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DEFINITION STUDY FOR SPACE SHUTTLE EXPERIMENTS INVOLVING LARGE, STEERABLE MILLIMETER-WAVE ANTENNA ARRAYS

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16. Abstract

This report documents a study in support of the definition of potential uses and techniques for the Shuttle Spacelab Millimeter Wave Large Aperture Antenna Experiment (MWLAE).

In addition to previously documented experiments, three additional potential uses are identified: applications to radio astronomy (and in particular to the identification of organic molecules in interstellar matter), the sensing of atmospheric turbulence by its effect on water-vapor line emissions, and the monitoring of oil spills by multifrequency radiometry.

It is demonstrated that IF combining is preferable to RF combining with respect to signal-to-noise ratio for communications receiving antennas of the size proposed for MWLAE.

A new design approach using arrays of subapertures is proposed to reduce the number of phase shifters and mixers for uses which require a filled aperture.

It is shown that the usual radiometry approach, using RF combination followed by a Dicke receiver (in the case of beam-forming, several such receivers) is unsuited to arrays as large as the proposed MWLAE. Correlation radiometry and a novel scheme utilizing synchronous Dicke switches and IF combining are proposed as potential solutions.

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PREFACE

This report documents a study in support of the definition of potential uses and techniques for the Shuttle Spacelab Millimeter Wave Large Aperture Antenna Experiment (MWLAE).

After an introduction (Section I), a brief administratative history of the contract is given in Section II. Unforeseen funding difficulties and a resulting mutually agreed redirection of effort forced abandonment of some of the original objectives, but significant results were achieved nevertheless. Section III reviews these results. Contributions were made to the definition of communications experiments, and three new potential remote sensing applications were identified. However, due to the redirection these were not pursued as fully as would be desirable. IF combining was shown to be a superior technique relative to RF combining for large arrays with respect to signal-to-noise-ratio. Phase shifters and mixers were identified as critical components with respect to cost and availability in quantity at the higher frequencies. It was shown that current satellite-borne radiometric systems cannot utilize the resolution of the MWLAE because of S/N, bandwidth, and integration-time problems. Two potential systems for achieving the desired resolution in such systems were proposed tentatively; further study is needed. A technique for designing large arrays of subapertures is suggested to alleviate the need for excessive numbers of phase shifters and mixers for applications requiring a filled-aperture MWLAE configuration.

Section IV lists publications and papers resulting from the contract. In addition to this report, two technical reports, a journal publication, and three presentations at scientific meetings have been prepared. The report concludes with a listing of new technology (Section V) and a summary of conclusions and recommendations (Section VI).

It is felt that proper utilization of very large arrays, such as the MWLAE, requires a major rethinking of systems concepts. This effort has uncovered some avenues which we feel to be of real value, but considerable further basic study is indicated.

CONTENTS

I. INTRODUCTION

This report documents work performed under Contract NAS 5-20521 in support of a proposed Millimeter Wave Large Aperture Antenna Experiment (MWLAE) which is in the process of being defined at the Goddard Space Flight Center with Dr. Louis J. Ippolito as Principal Investigator. Two technical reports [1,2] were prepared under the contract, one on the topic of the noise performance of large arrays, the other on the implications of this performance for radiometer systems. The material contained in these reports, which represents the primary area of endeavor under the contract, is summarized below but is not reproduced in detail. Other material is presented in more detailed form.

Certain technical concepts of the MWLAE changed in the process of its definition, as was to be expected. At the same time, funding constraints appeared which had not been anticipated. As a result, by mutual agreement, the effort was redirected to more limited objectives than envisioned in the original work statement. To put the results obtained properly into perspective in this context, a brief administrative history of the contract is included in this report.

II. ADMINISTRATIVE HISTORY

A. Background

The effective starting date of the contract was May 16, 1974. At that time, the MWLAE had been defined only in very preliminary form. Intended for utilization on certain flights of the Shuttle Spacelab, it was conceived as a modularly deployable, electronically steerable antenna with an aperture in the range of 10 to 30 or more meters, operable in the range 10-100 GHz with bandwidth on the order of 400 MHz. Three modes of operation were anticipated. In the communications mode, the MWLAE was to use multiple beams to acquire, track, and receive communications signals from various ground-based transmitters. In the propagation mode, the objective of the experiment was to characterize propagation effects during fog and precipitation periods and to evaluate potential interference by monitoring the electromagnetic spectrum. In the user mode, the array would be available for a wide variety of user experiments, both NASA and non-NASA, employing a diversity of instrumentation such as radar altimeters, scatterometers, synthetic aperture radars, and millimeter-wave radiometers. Not all these functions were to be achieved simultaneously, but it was hoped that many or most of the modules would be utilized in several modes of operation in order to reduce both cost and the time required for converting from one type of experiment to another. Missions were aimed for the 1979-90 time frame, with emphasis on the earlier flights. At the inception of this contract a brochure describing the experiment in this preliminary form was nearing completion [3]. The Principal Investigator of the MWLAE experiment was well aware that the experiment would undergo changes in the definition phase both for technical reasons and for reasons dictated by the potential users; indeed the principal purpose of the brochure was to achieve a productive interaction between the potential users and the designers of the experiment at the very start of the definition process.

B. Original Tasks

The tasks posed in the original work statement of Contract NAS5-20521 were the following:

1. To survey potential uses of the MWLAE,
2. To survey available technology and identify areas in which it will need to be extended,
3. To examine the effects of array organization on its performance.
4. To define useful and feasible experiments utilizing the MWLAE, utilizing the above results,
5. To perform as detailed a design of the selected experiments as practicable.

C. Coordination with Other Efforts

The work at The Ohio State University was closely coordinated, through the NASA Technical Officer, with that of two other contractors. Operations Research, Inc. of Silver Springs, Maryland, had certain responsibilities to aid the MWLAE Principal Investigator in documenting the experiment definition and in promoting interaction with potential users. The Hughes Aircraft Company (Aerospace Groups) of Culver City, California, became involved shortly after the inception of our contract in the detailed specification of a more restricted group of experiments. In order to speed progress and avoid duplication, joint meetings of the Principal Investigators under these contracts were called from time to time by the NASA Technical Officer. In addition information was exchanged in the form of Type I monthly progress reports and also informally. The experiment parameters, as conceived during the summer and fall of 1974, are shown in Figure 1. A consensus was reached that the communication mode and the radar mode could probably be implemented more readily as an extension of the current state of the art than the radiometer mode. It was therefore decided that Hughes would concentrate on the communications and radar modes while Ohio State would concentrate on the radiometry problem and on the possibility of using arrays of subarrays to reduce costs and complexity for both the communications and radiometry functions.

MODE	COMMUNICATION LINK FREQUENCY (GHz)		RADAR FREQUENCY (GHz)		RADIOMETER FREQUENCY (GHz)					
	20	30	13.9	13.9	10	18	22	33-37	55-60	94
TRANSMITTER	20W									
RECEIVER		X								
NUMBER OF BEAMS	1,3	1,3	1	1	← 2 →					
BANDWIDTH	← 500 MHz →									
	1500 MHz (3 BEAMS)									
SCANNING	±15°	±15°	← ±15°* →							
	(CONE, 2-DIMENSIONAL)		1-DIMENSIONAL		← 1-DIMENSIONAL →					
SIDELOBES										
POLARIZATION	LINEAR	ORTHOGONAL LINEAR	LINEAR		LINEAR BOTH HORIZONTAL AND VERTICAL IN TRACK PLANE					
BEAMWIDTH	0.1°	0.1°			← 0.3° →					
RESOLUTION			100 m							
*FOR A SWATH WIDTH OF 100 KM										

Figure 1. Proposed MWLAE parameters, as of summer 1974.

D. Redirection of Effort

The original contract award was in the amount of $69,948 for the year 5/16/74 to 5/15/75, partially funded in the amount of $40,000 to 12/15/74. The supplementary funds due 12/15/74 did not materialize. At the same time, it became more and more evident that the radiometric user experiments would require considerable extension of current technology and would be a high-risk item if considered for the early flights of the Shuttle Spacelab. On May 12, 1975 the contract was modified by mutual agreement to redirect the effort and to add $6,800 of new funds, decreasing the total contract by $23,148 with respect to the original award and extending it to 15 August 1975. It was subsequently extended to 30 October 1975 at no additional cost to the Government. The redirection specified that work performed prior to the redirection on the original tasks 1, 2, 4, and 5 would be documented, but no further effort would be devoted to these tasks. Effort on task 3 was to be continued within the funding limitations.

The Principal Investigator felt that this arrangement might leave the work under task 3, related to radiometry, at a rather unsatisfactory stage of completion. In an informal conversation with the Technical Officer, during which no contractual commitments were made or implied, he offered to continue this work to the best of his ability on his own or with University support, even after expiration of the contract, and to furnish any results of potential value to NASA and the scientific community at no cost to the Government. The second technical report [2] was furnished on this basis.

III. ACCOMPLISHMENTS

A. Survey of MWLAE Uses

1) Previously identified uses

Five documents, some very voluminous, were received from NASA/GSFC during the first month of the study as background for this task [4-8]. These were used as a baseline for documenting further uses and more specific experiments.

2) Communications and Propagation Experiments

At the direction of NASA/GSFC, Operations Research, Inc. (ORI) arranged a workshop to compile a description of potential Shuttle Spacelab Communications experiments. The workshop was held June 23-27, 1974 in Easton, Maryland, and was attended by 60 representatives of Government, industry, and the educational community. Ideas which had been generated at the Ohio State University were submitted to ORI before the workshop on forms supplied by ORI for that purpose. Dr. Daniel B. Hodge of Ohio State University chaired the Workshop Group on a proposed Synchronous Standards Package Experiment; Dr. Curt A. Levis chaired the Group on Antenna Array Experiments. Both participated in documenting the consensus of the Workshop [9].

3. Radiometric experiments

An important area which was found to have been overlooked in the previously identified uses was that of applications to Radio Astronomy. During the last few years, a multitude of organic molecular species have been observed in interstellar space by millimeter-wave spectroscopy [10,11]. Many of the observations were made near a wavelength of 3 mm, using apertures on the order of ten meters. It appears likely that further organic constituents of interstellar matter remain to be discovered. Many such molecules can potentially be identified through several transitions, some corresponding to longer wavelengths; e.g., the HNCO molecule has been detected at both 3.4 mm and 1.4 cm wavelengths [11]. An observation platform above the Earth's atmosphere would have obvious advantages over current ground-based observatories for such observations: less absorption and lower background radiation.

The possibility of sensing atmospheric turbulence at high altitudes radiometrically appears worthy of further exploration. Such turbulence seems to be correlated with water vapor anomalies [12]. While the present attempts to utilize this correlation are confined to the infra-red spectrum, the distribution of these anomalies may be amenable to mapping by oblique-looking radiometers at suitable frequencies close to the water-vapor absorption line near 22 GHz.

The possibility of mapping and monitoring oil spills at sea deserves careful exploration. Recent airborne measurements at 19.4, 31.0, and 69.8 GHz have been useful for identifying such slicks from low-flying aircraft [13]. To perform such observations synoptically from space would require very high resolution, such as that potentially obtainable from MWLAE.

It should be emphasized that, due to the redirection, these ideas have not been studied in any depth under this contract.

