specifies  $T'$  and  $R'_u$  - namely:

$$\left. \begin{aligned} T' &= \frac{1}{\text{prf}} \\ R'_u &= \frac{c}{2 \text{ prf}} = \frac{c}{4\gamma V} D = \frac{c^2 \delta_a}{4\gamma V} \end{aligned} \right\} (33)$$

Comparison of equation 17 with equation 32 shows that

$$D = n D' \quad (34)$$

Hence

$$R_u = n R'_u$$

and

$$W = n W' \quad (34)$$

Thus n beams in elevation are needed to span the desired swath width W.

Equation 27 is valid for Case II. Combination of this equation with equation 35 gives

$$H' = \frac{\lambda R_{\max}}{W' \sin \theta'} = \frac{n \lambda R_{\max}}{W \sin \theta'} \quad (36)$$

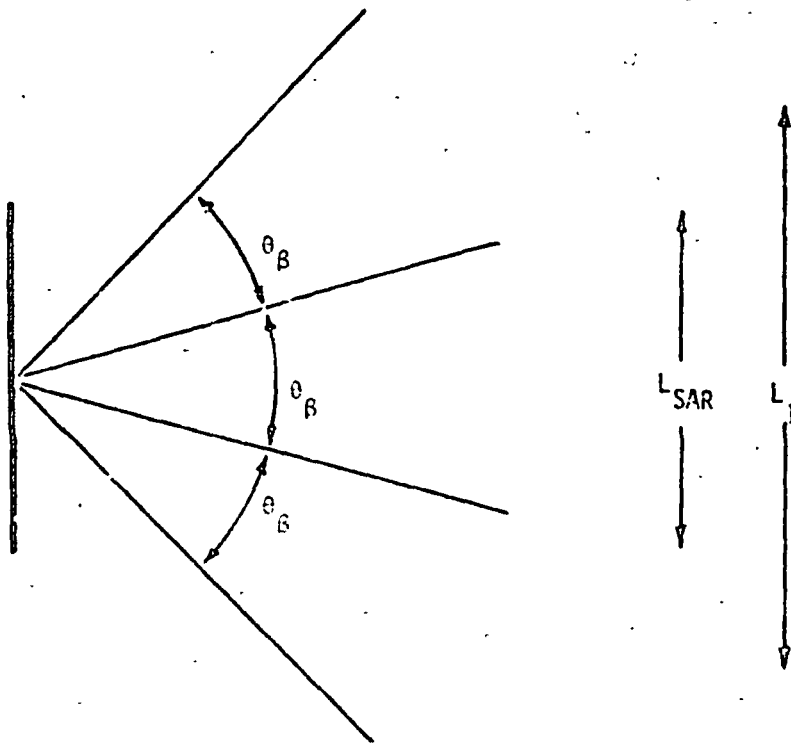


Figure 5. Use of multiple beams to illuminate the synthetic aperture length.

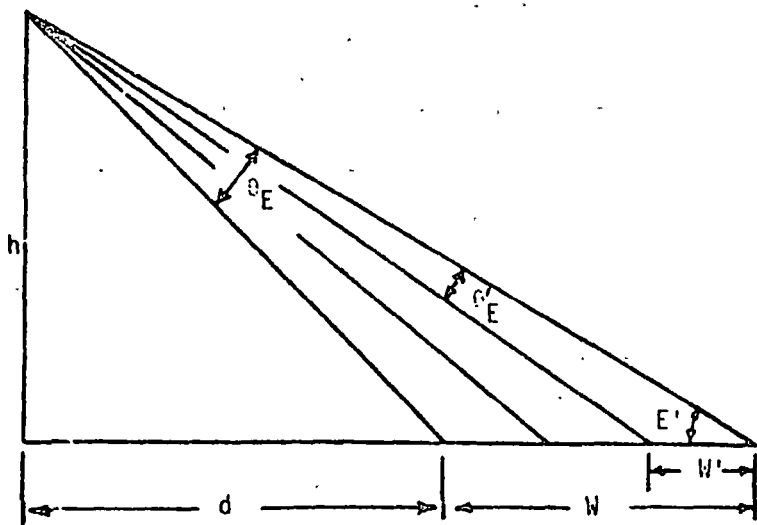


Figure 6. Partition of  $\theta_E$  into range channels  $\theta'_E$ .

