A circular active reflector atenna (CARA), energy distribution calculations, and an experimental test

Larry V. Knight
larry_knight@byu.edu

George H. Barry

Original Publication Citation

Knight, L., and G. Barry. "A Circular Active Reflector Antenna (CARA), Energy Distribution Calculations, and an Experimental Test." Antennas and Propagation, IEEE Transactions on 23.2 (1975): 228-36

A Circular Active Reflector Antenna (CARA), Energy Distribution Calculations, and an Experimental Test

LARRY V. KNIGHT AND GEORGE H. BARRY, SENIOR MEMBER, IEEE

Abstract—Conventional high-frequency (HF) circular phased arrays, such as the Wullenweber circular array, have a cost factor that increases at a greater-than-square law rate as its radius is increased to produce larger apertures. A new method of forming simultaneous beams in an HF circular array has been proposed in which beams are formed in the space within the array from pickup element energy that has been amplified and reradiated. Such a device is called a circular active reflector antenna (CARA), and its cost increases at a substantially linear rate as its radius is increased to form larger apertures.

This paper describes calculations of the distribution of reradiated energy within such an array in order to study the effect of changes in array configuration. A cost analysis is presented to establish the dependence of array cost on array size for both the conventional and CARA types of arrays. In addition, the performance of an experimental CARA array is reported.

An experimental CARA array consisting of a 120° partially filled sector of 1500 m radius, forming six beams over a 2° field of view was constructed at a site in Utah to demonstrate the feasibility of the concept. Measurements made on the experimental array showed that at 14-MHz, it formed beams 0.7° wide at the 3-dB points, which agrees closely to the calculated value. The sidelobe response also compared closely to the level and angular position calculated for the sidelobes of the partially filled sector array tested. No evidence of instabilities or intermodulation distortion was noted.

I. INTRODUCTION

A NEW type of antenna, called a circular active reflector antenna (CARA), has been proposed [1] as a means of achieving large apertures in the high-frequency (HF) spectrum at much lower cost levels than can be realized by conventionally designed arrays when simultaneous omni-azimuth beams must be provided.

The circular active reflector antenna provides an alternative beam forming mechanism, which will allow large aperture antennas at a much lower cost than the Wullenweber design.

Fig. 1 depicts a CARA array in plan view. The output of each pickup element, wherever located, is applied to an amplifier at its base which feeds a separate antenna directed toward the center of the array. (Only three amplifiers are shown in Fig. 1(a) for convenience). The amplified energy thus reradiated is intercepted by a single antenna located at the focal point of the circularly disposed reradiating antennas in the beam no. 1 sector of Fig. 1(a).

Manuscript received December 17, 1973; revised September 15, 1974.

L. V. Knight is with the Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602.

G. H. Barry is with Barry Research Corporation, Palo Alto, Calif.

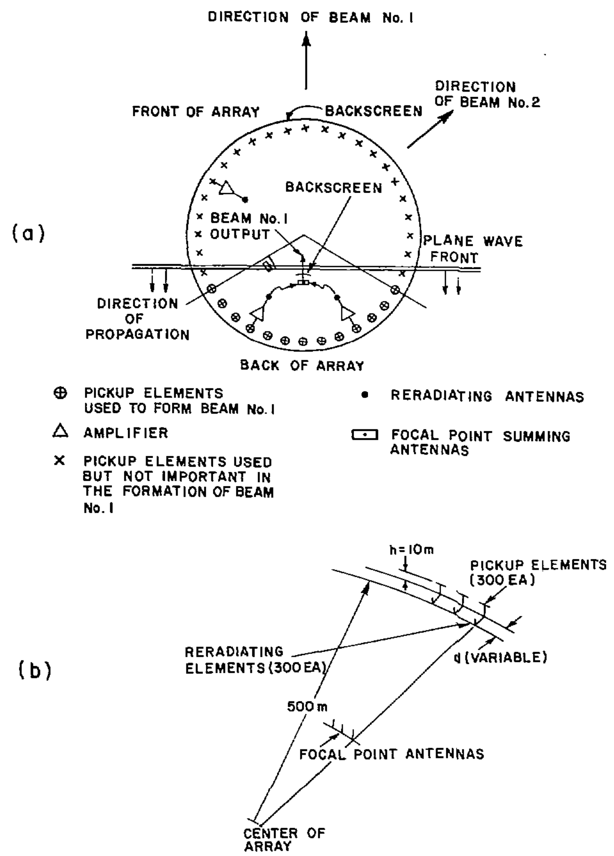


Fig. 1. (a) Diagrammatic view of circular active reflector antenna showing CARA concept of beam forming in space. (b) Perspective view of CARA configuration.

In the CARA array, each of the reradiated signals induced in the beam no. 1 focal point antenna, (primarily by the elements in the sector shown in Fig. 1), are essentially in phase by virtue of the varying distance each has traveled in reaching it. The output of this focal point antenna, then, is the beam no. 1 signal.

There are four reasons why only the elements in the sector shown in Fig. 1(a) are important in the formation of beam no. 1. First, a backscreen is constructed behind the pickup elements as shown in Fig. 1(a). Second, all of the pickup elements are designed to be radially directive. Third, the distances to the beam no. 1 focal point antenna are greater from the reradiating elements outside the beam no. 1 sector than from those within it. The attenuation caused by these greater distances further diminishes the contribution of the elements radiating over them. Lastly, the reradiating and focal point antennas can be designed to be radially directive.

Fig. 2 depicts a circular array of the Wullenweber [2] variety in plan view. To form a beam, say beam no. 1, outputs are taken from the individual array elements contained in a sector centered on the axis of beam no. 1, as shown in Fig. 2. The output from each pickup element in this sector is power amplified and then split into a number of identical outputs. One output from each splitter is brought to a time delay device associated with beam no. 1.

When the radius of an antenna built in this way is increased, the number of individual pickup elements increases in a linear fashion, giving rise to a bearable increase in cost. However, the number of sets of splitters, delay elements, summing units, and associated cabling increases much more rapidly. This is so because there is a larger number of pickup elements along the periphery of the larger array, because each of them is farther away from the combining point, and because more of the now-narrower beams must be formed with each of the element outputs to provide coverage in azimuth without gaps between adjacent beams. This gives rise to a greater-than-square-law increase in cost with array size.