At the inception of the contract, it was planned that ORI would conduct another workshop in Autumn 1974, similar to that conducted earlier for Communications experiments but directed towards user-mode remote-sensing experiments. This workshop did not materialize, and our survey was conducted on the basis of informal discussions and correspondence. In addition to the mailing of letters and brochures, we contacted eight potentially interested Radio Astronomers directly. Many were willing to devote a few hours to preliminary exploration, but none felt that their current financial support allowed them to devote sufficient time to arrive at any reasonably firm conclusion as to the potential feasibility of any specific experiment with respect to the Shuttle Spacelab.

On the basis of these limited contacts, it appears that definition of a reasonable number of worthwhile remote-sensing user experiments will be difficult unless specific funding is allotted to this task by either NASA or other appropriate Government agencies.

B. Technology and Components

1. SIMS phased array study

The final report for "A Study Program on Large Aperture Electronic Scanning Phased Array for the Shuttle Imaging Microwave Systems (SIMS)" appeared approximately a month after the inception of our contract [14]. While the philosophy of that study appears to differ greatly from that under our contract, it is useful nevertheless as a baseline for our study. The greater part of the report is devoted to a basic, broad, and necessarily sketchy tutorial survey of phased arrays in general, and of the Nimbus/PMIS antenna systems in particular. This material is useful as a general background, but will not be repeated here. More detailed information on the Nimbus systems can be found in the reports listed in the references [15,16]. The introduction to the SIMS Phased Array Study final report speaks of antenna sizes up to 20 meters by 20 meters, and a very brief section deals with antenna size effects in a tutorial manner. However, the general tenor of the report and its recommendations indicate that the objective of the study was a system spanning a broad spectral range using existing technology. For example, the recommendation for the 1-cm band imaging system bears a marked resemblance to the Nimbus F imaging system technology and utilizes an aperture only 1.37 meters in extent. In contrast, the MWLAE was conceived, in itself, as an experiment designed to stretch the state of the art. The intent of the MWLAE is to utilize an antenna larger by an order of magnitude than the Nimbus antennas and capable of a resolution corresponding to that size. Consequently we have gone into the effects of increasing antenna size in considerably greater depth and reached the conclusion (discussed in more detail below) that such an antenna would imply major changes in the imaging system with which it is to be used compared to current technology, e.g., the Nimbus microwave imagers.

2. RF versus IF combining

The high directivity of a receiving array, compared to that of its elements, is obtained by phase-coherent combination of the signals from the elements. This combination can occur either at the original frequency (RF) or an intermediate frequency (IF). The major problem with the RF combination approach is the requirement for many phase shifters and signal combiners with very low loss and high accuracy at the original system frequency in the range 10-100 GHz. Such devices are not readily available, especially in the upper part of the range. They are also expensive. The major problem with the IF combination approach is the need for many low-noise mixers. These devices also are expensive and not readily available, especially in the upper part of the range. In addition they require the local oscillator signal to be distributed to many mixers, which taxes the state of the art when the array is very large, both from the point of view of generating the necessary local oscillator power and of distributing it phase-coherently.

A compromise approach is possible, in which signals are combined at RF at the subarray level, then mixed to an intermediate frequency and finally combined at IF. The tradeoffs have been examined to some extent under this contract and are discussed below (section C).

3. Filled and thinned apertures

In many arrays, the elements are spaced regularly and closely, separated by a distance on the order of one-half wavelength. Such an array is called a filled array. With proper design, a single sharp beam, high gain, and uniformly low sidelobes may be achieved with this approach, but the number of elements can become very large. For example, a square 10-meter by 10-meter aperture at 30 GHz would require in excess of a million elements and a corresponding number of RF phase shifters or mixers.

An alternate approach is to space the elements farther apart in either a regular or randomized pattern. Such an array is termed a thinned array; if the thinning is substantial, it requires far fewer phase shifters, mixers, etc., than the filled array. The sharpness of the beam, i.e., the angular resolution of the antenna is preserved under thinning. The gain is not preserved but is roughly proportional to the number of remaining elements. Because of this, thinned arrays are not advantageous as transmitting antennas, nor for radiometry in conventional (non-correlation) systems. Even thinned arrays may contain a large number of elements when high resolution and low sidelobe levels are desired. In the concurrent study by the Hughes Aircraft Company, a preliminary design involving a 6-meter aperture and 30 dB sidelobes specified about 4000 elements [17].

4. Components

Based on these considerations, it is our conclusion that the most critical components are RF phase shifters and low-noise mixers. To survey the state of the technology of these components, visits were made to the Hughes Aircraft Company, Culver City, CA (Dr. R. J. Wagner, Mr. A. F. Seaton), The Aerospace Corporation, El Segundo, CA (Dr. Thomas S. Hartwick, Dr. C. J. Carter); Bell Telephone Laboratories, Murray Hill, NJ (Dr. Robert Ryder); and Airborne Instrument Laboratory Division of Cutler-Hammer, Inc., Melville, NY (Dr. J. Taub, Dr. P. J. Meier, Mr. J. Calviello, Mr. R. Domchick). The help of all those contacted is gratefully acknowledged, and expecially that of the group at AIL which was especially generous with their time and shared information.

Additional information was received by mail from Aerojet Electrosystems Azusa, CA (H. G. Pascalar) and from the National Radio Astronomical Observatory, Green Bank, WV (Dr. Sander Weinreb). Attendance at the Spring 1975 IEEE Symposium on Microwave Theory and Techniques and a limited literature survey were other sources of information.

Gallium Arsenide Schottky barrier diodes appear to be the most promising candidates for the front-end active element in the near future. The devices may be operated as resistive mixers or capacitive parametric amplifiers. These are not available as shelf items over much of the frequency range. Schottky mixers can be manufactured at present in moderate quantities in a semi-automated mode at the lower frequencies of the 10-100 GHz range, whereas in the higher range they are produced individually with jeweler's precision and corresponding cost. The paramps are made individually even at the lower frequencies.

An estimate of the noise performance of these devices operated at ambient temperature is shown in Figure 2. It is based on the survey mentioned above. A band or range is indicated for each mode of operation: the upper boundary of the band gives an estimate of the performance to be expected for quantity production, such as for several thousand units; the lower edge of the band corresponds to what is being obtained or appears likely to be obtained in the near future under laboratory conditions with a few selected units. The spread between these two values is least at the lower frequencies, where a substantial number of units has been built. The decided deterioration of the noise performance of paramps above 70 GHz even under laboratory conditions is due to the fact that the pump frequency should be much higher than the operating frequency for low-noise performance, and satisfactory pumps are unavailable at these higher frequencies.

In view of the considerable complexity and higher cost of parametric amplifiers as compared with resitive mixers, coupled with the rather modest improvement that seems likely to be achieved, it would appear that resistive Schottky mixers are the most likely devices to be considered for the initial (front-end) active element.

Lower noise figures may be achieved by cooling the Schottky diode in either the resistive mixer or parametric amplifier configuration [18], and even lower noise may be obtainable by recent developments involving supercooled Josephson-effect devices [19]. Since the study of array organization (see below) shows that it is not suitable to combine signals altogether at RF, so that many mixers are required, the added complexity of cryogenic cooling seems undesirable, and cooled devices had not been considered in this study at the time of its redirection. While we feel this judgment is probably sound, we would not want to make a categorical statement to this effect without further investigation of cooled mixers and amplifiers.

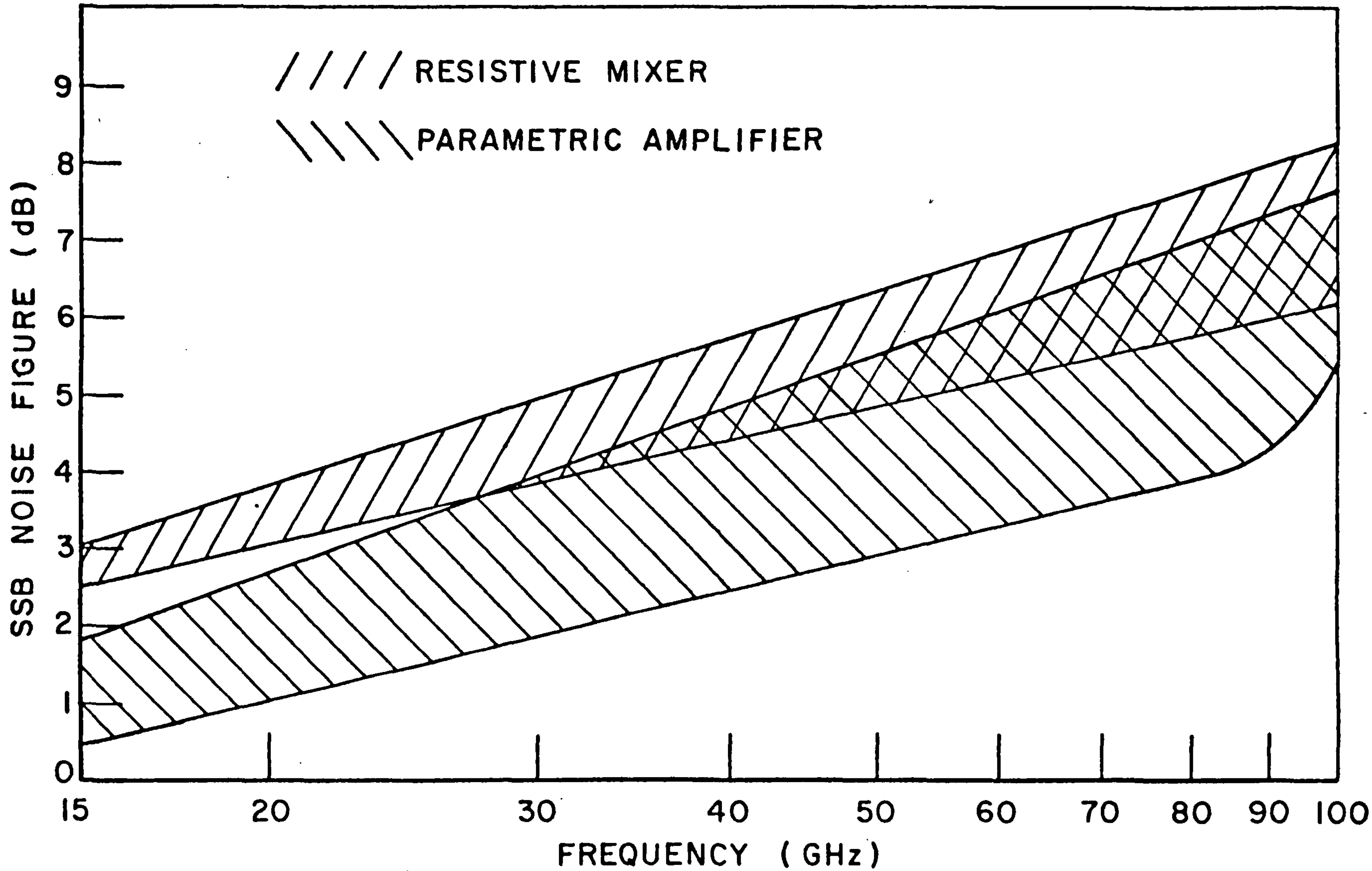


Figure 2. Estimated noise performance of uncooled Schottky diode mixers and parametric amplifiers.