As an approximation, let  $\theta$  be considered as being approximately equal to  $\theta'$ .

Comparison of (36) with equation 27 gives

$$H' = n H \quad (37)$$

Choice of  $\delta_a$  specifies  $D'$ , and  $R_u'$ . Choice of  $\theta_E$  (or  $W$ ) specifies  $n$ .  
Choice of system geometry specifies  $H'$ .

It will be noted from equations 52, 53, and 54, that for Case II, the value of  $H'$  is  $n$  times the value of  $H$  for Case I, but that  $D'$  is  $1/n$  the value of  $D$  such that the antenna areas remain constant.

The number of channels  $n$  for Case I and II are equal. In Case I, the channels are in the along track direction; in Case II, they are in the along range direction.

For both Cases I and II, there is a minimum antenna area required. This area is proportional to wavelength,  $\lambda$ , maximum range,  $R_{\max}$ , and satellite speed  $V$ . It also depends on geometric factors as shown in equation 49.

The total average power required is the same for both Cases I and II.

From equation 47, one notes that the total average power,  $P_{\text{Total}}$ , required varies directly as the square of  $\theta_E$ , and directly as  $M$ , directly with the noise temperature  $T_N$ , inversely as the target cross section  $\sigma$ .

The dependence of average power with range is as range cubed. However, at maximum range it varies as the square of range. This latter behavior is due to the fact that antenna area must be made proportional to  $R_{\max}$ .

The analysis above has been based on a flat earth approximation only for the simplicity of a first analysis. It is realized that the actual geometry needs to be considered. This will be done at a later date.

## 2.5 SIGNAL TO NOISE RATIO WITH CONSTRAINTS FOR CASE II

Equation (31) gives the signal to noise for Case II in the absence of constraints. The important constraints for Case II are given by equations 34 and 37. If one forms the product  $H'D'$ , one gets using these equations

$$H'D' = (nH) \left(\frac{D}{n}\right) = HD \quad (38)$$

Use of equation 38 in equation 31 shows that

$$\frac{\hat{S}}{N} \text{ Case II} = \frac{\hat{S}}{N} \text{ Case I} \quad (39)$$

Thus the signal to noise ratio for Case II is identical to that for Case I.

For Case II, one needs the same average power as for Case I.

In Case I,  $n$  beams are used in the along track case and  $D$  is given by equation 12. For Case II  $n$  beams along the range direction are used.

In Case I, the value of  $D$  is  $n$  times greater than the value of  $D'$ .

In Case II, the value of  $H'$  is  $n$  times larger than  $H$ .

In both cases the area of the antenna has the same value, - namely: that given by equation 30.

## 3.0 SUMMARY OF RESULTS

The major results of these analyses are the constraints on parameter values and the effects of these constraints on determining the average power required.

For Case I, the primary results are those given by equations 7, 12, 13, 14, 17, 18, 19, 23, 29, and 30. These are repeated on the next page.

