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Ka-Band Feed Arrays for Spacecraft Reflector Antennas With Limited Scan Capability–An Overview

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JPL and NASA are in the process of developing ground and spacecraft antenna systems at Ka-band frequencies for future deep space applications. The use of Ka-band (32-GHz down) communication will result in smaller ground and spacecraft antennas and associated equipment, and will provide larger bandwidths necessary for very high data rate communication and radio navigation. In this article, the use of a small phased array as a feed for a reflector antenna system with limited scan capability is addressed. Different feed and antenna configurations, as well as array architectures, are examined. Some theoretical and experimental parameters of a particular breadboard feed array developed by JPL and the University of Massachusetts are presented. Guidelines for the future direction of this effort are provided.

I. Introduction

JPL and NASA are in the process of developing ground and spacecraft antenna systems at Ka-band frequencies for future deep space mission applications, such as NASA's Solar Probe mission. Ka-band (32-GHz down) communication is planned to first supplement and perhaps ultimately supplant the X-band (8.5-GHz down) communication link presently used. This will result in smaller ground and spacecraft antennas and associated equipment, and will make available larger bandwidths necessary for very high data rate communication and radio navigation.

One crucial aspect of this development effort involves the design and development of advanced high-gain antennas on the spacecraft, which use state-of the-art monolithic microwave integrated circuits (MMIC) technology, solid state power amplifiers, and electronic beam steering. An important design consideration is that of the feed arrays for reflector antennas on the spacecraft. The feed array design depends on feed and reflector antenna architecture and configuration. A proposed method is the near-field Cassegrain (or Gregorian) dual reflector system in which a relatively small phased array is located very close to the subreflector, thus providing a plane wave incident on the subreflector.

The feed array is to be integrated with solid-state digital phase shifters and power amplifiers for transmission

and/or low noise amplifiers for reception. The advantages of using a small phased array in connection with a magnifying dual reflector system is threefold. First, it can provide vernier adjustment of the main reflector antenna beam by scanning the phased array beam incident on the subreflector. Second, the use of individual phase shifters and power amplifiers behind each radiating element means that the circuit losses at the dividers and phase shifters will occur prior to amplification and at very low power levels. Third, by using small solid-state amplifiers at the antenna element level, power from all amplifiers are in effect combined in space as opposed to the approach in which outputs from individual solid state amplifiers are circuit-combined at a substantial loss, before input to the array.

II. Near-Field Dual-Reflector Optics

A directly radiating phased array is usually used to obtain a robust electronically steered beam. To obtain a very narrow high-gain beam, however, a very large aperture array is required. However, a large phased array antenna is not a desirable option on a spacecraft due to its weight and loss, and the complexity of the required beam-forming network (BFN). Therefore, a large aperture reflector antenna is typically used on deep space probes and communication satellites. However, as discussed in [1], in a "happy medium" scenario, a small phased array can be combined with a large main reflector, via the intermediary of one or more small reflectors, to project a large image of the small array on the main reflector aperture.

The scan capability of the system is reduced, however, in inverse proportion to the magnification factor of the system, namely, the ratio of the reflector size to the array aperture size. For a magnification factor of 10, for example, an approximately ±1-deg reflector beam scan is achieved for a ±10 deg array beam scan. Thus, this concept of limited scan provides a practical way of increasing the gain of a small array at the expense of scan-angle coverage.

The small, or vernier, scan capability so provided for the high-gain reflector antenna will complement the large-scale antenna beam pointing provided by the spacecraft attitude control system, thus alleviating the need for mechanical vernier adjustments and the concomitant fuel consumption.

Figure 1 depicts two alternative scenarios. In Fig. 1(a), a symmetric confocal dual reflector Cassegrain system is presented in which both the reflector and the subreflector are paraboloids. In this arrangement, the small array is imaged by the subreflector onto the main reflector

aperture. However, this arrangement provides a very poor scan capability, since the center of the array and the main reflector are not conjugate points [1]. Furthermore, the blockage by the feed array can be substantial. The system in Fig. 1(a) is a simple mechanical structure due to its symmetry and can be used in cases where the array feed is employed not necessarily for the scan ability but for the low-loss spatial power combining that the array provides, as will be discussed later.

