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A Broadband Linear Array for Space Surveillance

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ABSTRACT

A broadband linear array with minimum side lobes has been developed to meet several special requirements of the U.S. Navy Space Surveillance System. These requirements include simultaneous monitoring of a number of frequencies in the 100 to 500 Mc/s band for the early identification and separation of satellites launched in multiple sets. The constructed arrays are 5600 feet long, consisting of 1080 biconical aluminum-rod elements above a ground screen. The VSWR is less than 2:1 over the frequency range 100 to 500 Mc/s. An "offset" harnessing technique has been used to provide an amplitude distribution for minimum side lobes while maintaining the equal line lengths required for broadbanding. Good suppression of grating lobes exists to above 300 Mc/s.

PROBLEM STATUS

This is an interim report on a continuing problem.

AUTHORIZATION

NRL Problem R02-35
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A BROADBAND LINEAR ARRAY FOR SPACE SURVEILLANCE

INTRODUCTION

The U.S. Navy Space Surveillance System is a bistatic cw radar consisting of four receiving stations interspersed by three transmitting stations along a great circle from San Diego, California, to Ft. Stewart, Georgia. Linear antenna arrays normal to the great circle form coplanar fan beams. Receiver stations utilize multiple array interferometers to measure the angle of arrival of signals in the fan beam. I-F preselectors are used to detect a signal in a wide Doppler frequency range and to automatically tune narrow-band receivers to the required frequency.

The antenna which feeds the i-f preselector has been designated the alert antenna. In general, this antenna is required to have excess gain over the pairs of interferometer antennas. The amount of excess gain required is a function of the pre- and postdetection bandwidths in both the i-f preselector and phase measuring channels as well as a function of system noise temperature and false alert rate.

While a single-frequency linear array with the required excess gain would satisfy the basic requirement, it was determined that a broadband array with minimum side lobes would provide several distinct advantages based on the following points:

1. A plan had been prepared to change the frequency of the Space Surveillance System to a military band near 150 Mc/s.

2. Many U.S. satellites transmit in the 100 to 500 Mc/s frequency band.

3. Minimum side lobes will reduce the extraneous side-lobe response for large signals.

The original plan called for an array to operate in the 108 to 150 Mc/s frequency band in anticipation of the planned frequency change for the Space Surveillance System. During the initial design phases it was determined that a significant increase in bandwidth could be achieved with a slight increase in complexity and cost. The extended bandwidth has proved valuable, since the approved frequency change now being instituted is near 217 Mc/s.

Many U.S. satellites have been launched in multiple sets. The broadband antenna with suitable output multiplexing has allowed early identification and/or separation of these multiple satellite launches based on their transmitted frequencies as they pass through the fan beam.

ELEMENT AND BALUN

The basic element for the receiving antennas is a dipole over a ground screen with the E plane normal to the great circle. The height above the ground screen is adjusted to provide a 3-db beamwidth of approximately 120° for maximum coverage in the plane.

The element for a broadband array had the following design objectives:

1. VSWR < 2:1 in the frequency range 100 to 500 Mc/s

2. H-plane beamwidth > 90° in the frequency range 100 to 500 Mc/s

3. E-plane response such that grating lobes are suppressed for the minimum spacing defined by the element size.

The following elements were given initial consideration as having properties consistent with the design objectives: cylindrical or sleeve dipole, discone, biconical, cylindrical V, and log periodic.

The discone is basically a bidirectional element and was discarded on the basis of its radiation patterns when located over a ground screen.

The cylindrical or sleeve dipole and the cylindrical V displayed bidirectional characteristics over the frequency range for most configurations, i.e., L/D ratios. The cylindrical V was promising for small L/D ratios; however, the large physical size ruled it out compared to the element selected.

In general, log periodic configurations behave like a simple dipole element at each of the resonant bands. This characteristic precludes any suppression of grating lobes as the spacing in wavelengths becomes large.

The element selected for final development was the biconical V. The biconical V has the following primary characteristics:* broadband impedance matching, increased gain with frequency, and back radiation at the low-frequency end of the band which can be controlled with the proper ground-screen spacing.

Initial measurements to determine size and height above ground screen spacing were made with a sheet-copper biconical V. Figure 1 shows the final development element, which was constructed of aluminum rods with nearly identical performance to the solid-sheet unit. The rod biconical element reduced cost and weight significantly. A balun for this balanced element was readily available from literature.† Figures 2a and 2b show the production version of the balun, which is approximately 0.5λ at the lowest frequency (100 Mc/s). Figure 3 shows the VSWR vs frequency for the final design element and balun. Figure 4a is a series of H-plane patterns in the range 100 to 400 Mc/s, and Fig. 4b is a series of E-plane patterns for the same frequencies.

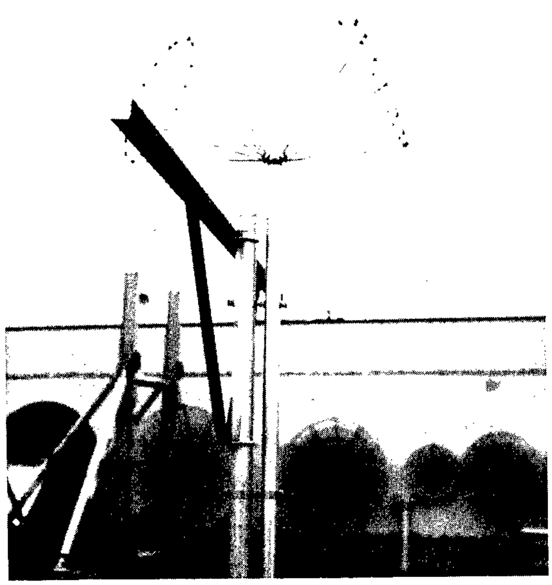

Fig. 1 - The element selected for final development

*"Very High Frequency Techniques," Vol. I. Radio Research Laboratory Staff, Harvard Univ., New York:McGraw-Hill, 1947, p 109.

†J. W. Duncan and V. P. Minerva, "Bandwidth Balun Transformers," Proc. IRE 100:1 (Feb. 1960).

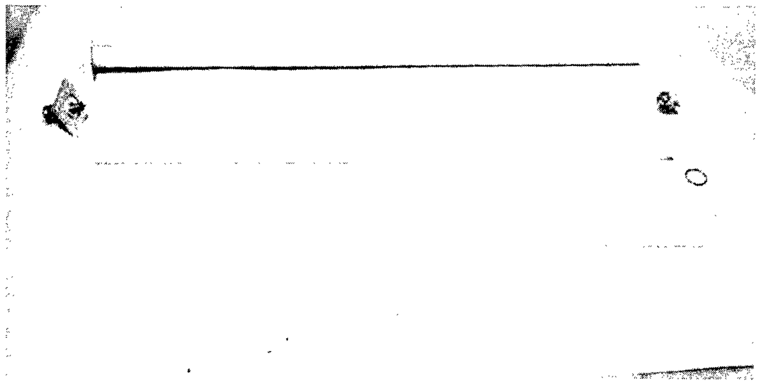

Fig. 2a - The balun (disassembled)

Fig. 2b - The balun (assembled)

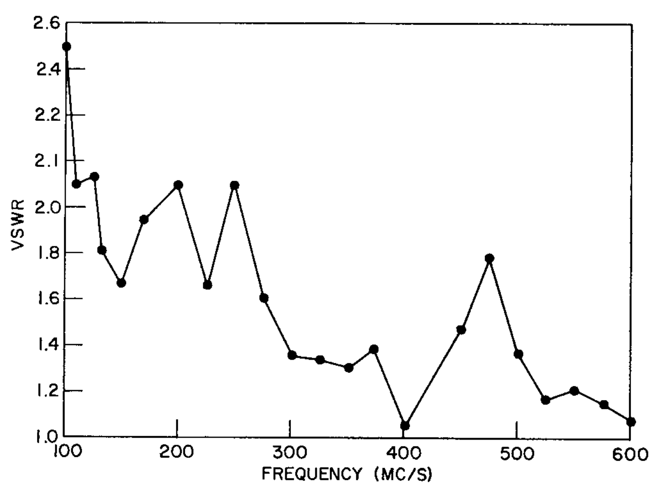

Fig. 3 - The VSWR in the frequency range 100 to 500 Mc/s for the rod biconical element and balun