To the extent that RF signal combination is practical, ferrite phase shifters appear to be the most promising devices for achieving the desired phase shifts over the entire range. At 15 GHz the insertion loss of a 360° phase shifter is estimated at approximately 1 dB, while at 70 or 94 GHz 2 dB is a more typical development goal. As in the case of mixers and paramps, the phase shifters are not readily available as "off-the-shelf" items especially at the higher frequencies.

C. Array Organization

1. RF-phased receiving arrays

A technical report issued under this contract [1] gives the results of a study of the signal-to-noise performance as a function of the organization of receiving arrays. By organization we mean the manner in which the elements are interconnected with each other and with active devices to form the desired output signal(s). By receiving arrays we mean those designed to receive spatially coherent signals, i.e., signals emanating from specific discrete directions, as in a communications application and opposed to radiometry. Only the salient conclusions are given here.

A relative signal-to-noise ratio may be defined for such arrays as the actual signal-to-noise ratio divided by the signal available per element and multiplied by kTB, where k is Boltzmann's constant, T is the absolute ambient temperature of the antenna and feed network, and B is the system bandwidth in Hertz (Hz). This relative ratio is a function of only the antenna and feed network parameters. As the array size is increased, the relative signal-to-noise ratio increases at first proportionally to the number of elements, then saturates, and finally decreases due to decreased efficiency when the array size becomes excessive. Computer codes were written for a number of specific configurations. Figure 3 shows the result for a regular square corporate-fed array in which adjacent elements are combined in groups of four, the resulting adjacent groups are again combined in sets of four, etc., as indicated schematically in Figure 4. The frequency assumed for the calculation is 30 GHz, the array spacing is 3 wavelengths, the phase shifter loss is 1.2 dB, the aperture distribution is uniform, and the waveguide attenuation coefficient is the parameter A given in dB/foot. In order to reduce the number of parameters, no signal combiner loss is assumed; this yields an optimistic estimate of the relative signal-to-noise ratio. The behavior of Figure 3 is typical of the better array organizations. At 30 GHz, apertures on the order of 1 meter square can be utilized efficiently; at 10 meters square, considerable loss of gain occurs for practical values of waveguide attenuation and the signal-to-noise ratio no longer rises in proportion to the number of elements; in the range of 10 to 100 meters square the signal-to-noise ratio actually begins to decrease with added array size. Of course the ratio decreases even more strongly when combiner loss is included.

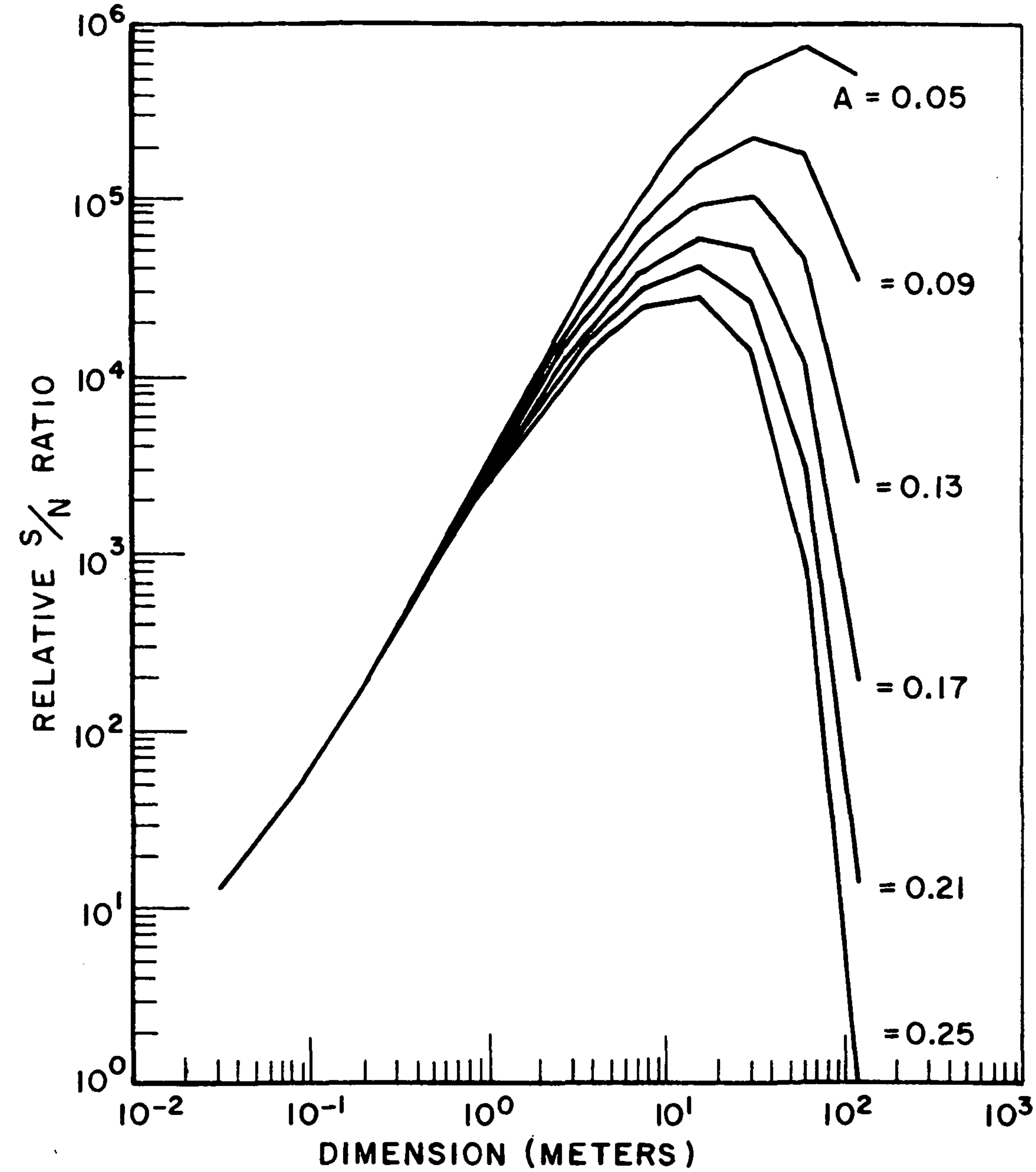


Figure 3. Calculated relative signal-to-noise ratio of corporate-fed array. Elements are spaced 3 wavelengths, phase shifter loss is 1.2 dB, waveguide attenuation is A dB/foot, frequency is 30 GHz.

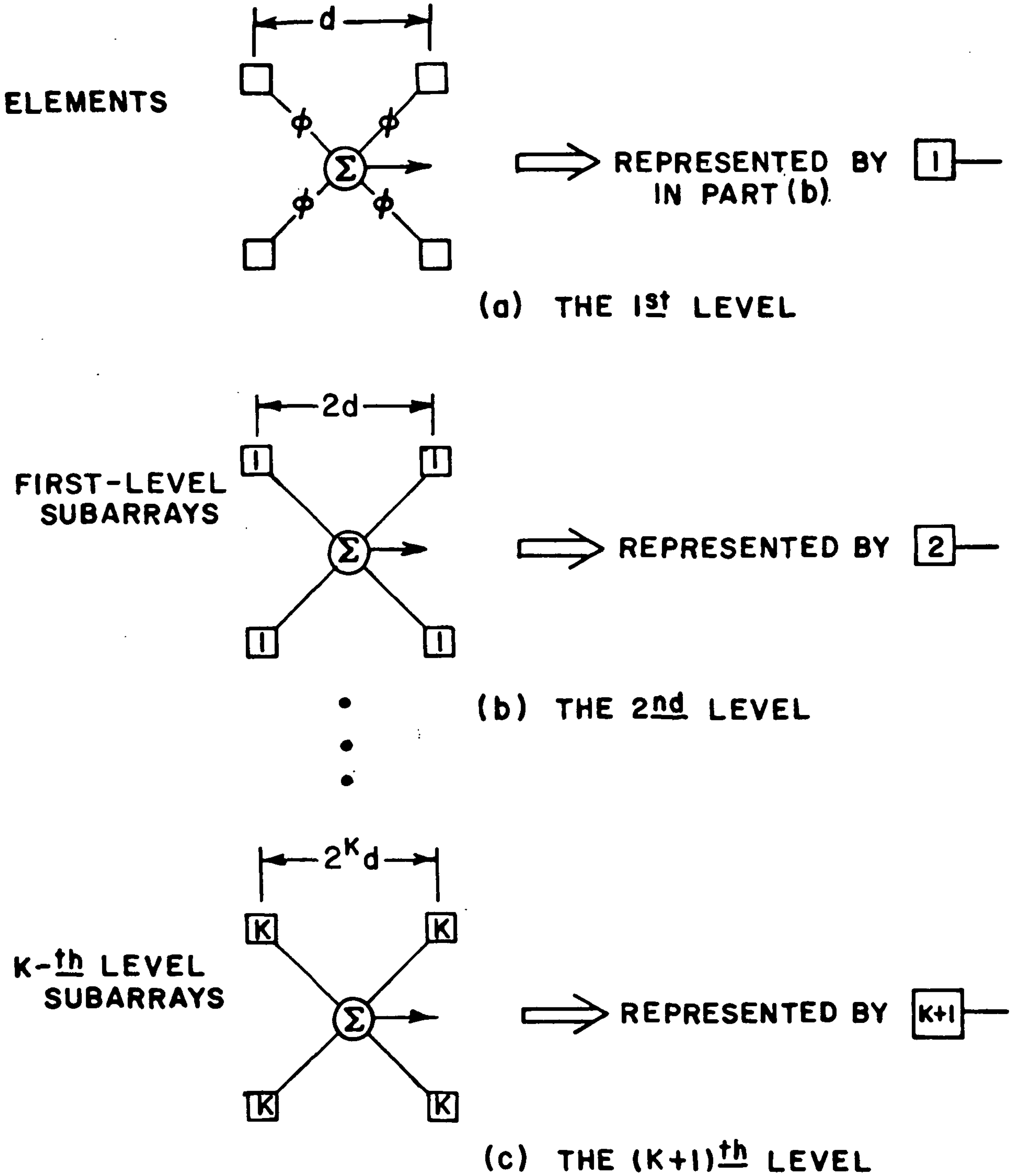


Figure 4. Recursive scheme for obtaining the corporate-fed array for which calculations are given in Figure 3.

2. IF-phased receiving arrays

An IF-phased array may be represented as in Figure 5a, where the S_i, T_i represent the signal and noise temperature of the elements (up to the combining network), G_i, F_i represent the conversion gains and standard noise figures of the converters, and S_{out}, T_{out} represent the output signal and noise temperature at the combiner output. Transmission lines, phase shifters, etc. are considered to be internal to the combiner network. While formulas for the general case are developed in the technical report [1], we shall here consider identical converters, so that the subscripts may be omitted from the F_k, G_k. The antenna element noise T_k is assumed negligible compared with that contributed by the converters and combining network. Under these conditions, the output signal of the IF-phased array is

$$S_{out} = G \left| \sum_{k=1}^{n} \sqrt{S_k} \exp(j\phi_k) S_{mk} \right|^2 , \qquad (1)$$

where the S_{mk} are the scattering matrix elements relating ports m and k of the IF signal combiner, normalized with respect to identical characteristic impedances at all ports, and ϕ_k is the phase associated with the signal at port k. The output temperature is given by

$$T_{out} = G(F-1)\ T_o A + (1-A)T_a , \qquad (2)$$

where T_o is the standard temperature (290°K), T_a is the ambient temperature, and

$$A \equiv \sum_{k=1}^{n} |S_{mk}|^2 \qquad (3)$$

is the efficiency of the combiner network which would be measured if power were applied at the output port with all input ports matched. The condition for a lossless combiner is A=1.