In Fig. 1(b), the two confocal paraboloid reflectors are in an offset Gregorian arrangement. In this arrangement, the feed array is placed so that the center points of the main reflector and the feed array are conjugate points. That is, rays originating at one point pass through the other upon reflection from the small subreflector. This arrangement provides for a better scan capability. Furthermore, ideally, the possible phase errors due to small imperfections on the large main reflector can be easily compensated for by the phase variation of the array elements. Also, blockage effects have been completely circumvented. This is the more appropriate arrangement for a limited-scan reflector antenna system.

III. Feed Array Architecture

There are several advantages to using a small phased array in connection with a magnifying dual reflector system. This approach can provide vernier adjustment of the main reflector antenna beam by scanning the phased array beam incident on the subreflector. Furthermore, the use of individual phase shifters and power amplifiers behind each radiating element means that the circuit losses at the dividers and phase shifters will occur prior to amplification and at very low power levels. This active array approach is contrasted with a passive approach in which the amplification is performed before the corporate dividing network and phase-shifting stages. In addition, the active array approach is more reliable and provides for a more graceful degradation of the performance, since the failure of a few active components does not affect the entire array.

Finally, by using small solid-state amplifiers at the antenna element level, the power from all amplifiers are in effect combined in space as opposed to the approach in which output from individual solid state amplifiers are circuit-combined at a substantial loss before input to the array. The spatial combining thus circumvents this network loss. For example, consider the fact that at Ka-band frequencies, the dividing network loss for the 21-element array at 32 GHz, which is discussed below, could be as much as 5 dB and that of a 4-bit digital phase shifter can

be as much as 11 dB; the advantage of the active array approach, in which these losses occur before amplification, is quite evident. Indeed, this is the only realistic approach to obtaining high power transmission (few to tens of watts) using solid state amplifiers with individual output power levels of a few tenths of a watt.

The integration architecture of the amplifiers and the array is another very important aspect of the design. Three approaches to the array architecture are shown in Fig. 2. Each approach has certain advantages and disadvantages, and each is appropriate for certain types of radiating elements. One approach is a so-called brick architecture. The two-dimensional planar array is composed of planar layers. Each layer, in turn, is composed of a subarray of radiating elements. The phase-shifters, amplifiers and radiating elements are integrated on the same layer. Each layer is normal to the face of the planar array (hence the term brick). A two-dimensional array is obtained by stacking several layers of linear subarrays. A divider layer normal to the subarray layers connects them together. This approach is contrasted with a so-called tile approach where radiating elements are located on the planar face of the array in a two-dimensional grid and the amplifiers and phase shifters are arranged on separate layers stacked behind and parallel to the radiating layer. Hybrid approaches are also possible.

IV. Array Development

A two-dimensional Ka-band array has recently been developed at JPL and has been reported in the literature [2–8]. It is a power-combining array intended primarily for transmitter applications. The prototype array is designed for use in future spacecraft antenna applications where Ka-band is planned to supplement the X-band communication link.

The array uses MMIC 4-bit phase shifters and power amplifiers in conjunction with Vivaldi (exponentially tapered slot) elements operating at Ka-band frequency (32 GHz). As shown in Fig. 3, the two-dimensional array is composed of five planar layers (3 inner layers with 5 elements and 2 outer layers with 3 elements, for a total of 21 elements. Figure 4 is a photograph of the array hardware.

The power dividers and the array support frame were designed and fabricated in-house at JPL. The phase-shifters were procured from Honeywell. The very large-scale integration (VLSI) phase-control circuitry is designed by JPL and built at the Defense Advanced Research Projects Agency (DARPA) foundry, and the solid-state power amplifiers (pseudomorphic high-electron mobility transfer) were procured from Texas Instruments.

