AD-A121 659 PHASED ARRAY LENS RADAR SYSTEM WITH SHARED SOLID-STATE MODULES(U) NAVAL RESEARCH LAB WASHINGTON DC T C CHESTON 26 NOV 82 NRL-MR-4963 1/1

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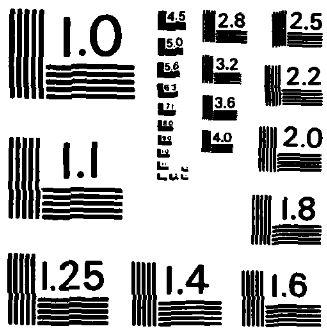

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 4963	2. GOVT ACCESSION NO. AD A121659	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PHASED ARRAY LENS RADAR SYSTEM WITH SHARED SOLID-STATE MODULES		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) T.C. Cheston		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62712N; SF12131691; 0611-00
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Washington, D.C. 20362		12. REPORT DATE November 26, 1982 13. NUMBER OF PAGES 12
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOT

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Phased array radar
Beam steering
Solid-State T/R modules

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A novel phased array system is described where solid-state T/R modules, which include diode phaseshifters, are shared between two apertures. Two such systems are required for hemispherical coverage. Efficient and cost-effective operation is claimed.

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S/N 0102-014-6601

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CONTENTS

PHASED ARRAY LENS RADAR SYSTEM WITH SHARED SOLID-STATE MODULES

SUMMARY

A novel cost-effective phased array radar system has been studied. It uses advanced technology with high reliability and offers the flexibility to adapt to future requirements; it seems particularly suitable for shipboard application. This report contains a general description of the system and gives some parameters for a possible S-band configuration with wide bandwidth.

Cost-effectiveness is obtained through the use of solid-state amplifying transmit/receive (T/R) modules which include diode phase shifters and their drivers, and which are shared between two corresponding radiating elements of adjacent array apertures. These apertures form part of a space-fed lens system with entrance and exit surfaces separated, approximately at right angles, and reversible in function. The solid-state modules form part of the interconnection of the two apertures, giving T/R amplification within the lens. Transmitters and phase shifters with their drivers typically account for up to 80% of the total hardware cost of phased array radars. Sharing reduces these costs significantly. With distributed solid-state modules, power distribution losses are small, leading to high overall efficiency, and phaseshifter requirements are simplified; life cycle costs are reduced from those of conventional systems using vacuum tubes that have to be replaced periodically. Solid-state components are beginning to be readily available, at least in demonstration models, to S- through X-band. The system has the potential of wide bandwidth, high reliability, and can use methods for diagnostics and self grooming.

INTRODUCTION

Phased arrays offer considerable flexibility to a radar system. With complete control of phase to every element of the aperture, the radar beam may be steered rapidly through a wide range of scan-angles. High data rates are available for adaptively interlaced functions including fire-control, surveillance and even communications. For shipboard applications, the four phased array faces which are required for hemispherical coverage, are split between fore and aft to eliminate obstructions caused by the superstructure. A phased array radar may interact freely with a multiplicity of targets under a variety of conditions and adjust its time allocations to give preference to the most pressing immediate needs. That phased arrays have not proliferated is due to their very high cost. With traditional phased arrays using high power tubes, typically about 30 to 40% of the total radar cost is accounted for by the antenna, mainly due to the cost of the phase shifters and their drivers, and about 40 to 50% of the cost is due to the transmitter. The system described below is an attempt to reduce these costs for shipboard application, without prejudice to the performance: in fact, it is found that it results in a number of advantages.

Manuscript approved September 23, 1982.

DUAL APERTURE LENS

Figure 1 shows schematically two phased array apertures, I and II, which might be found both fore and aft on a ship. The apertures are substantially at right angles to each other but are tilted back for better vertical coverage.

The radiating elements of the two apertures (dipoles are shown) are interconnected with semi-rigid coaxial lines of approximately equal total length and include a solid-state T/R module with diode phase shifters and drivers. When aperture I is illuminated with relatively low RF power from feed "A", then a beam "A" will be radiated with high power from aperture II and can be steered with the phase shifters in the modules. Similarly, feed "B" will give rise to a beam "B" from aperture I. In this way, one set of solid-state modules can be shared by the two apertures and give over 180° of coverage in azimuth. Two such systems are required for complete hemispherical coverage.