An RF-phased array may be represented as in Figure 5b. Its signal output, under the same assumptions as before, is given also by Equation (1), in which the S_{mk} now represent the parameters of the RF signal combiner. The output temperature for this case is given by

$$T_{out} = G[(F-1)T_o + (1-A)T_a] , \qquad (4)$$

where A is defined as before but refers to the RF-combiner parameters.

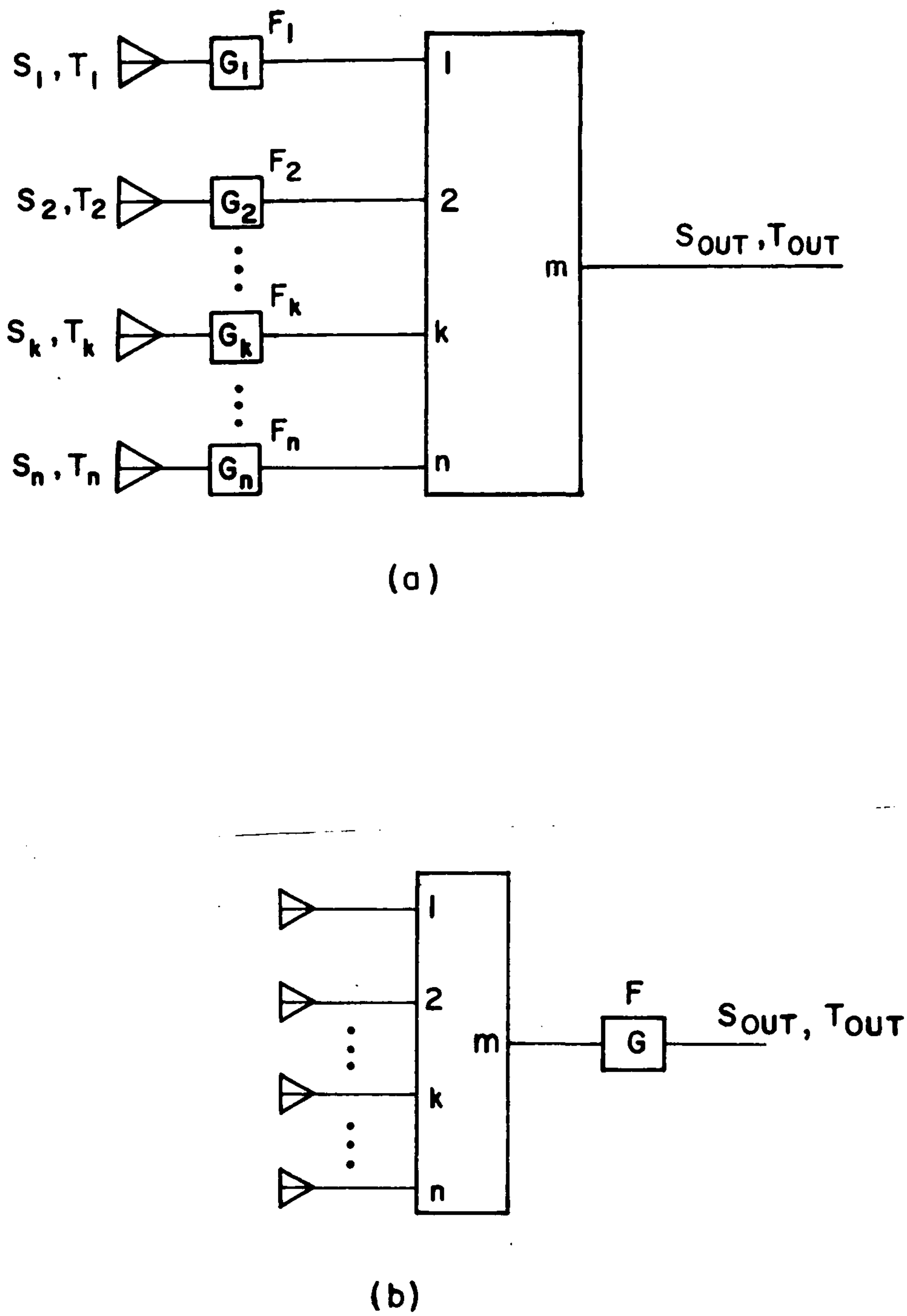


Figure 5. Representation of arrays.
(a) with IF phasing
(b) with RF phasing

If in the preceding equations F and G are taken as pertaining to the mixer-IF amplifier combination, G is very large. In that case manipulation of the equations gives the ratio of the S/N ratio for IF combination relative to that for RF combination as

$$(S/N)_{IF}/(S/N)_{RF} = [(F_b-1)T_o + (1-A_{RF})T_a]/[(F_a-1)T_o] \quad . \qquad (5)$$

Here F_a refers to the noise figure of the converters used as in Figure 5a and F_b to the noise figure of the single converter in Figure 5b (which may be better since more money can be spent on a single device than on many). A_{RF} denotes the efficiency parameter A of the RF combiner in Figure 5b. The corresponding IF parameter does not enter the equation since the high gain ahead of the IF combiner has established the signal-to-noise ratio prior to that device.

The noise figures for available converters were discussed above. Their range is quite limited. On the other hand the efficiency of RF combiners becomes very small when antennas as large as 10 meters on a side are considered for frequencies on the order of 30 GHz. Thus for non-cryogenic converters, signal-to-noise considerations definitely favor the IF-combiner system. We have not obtained data on the expected noise performance of very sophisticated cryogenic systems, but it seems unlikely that even with such systems the RF combiner would have any significant advantage from the S/N viewpoint, while it would have very definite disadvantages from the viewpoint of reliability.

3. Radiometric arrays

A technical report on the implications of very large array antennas on radiometric system design has been prepared [2]. Only a brief summary of results is given here.

Current airborne and satellite radiometers use RF combining in order to allow Dicke-switching (Figure 6) for good temperature resolution. When an attempt is made to improve directional resolution by increasing the antenna size substantially above current ones, three difficulties develop. First, it is difficult to obtain large RF bandwidth. Since the sensitivity or temperature resolution varies inversely as the square root of predetection bandwidth, this degrades the sensitivity. Second, since the swath width decreases with increasing spatial resolution it is necessary to increase the scan rate to cover the same area in the given time; at the same time more resolution cells must be covered per scan. The result is a loss of available integration time, which also reduces the radiometric sensitivity. Thirdly, the efficiency of the antenna-feed combination decreases due to longer transmission paths and more levels of combining. This degrades the relative radiometric signal-to-noise ratio as shown in Figure 7. The array configuration pertaining to Figure 7 is the same as discussed above under "RF-phased receiving arrays", and the frequency is 30 GHz. A possible scheme for avoiding the signal-to-noise degradation is shown

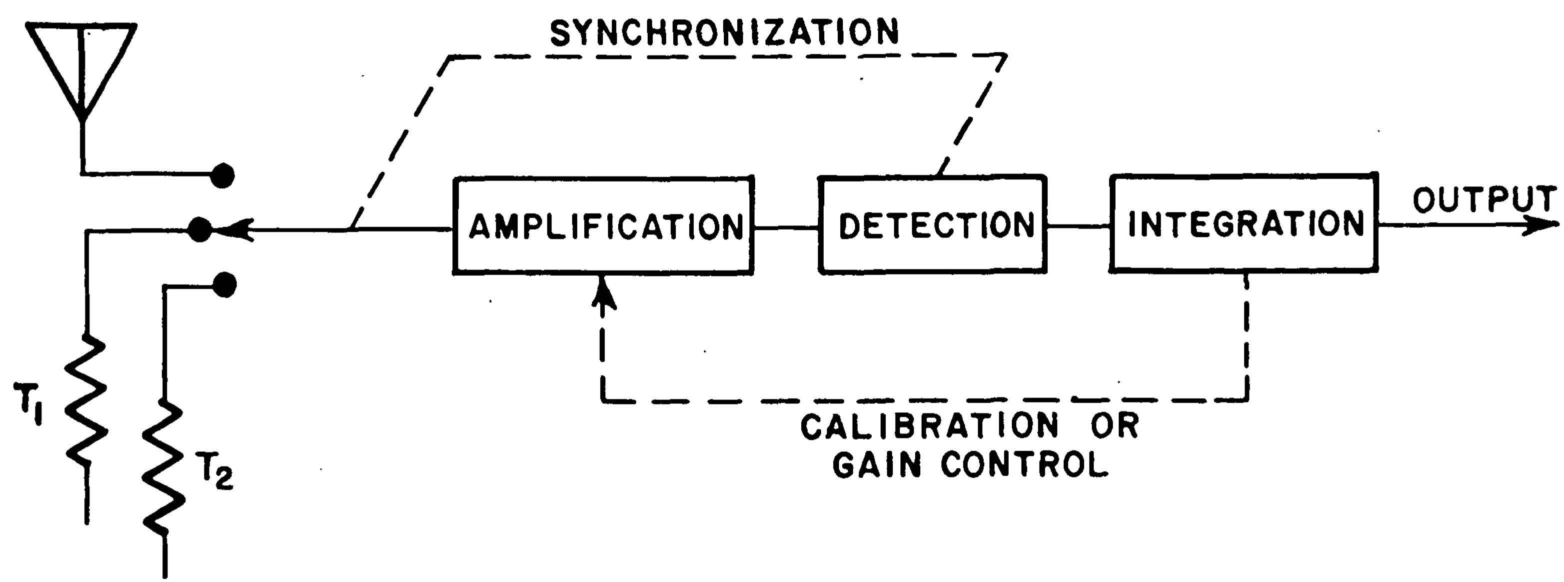


Figure 6. Calibrated Dicke radiometric receiver.