The design and fabrication of the array of tapered slots (Vivaldi) elements were performed via a contract with the University of Massachusetts [6–7]. Since Vivaldi elements are linearly polarized, an investigation was made to find ways to produce circular polarization. It was concluded that for a Vivaldi array, the most feasible method would be to place of a polarizer screen in front of the array, although other techniques, such as orthogonal and interleaved placement of the array elements, also offer possibilities that need to be further explored in the future.

V. Experimental Results

The 21-way divider fabricated by JPL has a loss of about 5 dB. The 4-bit phase shifters procured commercially have a loss of about 11 dB. As mentioned previously, however, these losses are irrelevant in an active array configuration where power amplifiers are located after the dividers and phase-shifters, right behind the antenna radiating elements. For this reason, the gain of the array will always be referred to a reference plane right after the power amplifiers and at the input to the microstrip feedlines of the antenna elements.

In this arrangement the only significant losses are the microstrip feedline and transition-to-element losses, the cross-polarization loss, and the loss due to amplitude and phase irregularities. These losses determine the efficiency of the array with respect to an ideal lossless antenna with no cross-polarization. The frequency region of primary interest is 31.5 to 32.5 GHz, with 32.0 GHz being the nominal center frequency (wavelength $\lambda = 9.37$ mm). Several different array element lengths and spacing were tried and tested. The achieved gain of the array with an element length of 2.3λ and interelement spacings of 1.22λ, was approximately 23 dB over the frequency region of interest. The average element and array beamwidths in the E and H planes were in the range of 30–40 deg and 7–9 deg, respectively. Even higher gains and narrower beams have been achieved by increasing the length of the elements. Figure 5(a–d) shows the results of an experimental study of the gain variation versus frequency for different array parameters.

Tests have been performed to obtain the far-field patterns and ascertain the scan capabilities of the array. Both individual layers and full two-dimensional arrays have been tested, and co- and cross-polarized patterns have been obtained. Figure 6 presents some typical far-field patterns.

An area of particular concern is the spurious radiation from the beam-forming network which tends to corrupt the sidelobe and cross-polarization regions of the patterns.

Another area of particular interest has been the determination of the phase centers of the array. It is shown that the phase centers of the array in the E- and H-plane are far apart, and this must be taken into account in feeding the reflector antenna. Figure 7 shows the phase variations in the E- and H-planes of the array within the vicinity of the phase centers. Figure 8 shows the experimentally obtained locations of the array phase centers in the two principal planes. There is no single phase center for the array; each cut through the pattern has a different phase center point. This property is not unique to this particular array. Rather, it seems to be a peculiarity of arrays composed of linear traveling-wave radiating elements. In any case, it must be taken into account where the array is used as a focal point feed for a reflector system. This effect, however, may not be significant in cases where it is used as a near-field array feed, and requires further investigation.

In the course of the array development, several array element configurations were designed and investigated. Gain improvements were obtained by proper tapering and increasing the length of the slots. The final configuration with an element length of 3.2λ and interelement spacing of 1.22λ (at 32.0 GHz) produced gain figures in the range of 23.4 to 24.5 dB for the frequency range of 31.5 to 32.5 GHz. The active element gain (i.e., gain in the presence of other elements) was measured in the range of 10.5 to 11.5 dB.

No appreciable improvement, however, was obtained by modifying the microstrip feedline. The measured loss due to the feeding structure (microstrip and feed transition) was about 1 dB. The overall loss due to the microstrip feedline, transition to element, cross-polarization, and amplitude and phase errors ranges from 1.5 to 2.5 dB over the frequencies of interest (56- to 70-percent efficiency). The measured array sidelobes are below 16 dB and the cross polarization level is below 18 dB. The total power lost to the cross-polarization was estimated to be approximately 0.5 dB.

An attempt was also made to evaluate the mutual coupling between adjacent array elements. This was done by inverse Fourier transforming the measured far-field patterns to obtain the near field of the array. Only selected pattern cuts [one-dimensional fast Fourier transforms (FFT's)] were used and not for the entire pattern (two-dimensional FFT). The results, in this case, have a mostly qualitative value. It was shown, however, that the coupling can be significant.