When the radius of a CARA antenna is increased, the number of individual pickup and reradiating elements increases in a linear fashion. The only added cost for forming the increased number of beams required in larger arrays is the cost of the additional focal point antennas. This cost increases nearly linearly with array size, thereby breaking the stranglehold of a greater-than-square-law cost rise with increased array size.

II. CARA ENERGY DISTRIBUTION CALCULATIONS

A. Approach

In this section, the CARA concept is carefully examined by a computer modeling the array. As discussed earlier, the CARA concept is based on the expectation that signal energy from a given azimuth and elevation angle will be brought to a focus at a point within the array. The task of designing an array based on that concept begins with the specification of a reasonable configuration for a practical structure. Calculations are then made of the distribution of reradiated energy within this array in the vicinity of the expected focal region, and changes in the distribution are noted as the array is altered. The most promising configuration is identified, and conventional antenna patterns are then calculated for it.

B. Energy Distribution in CARA Array

1) Effect of Elevation Angle and Pickup/Reradiating Element Spacing: A configuration having the characteristics listed in the following was arbitrarily selected to investigate the energy distribution within a CARA array.

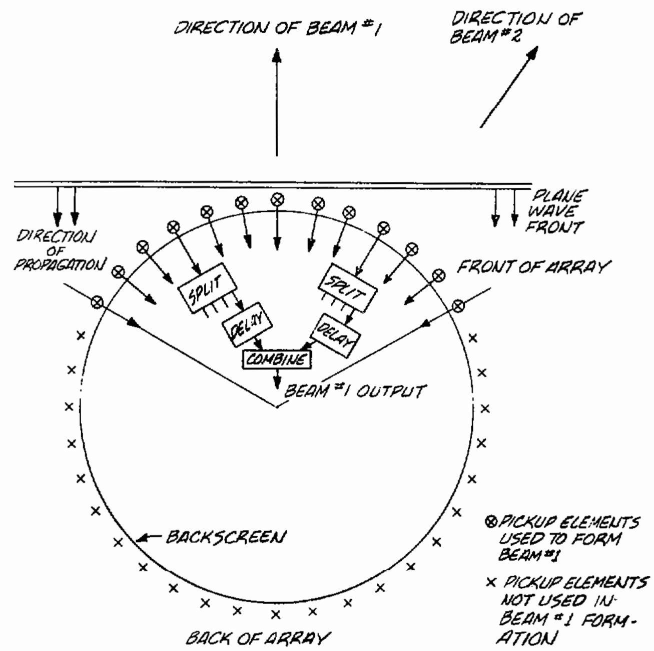


Fig. 2. Diagrammatic plan view of circular phased array showing conventional beam-forming circuitry.

Array radius	500 m
No. of pickup and reradiating elements	300
Spacing between adjacent pickup elements	10 m
Pickup elements	horizontally polarized dipoles
Height of pickup elements	10 m
Reradiating elements	vertically polarized linear elements
Spacing between pickup elements and reradiating element	d = variable
Pickup element directivity	horizontal dipole pattern (no backscreen)
Reradiating antenna azimuthal directivity	none

The pickup antennas, the reradiating antennas, and the focal point antennas were assumed to be completely isolated. The direct signal was assumed to be much larger than any scattered or indirect signal. That these conditions could be substantially achieved in practice is demonstrated by experimental measurements that agree with calculations using these approximations.

A calculation was made of the energy distribution within this array under the condition that the spacing d between the pickup and reradiating elements was varied. The frequency of the incident plane wave was 20 MHz, incoming at an elevation angle of 5°. All 300 pickup and reradiating pairs (around the full circle) were active. Fig. 3 is the resultant energy distribution in a rectangular region within the array. It shows a focal point at approximately 250 m (one-half the array radius) with a cusp-shaped spread of energy tapering symmetrically back to the circumference of the array. The cusp-shaped spread