$$\text{prf} = \frac{c}{2R_u} \quad (40)$$

$$D = \frac{4\gamma V}{c} R_u \quad (41)$$

$$\dot{A} = R_u V = \frac{c}{4\gamma} D \quad (42)$$

$$L_{\text{SAR}} = \frac{R\lambda}{2\delta_a} \quad (43)$$

$$n = \left[ \frac{D}{2\alpha\delta_a} \right]_{\text{GE}} = \left[ \frac{2\gamma V R_u}{\alpha c \delta_a} \right] \quad (44)$$

$$R_{\text{max}} = M R_u \quad (45)$$

$$n M = \frac{\gamma}{\alpha} \left( \frac{2R_{\text{max}}}{c \delta} V \right) \quad (46)$$

$$P_{\text{Total}} = \left( \frac{\hat{S}}{N} \right) \left[ \frac{4\pi R^3 k T_N \theta_E^2}{\alpha \sigma \lambda} \right] \left[ \frac{cM}{4\gamma R_{\text{max}}} \right] \quad (47)$$

$$H = \frac{1}{\beta} \left( \frac{\cos(\theta - \theta_E/2)}{\cos(\theta_E/2)} \right) \left( \frac{\lambda R_{\text{max}}}{\sin \theta R_u} \right) \quad (48)$$

$$A = HD = 4 \left( \frac{\gamma}{\beta} \right) \left( \frac{V}{c} \right) \left( \frac{\cos(\theta - \theta_E/2)}{\cos(\theta_E/2)} \right) \left( \frac{\lambda R_{\text{max}}}{\sin \theta} \right) \quad (49)$$

0.2

For Case II the primary results are given by equations 32, 33, 34; 37, 38, and 39. These are repeated below

$$D' = 2 \alpha \delta_a \quad (50)$$

$$\alpha \leq 1$$

$$R_u = \frac{c}{2prf'} = \frac{c}{4\gamma V} D' = \frac{c \delta_a}{2\gamma V} \quad (51)$$

$$D' = D/n \quad (52)$$

$$H' = n H \quad (53)$$

$$H'D' = H D = A \quad (54)$$

$$\left( \frac{\hat{S}}{\hat{N}} \right)_{TL} = \left( \frac{\hat{S}}{\hat{N}} \right) I \quad (55)$$

For Case I, it will be noted that  $R_u$  and  $\delta_a$  are chosen independently. For Case I choice of  $R_u$  leads to the specification of  $prf$ ,  $D$ , and  $\dot{A}$ . Choice of  $\delta_a$  then leads to a specification of  $L_{SAR}$  and  $n$ .

Choice of  $R_{max}$  and the system geometry leads to the specification of  $M$ ,  $H$ , and  $A$ .

All of these constraints lead to the expression for total average power required.

For Case II,  $R_{max}$ ,  $\delta_a$ , and  $\theta_E$  (or its equivalents such as  $W$ ) are chosen independentl;.

## GLOSSARY OF TERMS

$A, A_{rec}$	Area of Receiving Antenna
$\dot{A}$	Area mapped per second in slant range plane
B	Receiver Bandwidth
c	Speed of propagation of radar signals
D	Horizontal antenna aperture
d	See Figure 1
E	Elevation angle (see Figure 1)
$f_d$	Doppler frequency shift (see eq. 10)
$G_T$	Gain of Transmitting antenna
H	Vertical Antenna aperture
h	Altitude of radar above earth
k	Boltzmann's constant
$L_{SAR}$	Length of synthetic aperture
$L_I$	Length of illuminated segment
M	Number of pulses under way (see eq. 6 and 18)
N	Noise power in radar receiver
n	Number of radar channels
$P_T$	Peak transmitter power (one channel)
$P_{ave}$	Average transmitter power (one channel)
$P_{Total}$	Total average transmitter power (n channels)
R	Radar Range
$R_{min}$	Minimum Radar Range
$R_{max}$	Maximum Radar Range
$R_u$	Unambiguous Radar Range
S	Signal Power at Radar Output
T	Interpulse period
$T_N$	Receiver Noise temperature
V	Speed of translation of radar
W	Swath width

### GLOSSARY OF TERMS (cont'd)

$\alpha$	Constant (see eq. 16)
$\beta$	constant (see eq. 5)
$\gamma$	Constant (see eq. 11)
$\delta_a$	Synthetic Aperture Resolution
$\delta_r$	Range Resolution
$\lambda$	Radar wavelength
$\sigma$	Target cross-sectional area
$\tau_i$	Duration of uncompressed pulse
$\tau_o$	Duration of compressed pulse
$\theta$	Elevation Angle (see Figure 1)
$\theta_E$	Elevation Beamwidth (see Figure 1)

### SPECIAL SYMBOL

$\lceil x \rceil_{GE}$  Signifies smallest integer greater than or equal to x.