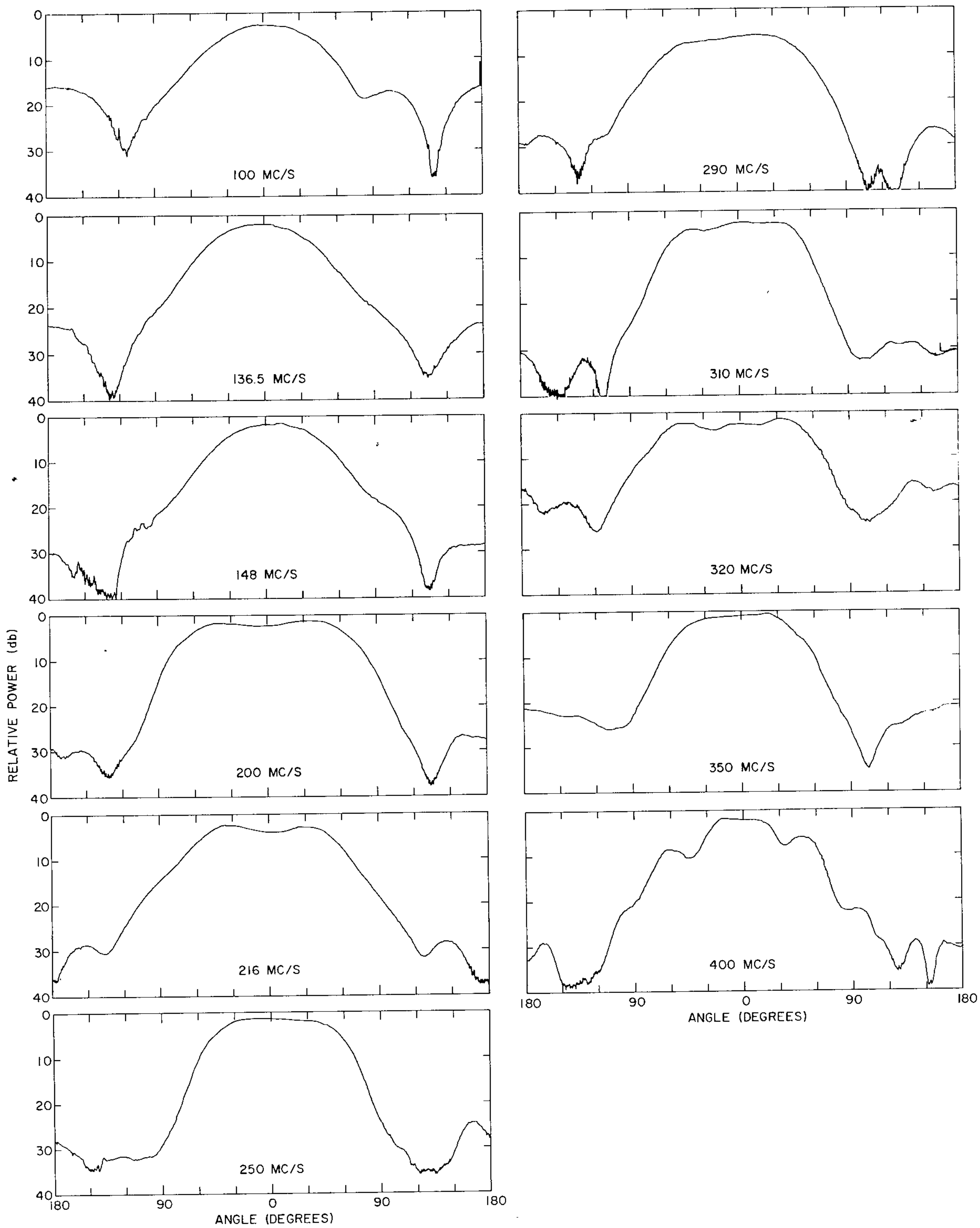

Fig. 4a - H-plane patterns for a series of frequencies from 100 Mc/s to 400 Mc/s

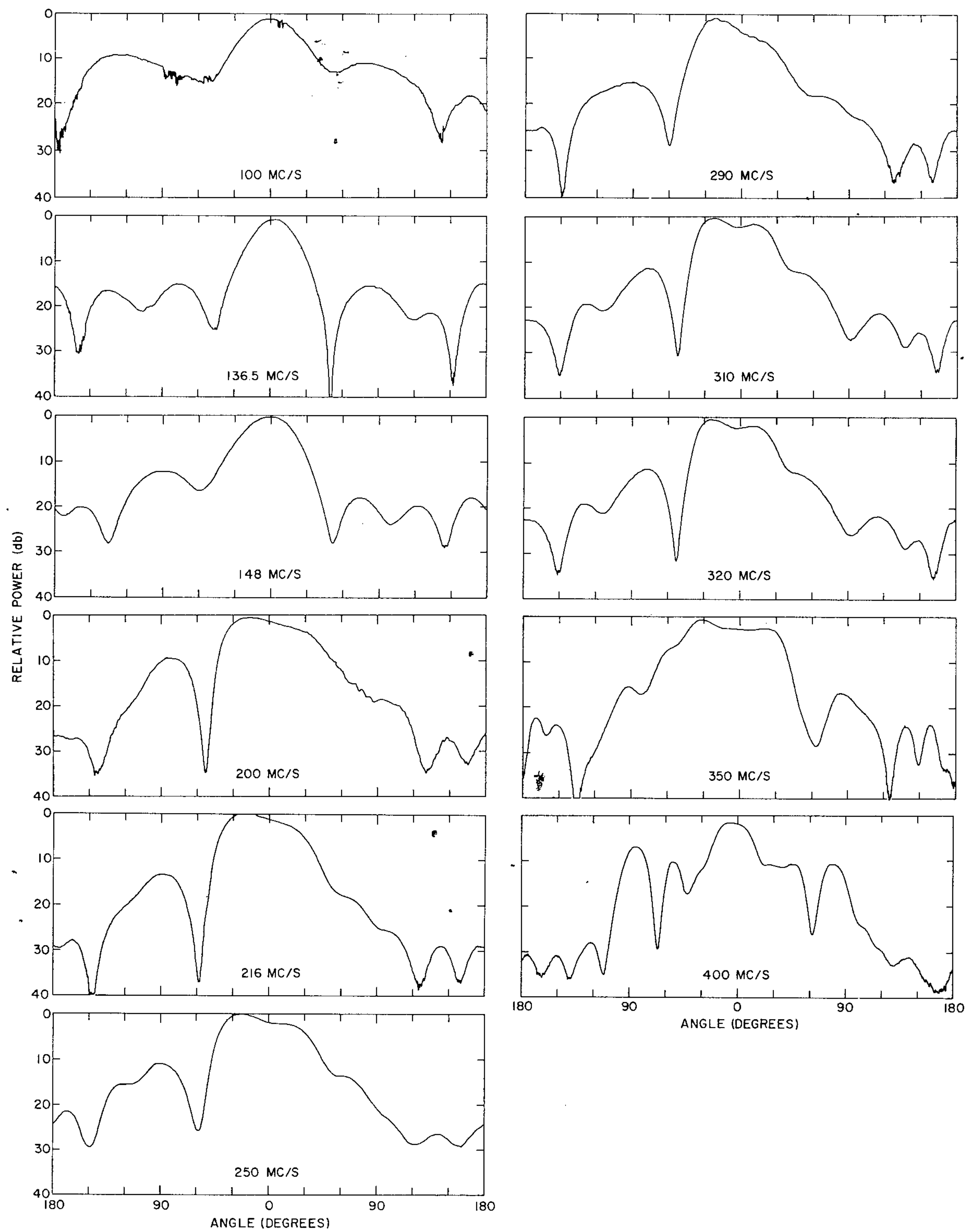

Fig. 4b - E-plane patterns for a series of frequencies from 100 Mc/s to 400 Mc/s

HARNESS

The combining harness for this array was designed to have the following characteristics: (a) minimum loss consistent with cost, (b) amplitude distribution for minimum side lobes, and (c) minimum reflection coefficient over the 100 to 500 Mc/s passband.