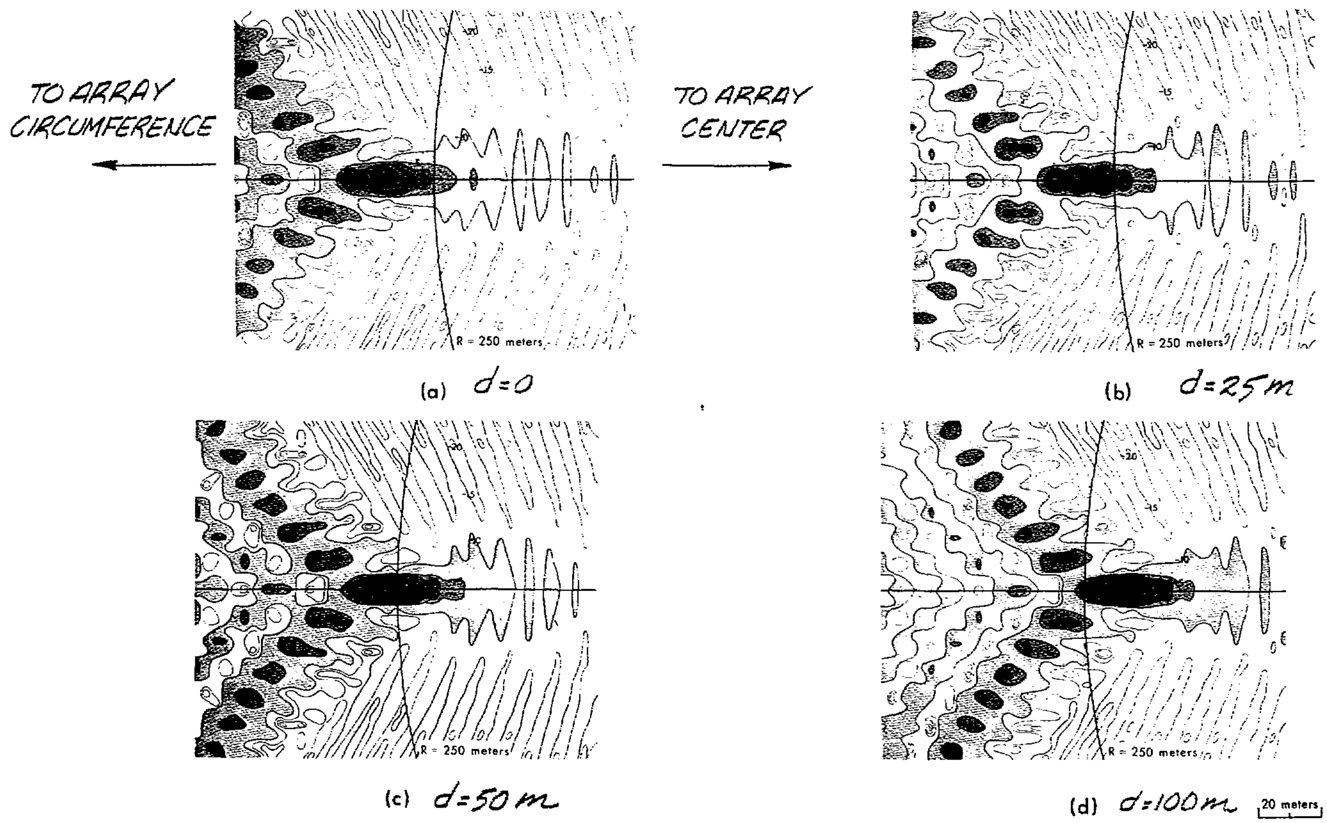


Fig. 3. Variation in energy distribution in CARA array with changes in spacing between pickup and reradiating elements. Frequency is 20 MHz, elevation angle is 5°.

is, of course, due to circular aberration. It can be seen readily from Fig. 3 that the only significant effect of increasing the spacing d is to move the focal point toward the center of the array.

Fig. 4 shows a calculation under the same conditions illustrated in Fig. 3 except that the elevation angle has been raised to 30°. The only qualitative change is that the focal point has moved toward the center of the array. The analytical relationship between the radius of the focal point r and the elevation angle β is

$$r = \frac{R \cos \beta}{1 + \cos \beta} \tag{1}$$

where R is the radius of the array.

These results indicate that a CARA array could have two or three concentric rings of focal point antennas to enable it to receive incoming energy at various elevation angles.

The movement of the focal point toward the center of the array with increasing separation between the pickup and reradiating elements was of itself not surprising. Wherever they are located, the reradiating elements merely form a circular array of smaller radius than the circle of pickup elements, and one might expect that the energy from them would be brought to a focus closer to the center of the circle. However, it was hoped that other effects, which proved to be second order and too small to be of significance, would reduce circular aberration when d was increased. It is concluded that no simple geometric arrangement that maintains circular symmetry will be useful in eliminating circular aberration. The value of d can be chosen as necessary in preventing oscillation when the pickup element-amplifier-reradiating element package is designed.

2) Effect of Pickup Element Backscreens for Focal Point Antenna Directivity: It is clear that if backscreens were placed behind each pickup element, the contributions from these front-of-array sources would be greatly diminished. In the computer program, these backscreens can be simulated by assigning zero gain to an element over the 180° sector centered on its backscreen axis.

If contributions to the energy distribution are limited to those from the reradiating elements at the rear of the array clustered about the axis of the beam, circular aberration should be reduced, since the disposition of those elements does not depart markedly from a paraboloidal disposition. Shading the contribution of each reradiating element in this manner is easily accomplished in any or all of these ways: i) by making the pickup antenna directive toward the center of the array, ii) by making the reradiating antenna similarly directive, or iii) by making the focal point antenna directive radially outward (in the direction of the desired element assemblage). With a cosine focal point antenna response so oriented, the effective aperture is reduced but is still nearly 90 percent of the aperture with no shading.

Calculations were made of the energy distribution in an array with pickup element backscreen and with the