### 4.0 REFERENCES

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2. Cutrona, L. J., "Additional Characteristics of Synthetic Aperture Sonar Systems and a Further Comparison With Non Synthetic Aperture Sonar Systems," J. Acoust. Soc. Am., 61, 1213-1217 (1977).
3. Cutrona, L. J., "Synthetic Aperture Radar," in Radar Handbook, M. Skolnik Ed. (McGraw-Hill, New York, 1970) Chapter 23.



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CAPTIONS FOR FIGURES

- Figure 1. Geometry (Flat Earth Approximation)
- Figure 2. Plot of  $W/(R_{\max} - R_{\min})$  vs  $\theta_E$
- Figure 3. Relations among  $R_{\max}$ ,  $R_{\min}$ ,  $T$ , prf, and  $\tau_i$ .
- Figure 4. Doppler Frequency Shift For a Moving Antenna
- Figure 5. Use of Multiple Beams to Illuminate the Synthetic Aperture Length.
- Figure 6. Partition of  $\theta_E$ , into Range Channels  $\theta_E$ .

SYNTHETIC APERTURE RADAR TECHNOLOGY CONFERENCE

Summary Session

March 10, 1978

Panel Members:

K.R. Carver - New Mexico State University, Physical Sciences Laboratory

R.H. Duncan - White Sands Missile Range, New Mexico

R.K. Moore - Remote Sensing Laboratory, University of Kansas

R.G. Fenner - Microwave Systems Section, NASA Johnson Space Center

F.T. Barath - Jet Propulsion Laboratory

D. Held - Jet Propulsion Laboratory

(transcribed from tape)

K.R. Carver (moderator)

*The panel members of this morning's session are the chairmen of their respective sessions. We would like to equally divide the time we have, roughly an hour or so, between the topics that were covered in the individual sessions. The purpose of the session is to try to highlight some of the points raised during the conference and to provide an overview of where we now stand with respect to synthetic aperture radar technology. It seems to me that there are two points which are made when you begin to talk about this field. One is the problem of getting the program funded. The other is what should we do to make things better; these, of course, are not necessarily compatible.*

*I would like to begin with some comments on the opening session; for those*

of you who got here late, Dr. Merrill Skolnik and Dr. Fawwaz Ulaby both gave very interesting overview talks. It seems to me that their comments and several of the following papers have highlighted two key problems that we must face. One certainly is swath width and we have heard a great deal about that. Going along with that is the revisit time, as Dr. Skolnik pointed out. The other problem was also brought up by Dr. Skolnik on a viewgraph which listed the issues concerning the applications of SAR, and he titled it Sustaining Applications and Competitors. You can equate that to LANDSAT or whatever you like, but certainly there is ample competition for SAR and I think we all realize that. Fawwaz Ulaby mentioned several applications of SAR data, mostly in the context of remote sensing and extended targets; among these were applications requiring the use of SARs at higher frequencies, specifically at C-Band and X-Band. As far as space-borne remote sensing SARs are concerned there are at present systems designs based primarily on the L-Band SEASAT and SIR-A requirements; so we are faced with a number of technical problems in the near future stemming from the need to go to shorter wavelengths.

We will now go to each respective session chairman and take about five or ten minutes each; after that, we will attempt to address the specific questions that have been submitted on cards by some of the audience. The first session was on SAR Calibration and was chaired by Dr. Dick Duncan of White Sands Missile Range.