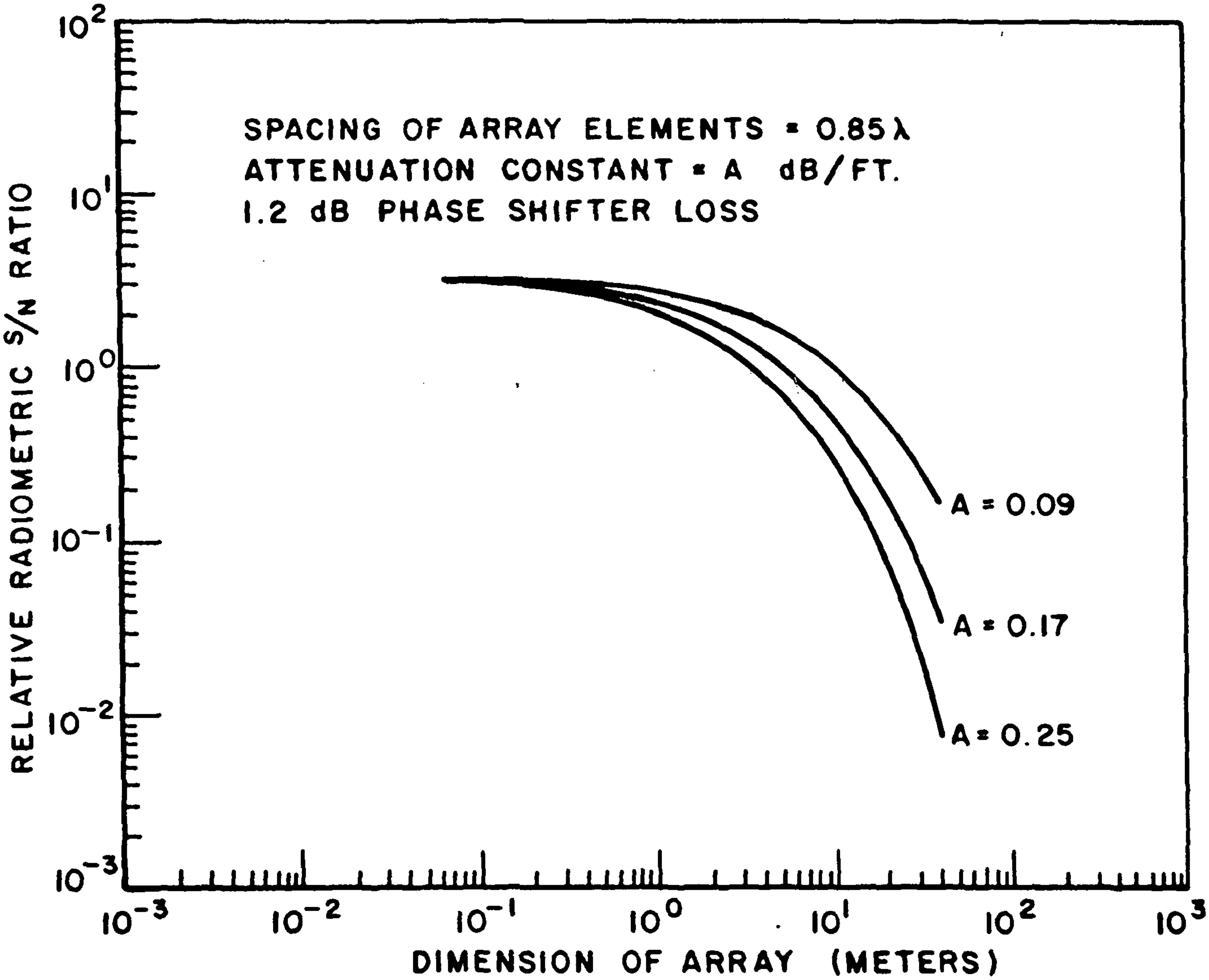


Figure 7. Relative signal-to-noise ratio of the corporate array for reception of a spatially uniform radiometric signal at 30 GHz.

in Figure 8. Subarrays or subapertures of conventional size are shown stabilized by Dicke switches in the conventional way. The Dicke switches are synchronized. The signals are then combined at IF in a beamforming matrix. Since the signal-to-noise ratio is established at the first active element, frequency conversions can be chosen to allow the best possible realization of linear phase shifts (true time delays), to avoid the bandwidth problem, and to allow construction of the beamformer in a convenient frequency range. Losses in these devices also play a much less important role in this system than in the conventional; thus easing their design constraints. The stage of premplification shown in the figure would be omitted in the frequency range of concern here, since suitable preamplifiers are not available. No detailed investigation of this scheme has been carried out, but it is believed to warrant consideration as a possible solution.

Another solution might be the correlation radiometry technique finding increasing application in radio astronomy [20-23]. The problems for the two applications are related but not identical, and it is not clear to what extent correlation techniques can aid in the earth-imaging application. Both of these approaches appear to warrant further investigation.

4. Arrays of subapertures

The number of elements in a large filled aperture becomes excessive if the usual spacing criteria for grating lobe prevention are observed. For example, a 10 meter by 10 meter array at 30 GHz with half-wavelength spacing would contain four million elements. The cost of phase shifters and RF combiners, or alternatively of mixers and IF combiners, would be formidable. However, thinning causes grating lobes if done on a regular basis and an increase in general side lobe level if done randomly; in either case the gain is reduced greatly to a value commensurate with the number of remaining elements, not the total aperture.

Conceptually, there should be a way to avoid this problem and still reduce the number of terminals to be connected to phase shifters or mixers. A proposed design procedure is developed in Figure 9. Figure 9a shows a cosine-on-a pedestal distribution, such as might be applied in a long continuous slot aperture in a ground plane. Since this is a continuous distribution, it generates no grating lobes. The side-lobe level is controlled by the taper and pedestal. In Figure 10 the pattern of a cosine-on-pedestal distribution 50 wavelengths in extent is shown as the solid line, and the absence of grating lobes can be noted. The cosine-on-a-pedestal distribution is used here simply for illustration, the method is applicable to any continuous distribution. In Figure 9b we have the same distribution, but we now consider it to be made up of a number (here seven) of adjacent subaperture distributions. If the signals from the subapertures are added, the resulting pattern will clearly still be the same as before, i.e., the solid curve of Figure 10. Note that the configuration of Figure 9b is an array but not one of identical elements, so that the usual array theory (such as pattern multiplication) does not apply. Thus there is no reason to expect grating lobes, and of course none exist.

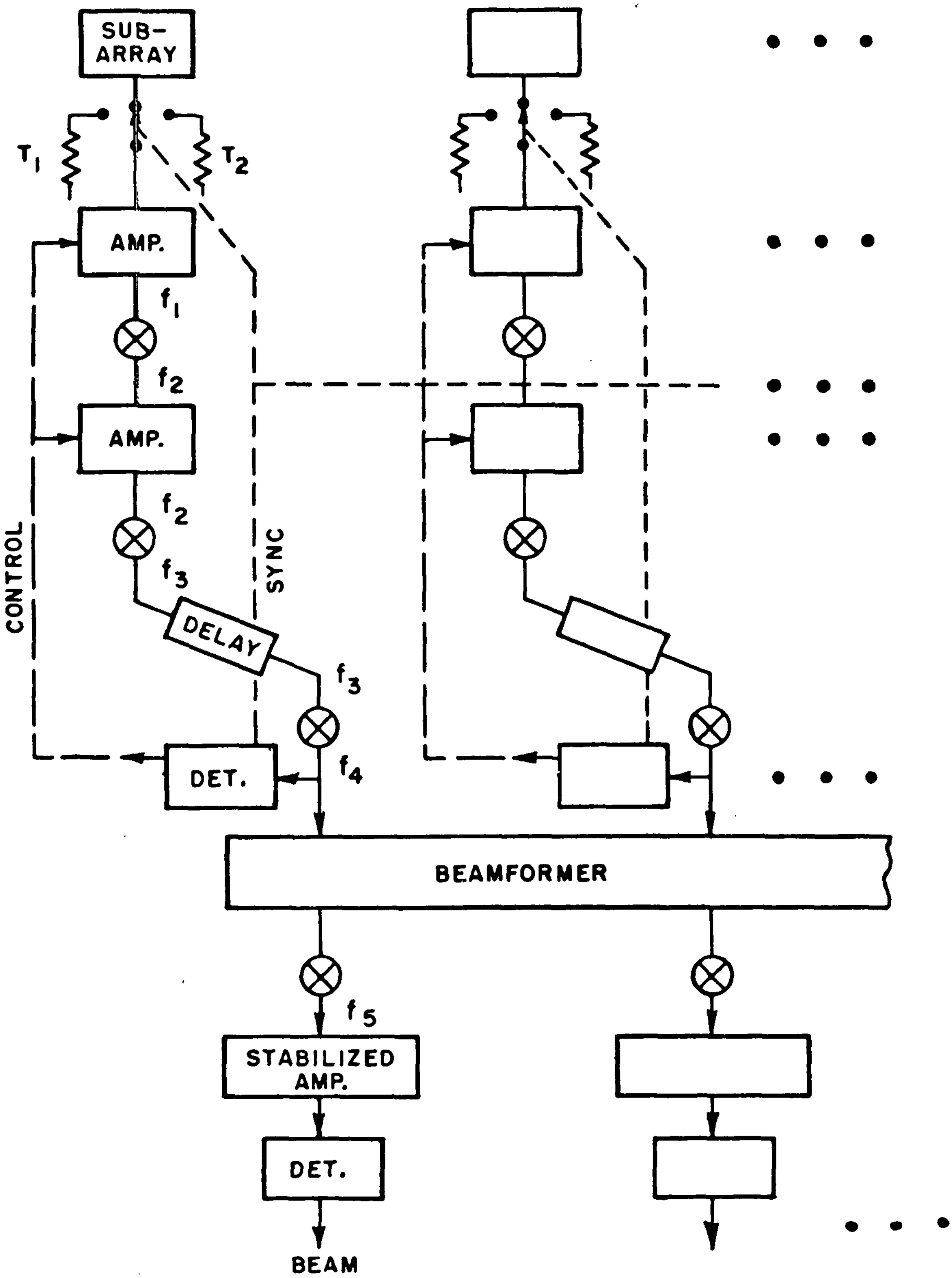
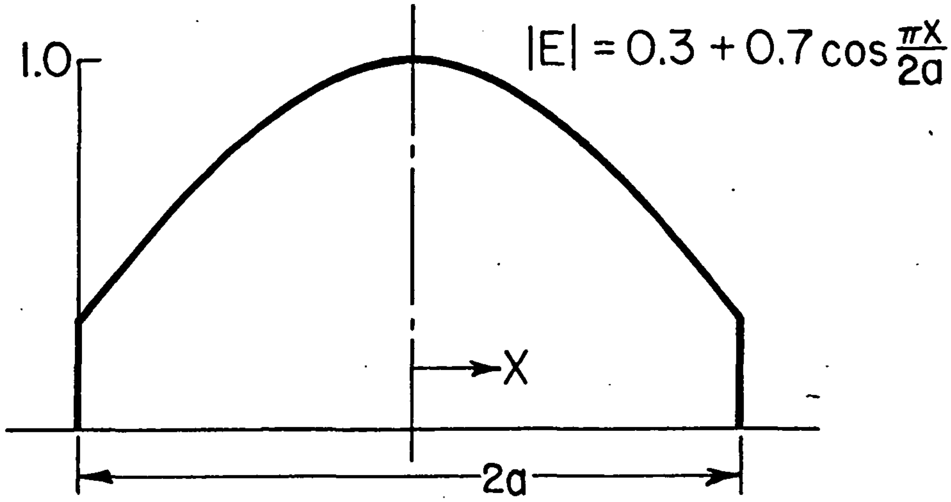
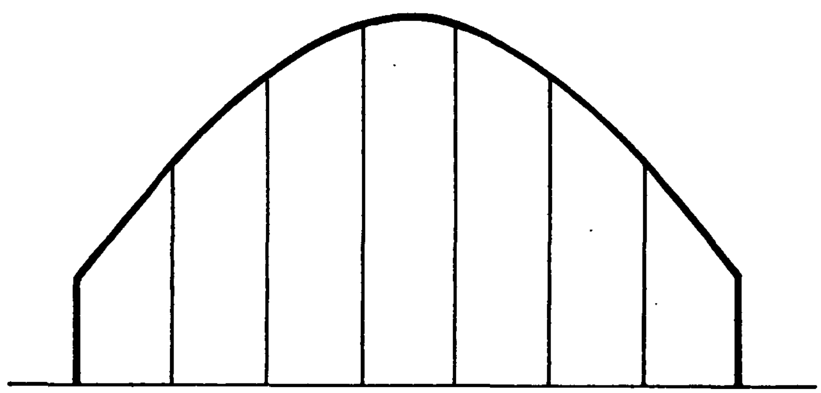


Figure 8. Modified Dicke receiver using distributed switching.