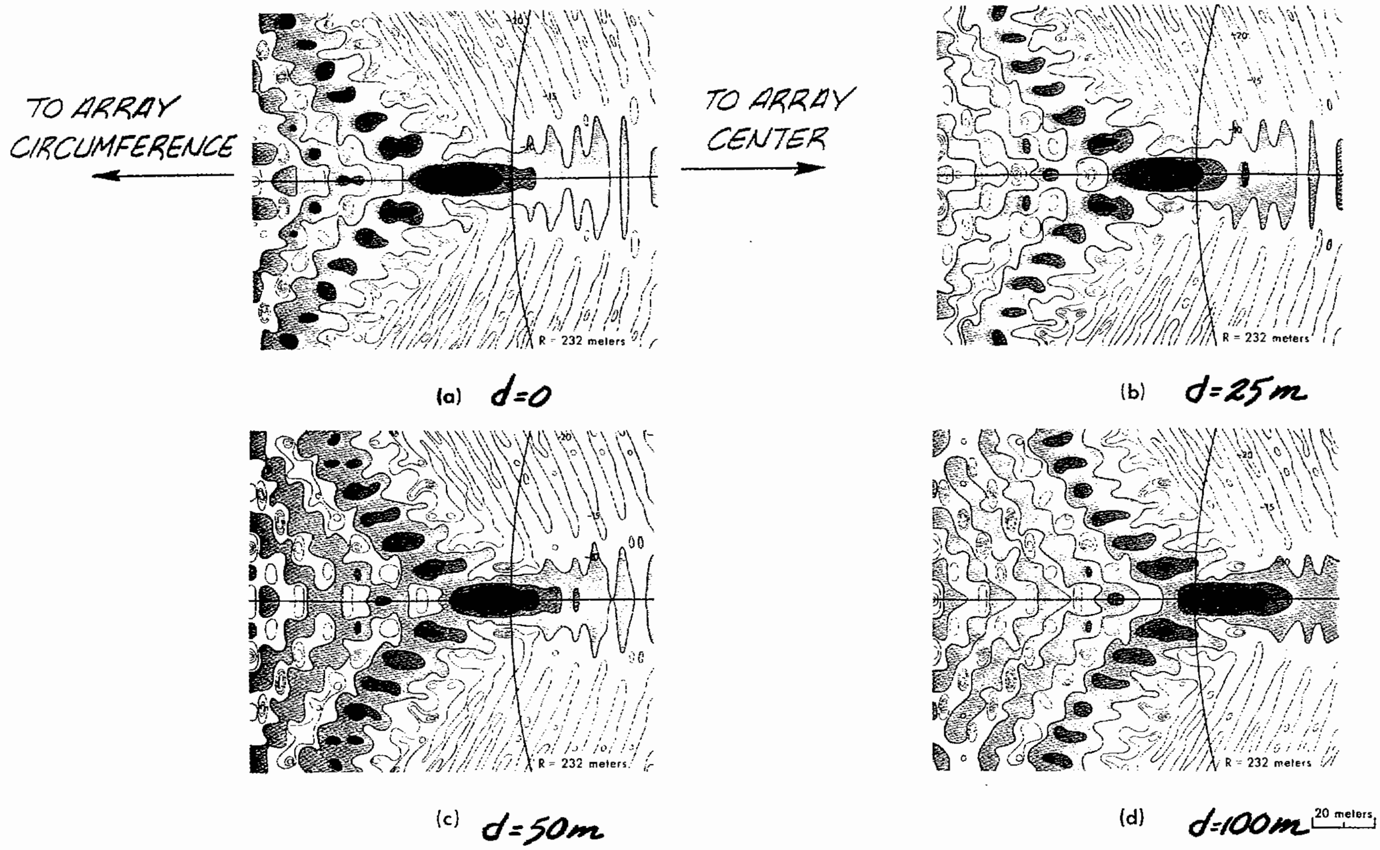


Fig. 4. Variation in energy distribution in CARA array with changes in spacing between pickup and reradiating elements. Frequency is 20 MHz, elevation angle is 30°.

output of each program "probe" modified by giving it a radially oriented cosine response with no rear lobe. These calculations resulted in a great reduction in circular aberration.

Focal point antenna directivity is a practical means of correcting circular aberration without destroying the circular symmetry of the array. If focal point directivity alone is used, this correction is bought at the price of reduced aperture. On the other hand, a great deal of work has been done on feeds for correcting spherical aberration [3]–[8]. A traveling wave focal point feed could provide directivity and also phase correction at the price of added complexity.

To form a measure of sidelobe response, calculations were made of the energy falling on a nondirective focal point antenna fixed at a radius of 250 m in an array having no pickup element backscreens. The energy came from a plane wave front incident on the array at different out elevation angles. The spacing d between pickup and reradiating elements was zero. The calculations were made at frequencies of 10, 20, and 30 MHz.

The radial lines of the diagrams represent the various azimuth angles of arrival of the incident plane wave front, marked in degrees off the axis of the beam associated with the focal point antenna. The elevation angles of the arrival of the plane wave front were plotted as distances along these radii, marked in degrees above zero degrees. Contours were drawn between points of equal value, and areas between contours of greater value were shaded to make the figures easier to read.

Fig. 5 shows the results of these calculations plotted in this manner. The plots represent the values of energy existing at one location within the array produced by a plane wave front having the combination of azimuth and elevation angles of arrival indicated at any point on the diagram. The shading between the contours of greater value allows the observer to quickly locate those combinations of zimuth and elevation angles that caused the larger responses in the fixed point antenna.

It can be seen in Fig. 5 that energy values 3 dB down from peak value do not occur on off-axis azimuths below elevation angles of 40° at any frequency. At higher elevation angles, sidelobes occur at a variety of azimuth and elevation angles at 10 MHz and 30 MHz (Figs. 5(a) and 5(c)). Their absence at 20 MHz (Fig. 5(b)) is accounted for by the directive pattern of the horizontally polarized dipole antennas used as pickup elements, which is taken into account by the computer program. The resonse of a horizontally polarized dipole h meters above ground at an elevation angle β is given by

$$\cos \frac{2\pi}{\lambda}\left(h \sin \beta - \frac{\lambda}{4}\right) \qquad (2)$$

which is zero at all frequencies when $\beta = 0$ degrees. At 20 MHz (2) is also zero at approximately 50°, for $h = 10$