In general, fewer different sizes of transmission line will minimize cost with no significant effect on loss. A 7/8-inch semiflexible cable with a loss of 0.4 db per 100 feet at 100 Mc/s was chosen as the largest cable to be used for the element feed. The harness loss design aim of less than 2 db required that the remaining harness consist of 6-1/8-inch rigid line with copper inner and aluminum outer conductors. The loss for this line is 0.05 db per 100 feet at 100 Mc/s.

In order that the harness be broadband the length of feed cable must be equal for every element. This requires that the lengths of each size of cable must be equal when traced to every element. Figure 5 is a graph which shows the harness loss reduction plotted against cost for additional 6-1/8-inch line. Increased loss with less 6-1/8-inch line is shown as cost reduction or savings. The primary significance of this plot is that the design point is at the knee of the curve, where decreased loss becomes extremely costly and nominal savings result in high loss.

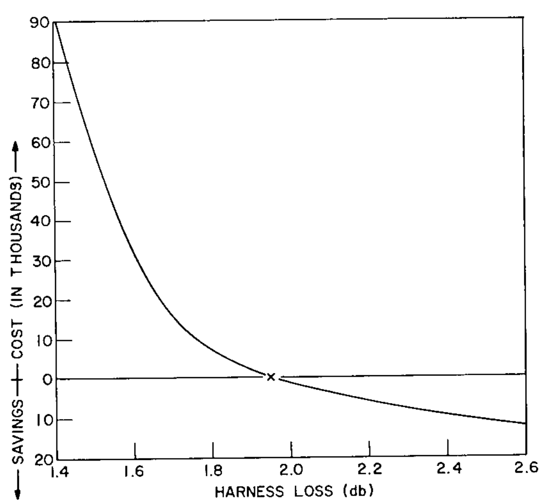

Fig. 5 - The cost of additional 6-1/8-inch line to reduce the harness loss from the 1.95-db value, or the savings resulting from less 6-1/8-inch line but increased harness loss

The line impedance was chosen at 75 ohms for nearly optimum loss per unit length and additional cost reduction due to reduced copper inner conductor size.

Various amplitude distributions may be applied for reduced side lobes. If maximum gain is desired and a specific side-lobe level is acceptable, then the Dolph-Tchebycheff distribution is optimum. Since an element-by-element amplitude distribution for more than 1000 elements is impractical, a compromise or approximation was selected. A 90-element Dolph-Tchebycheff amplitude distribution had been previously* tabulated for 40-db side lobes. Figure 6a shows the approximate distribution compared to the tabulated Dolph-Tchebycheff distribution. Figure 6b is the computed response comparing the two distributions.

*M. L. Reuss, "Some Design Considerations Concerning Linear Arrays Having Dolph-Tchebycheff Amplitude Distributions," NRL Report 5240, Feb. 1959.

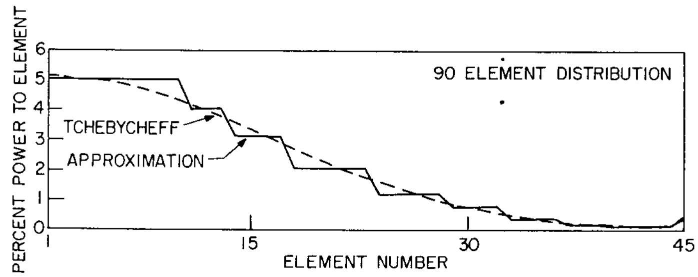

Fig. 6a - Comparison of a 90-element Dolph-Tchebycheff amplitude distribution tabulated for 40-db side lobes and the approximate distribution

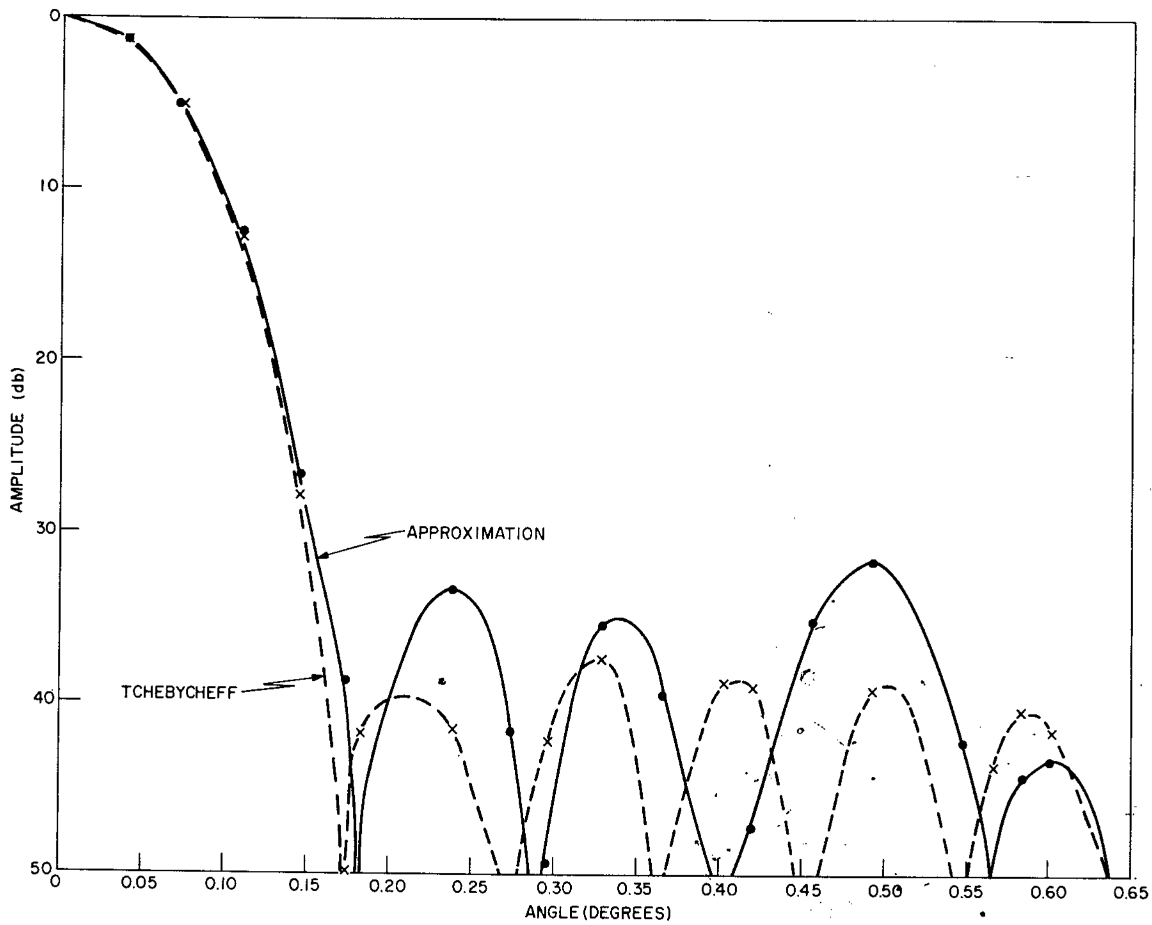

Fig. 6b - Comparison of the responses to the distributions of Fig. 6a

Broadband performance requires transmission line lengths to all elements be equal. Efficiency requires minimum line loss throughout the harness. In order that these requirements are met and at the same time an amplitude distribution be effected an offset feed system was designed. The basic technique consisted of selecting the end element group and assigning its signal amplitude as the level required by the calculated distribution. Working from that point toward the array center, groups were selected and combined to approximate the Tchebycheff distribution. Since the number of groups combined varied along the array, it was necessary to offset the tee combining points to maintain constant line lengths to all elements. Figure 7 is a diagram showing the offset technique and other harness details.