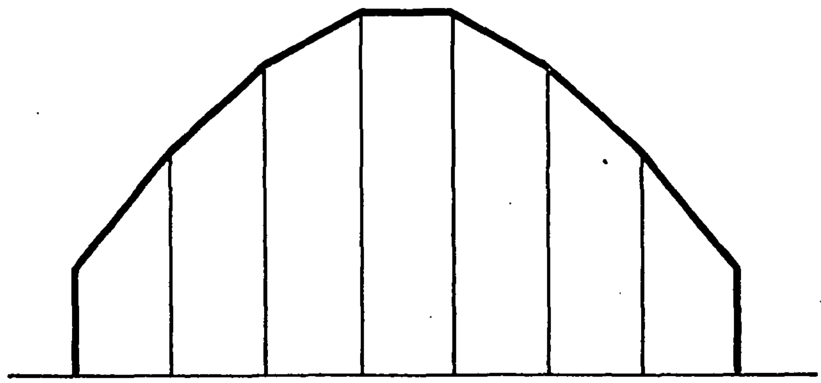


a. continuous distribution

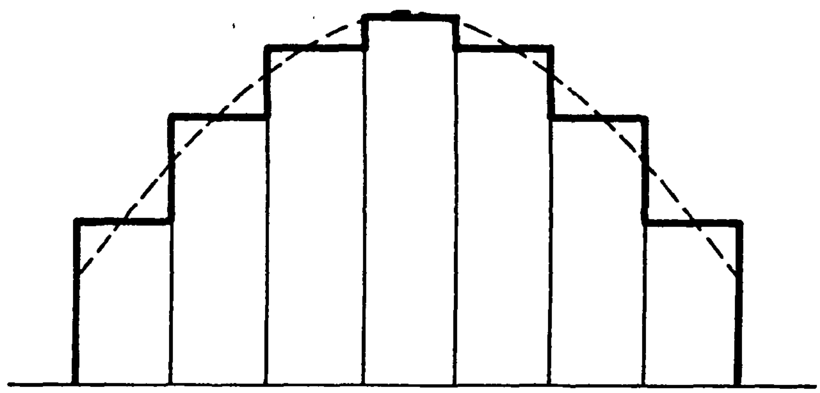


b. continuous distribution
divided into subapertures

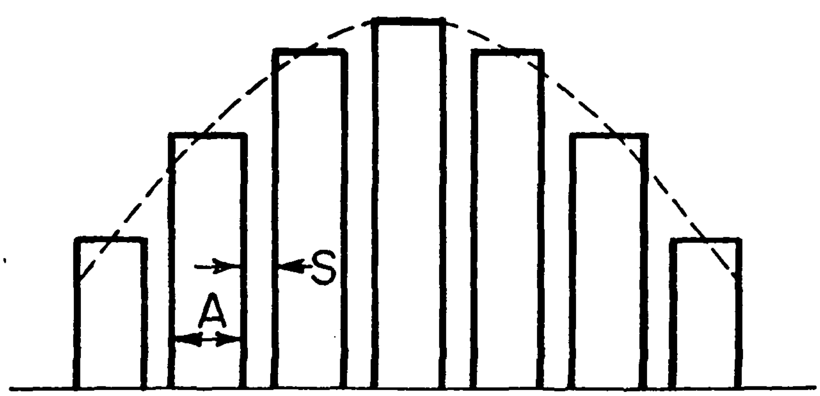
Figure 9. Array design concept.



c. linear approximation



d. staircase approximation



e. staircase approximation with spacing between subapertures

Figure 9.

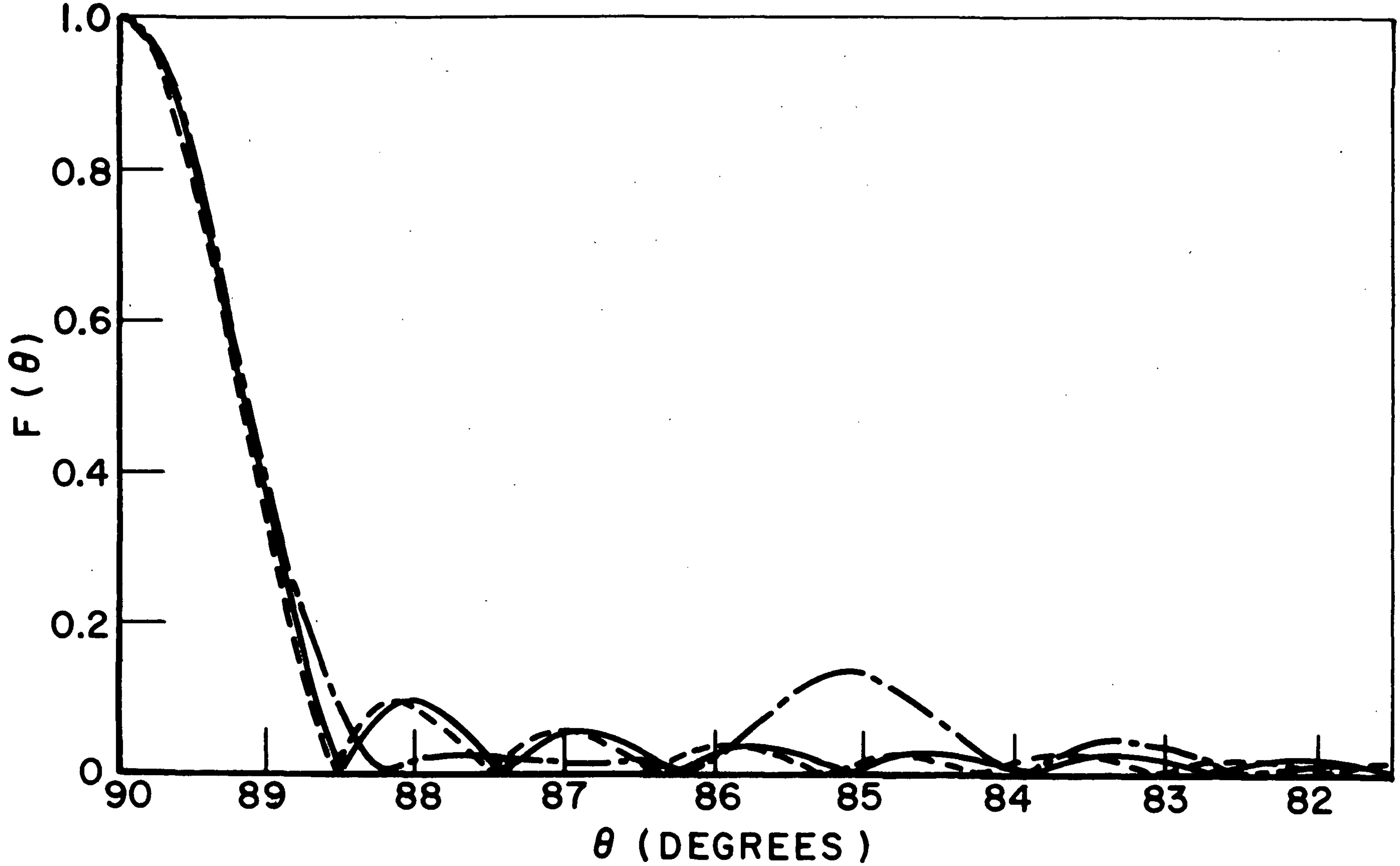


Figure 10. Calculated patterns for the distributions of Figures 9a to 9d based on the continuous distribution $[0.3 + 0.7 \cos(\frac{\pi x}{2a})]$. (Solid curve, 9a & b; dashed curve, 9c; dot-dashed curve, 9d.)

Consider next the approximation of Figure 9c, in which the distribution along each subaperture has been replaced with a straight-line approximation. The number of subapertures chosen for this calculation was five. The calculated pattern appears in Figure 10 as the dashed curve. Since the approximate aperture distribution is a good approximation to the original one, the patterns approximate each other closely also. No grating lobes are present. Again this does not contradict array theory since the elements are not identical. The distribution of Figure 9c can, however, be considered as the superposition of two identical-element arrays; one with elements which have uniform distributions equal to the average value over the subaperture, and the other with a linearly varying zero-mean distribution of amplitude equal to the slope of the linear approximation. Alternatively, we can think of this case as an array of elements each of which has two feeds. One feed creates the uniform distribution, while the other creates the antisymmetrical or slope distribution. Since the ratio of the two distributions varies from element to element, they are not identical.

As a next step, we omit the slope distribution, as shown in Figure 9d. This yields a true array of identical elements, since the distribution of each is uniform. The corresponding pattern is shown in Figure 10 as the dot-dashed curve. Since the spacing of the subapertures is 10 wavelengths, one might expect a grating lobe to appear at 84.2°. Instead we find a null at this position, but distinct lobes on each side of it. It turns out that when the elements are uniform distributions of the same length as the spacing, i.e., continuous distributions with no "empty" space between, the grating lobes become degenerate because the element pattern has nulls at precisely the locations where grating lobes ought to appear. Moreover, these degenerate lobes decrease in amplitude as the number of steps in the "staircase approximation" of Figure 9d increases. The formulas used to calculate the patterns of Figure 10, and which are the basis of the previous statement about the degeneracy of the grating lobes, are given in the Appendix.

In practice, there may be some difficulty in obtaining the staircase approximation precisely. The subapertures are likely to have metal walls, and the electric field tangential to a metal wall goes to zero in the vicinity of the wall. Also, spacing may be needed between subapertures for mechanical reasons. The result is a configuration of the type shown in Figure 9e. Figure 11 shows the pattern for this configuration when the total aperture length is 1000 wavelengths (10 meters at 30 GHz) and 51 subapertures are used. The dependence of the grating lobes on spacing is evident, and it is clear that the spacing should be kept as small as possible. It is also evident from Figure 11 that for zero spacing the degenerate grating lobes become very small (too small to show on the scale of the graph) when 51 subapertures are used. The physical explanation is that the staircase approximation becomes closer and closer to the original continuous distribution as the number of steps is increased.