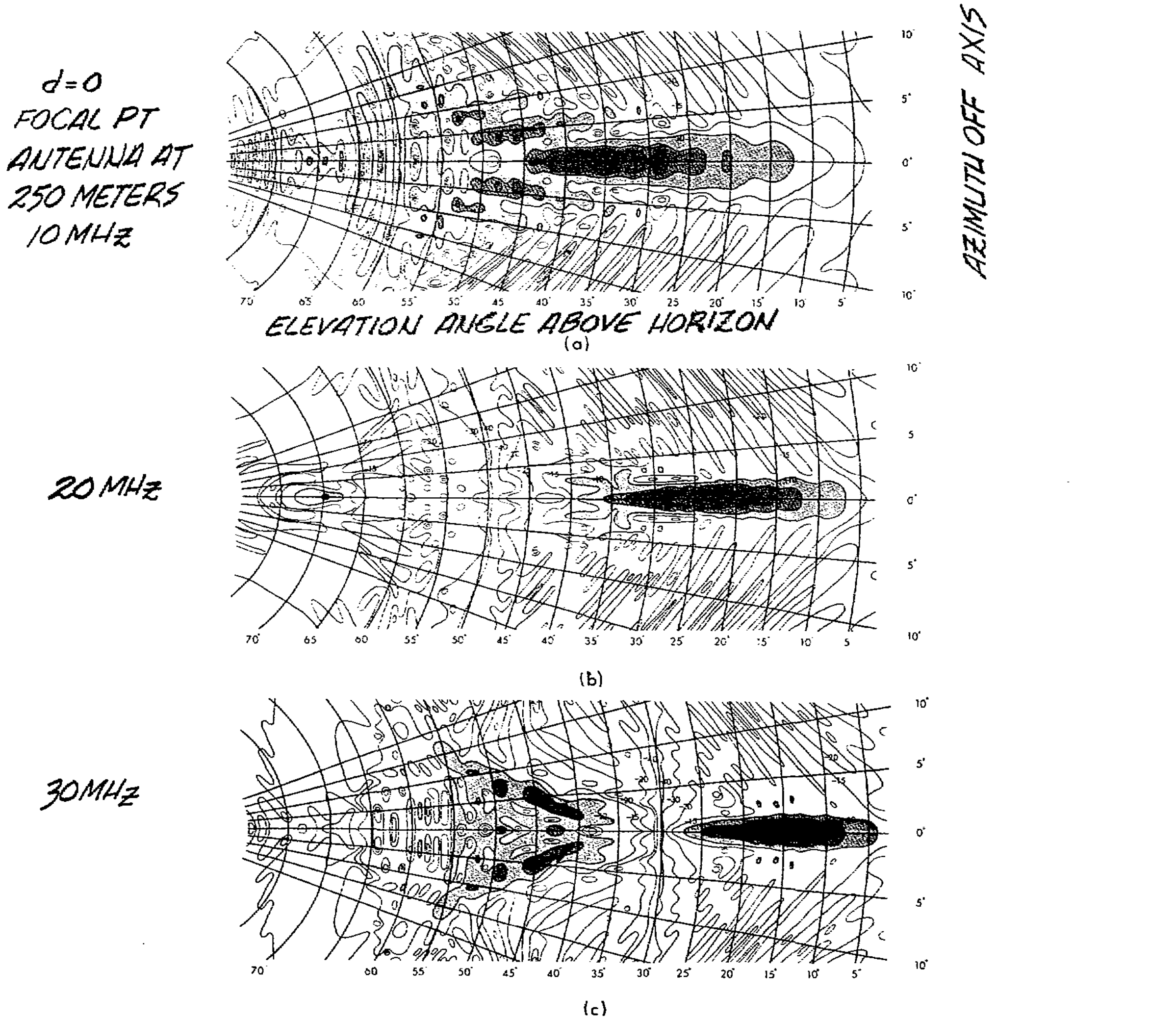


Fig. 5. Values of energy at fixed focal point antenna in decibels down from peak value, created by plane waves having combination of azimuth and elevation angles of arrival shown.

m. Therefore, a null in the pattern of the pickup elements occurs at 20 MHz.

III. COMPARISONS

Three classes of antennas are currently widely used at HF: wave antennas (rhombic [2, pp. 4-12–3-33], long wire [2, p. 4-1], Beverage [9]), phased arrays (linear [2, pp. 5-1–5-28], circular [2], mattress [2, pp. 25, 26], and optical antennas (Luneberg lens [2, pp. 15-3–15-8], corner reflector [2, pp. 11-1–11-10], and spherical reflector [2, p. 15-21]). Wave antennas are not electrically steerable. Only the phased arrays and the other optical antennas can be directly compared to the CARA antenna.

Optical antennas have been commonly used at microwave frequencies, but they have not found much favor for use at HF because of the enormous physical size of the required lenses or reflectors. The active reflector antenna avoids this difficulty by substituting active amplification for antenna size.

Phased array antennas having apertures on the order of several hundred meters have been used as direction finders [2]. Unfortunately, phased array HF antennas tend to become prohibitively expensive when their size exceeds a few hundred meters. To illustrate the relative economic factors between a passive phased array, typified by the Wullenweber design, and the circular active reflector array, a rough cost was made.

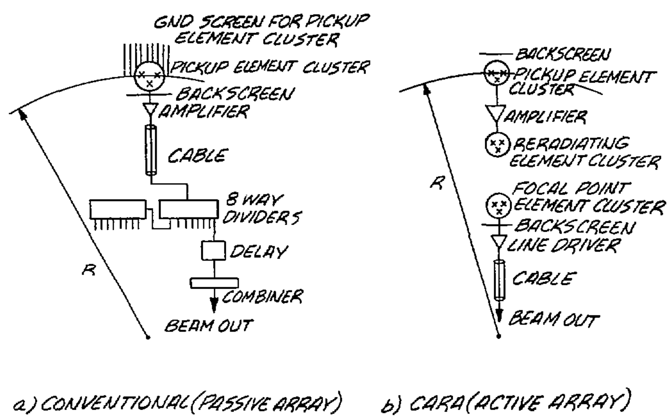


Fig. 6. Beam-forming chain in conventional phased array (passive antenna) and CARA array (active antenna), diagrammatically arranged for cost comparison study.

Fig. 6 shows the elements in a beam-forming chain in each of the two kinds of arrays. The quantity of com-

TABLE I
COST FACTORS

Item	Quantity Used in Passive Antenna	Quantity Used in Active Antenna	Unit Cost Per Item
No. of 10 m x 100 m ground screen areas (one per pickup element cluster)	$\pi R/5$	N/A	$2000
No. of pickup element clusters	$\pi R/5$	$\pi R/5$	500
No. of pickup element cluster backscreens	$\pi R/5$	$\pi R/5$	1000
No. of amplifiers	$\pi R/5$	$\pi R/5$	300
Length of cable from amplifier to array center	$\pi R^2/5$	N/A	1.20
No. of eight-way dividers	$\pi R^2/150$	N/A	200
Total length of delay cable	$0.06\ R^3$	N/A	1.20
No. of combiners	$4R/5$	N/A	400
No. of reradiating element clusters	N/A	$\pi R/5$	500
No. of focal point element clusters	N/A	$4R/5$	500
No. of focal point element cluster backscreens	N/A	$4R/5$	1000
No. of line drivers	N/A	$4R/5$	100
Total length of cable from focal point element cluster to array center	N/A	$2R^2/5$	1.20

ponents needed for each configuration as a function of array radius and a cost estimate of each item are shown in Table I. From this table the equations for cost versus array radius can be derived:

$$\text{cost of passive array} = 2707R + 4.94R^2 + 0.672R^3 \quad (3)$$

$$\text{cost of active array} = 2725R + 0.48R^2. \quad (4)$$

Equations (3) and (4) were evaluated at radii of 150, 250, 500, 1000, 1500, and 2500 m. The resulting cost curves are shown in Fig. 7.

Based on these considerations the CARA antenna could operate in a regime in which the passive circular phased array antenna would be eliminated for economic reasons.

The sidelobe performance of the conventional array will be much better than the CARA. Sidelobes on a Wullenweber design are typically 20 to 40 dB down [2]. However, the sidelobe performance of the CARA antenna should be good enough to make it useful for applications where a narrow beam is desirable.

The possibility of improving the sidelobe response of the CARA arrangement should be investigated. The techniques for reducing spherical aberration mentioned in [3]–[8] could be applied to the focal point antennas with due consideration being given to economic factors.

The CARA antenna design gives a clear economic advantage over other circular arrays for diameters greater than 250 m. It appears that further experimental and theoretical studies of the CARA configuration would be appropriate.