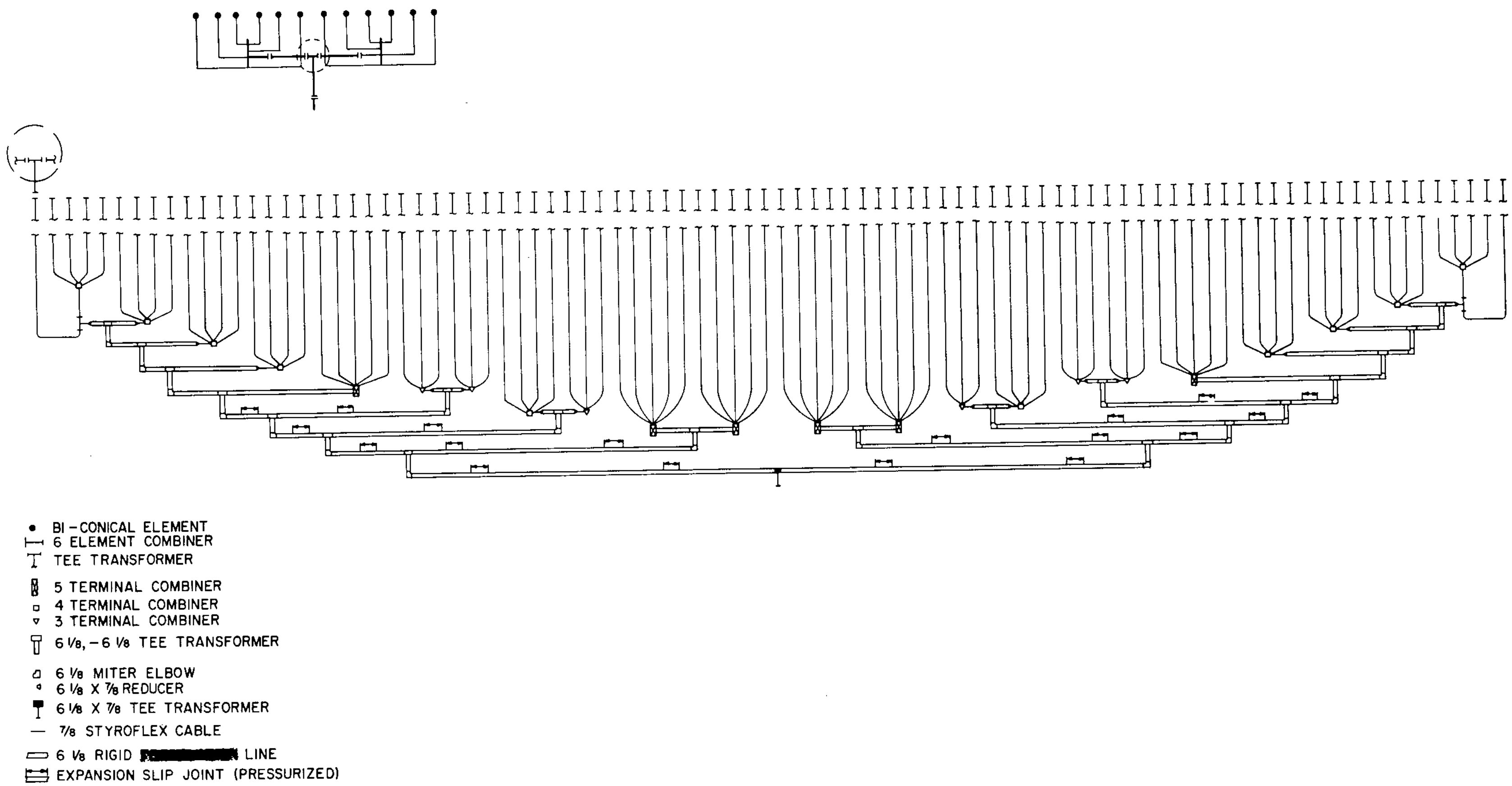

Fig. 7 - The offset technique to achieve equal line lengths and equal cable lengths in the harness

The expected gain reduction compared to a uniform array had been previously* computed for 40-db design side lobes as approximately 1 db. A simple computation can be used to illustrate the effect: Consider a uniform array of n elements fed by equal voltages e_u; at a distant point $\Sigma e_u = ne_u$. For the case of an amplitude distribution at the same point we have Σe_t, where the subscript t indicates Tchebycheff. If we normalize the power radiated,

$$\sum e_t^2 = \sum e_u^2 = ne_u^2$$

or

$$e_u = \sqrt{\frac{\sum e_t^2}{n}} .$$

The gain may be expressed as

$$G = \frac{ne_u}{\sum e_t} = \frac{n\sqrt{\sum e_t^2/n}}{\sum e_t} = \frac{\sqrt{n\sum e_t^2}}{\sum e_t} .$$

From the tabulated values, we have $\Sigma e_t^2 = 411.72$ and $\Sigma e_t = 170.84$, which along with $n = 90$ gives $G = 1.123 = 1.02$ db.

The large number of transformer combiners required for this array presented a special problem. Simple linear transformers would have to be many wavelengths long to preclude additive mismatch to the existing VSWR of the elements. It is possible using the Tchebycheff transformer† to prescribe a maximum reflection coefficient for a given frequency band. The transformer selected was a ten-section unit with a 0.57λ length at the lowest frequency and a design maximum reflection coefficient of 0.01 in the 100 to 500 Mc/s band. Figure 8a is a sketch of one such transformer and Fig. 8b is the measured reflection coefficient for that unit. It should be noted that the transformer portion of the work was straightforward, while the combiner portions presented relatively difficult developmental techniques. The design was such that only tee transformers were used throughout the 6-1/8-inch line and multiple combiner units of two, three, four, five, and six ways were used in 7/8-inch line.

THE ARRAY

The final array was constructed by mounting the 1080 element and balun combinations on individual steel posts. The steel posts also served to hold support rails for ground-screen wires and transmission line. Figure 9 shows a single element and balun mounted on its post. Figure 10 shows a section of the completed array.

The offset line technique cannot be as broadband as a corporate harness unless thermal expansion can be compensated or is small in the different sections. The simplest solution to this problem was to tie the major portions of the harness to maintain a constant physical length. Pressurized expansion joints were designed to compensate for thermal expansion. Figure 11a shows one expansion joint. Figure 11b shows a tee section with the tie cables. Teflon bands were used on the support rails to facilitate line slide. Differential expansion between inner and outer conductors was compensated with extra long bullets.

*Ibid.

†"Antenna Engineering Handbook," edited by Henry Jasik, New York:McGraw-Hill, 1961, Section 31-14 by D.F. Bowman.