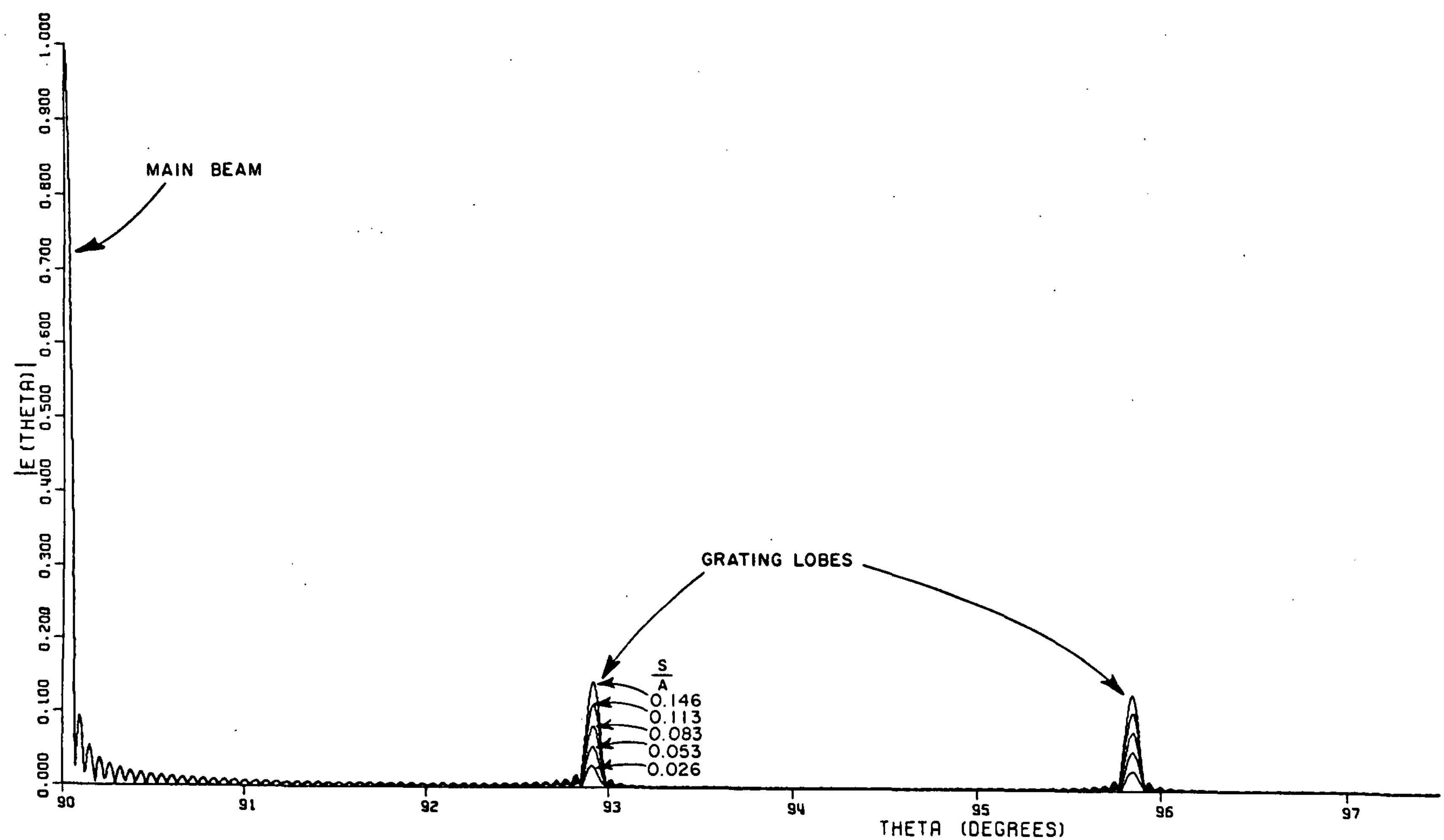


Figure 11. Calculated pattern for the distribution corresponding to Figure 9e. The aperture is 1000 wavelengths long and divided into 51 subapertures. The parent distribution is [0.3 + 0.7 cos ($\pi x/2a$)].

The preceding discussion applied to the case when the array was scanned in the broadside direction. Figure 12 shows that the character of the pattern does not change greatly with scanning. The calculations assumed that the subaperture distributions were uniform in amplitude and had a uniform phase progression across each subaperture of such magnitude that its beam maximum occured at 95° (5° from broadside). Likewise the phasing of the subapertures with respect to each other was such as to cause the main beam to appear at 95°. The total aperture length is 1000 wavelengths, and it is divided into 51 subapertures with one-wavelength spacing between adjacent edges, giving an S/A ratio of 0.54. Except in the grating lobe regions (at 92° and 98°) which are caused by the spacing S, the pattern is indistinguishable from that of the parent cosine-on-pedestal distribution when scanned in the same direction (95°).

Means of realizing the scannable subapertures were not investigated. Electrical subaperture scanning would of course be excellent if a means of implementing it with low loss can be found. Another possibility might be scanning by mechanical motion of a low-inertia element, as was utilized in the Eagle scanner [24]. No attempt was made to see whether this concept is compatible with the required scan rates. The realization of appropriate elements needs further investigation, and the preceding comments were offered only as suggestions.

In the type of array discussed here, the subapertures must be scanned at least roughly in the direction in which the array is scanned, but it would be a severe requirement to require each subaperture to scan precisely in the right direction. For precise scanning, the phase progression along the aperture (in the case of no spacing) would be entirely uniform; for imprecise subaperture scanning, random phase jumps occur between subapertures. Since the spacing is periodic, these phase jumps can be expected to cause grating lobes, but a preliminary calculation has shown that this effect is not serious. Figure 13 shows the average effect on both main and grating lobes of normally distributed random perturbations of the subaperture phase slopes about their correct values for the same 51-element stair-case array with one-wavelength spacing between subapertures. The main beam deteriorates at about the same tolerance level at which the grating-lobe effect becomes significant; thus the latter might increase the phase-tolerance requirements a little, but not much. This result appears to hold over a wide range of scan angles.

Our conclusion at the present stage of this investigation is that the large-subaperture approach appears to hold promise provided a suitable element can be designed for the subapertures.

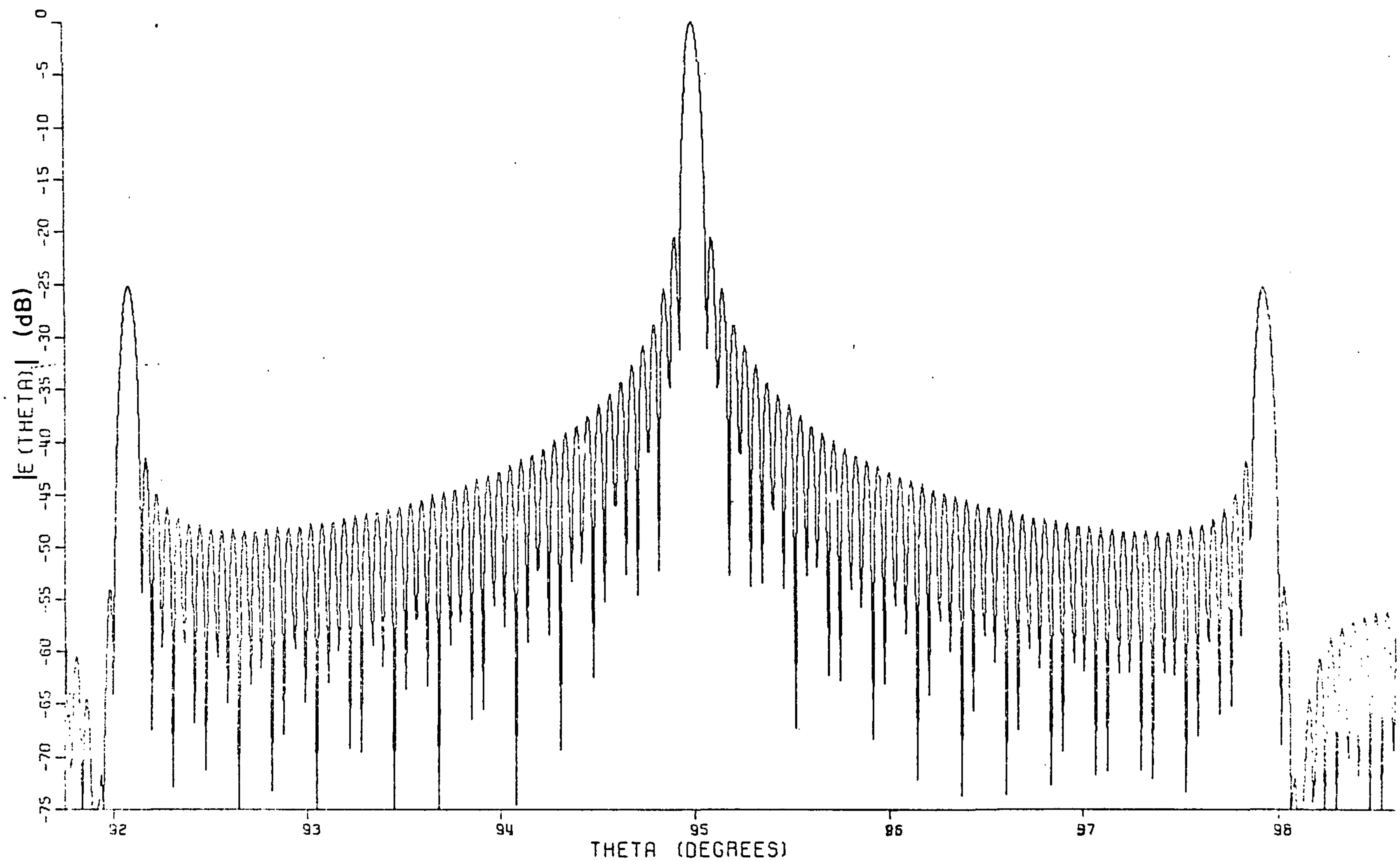


Figure 12. Same as Figure 11, but phased to scan beam to 5° from broadside.