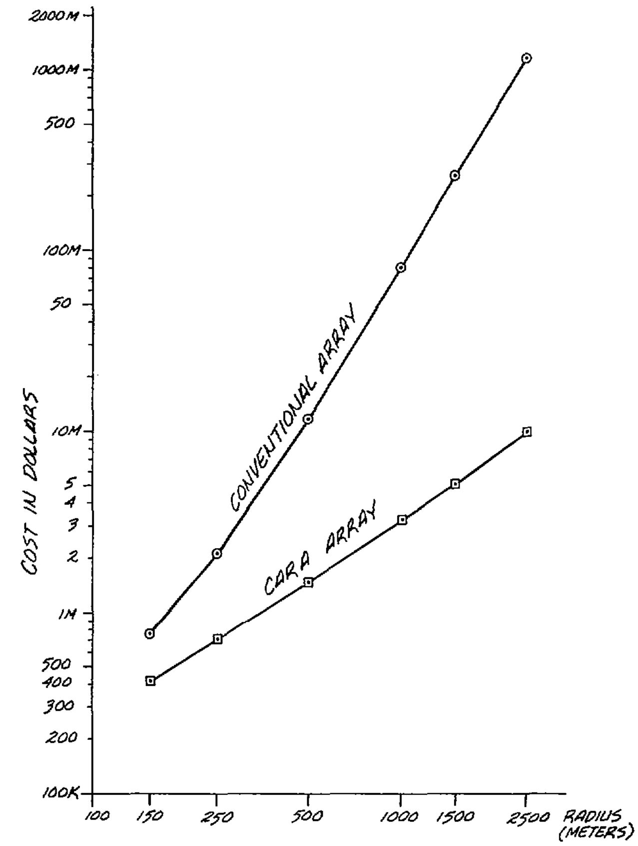


Fig. 7. Variation of array cost versus array radius for conventional and CARA arrays.

TABLE II
COMPARISON OF EXPERIMENTAL SECTOR AND FILLED FULL-CIRCLE CARA ANTENNA

	Experimental Sector	Filled CARA
Diameter	3000 m	3000 m
Number of Beams	6	1080
Coverage	2°	360°
Frequency Range	6–30 MHz	3–30 MHz
Approx. 3-dB Bandwidth	0.32°–1.6°	0.32°–3.2°
Approx. Gain	6 dB	30 dB
Pickup Elements	60 m spacing	10 m spacing

IV. EXPERIMENTAL TEST

A. Design

The largest current HF antenna is a linear array that has an aperture of 2560 m [10]. In order to realize a comparable aperture with a circular array, an array radius of 1500 meters was chosen. For reasons of economy, it was decided not to fill the entire array, but rather to install only 15 elements spaced across a 120° sector. The economy resulted in two limitations. First, because the array was not a full circle, it could be scanned over only a few degrees and, second, because the sector was not filled, the response of the antenna would exhibit frequency-dependent grading lobes every few degrees. Table II compares the characteristics of the experimental sector with those for a filled CARA array.

Ideally, none of the reradiated fields should reach the pickup antennas so these two elements were made cross polarized in the experimental array. Short horizontal dipoles oriented tangent to the array circle at a radius of 1500 m were used as pickup elements. The Beverage antenna was selected from among several possible vertically-polarized reradiating element types. The choice was made from the standpoint of constant independence, directivity, and economy of construction [9]. The focal point elements were simple vertical monopoles.

The isolation between the pickup antenna and the reradiating element was provided by cross polarization, directivity of the reradiating Beverage antenna, and separation. The reradiating Beverage antennas were positioned on a radius of 1000 m. This provided 20-dB isolation.

With this geometry the focal point antennas were located on a radius of 625 m. This is the radius of a focal point for low-angle incident signals as determined by computer analysis.

The requisite amplifier gain for each active reflector element was determined by measuring the loss between a reradiating antenna element and a focal point antenna element separated by approximately 500 m. Because the focusing signals are vertically polarized, this loss is a strong function of the characteristics of the ground. Measured losses in the frequency ranged from 6 to 30 MHz and from 55 to 80 dB. A design net gain of 70 dB was chosen for the active reflector elements with the objective of producing a field strength at the focal point from a single reflector element about equal to the incident field strength.

It was felt that this gain would be sufficient to test the concept and still keep the possibility of oscillations in the amplifier at a minimum.

The gain was divided between a preamplifier located at the pickup antennas and a power amplifier located at the reradiating antennas. The preamplifiers were designed for a frequency range from 3 to 30 MHz with a phase response within $\pm 3°$ of a specified phase response across this band. The preamplifier gain was made a function of the frequency designed to equalize the loss of a 500-m length of the RG-58/U coax cable used to connect the pickup antennas with the reradiating antennas. The resulting net gain of the preamplifier-cable combination was 10 dB. The amplifiers at each of the reradiating antennas were designed with a gain of 60 dB $\pm$ 1 dB over the frequency range from 3 to 30 MHz.

B. Test and Results

Two tests were conducted on the performance of the antenna as a whole. First, the array was used to receive a signal from a known stationary transmitter while the receiver was commutated among the six focal point elements to produce a beam scanning across the azimuth of the fixed transmitter. Second, the array was used to recieve signals from an aircraft flying through the array beams.

1) Scanning Beam Test: A continuous wave (CW) beacon transmitter was set up approximately 98 km from the CARA array. The beacon was located on a mountain ridge 600 m above the desert floor where the CARA was located. The beacon had a clear line-of-sight to the CARA and the bearing of the beacon from the CARA was 258.1°. The locations of the beacon relative to the CARA array is shown on the map of Fig. 8(a).