R.H. Duncan (chairman of SAR Calibration Session)

I have a note here for us old diehards around who still use the term

megacycles instead of megahertz; we also use letter band designations such as C-Band, X-Band, etc. I just want to let you know that you are in violation of the Department of Defense directives and various Army regulations; you have my sympathy. I also noticed that I'm the only session chairman who did not present a paper. I don't know why Keith invited me--probably because we're old friends.

The first thing that I heard about calibration is that it is very difficult and not very important. But then someone said that relative calibration is very important. I then started to grapple with this problem of "Why calibrate?" Unfortunately the usual answer that you want to calibrate is like the guy who says he wants to climb the mountain because it's there. Then, realizing that SAR is a system which is to deliver a product to its user, I said "Aha, I'll look at this from a systems engineering point of view. Why would he want to calibrate?" So it didn't take very long to decide that systems engineers need to calibrate, either absolutely or relatively. I take it for granted that most of you, whom I assume to be systems engineers, want good calibration. Then I turned my attention to the users; I found I had to listen to some material in other sessions. I decided to look at some of these nice images that got put on the board. I wasn't getting anywhere with that because it's kind of like a grandmother who shows you a picture of her new baby and you say, "Gee, ain't that a nice picture." So I looked at some of this imagery and the speaker said that it was a one-look image and I said, "Gee, ain't that a nice picture." Then he showed another one and said that it was an average of four looks and I said, "Gee, ain't that a nice picture." So I wasn't getting anywhere because I was

not a trained user. But I think it is an important point to identify what the user wants, having established that the system engineer wants to do the best job of simulation and design. I then thought about what does the user know about calibration and why would he want to calibrate.

I haven't answered all those questions of which users need what, but I did get some ideas. I heard one speaker talk about classification of mobile homes. I mentioned this to Keith who said the "You have just discovered that there are hard target users and there are soft target users." I noted that mobile homes are detectable 37 times out of 37 and that sometimes wheat looks like corn. So I've decided that maybe that if you're a hard target fellow and are looking for mobile homes, missile sites, convoys of tanks and things like that, who cares? If you can detect it 37 times out of 37, who cares about what is seen being relatable to a calibrated image. I don't know if I've reached the wrong conclusion.

I also decided maybe I could take these various kinds of users and put them on a totem pole as to who cares about calibration and who doesn't. I found one guy who doesn't care about calibration - and that was that fighter pilot. He is in a see and shoot situation. Whether or not what he sees is related to a calibrated image, he couldn't care less. So I put him down at the bottom of the totem pole. He doesn't care about calibration, although he may have the indirect benefit of calibration information obtained in the design and simulation process. Then I thought that the rest of the job would be easy; I would identify all the users and put them on the totem pole. He doesn't care about calibration, although he may have the indirect benefit of calibration information obtained in the design and simulation process.

Then I thought that the rest of the job would be easy; I would identify all the users and put them on the totem pole. That's when I flunked out. Yesterday evening, I found out from Dick Moore that the people who are interested in ground moisture and changes thereto are really interested in relative calibration; so I put the ground moisture people on top of the totem pole. If I've made a mistake and anybody else wants up there, it's all right by me.

I'm not going to try to summarize the papers in my session. However, I did talk to Walt Brown (JPL) briefly and asked him a point blank question about what he believes the state-of-the-art to be in calibration today. He said that he believes that it is around  $1\frac{1}{2}$  dB, which sounds pretty good, and with some work we can get it down to  $\frac{1}{2}$  dB. I asked him what is the most critical element in the whole end-to-end job, and he said it is in getting a good measure of transmitter power. I did hear one speaker say that the absolute antenna gain was a problem. I don't think that antenna people are going to agree with that. I was certainly delighted to see the use of deliberately selected noise spectra to go from the receiver to the image density. I did note that all my speakers are well down the road in what they're doing; they all say they have more work to do. So I'm somewhat reminded of the young bride who complained to her mother that her husband had not yet consummated the marriage. She said, "Mother, you keep sitting on the edge of the bed and telling me how good it's going to be "

K.R. Carver: The next session was the one on Image Simulation and Interpretability, chaired by Dick Moore from the University of Kansas.