A linear segment of the array has also been tested with the phase shifters with promising results. Additional tests including the phase shifters and amplifiers for the entire array would have to be performed in order to completely ascertain the active array performance.

VI. Conclusions

The design and breadboard of an active transmitting array at Ka-band frequencies and its application to a reflector antenna system have been described. The array is intended as a feed in a near-field Cassegrain or Gregorian dual reflector antenna system. It uses tapered slot (Vivaldi) elements in a brick architecture. The passive array (without the phase shifters and amplifiers) has been tested for RF performance. Its performance is acceptable, but there are some areas where improvements in the performance are desirable and possible. Particular attention must be paid to the losses at the input to the array elements and in the elements themselves. Variation of the array phase center in different azimuth planes is another area of concern and attention. The Vivaldi elements have a linear polarization and do not easily lend themselves to a circularly polarized arrangement. For lower losses and circular polarization, microstrip patch arrays in a tile configuration may prove to be more advantageous.

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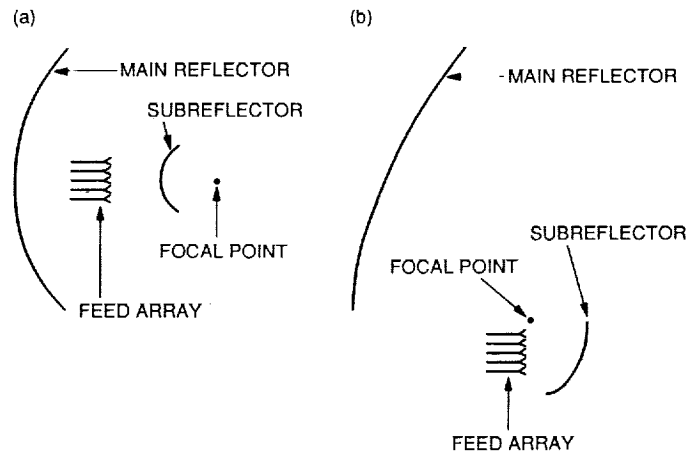
Fig. 1. Near-field array-fed dual reflector systems: (a) A symmetric Cassegrain system and (b) An offset Gregorian system
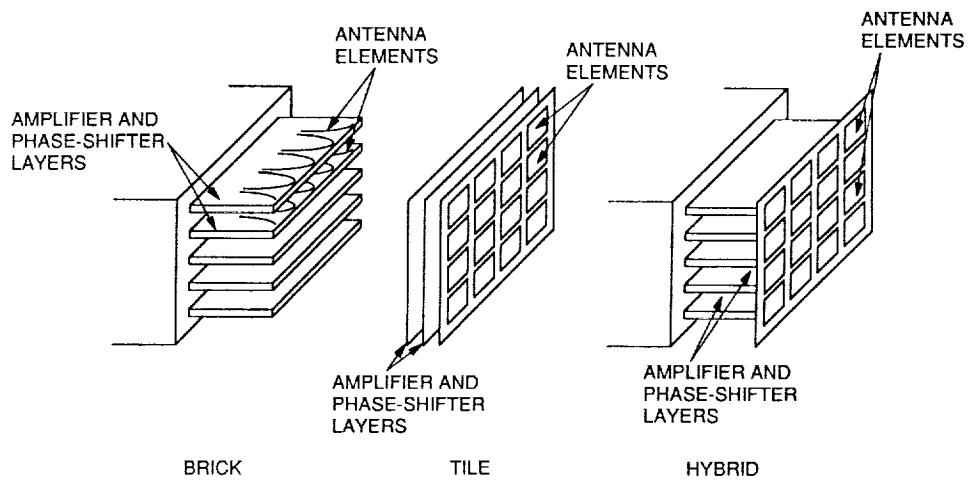

Fig. 2. Various feed array architectures.