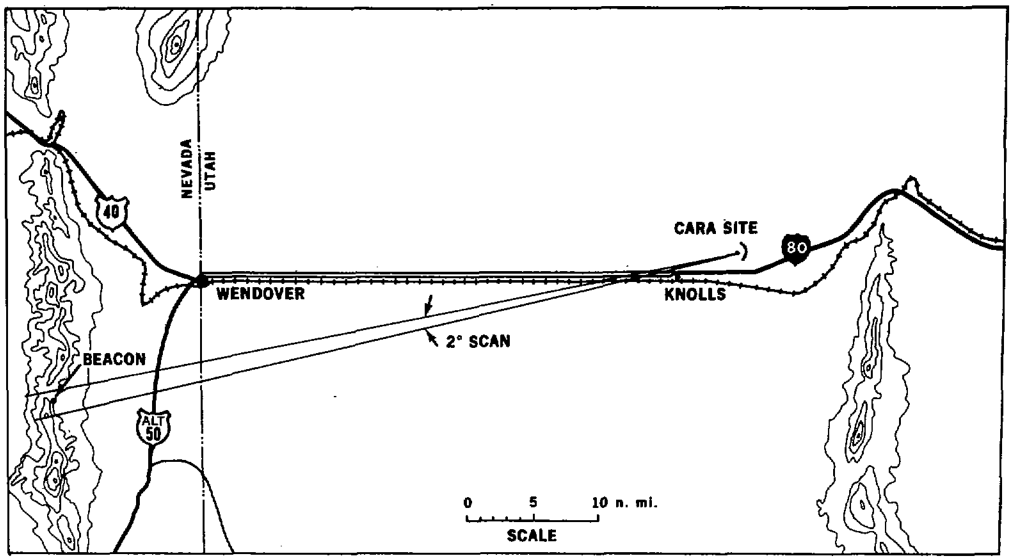
A 10-W CW transmitter and a 14-MHz horizontal dipole antenna was installed at the beacon site. Signals from this transmitter were received at the CARA using a six-position electronic commutator to generate a scanning beam.

The output of the receiver was displayed on an oscilloscope and Fig. 9 shows an example of the resulting display. The upper trace is a synchronization signal from the beam commutator and identifies the time of occurrence of beam no. 1. The lower trace shows the detector output amplitude on each of the six beams and indicates that a beam was indeed formed at an azimuth within about 0.3° of the CARA array boresight.

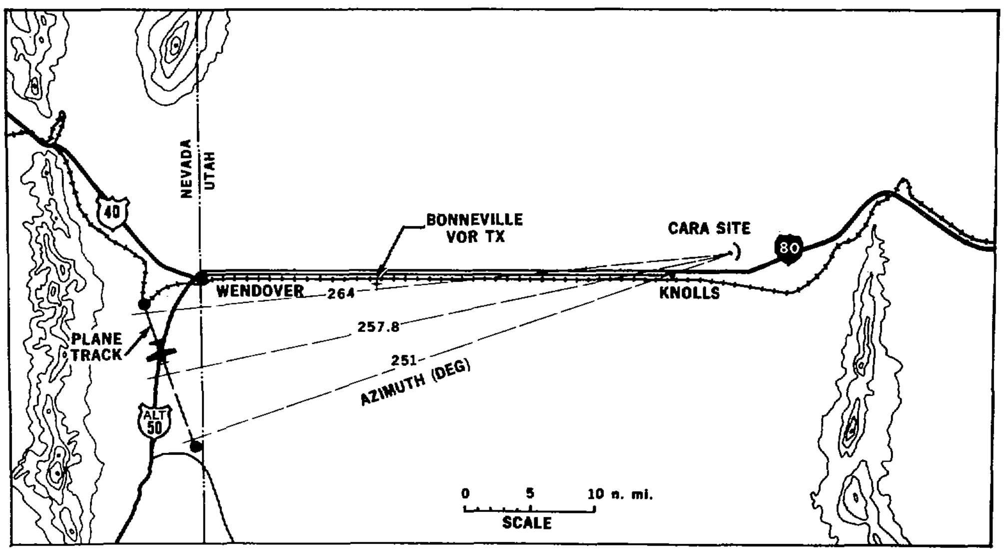
Signals from the beacon were quite weak because the elevation angle of the received signals was less than 0.4°, and the response of the low-horizontally-polarized CARA pickup dipole antennas approached zero at low elevation angles. However, the scanning beam pattern was stable and nonfading, indicating that the array was receiving a directly propagating signal (rather than one involving an anomalous propagation path such as sporadic E reflection or tropospheric inversion). The received signals were positively identified by carrier breaks on the beacon transmissions, and the receiver output was observed to drop into the noise level (approximately 15 dB lower) when the CARA reflector amplifiers were turned off.

2) Aircraft Pattern Measurements: A much more complete picture of the CARA beam patterns was obtained by flying the 10-W 14-MHz CW beacon transmitter aboard a light aircraft. The aircraft was flown repeatedly along a track shown in the map of Fig. 8(b). The azimuths of the CARA boresight (257.8°) and points near either end of the airplane track are indicated. The range to the aircraft from CARA was approximately 80 km. The position of the aircraft was determined by visual check points at each end of the track, and the aircraft flew at a constant speed between these points. A further check on the aircraft position was provided by recording the bearings of the Bonneville VOR aircraft navigation facility at intervals along the track. The absolute error in estimates of aircraft position corresponds to an expected uncertainty in bearing from the CARA antenna of approximately $\pm 0.5°$.

In the CARA receiver van the outputs from the focal point antennas were repetitively switched in sequence to the input of a single receiver. The output of the receiver was used to drive a pen chart recorder. A typical record obtained in this manner is shown in Fig. 10(a). The six simultaneously measured beam patterns have been separately traced in Fig. 10(b). It can be seen that six beams were formed clustered about an azimuth of approximately 258°. The beams are separated by 0.3–0.4°, and each is



(a)



(b)

Fig. 8. (a) Location of CW beacon transmitter relative to CARA. (b) Track of airborne CW beacon relative to CARA array.

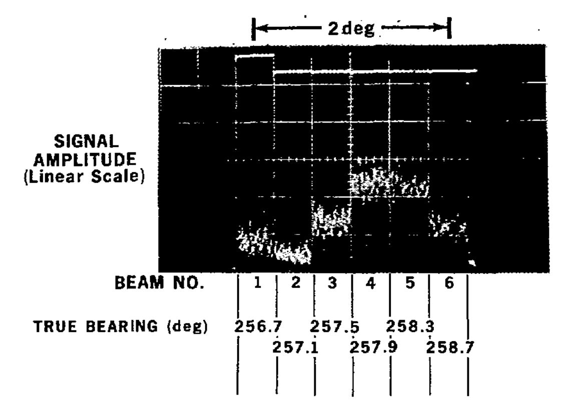


Fig. 9. Received signal amplitude from beacon transmitter on fix beams.