R.K. Moore (chairman of Image Simulation & Interpretation Session):

I don't know how I can live up to Dick Duncan; I don't have such short stories and I'm not sure mine are as tellable. When I lived in Albuquerque I used to have some stories about New Mexico A&M, but I've forgotten them; they tell me it wouldn't be appropriate here anyway.

My session dealt with simulation and related topics such as what resolutions would be and so on. It is obvious that there is a need for good simulation programs and that these things do exist, and that the need is for a couple of different kinds of simulation programs. One kind is a system simulation program; Gary Crow talked about one and system simulation programs exist in various other places. JPL has one that I've seen the documentation on. When I walked into the meeting, I was handed a copy of one that was produced by the European Space Agency. So a lot of these synthetic aperture in space simulation programs are around; I just wish that I had the time or that somebody had done it right so we could really stick a program onto everybody's computer and then anytime that we wanted, all we would have to do is go type a few things into the remote terminal. Although I have seen the documentation on some, I hope someone will tell us which one is the easiest one to implement on everybody's computer (whatever kind of computer he has) so we can get that done. I think all of us need to use these programs as we do this kind of study. Obviously it is an important activity, because there is just no way like programming a big computer to beat the cost of putting a system up in space and making a big mistake.

The other kind of simulation that we need is image simulation. Jo Abbott talked about one type of image simulation program; no doubt there are a lot of others around. But I think one of the most significant things is that

a lot of questions relating both to system parameters and to user needs are unanswered. Some of them can be answered by additional aircraft flights and some of them will be answered by looking at what the SEASAT-SAR observes, but a lot of them can really be answered best, I think, by going through some kind of a simulation exercise or starting with original images and degrading them, as we did in the study that I talked about. Questions like these need to be answered and simulation seems like a good way to do it, including such things as what resolutions do you need or what aspect ratio between length and width can you get away with?

Do the radiometer guys really have something when they say you can measure soil moisture with their system, which has a hard time distinguishing one state from another? It certainly can't distinguish one county from another, unless it's in a state like Texas or New Mexico where counties are big and they count the area by the number of acres per cow. If those people are right, then I don't know what we're about in the soil moisture business. On the other hand, I suspect they are not right and that the guy that wants to count the stars on the general's shoulder board may have a problem in that he's got a lot more data than he needs for soil moisture.

Maybe the real aperture radars, for example, will do some of the tasks, if we get the range resolutions short enough, or it may be that unfocused radars will be good enough. Every time you increase the resolution it costs you something in complexity and perhaps in power; we ought to answer these questions for the different problems. The only reason I would consider a real-aperture radar in space is that it's the ultimate way to beat the swath width problem that was talked about this morning. Maybe for some uses it's OK,



but we'll never know unless we do it by some kind of simulation or someone puts one up so we can use it.

We really do need to know what are the right kinds of pixel dimensions and how much averaging is needed. Some studies have been done at the University of Texas on the advantage of over-sampling. If you just barely sample at the Nyquist rate, your samples are independent, but if you sample at twice the Nyquist rate that doesn't say that the samples are 100% correlated. So you get some advantage from that theoretically and the pictures do look better.

I think that these studies need to be done with reference to very specific applications because each application is going to have a different need for all of these image and system parameters and the guys who know that application ought to be the ones to help us in doing this. This is not to say that you make a special system for each one, but if you have each one do it, then maybe you can group systems into a few classes and have one class serve one group of users and another class serve another group of users.

Mr. Rasco (U.T. at Austin) talked about his various kinds of variance, the last two of which I would call textures. It looks like that if there is some texture information available between the multiple looks, we would like to find out. The problem I had was that his study hasn't gone far enough; he showed he could do some good by using all four looks, but he didn't show what he could do by using the average all by itself, so we don't know what the gain was from that. It would be interesting to find out about some of these things. The kind of study I was talking about in terms of getting the users to work was exemplified by the paper by Hershberger (Hughes Aircraft)

where he got these tactical operators to show what happens. That's a very specific class of users. Lots of others need to work with these real and simulated images with various performances.