POWER
AND DATA
CONNECTORS

THREE ACTIVE-
ELEMENT
SUBARRAY

FIVE ACTIVE-
ELEMENT
SUBARRAY

83.8 mm

VIVALDI
SLOTLINE
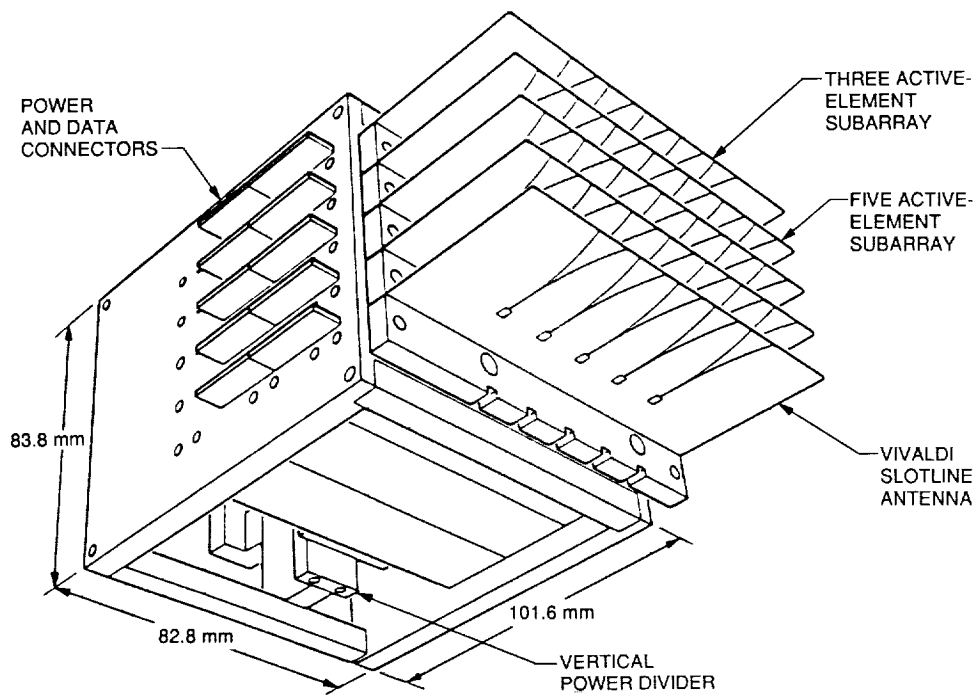ANTENNA

101.6 mm

82.8 mm

VERTICAL
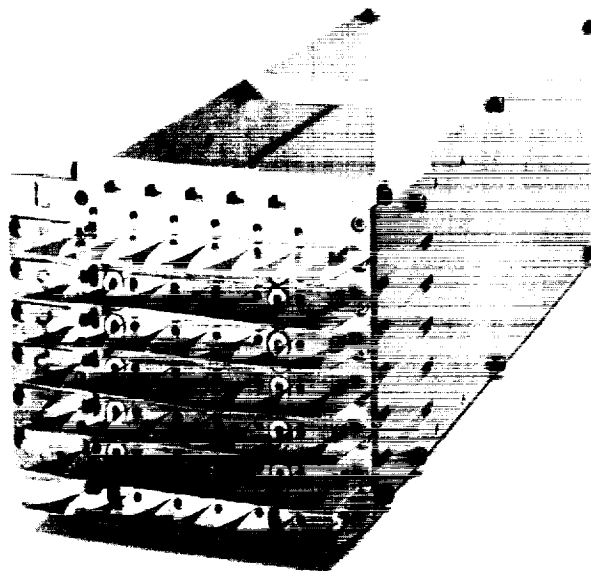POWER DIVIDER

Fig. 3. A 21-element Ka-band Vivaldi array layout.