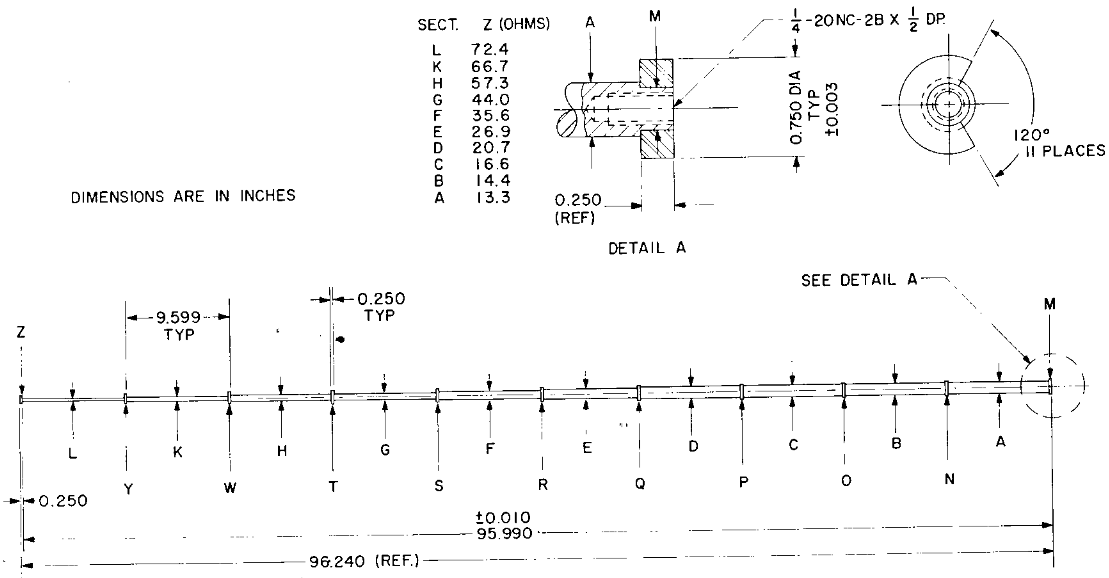

Fig. 8a - Ten-step Tchebycheff transformer

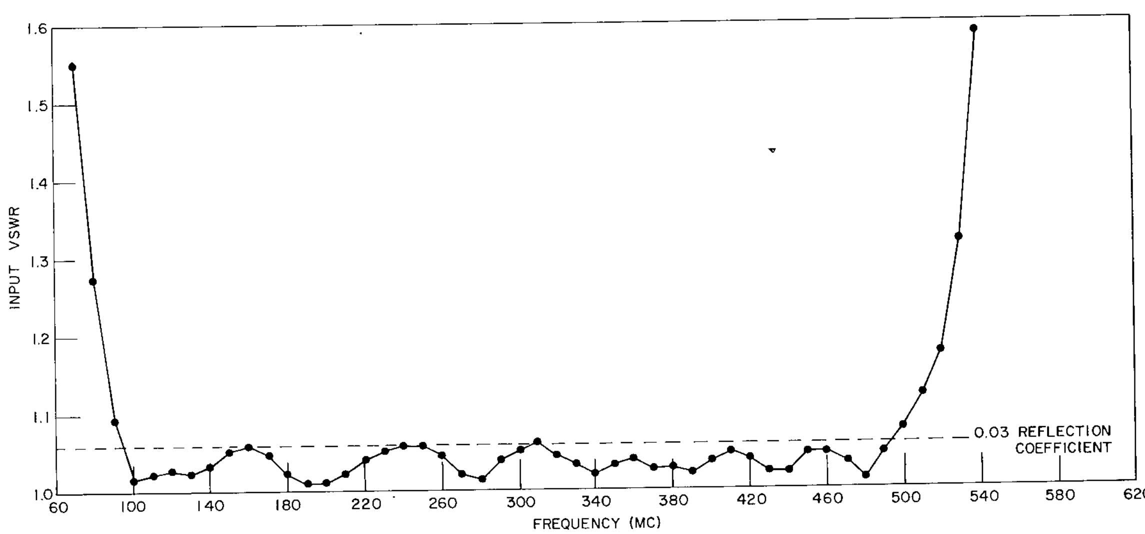

Fig. 8b - Measured reflection coefficient for the transformer sketched in Fig. 8a