The low power feeds "A" and "B" are offset so as not to create shadows in front of the radiating aperture. The efficiency of coupling from the feeds to the corresponding entrance aperture is not important since amplification takes place within the lens; this allows much flexibility in aperture illumination, which can be further enhanced by trimmers in the modules. Similarly, the phase shifters are exposed to low RF power only and their insertion loss is compensated by amplification.

There is much flexibility in designing the offset feeds. Several feeds may be instrumented with switching arranged to select any one at a given time, accompanied by an appropriate change in phase shifter setting to allow for the shift in focal position. The feeds may be optimized for monopulse sum and difference channel operation, and for either low sidelobes or high gain. Separate feeds may be used for transmitting and for receiving. A small transmit feed, for example, could illuminate the aperture with almost constant amplitude, leading to maximum gain-on-target, but with high sidelobes. Low sidelobe designs require not only carefully adjusted amplitude tapers over the aperture but also very precise phase control.

The two lens apertures are interconnected with semi-rigid coaxial cables of approximately equal length for maximum instantaneous bandwidth. Figure 1 indicates one way this can be done. The method shown gives exactly equal line lengths when the apertures are vertical and the solid-state modules are equally spaced on a vertical plane. The modules are then readily accessible from the rear. When the apertures are tilted back, the geometry becomes more complicated and the vertical plane may most conveniently be changed to a curved surface with variable module spacing. A careful layout is required; it may be advantageous to bend some of the cables. Ideally, for maximum instantaneous bandwidth, the line lengths are trimmed to keep the total feed-to-radiating-aperture pathlengths constant for all elements.