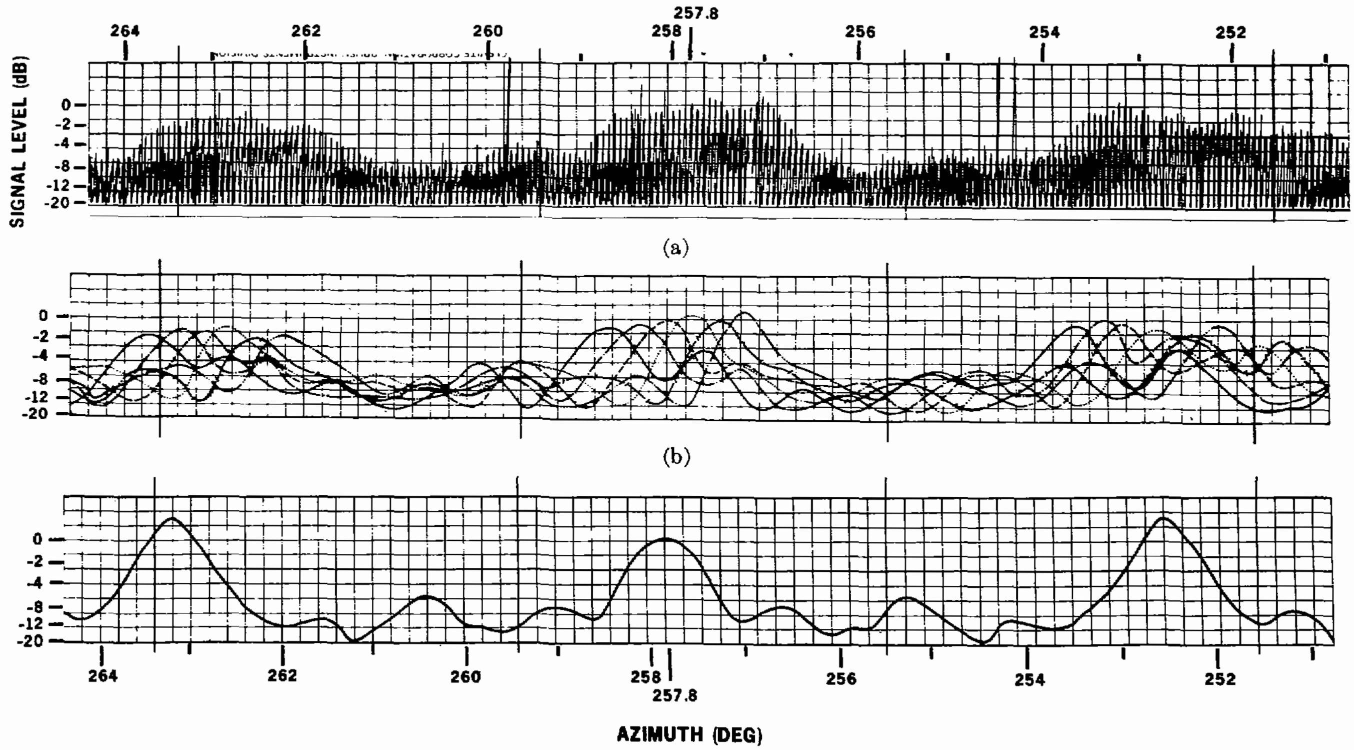


Fig. 10. Beam patterns using airborne beacon.

approximately 0.7° wide at the decibel points. The sidelobe responses clustered near 253° and 263° are the expected grating sidelobes that arise because the CARA is unfilled.

Signals observed from the airborne beacon were much stronger than those from the fixed beacon. The difference is attributed to the better response of the CARA pickup antennas at the higher angle of elevation to the aircraft beacon. The aircraft was at an altitude approximately 2000 m above the CARA, resulting in an elevation angle of arrival over three times greater than that from the ground beacon transmitter.

A computer calculation was performed of the boresight response pattern of the unfilled 120°-CARA sector. This result is plotted in Fig. 10(c) for comparison with the preceding experimental results. It can be seen that the computed main lobe beamwidth, the computed grating sidelobe separation, and the computed general sidelobe level between the main lobe and the grating sidelobe separation, and the computed general sidelobe level between the main lobe and the grating lobes are all in good agreement with the CARA behavior experimentally observed.

These results indicate that the CARA concept of forming beams in space is a sound one. The CARA antenna should prove useful when a large aperture HF antenna is needed.

REFERENCES

[1] G. H. Barry, "HF active-reflector reflector receiving antenna," Electron. Labs., Tech. Rep. 1, Jan. 1967.

[2] H. Jasik, *Antenna Engineering Handbook*. New York: McGraw-Hill, 1961, pp. 28-21, 22.

[3] R. C. Spencer, C. J. Sletten, and J. E. Welch, "Correction of spherical aberration by a phased line source," in *Proc. Nat. Electronics Conf.*, vol. 5, 1950, pp. 320–333.

[4] A. F. Kay, "A line source feed for a spherical reflector," AF Cambridge Res. Labs., Bedford, Mass., Tech. Rep. AFCRL-529 (TRG, Somerville, Mass., Rep. 131), May 1961.

[5] A. W. Love, "Spherical reflecting antennas with connected line sources," *IRE Trans. Antennas Propagat.*, vol. AP-10, pp. 529–537, Sept. 1962.

[6] G. G. McCormick, "A line feed for a spherical reflector," *IEEE Trans. Antennas Propagat.*, vol. AP-15, pp. 639–645, Sept. 1967.

[7] F. S. Holt and E. L. Bouche, "A Gregorian corrector for spherical reflectors," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 44–47, Jan. 1964.

[8] M. L. Burrows and L. J. Ricardi, "Aperture feed for a spherical reflector," *IEEE Trans. Antennas Propagat.*, vol. AP-15, pp. 227–230, Mar. 1967.

[9] S. M. Reynolds, "A beverage-element array," in *Proc. OHD Technical Review Meeting*, volume III, 1969.

[10] L. E. Sweeney, Jr., "Spatial properties of ionospheric radio propagation as determined with half-degree azimuthal resolution," Stanford Electron. Labs., Tech. Rep. 155, June 1970.