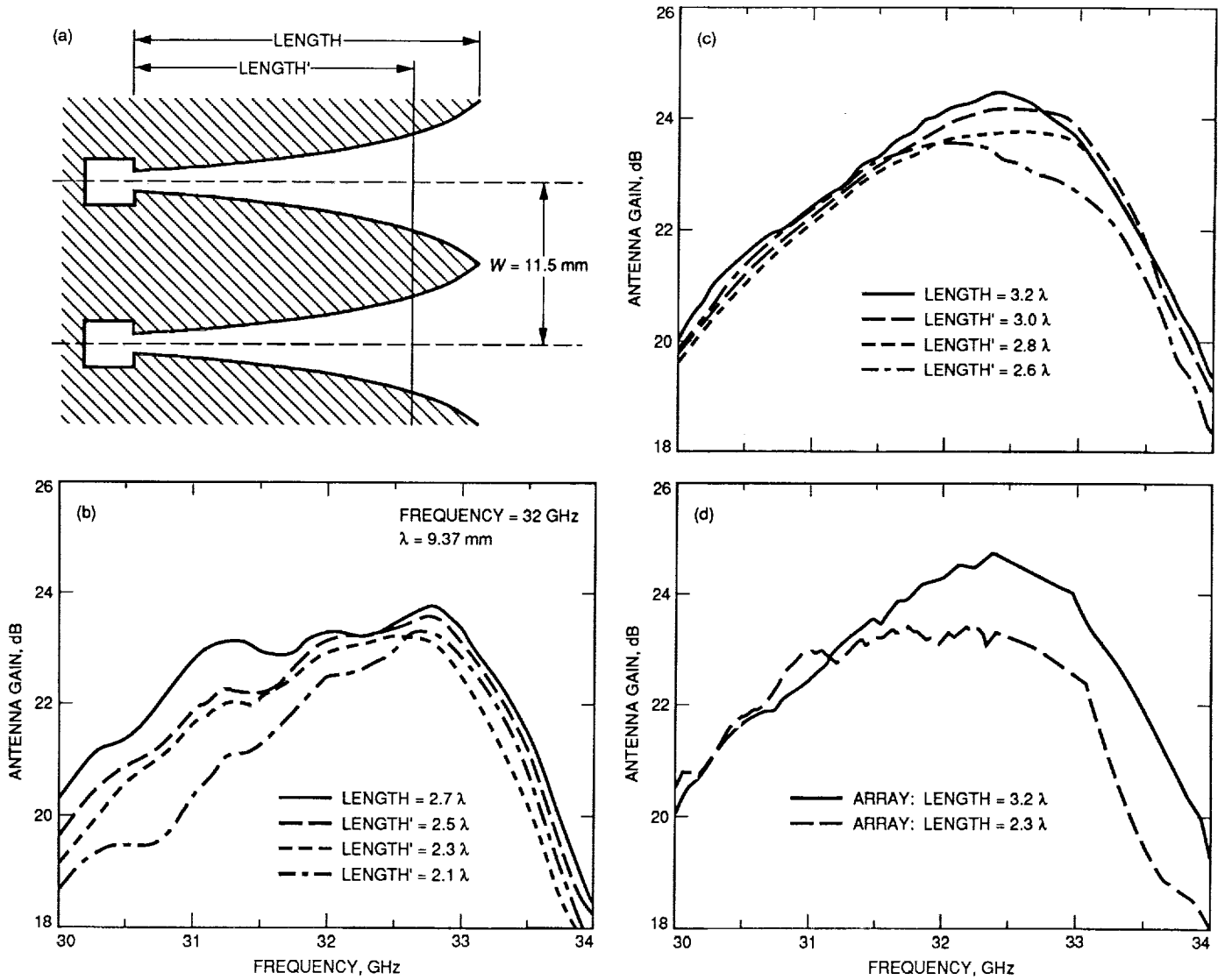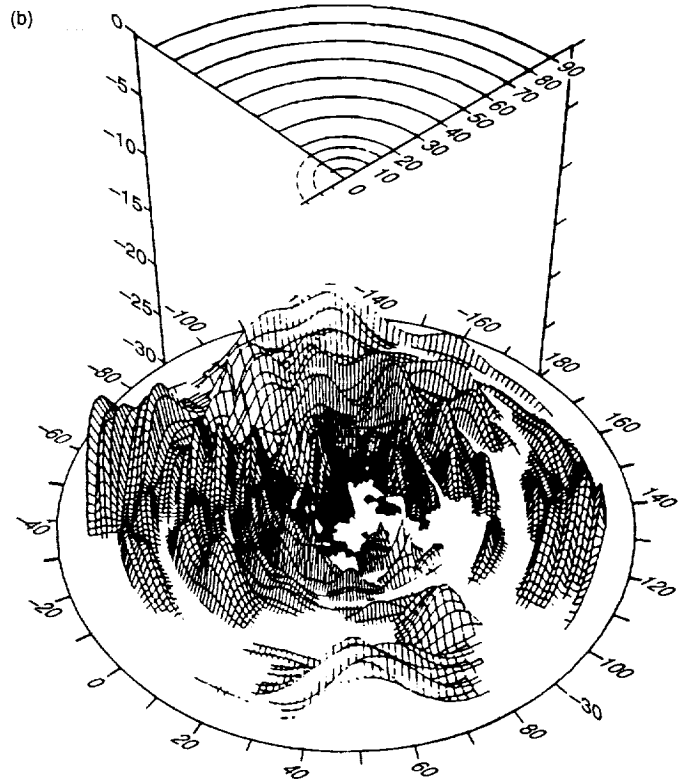