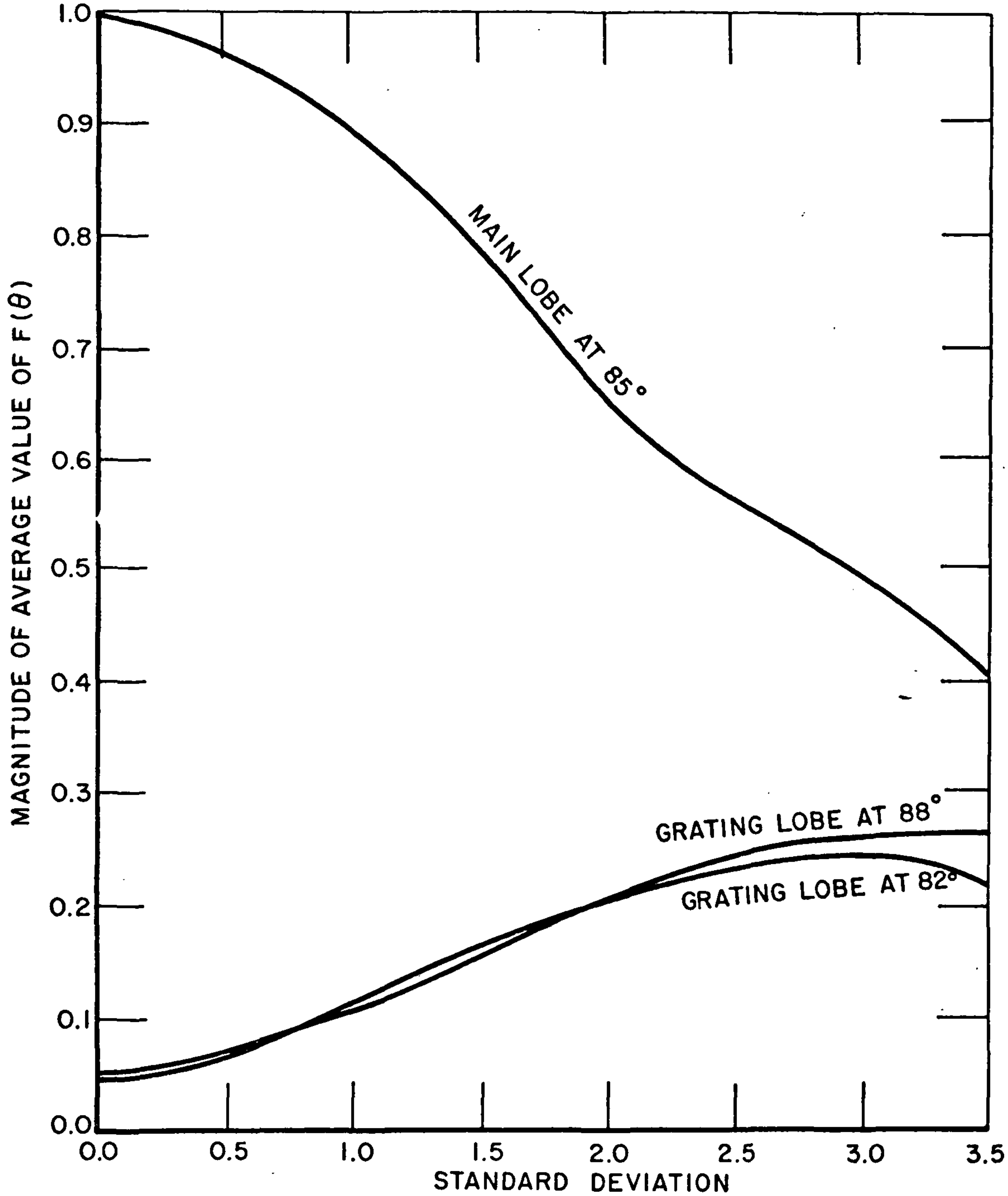


Figure 13. Average levels of main-beam and grating-lobe maxima as functions of normally distributed random errors in the subaperture phase slopes. All curves normalized with respect to the unperturbed main beam maximum.

IV. PUBLICATIONS AND ORAL PAPERS

A. Technical Reports

The following technical reports were published under this contract:

1. H. C. Lin, "Noise Performance of Very Large Antenna Arrays", ElectroScience Laboratory Report 3931-1, September 1975. NASA-CR-144716, NTIS No. N76-15333/7WY.

2. C. A. Levis and H. C. Lin, "System Implications of Large Radiometric Array Antennas", ElectroScience Laboratory Report 3931-2, June 1976. (NASA and NTIS numbers not yet assigned)

B. Journal Publications

C. A. Levis and H. C. Lin, "System Implications of Large Radiometric Array Antennas", submitted for the February 1977 Low-Noise Technology Issue of the IEEE Transactions on Microwave Theory and Techniques.

C. Oral Presentations

1. L. J. Ippolito, W. H. Kummer, C. A. Levis, "Space Shuttle Millimeter Wave Experiment," 1975 IEEE International Convention, Session E, New York, April 1975.

2. C. A. Levis, T. K. Lai, H. C. Lin, "The Organization of Radiometric Arrays", 1975 Spring Meeting of the US National Committee of the International Scientific Radio Union, University of Illinois, June 1975.

3. C. A. Levis and H. C. Lin, "System Implications of Large Radiometric Array Antennas", accepted for the 1976 IEEE International Symposium on Antennas and Propagation, The University of Massachusetts, October 1976.

(Note: Printed abstracts or summaries are published in the case of all three meetings. In the case of item 2, the oral presentation did not take place because of an injury suffered by the speaker the day before the meeting.)

V. NEW TECHNOLOGY

The distributed-switch Dicke radiometer discussed in section III.C.3 and shown schematically in Figure 8 is believed to be a new concept. So is the large-aperture design procedure using subaperture approximations to a continuous distribution as discussed in section III.C.4.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Additional MWLAE Uses

A class of radio-astronomical experiments involving the search for organic molecules in interstellar space could take advantage of the MWLAE radiometric sensor if it is implemented. The sensor could also be useful for sensing atmospheric turbulence by means of anomalies in water-vapor related emission near 22 GHz. Large oil spills may potentially be monitored and mapped by multispectral radiometry utilizing the MWLAE. These tentative applications warrant further exploration.

While there is interest in the MWLAE user-mode experiments in the scientific community, potential investigators are apparently deterred by lack of resources from anything beyond a cursory look at possible experiments. A modestly funded program to encourage definition of suitable user experiments by potential experimenters may be needed.

B. Technology and Components

In the case of RF combining, phase shifters and signal combiners are of great importance because of the large numbers required in filled arrays. The same is true of mixers for IF combining. Efforts to reduce the production costs of such devices are indicated. Noise performance of these devices is estimated in section III.B.4.

C. Array Organization

At 30 GHz, RF combination is satisfactory from a signal-to-noise viewpoint for apertures on the order of 1 meter square. Gain loss is substantial when the aperture is 10 meters square and catastrophic for much larger apertures. Signal combination at IF can be shown to have significant signal-to-noise advantages over RF signal combination when the array is large. Formulas for computing the advantage for specific conditions are given in section III.C.2.

Radiometric arrays utilizing RF combining ahead of a Dicke receiver (or multiple Dicke receivers) fail because of signal-to-noise, bandwidth, and integration time considerations when the array is made large in order to achieve spatial resolution. An original design conceived on this contract, using coordinated Dicke switches and IF combining, and the application of correlation receiver techniques are two approaches recommended for further study in order to avoid this difficulty. Details are given in Section III.C.3.

To avoid the cost of an excessive number of mixers while retaining the advantages of a filled array, the arraying of sub-apertures is proposed. It is shown in Section III.C.4 that grating lobes are not a problem if the subapertures are fed as a staircase approximation of a continuous aperture provided the effective spacing between subapertures is small. The effect of spacing on grating lobes is demonstrated. It is shown that such arrays can be scanned. Random errors in the phase slopes (i.e., mis-pointing) of subapertures are shown to have small effects on the grating lobe levels. Further study of this approach, which is also believed to be original, is recommended.

VII. REFERENCES

1. H. C. Lin, "Noise Performance of Very Large Antenna Arrays", Report 3931-1, September 1975, The Ohio State University ElectroScience Laboratory, Department of Electrical Engineering; prepared under Contract NAS 5-20521 for NASA, Goddard Space Flight Center. (NASA-CR-144716, NTIS N76-15333/7WY)

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APPENDIX

In accord with Figure 9c, we assume an aperture distribution of the form

$$\vec{E} = \hat{a}_x \, (A_n + k_n y) \tag{A-1}$$

where coordinates and dimensions are defined in Figure 14.

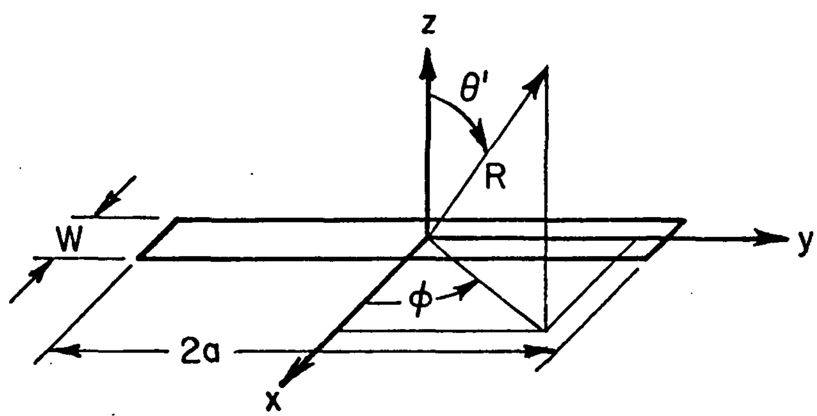

Figure 14. Slot aperture geometry.

The n-th segment is defined by

$$(2n-1)a/N < y < (2n+1)a/N \;, \tag{A-2}$$

and N, the total number of segments, is odd.

Standard antenna theory [25] gives

$$\vec{E} = w(\hat{a}_x \cos\theta' - \hat{a}_z \sin\theta' \cos\phi)(jk/2\pi R)e^{-jkR} \times$$

$$\int_{-a}^{a} E_x(y) \, e^{jky \sin\theta' \sin\phi} \, dy \;. \tag{A-3}$$

Setting $\phi=\pi/2$ and $\theta=\theta' - \pi/2$ transforms this to

$$\vec{E} = -\hat{a}_x (jkw/2\pi R)\ F(\theta)\ , \tag{A-4}$$

where

$$F(\theta) = \sin\theta \int_{-a}^{a} E_x(y) e^{jky\cos\theta} \quad . \tag{A-5}$$

Denoting the distance between element centers as d,

$$d \equiv 2a/N \quad , \tag{A-6}$$

substituting for E_x from Eq. (A-1), and performing the indicated integrations in the various intervals gives

$$F(\theta) = \sin\theta\ \{f_1(\theta)S_1(\theta) + f_2(\theta)S_2(\theta)\} \tag{A-7}$$

where

$$f_1(\theta) = \left[2d \sin\left(\frac{kd}{2} \cos\theta\right)\right]/(kd\cos\theta), \tag{A-8}$$

$$S_1(\theta) = A_o + 2 \sum_{n=1}^{(N-1)/2} (A_n + nk_n d) \cos(nkd\cos\theta), \tag{A-9}$$

$$f_2(\theta) = \left[kd \cos\theta \cos\left(\frac{kd}{2} \cos\theta\right) - 2\sin\left(\frac{kd}{2} \cos\theta\right)\right] \Big/ (k^2\cos^2\theta), \tag{A-10}$$

$$S_2(\theta) = 2 \sum_{n=1}^{(N-1)/2} k_n \sin(nkd\cos\theta), \tag{A-11}$$

where use has been made of the symmetries apparent from Figure 9c,

$$A_{-n} = A_n \tag{A-13}$$

and

$$k_{-n} = -k_n \ . \tag{A-14}$$

Equation (A-7) may be interpreted as the superposition of two array patterns. The quantity $[\sin\theta \, f_1(\theta)]$ is the element pattern function of a uniform distribution. The element amplitudes are given by $(A_n + nk_n d)$, which is just the average value of E_x in the n-th interval. $S_1(\theta)$ is the corresponding array pattern function. Thus the first term in the bracket of Equation (A-7) is the pattern for the staircase distribution of Figure 9d. The degeneracy of the grating lobes of that pattern follows from the fact f_1 vanishes for

$$kd \cos \theta = 2n\pi \ , \qquad \text{(A-12)}$$

which is precisely the condition which causes all the terms of S_1 to add in a positive sense, i.e., which defines the grating lobe maxima.

The second term of Equation (A-7) is the pattern of the asymmetrical distribution due to the slopes in Figure 9c. The quantity f_2 is the pattern of a distribution having zero mean and unity slope, while S_2 is the array pattern for an asymmetrical distribution in which the n-th element has amplitude k_n.