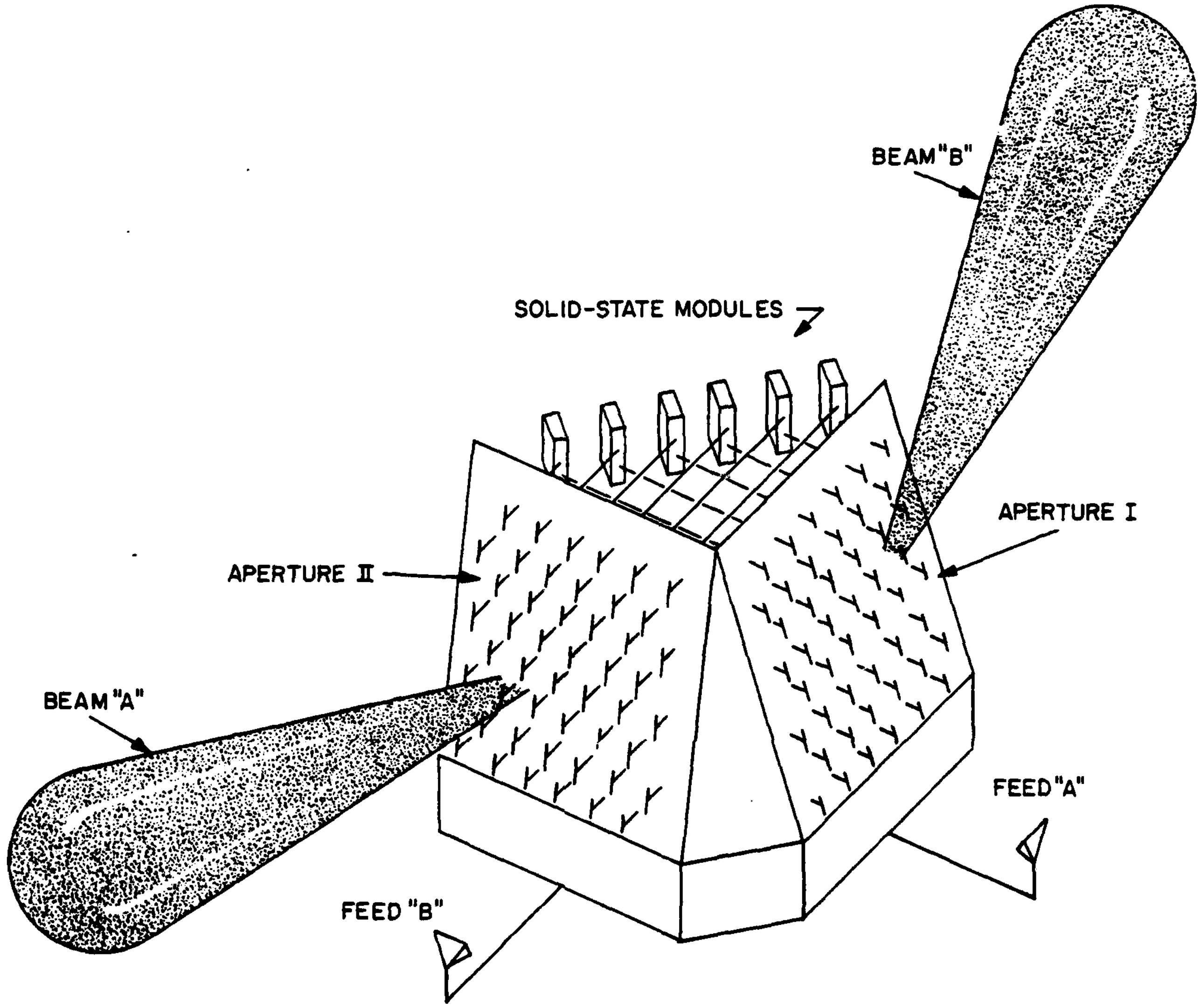

Fig. 1 — Phased array system

MODULES

Figure 2 is a schematic of the module. The power amplifier is likely to be a transistor chain——rather than a phase-locked oscillator. Trimmers in the transmitting and receiving channels may be provided to adjust the aperture amplitude distributions. A diode reversing-switch is used to select the proper apertures for beams into the one or the other quadrant. It has to pass the full output power of one module, which is not difficult. The diode phase shifters are low power and can be switched in fractional microseconds; they may require as many as 6 bits for low sidelobe performance. Their insertional loss may be high since it is compensated by module amplification; variations in insertion loss as a function of phase-setting should be kept small to avoid random aperture amplitude variations which cause sidelobes.

Transmit/receive circuits are separated by circulators, and a diode switch for additional protection of the receiver.

A different approach for the transmitter would employ limiters giving maximum and equal outputs at all modules, and maximum power on the target.

APERTURE DESIGN

The apertures have to be filled with elements spaced by approximately half-a-wavelength at the highest frequency in order to avoid grating lobes. Figure 3 shows elements using printed circuit techniques and giving an aperture with low scattering cross section in the H-plane. The element has not been either built or tested before, but may well be suited for wideband matching and is simple to feed from a single coaxial line. It is based on an element previously reported for wideband application (Ref. 1), but does have the advantage of including its own balun.

FREQUENCY AND BANDWIDTH

Solid-state components are quite readily available not only at UHF (Pave Paws AN/FPS 115), but also at L-band and are being used in at least one production radar, the TPS-59. They are also beginning to be readily available at higher frequencies, at least in demonstration models, at S-through X-band with nominal efficiencies of 30%.

Bandwidths of up to 15% are typically being obtained. This seems more than adequate at this time but much wider bandwidths should be aimed at for maximum flexibility in an unfriendly environment. The tuneable bandwidth is limited only by the performance of the components. Forty percent (1.5:1) bandwidth should be quite achievable. Re-phasing is necessary and can be done in microseconds or less with diode phase-shifters.