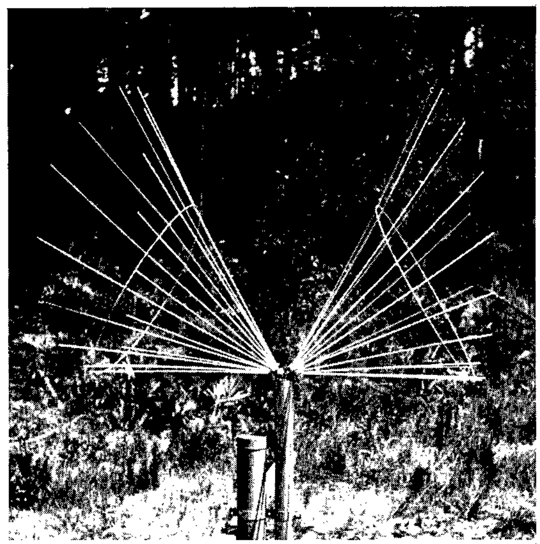

Fig. 9 - Single element and balun mounted on its post

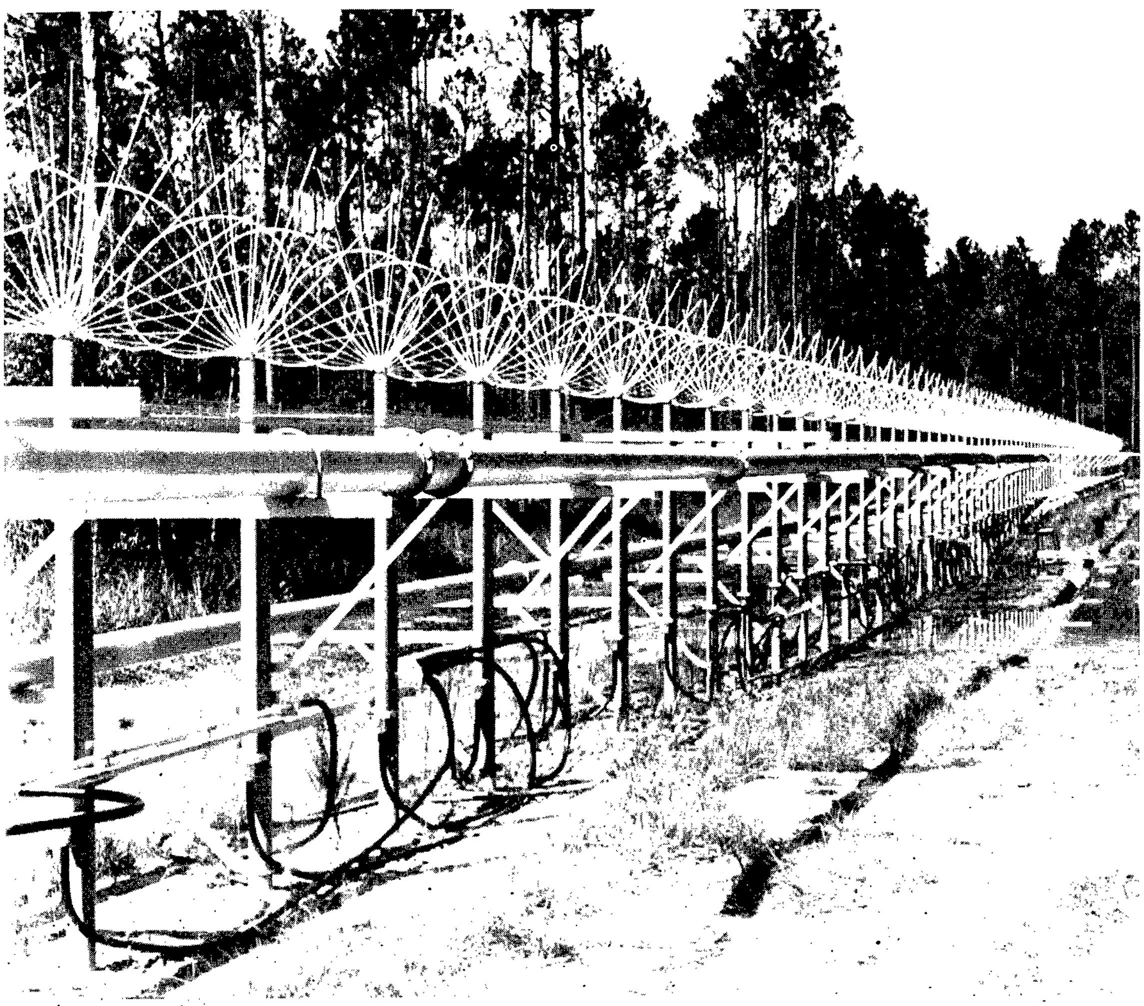

Fig. 10 - Section of the completed array

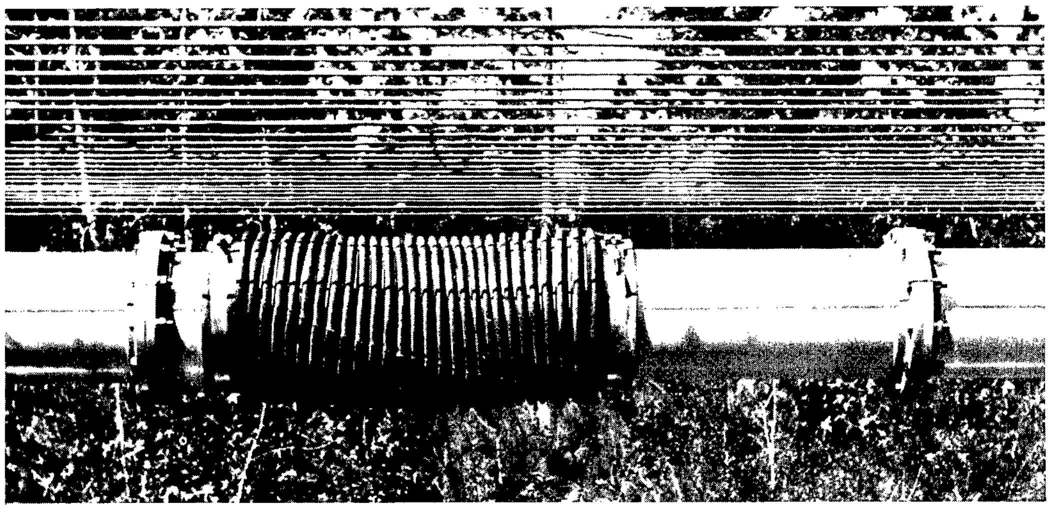

Fig. 11a - Expansion joint to compensate for thermal expansion

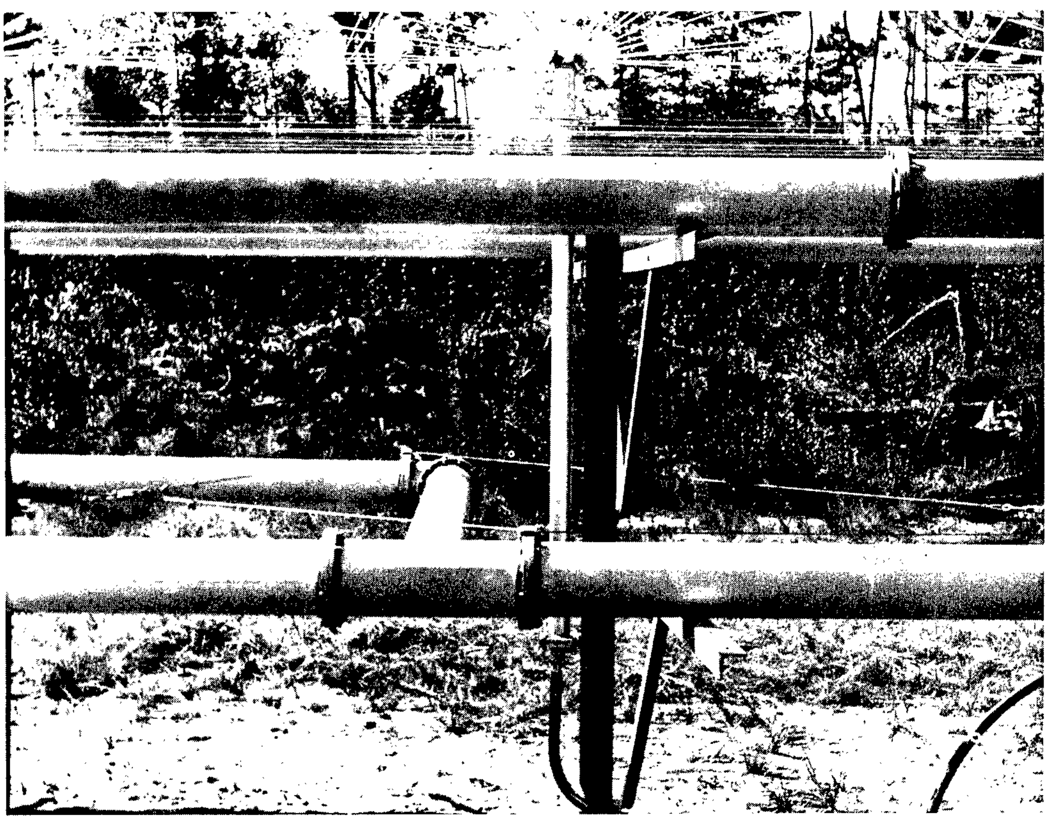

Fig. 11b - Tie cables to maintain constant physical length

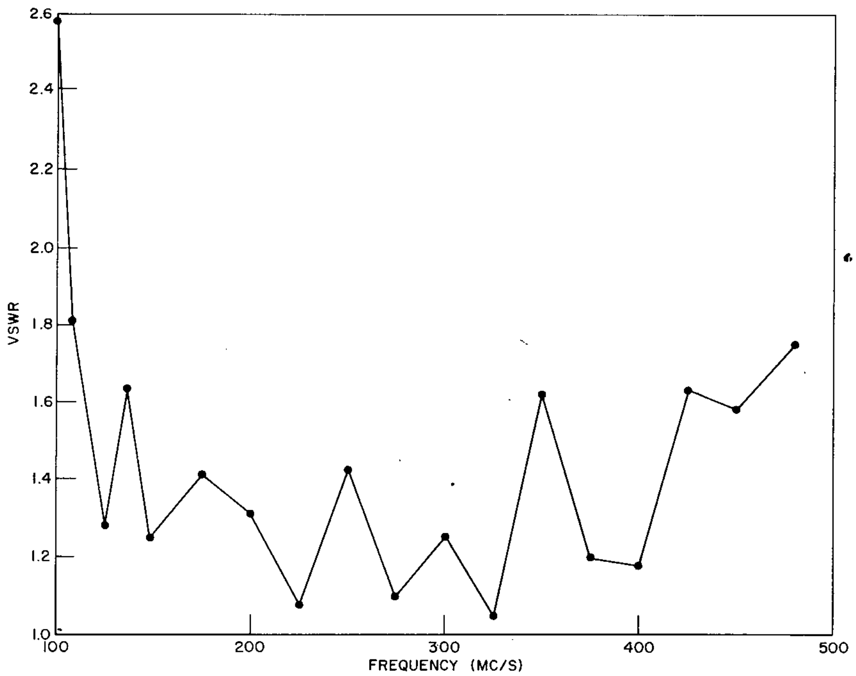

Fig. 12 - The VSWR for the completed array

Figure 12 is a graph of VSWR vs frequency for the completed array. Figures 13a and 13b are the relative phase measurements for the array at sample points north of the center and south of the center.