There are problems also that were addressed having to do with what's the appropriate distribution; I think I've got a pretty good idea on what the right distribution is for different things where the log normal may be good and where the Rayleigh may be good. But some of the answers we really don't have and there needs to be some more work and actual data to pin this down. I think some of the problems come up because people mix apples and oranges with regard to these distributions.

Finally, I thought the paper on the inverse synthetic aperture was interesting. I know there has been a lot of work done on inverse synthetic aperture, not just in radar astronomy, but in looking at things flying around in space from the earth. I haven't come up with the way this kind of information can be made to fit directly into the problem that we are involved in and looking down at the earth, but I can't help but think that there is something there that we ought to be thinking about that will give us some new ideas as to how to do what we want to do. I hope other people are thinking like I am, only more successfully.

K.R. Carver: The next session was the one on Antennas, chaired by Dick Fenner from NASA Johnson Space Center.

R.G. Fenner (chairman of Antennas Session):

Looking at the antennas session, I came away with a strong feeling that we have really crossed a milestone in Synthetic Aperture Radar systems in space. We are moving from the period of feasibility studies and definitions into

a period of actually building some fine hardware. SEASAT as a radar system is a reality, in final testing at JPL, and due to be launched this summer. SIR-A is past the definition as a program and hardware has been built. To me, that's exciting; it's exciting to be a part of that and certainly is a combination of the long period of effort by a lot of people starting with Lou Cutrona (who is sitting in the audience), Dick Moore on my left and Frank Barath on my right. These gentlemen have been a part of this much longer than I have. It ought to be satisfying to all of us that we're making that quantum jump of finally getting the radar out in space. You might not like that specific radar and it might not do everything you want it to do, but the first step is frequently the hardest part of any program for a new sensor - namely, in getting one up there that you can talk about. The SEASAT and SIR-A antennas represent a really new concept in spaceborne radars, in that they are probably some of the largest that have ever been flown. They represent one of the first space-borne applications of printed circuit or stripline techniques for antennas. The antennas described (in the Semulen) show that those printed circuit techniques can satisfy the space requirements, which is a credit to the people that specified and designed them. However, the development of these large antennas has highlighted the problems of testing antennas. It is very difficult to test an electrically large antenna, and there were numerous techniques presented that described how you ought to test them. The paper by Bob Seal (from AFRL - Johns Hopkins) presented a technique that had been used successfully in the past and perhaps would not satisfy these more stringent requirements of remote sensing, but that technique has been used and it works. The near-field technique

which Keith Carver and Allen Newell talked about is a relatively new technique for evaluating antennas. The problem is, as Keith said, one of emotion rather than its ability to do the job. One of the things that I felt strongly about was that the modelling efforts that have been done at New Mexico State and other places on these antennas has really highlighted the difficulties in building large antennas. Some of the products that have come out of these studies have shown us what the effects of the environment are on the antenna system. Certainly, without those modelling efforts and without the products they put out, we would have a really difficult problem in trying to understand the antenna after we've got it into space.

The paper that was presented by Henry Burger from Goodyear showed an application of the relatively new technology in polarization control - by a unique way. I'm told by the antenna professionals that this meanderline technique represents a push of the state of the art. Certainly, it was something that had not been achieved before, in that approach to changing the polarity of an antenna. Finally, the paper by Dave Lewis (Hughes Aircraft Co.) was very interesting and shows that you can make an antenna for a space application using some well-known, old, established waveguide techniques. When we first got into the business of defining large antennas for space application of SARs, I said that we'd never build an L-Band space antenna using waveguides. I think that Hughes and Dave Lewis have put that idea to bed; he showed that you can, at least on a one-time basis, build an antenna like that. And it really does compete with the microstrip and stripline techniques.