The instantaneous bandwidth of a phased array is dependent on the sine of the scan angle and the beamwidth. There are no limitations for the non-scanned beam positions; when scanned to 60°, the instantaneous

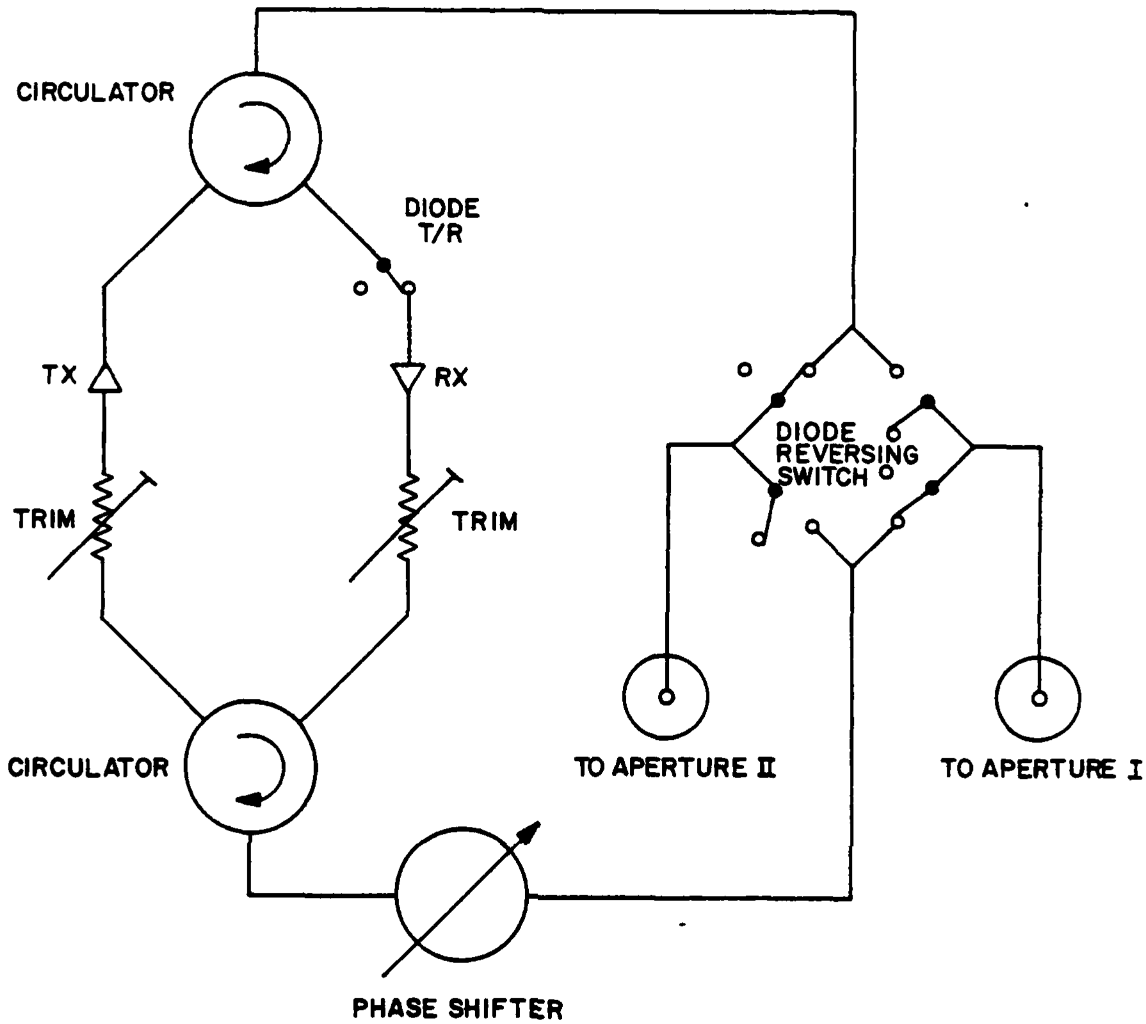

Fig. 2 — Schematic of module

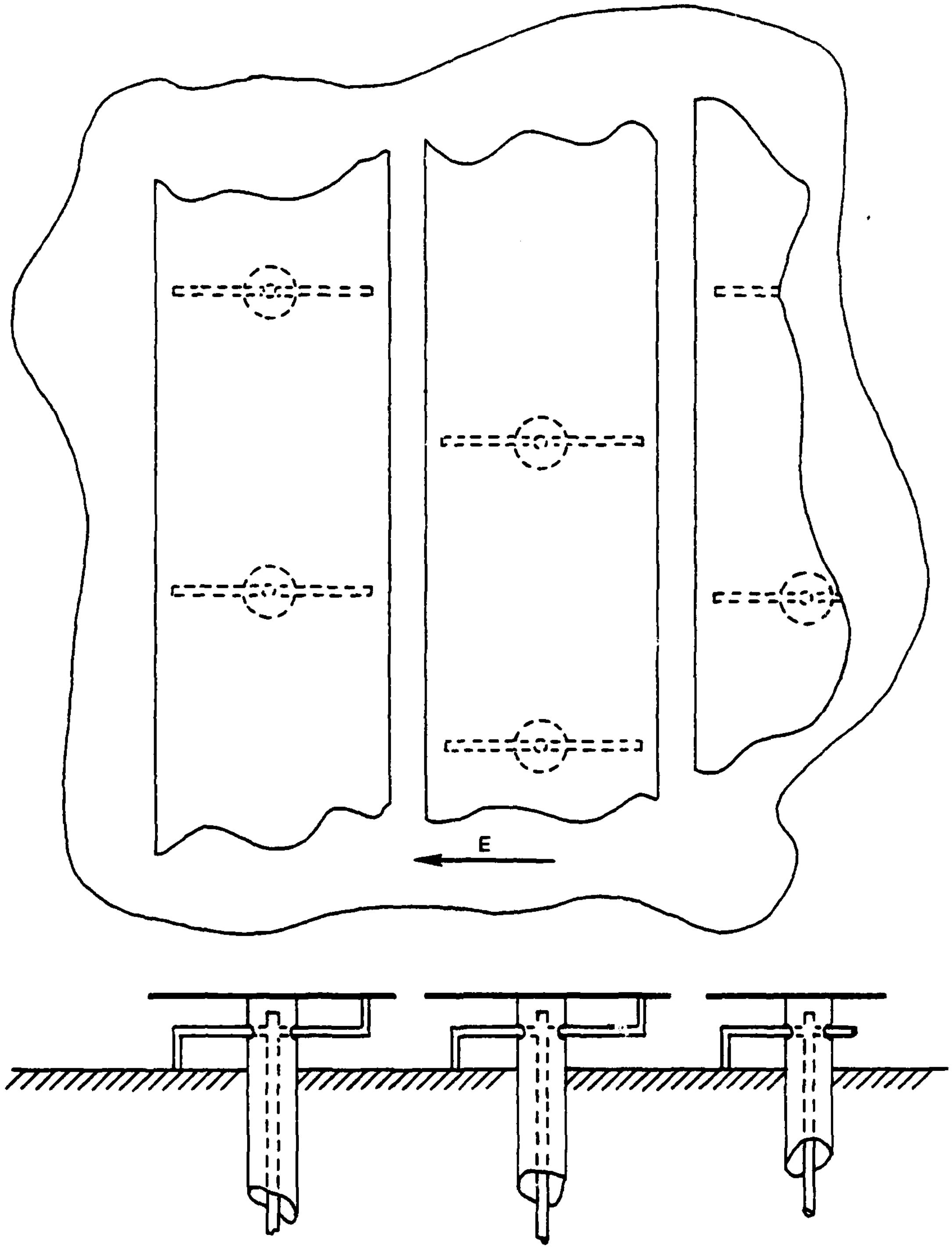

Fig. 3 – Radiating elements

bandwidth for a 2^{o} beam is 2 to 4%. In a paper by R. Mailleux in which he refers to work by Rotman and Franchi (Ref. 2), he points out that multiple feeds may be used with a lens, displaced relative to each other to correspond to different scan-angles with the same setting of phase shifters. Each beam may then be phase-scanned about its 0-phase shift direction, with corresponding increase in instantaneous bandwidth. To a first order, N feeds (in one plane) will give N-times the instantaneous bandwidth.