Several techniques have been used to evaluate the arrays. Of these, radiating satellites have been the most graphic. Most of the existing radiating satellites are at ranges of less than $2d^2/\lambda$. Figure 14 is a recording of a radiating satellite with a beacon frequency of 108 Mc/s at a range of approximately d^2/λ. The bottom channel is the agc recording of a receiver fed by a 1600-foot uniform array. The second channel from the top is a similar recording from the 5600-foot array. The maximum side-lobe levels measured from a calibration of the agc are -11 db and -20 db respectively. The top channel is a phasemeter recording measuring the angular position of the satellite. Its full-scale value is 0.435°. The angular measure to the first null for the 1600-foot antenna is 0.32° and for the 5600-foot array is 0.16°. These values compare favorably with the computed values for the two cases as shown in Fig. 15. The computed response for the satellite altitude of 600 miles shown in Fig. 16 however indicates the first minimum should occur at 0.2°. Figure 17 is a recording of two satellites passing through the fan in close sequence. The first satellite, radiating on 108 Mc/s, is seen on the bottom channel for the 1600-foot uniform array and for the 5600-foot array on the fourth channel from the bottom. The second satellite, radiating on 400 Mc/s and 150 Mc/s simultaneously, is seen on the second and third channels from the bottom respectively.

Measurements of beam patterns, side-lobe level, and harness loss have given a fairly graphic analysis of antenna performance. Analytical measurements have been made by comparing the relative signal levels received on this array and on the 1600-foot uniform array to show relative gain difference. Agreement is remarkably good.

Low-insertion-loss multiplexers feeding low-noise amplifiers have been used to allow the operational use of the antenna at 108 Mc/s and also allow the simultaneous monitoring of a number of frequencies in the 100 to 500 Mc/s band.

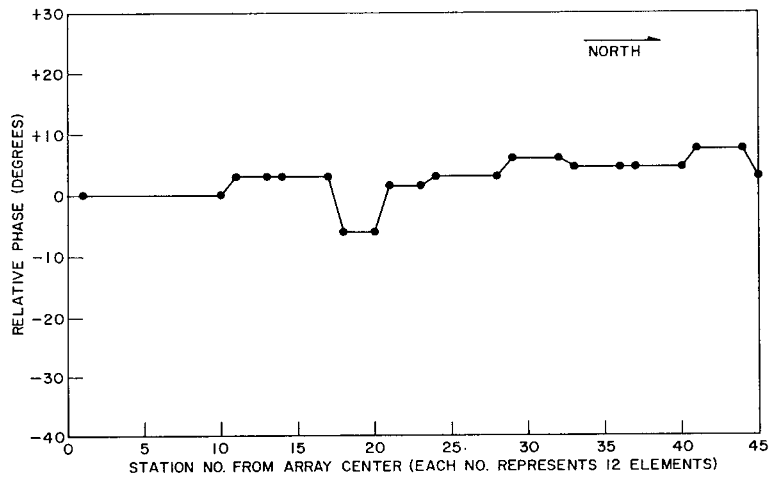

Fig. 13a - Relative phase measurements at points north of the array center

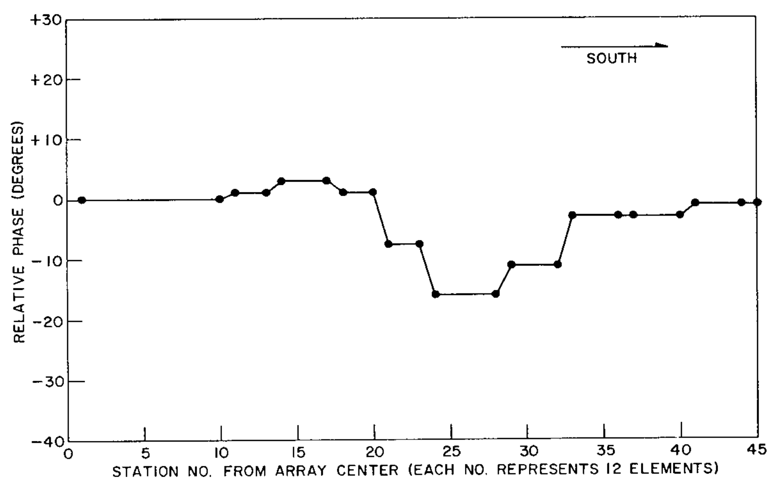

Fig. 13b - Relative phase measurements at points south of the array center

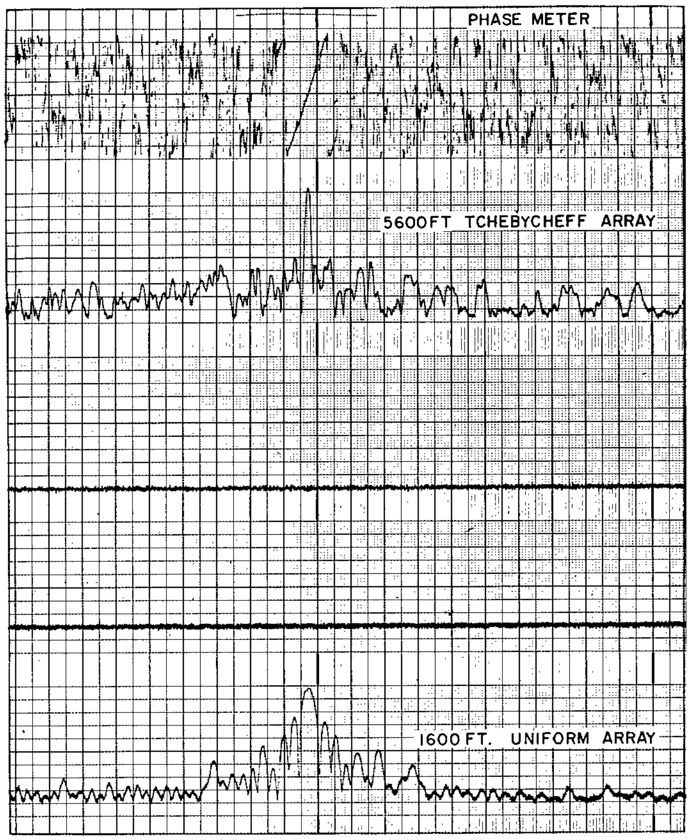

Fig. 14 - Recording of a satellite radiating at 108 Mc/s. The top channel is a measure of the angular position, and the second and bottom channels are the agc levels of the receivers fed by the respective arrays.