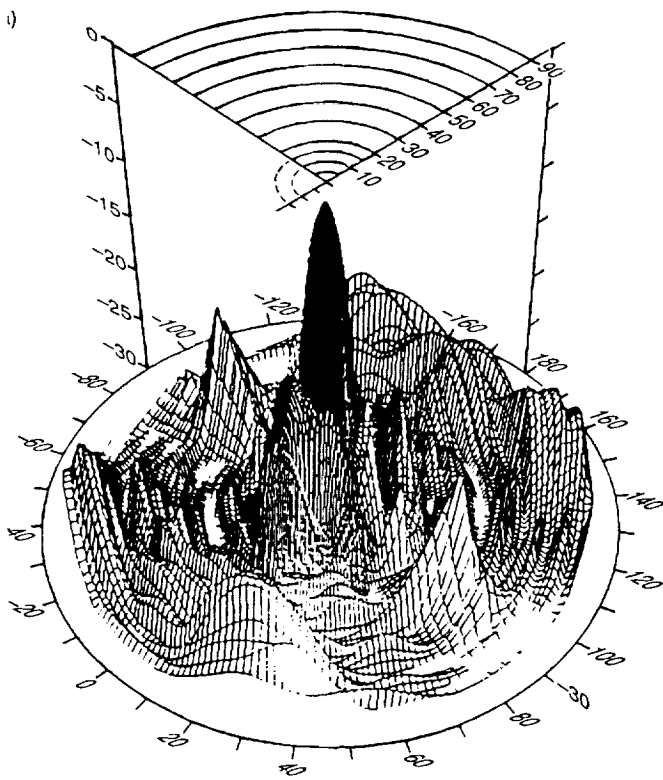Fig. 4. A view of the 21-element Ka-band Vivaldi array
breadboard.