LOSSES

A distributed amplification system, such as described and shown in Figure 1, is significantly more efficient than conventional systems where there are additional losses due to the power dividing networks and phase shifters. These additional losses are conservatively estimated at 2-4 dB one-way.

RELIABILITY

System reliabilty should be very high. The transmitter should be designed to operate well below its peak and average power limits, and would then be highly reliable with its low voltage circuitry. The phase shifter operates at low power and again should be reliable. The whole system of distributed modules is fault-tolerant and leads to graceful degradation. Signal processing, however, is more demanding, since high pulse compression ratios are necessary; probably they would form the most vulnerable area.

COST

Most of the system costs will be due to the cost of the modules which also supply the transmitter power. The phased array antenna cost by itself appears to be quite low in comparison. Phase shifters and drivers traditionally are the most expensive items; here, their cost has been absorbed in the module and is believed to be relatively insignificant, not only because they are shared between two apertures, but also because they are used in a mode that places no heavy emphasis on low insertion loss. The solid-state transmitter which typically accounts for 40 to 50% of the overall phased array radar cost, should be quite cost-effective on its own ground and require some 2-4 dB less output power than an equivalent traditional system with power distribution and phase shifter losses. The maintenance cost should be quite low since there are no expandable parts.

MULTIPLE SIMULTANEOUS AND INDEPENDENT BEAMS

Multiple simultaneous and independent beams may be desirable so as to make better use of the available time. Such independent beams may be obtained with a phased array lens by dividing the aperture into sections and illuminating each with a separate feed. The output from each feed will then correspond to a beam with a beamwidth determined by the size of the aperture section. The beams may be scanned in the usual way by phase shifting. With equal aperture segments the overall gain is reduced in direct proportion to the number of beams. This method is not suitable for transmitting, since an additional and equal loss arises due to sharing the transmitter power between the various feeds; this results in a net loss of 6 dB every time the aperture is halved. For transmitting, either pulses may be sent to the several directions sequentially, or the whole aperture may be phased to generate simultaneous beams to these various required directions, with a loss in gain corresponding to the number of beams (Ref. 3). This last method gives rise to beams with large sidelobes but the beams are narrow since the whole aperture is used, and all the beam outputs are contained in one channel. It may also be convenient to use this method for receiving.

DIAGNOSTICS/SELF-GROOMING

A quiescent feed on the exit aperture side of the lens can be used to check the array in either transmit or receive modes but focused onto the feed. The focal spot is then raster-scanned and the received signal is recorded in both amplitude and phase. This is the Near Field equivalent of a diagnostic method developed at the University of Sheffield (Ref. 4) and allows an accurate calculation of the actual amplitude and phase distribution on the aperture. The extent of scan of the focal area determines the spot size on the aperture. An alternate system may be used for grooming to a proper phase trim by adjusting each phase shifter to conform with the phase of the average signal, after due correction has been made for the different path lengths. A simpler test would just check the actual functioning of all bits by sequentially exercising the phase shifters at a given rate and observing the received signal at the modulating frequency.

S-BAND CONFIGURATION

The following table lists some possible parameters for an S-band configuration. A very modest average power requirement of a few watts per module will satisfy even the most ambitious performance aims. Modules are quite realizable up to X-band. Peak power is limited to a perhaps conservative 2-4 times the average value; this does set the requirement for very high pulse compression.

TABLE I

PARAMETERS OF A POSSIBLE SYSTEM

Frequency	S-Band
No. of elements/face	5000
Total No. of elements (2 faces)	10,000
Total No. of modules (2 faces)	5000
Radiating element type	printed circuit
spacing	triangular
Sidelobes	low (Hamming)
Aperture size	14' x 14'
Beamwidth - sum pattern	
azimuth	1.7°
elevation	1.7°
Monopulse	az. & el.
Max. scan angle/aperture	$\pm 60^{\circ}$
Bandwidth - instantaneous	
60° scan	1.7 - 3.5%
without scan	10% now, 40% later
tuneable ($<1\mu$ sec)	10% now, 40% later
Transmitter power/module peak	15W
average	5W
Transmitter power/antenna face peak	75kW
average	25kW
Phase shifters	diodes
No. of bits	6

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