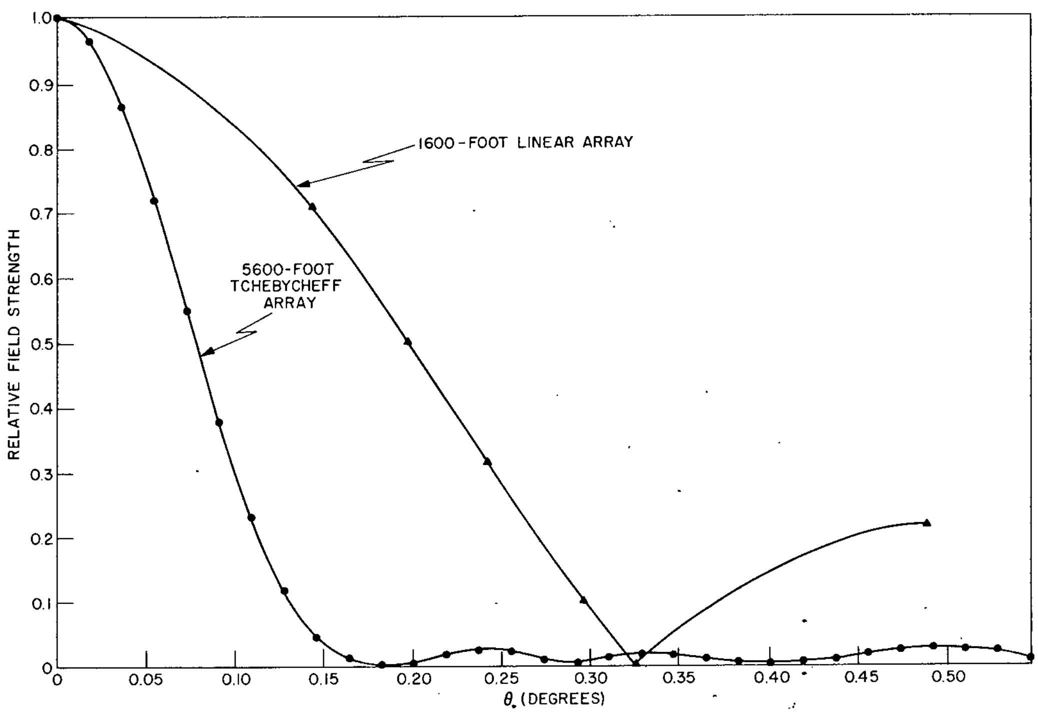

Fig. 15 - Computed antenna patterns for the two antennas indicated in Fig. 14

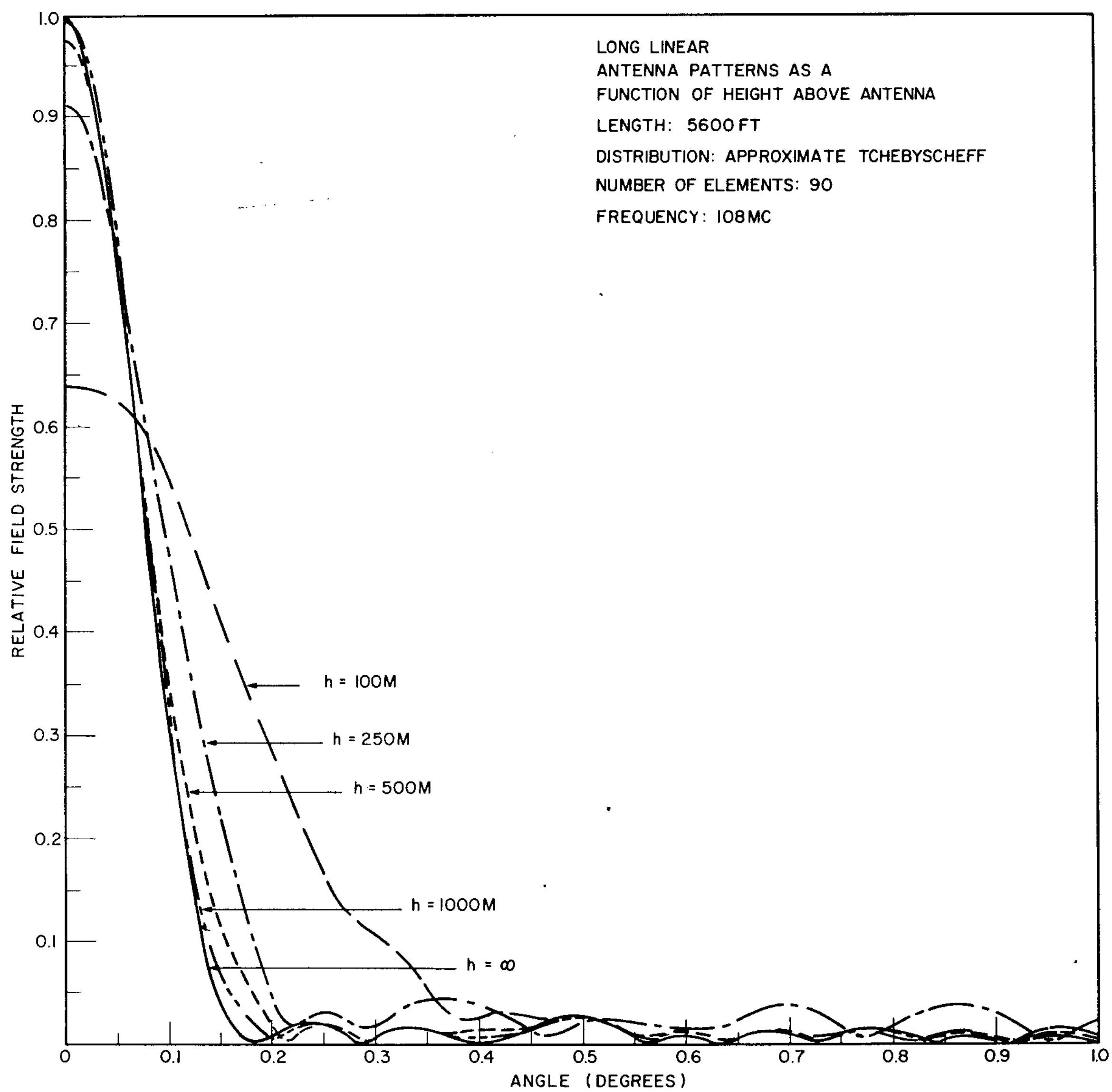

Fig. 16 - Computed response of the 5600-foot Tchebycheff array for satellites at various heights in miles radiating on 108 Mc/s

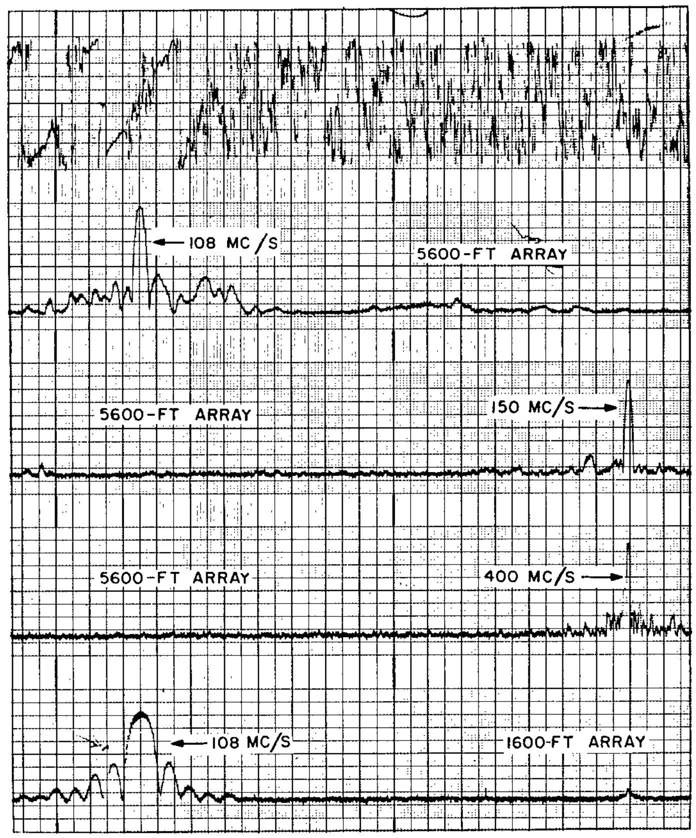

Fig. 17 - Recording of two satellites in close sequence, one radiating at 108 Mc/s and the other radiating simultaneously at 150 and 400 Mc/s

CONCLUDING REMARKS

It is felt that the primary objectives in this work have been attained. The final measurement of VSWR is consistent with the element and the harness loss, especially at the higher end of the frequency band. The observed side-lobe levels of -20 db are considered reasonable compared to a computed value of -30 db for an approximation to a Dolph-Tchebycheff distribution. The measured E-plane patterns indicate good suppression of grating lobes to above 300 Mc/s. The expected grating lobes at 400 Mc/s have been observed.

Some forms of value engineering have been applied as indicated in the graph of cost vs harness loss.

If we compare the gain of this linear array to a parabolic reflector, the reflector diameter would be approximately 280 feet.

ACKNOWLEDGMENTS

The basic antenna was originally proposed by Roger Easton and developed under his direction. Messrs. Walter Babington and Frank Keller performed thousands of measurements in the development of the element and balun as well as in the field installation and evaluation. The final arrays were designed for production, constructed, and installed by the Technical Appliance Corporation (TACO) of Sherburne, New York. The ten-step Tchebycheff transformers and combiners were designed and developed by Scanwell Laboratories, Inc., of Springfield, Virginia, for TACO. Some timely modifications to the pressurized expansion joints and mechanical ties were devised and installed by Mr. David Phillips.

The computed response characteristics for the Tchebycheff distribution compared to its approximation and the Fresnel zone performance characteristics were prepared under the direction of Mr. D. W. Lynch.