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Fig. 5. Parametric study of gain versus frequency: (a) Array parameters; (b) Starting with $L = 2.7$ and cutting to shorter L' lengths; (c) Starting with $L = 3.2$ and cutting to shorter L' lengths; and (d) A gain comparison of element lengths of $L = 2.3\lambda$ and $L = 3.2\lambda$.

PEAK GAIN = 23 dB
MAXIMUM SIDELOBE = –16 dB
MAXIMUM CROSS-POLARIZATION = –19 dB

Fig. 6. Typical 3-dimensional far-field patterns of the Vivaldi Array: (a) Copolarized pattern and (b) Cross-polarized pattern.
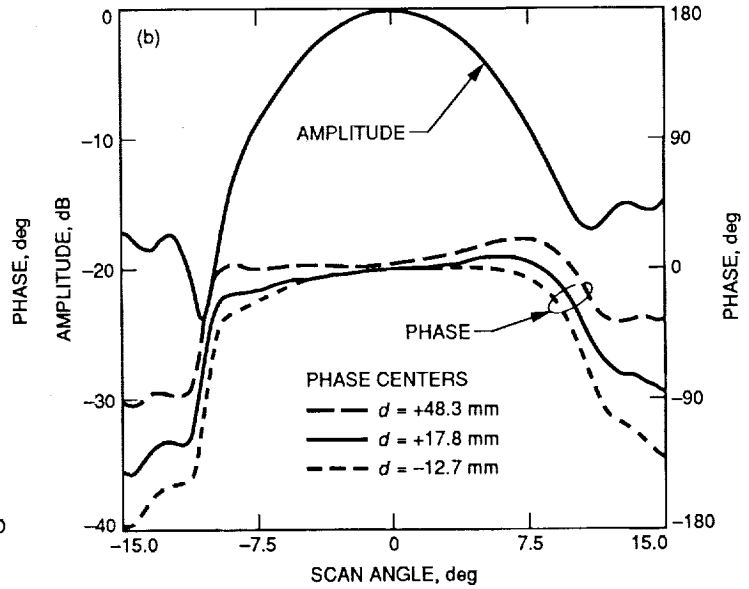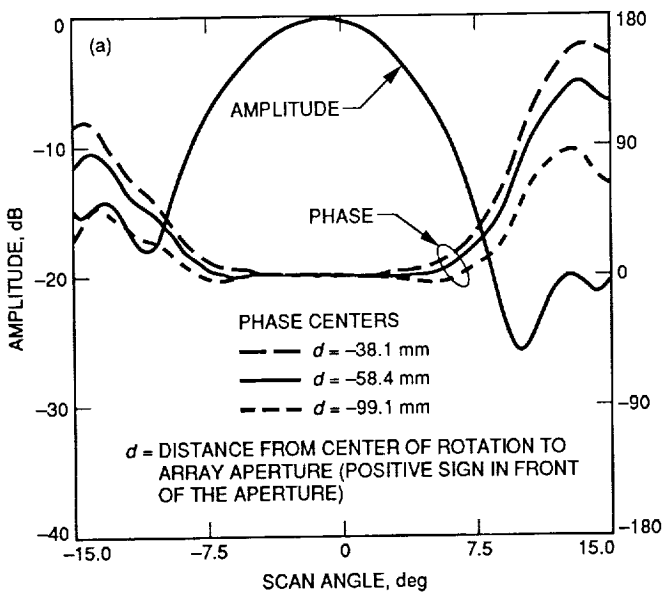

Fig. 7. Pattern phase variations near phase centers in two principal planes: (a) E-plane phase variations and (b) H-plane phase variations.
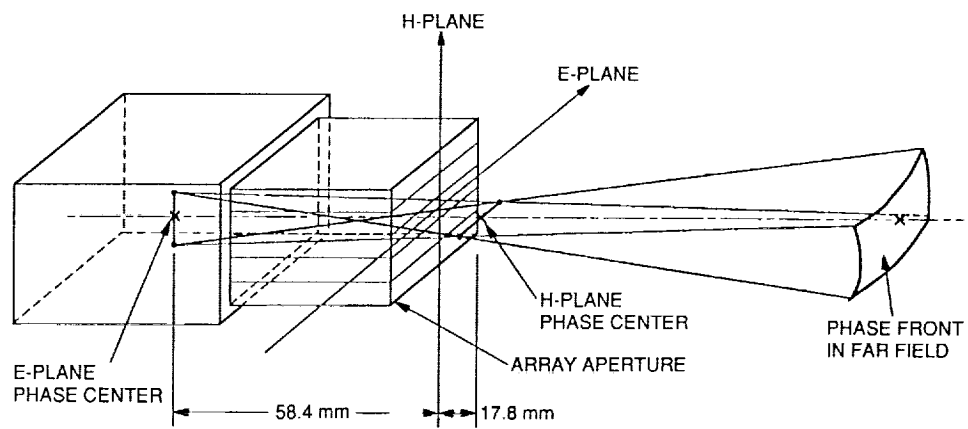
Fig. 8. Locations of the array phase centers in two principal planes.