K.R. Carver: The next session was on Data Processing and was chaired by

Frank Barath from JPL.

F.T. Barath (chairman of Data Processing Session):

*It is evident that we are in the middle of a revolution for the SAR data processor design and implementation. Until now, as you all know, most of the data processing from SARs was done optically for a number of reasons. One, of course, is the relative theoretical simplicity of such a process. A lot of the shortcomings of this kind of processor has been realized at the onset and a number of electronic processors have been also developed in parallel with the optical processors. These are exemplified by the FLAMMR processor. The optical correlators suffer from a number of problems which necessitate going through these visual processors. There is a problem with the quality of the data that comes out, there is a swath width limitation problem, dynamic range problems (since you're going in and out of the film), bulk, cost and so forth. The glamour of the SAPPHIRE processors represents the alternate to these optical processors and they also suffer from shortcomings. They have a fairly narrow swath or are highly specialized to a particular type of system. There are a number of developments, two principal developments in fact, that are changing this picture drastically. One is the advent of non-military synthetic aperture radar systems, particularly space-borne systems such as the SEASAT-A and SIR-A. As Dick Fenner pointed out, these are hard realities of today. This is due to the recognition that visible/IR type of imaging sensors have their limitations, and also the recognition on the other hand that radar, particularly of the synthetic aperture type, has very distinct advantages and unique capabilities. It is highly desirable to process the data from these SARs in real*

time and hopefully on board the vehicle where the system is carried. The other major development is the incredibly fast advance of semi-conductor device technology. We can now put on a chip just a few millimeters square the equivalent of a whole rack of electronics from just a few years ago. This not only shrinks the size of the volume of the necessary gear but reduces the power requirements to levels compatible with spacecraft use.

The task of designing and building these real-time, possibly on-board, correlators is enormously complex as you found out and very costly. They are also quite specialized. I see a couple of problems in this arena. One is the possible over-specialization of these processors. It's very easy to take the specific requirements of a particular radar system and tailor-make a correlator to it. It is important in my mind to keep the system architecture that we're developing and the devices that were designed to implement them as general as possible. Another problem lies in the area of how do we integrate a digital correlator, real-time, on-board into the radar system as a whole. We have to handle serial inputs into the correlator from the spacecraft and for the determination of the system, the orbit parameters and so forth. There is a real concern on my part, shared by many in the design of the systems, on how all these things play together into a workable system. There are several places where this type of work is going on, with thoughts on how possibly to make these correlators self-sufficient and self-contained. By that I mean that there is an attempt and there are some thoughts that in designing correlators we can derive the parameters that they need for their successful processing of the data directly from the synthetic aperture raw data itself. We heard a paper by Dr. Wu, who

described for instance a clutter-lock system that looks after multiple-look imagery and determines where the zero-doppler is. These kinds of thoughts and this kind of approach, which have tried to make this system as self-sufficient as possible, are a very desirable goal and unless we keep these in mind right from the onset, we might get into problems.

I'm confident that all these problems will be overcome and within a few years we will in fact see correlators doing their job in real-time and as part of the synthetic aperture systems themselves, so that essentially they will become a part of the system and there will be correlators inseparable from the SAR as a whole. Of course, the result of all this is that we will get imagery coming out of the synthetic aperture radar just like imagery now comes out of the optical/visible sensors for direct application by the users.

K.R. Carver: The next speaker is Dr. Held of JPL, who chaired the session on SAR System Design.

D. Held (chairman of the SAR System Design Session):

Editor's note: Due evidently to a microphone placement problem, Dr. Held's comments were nearly inaudible on the tape playback and could not be accurately transcribed.

Following Dr. Held's comments, a round-table discussion on major problems in SAR technology was held and several questions submitted by members of the audience were discussed. These were also insufficiently clear on the tape recording to allow an accurate transcription.