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Wullenweber Arrays

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Summary

Two configurations of Wullenweber Arrays with extended frequency range are examined and their essential parts described. These antennas provide a multiplicity of fixed high gain beams, and low gain sector beams covering 360° in azimuth and giving broad elevation coverage. With the use of a suitable beam forming system, multicouplers, and an elaborate RF distribution system, a receiving system requiring a relatively small area and providing multiple access for a large number of receivers, which can be attached to any combination of beams, is obtained.

Great progress has been made in the development of DF instrumentation. Precise signal direction of arrival with accuracies of better than one degree have been obtained with a low insertion loss goniometer, and the phase interferometer technique. Significant improvements in system performance were achieved in high gain, low noise solid state amplifiers, low insertion loss power dividers and combiners, highly stable delay lines with very tight amplitude and phase tracking, and broadband multicouplers. Overall system and design considerations as well as performance characteristics of a typical system are presented.

Introduction

The word Wullenweber is a code name used by the German Government during World War II, and refers to the 'spinning wheel' of a rotating goniometer. The original Wullenweber Array was a circular array with a reflecting screen. It had a diameter of about 240 m and the frequency range was rather limited. Top loaded fat monopoles with loading resistors were used as antenna elements.

After the war, Wullenweber Arrays were developed in the United States, and both frequency range and performance considerably improved. The developments were mainly concentrated at the Naval Research Laboratory (NRL) in conjunction with the University of Illinois, and at Rome Air Development Center (RADC) with Sylvania Electronic Systems as commercial contractor for the U.S. Air Force.

Wullenweber Arrays can be used for a number of purposes. Originally it was an antenna for direction finding but later the inherent capability of providing high gain beams which can be oriented in any desired direction was exploited and opened new applications in research areas for the investigation of ionospheric propagation phenomena and as an HF receiving antenna for communications.

The development in the United States concentrated on an extension of the frequency range to cover the entire HF band, on increasing the aperture to about three times the original size up to 1200 feet diameter and on increasing the stability, sensitivity and accuracy of the Wullenweber Array. A main problem was the extension of the frequency coverage. The concept of a multi-band array for the solution of this problem was proposed by E. C. Hayden of the University of Illinois. In effect, two or more arrays, for two or more portions of the frequency range are arranged concentrically on the same site. Two basic configurations were investigated and developed: (a) a single reflecting screen with two rings of elements (Sylvania) and (b) two reflecting screens with two rings of elements (NRL and University of Illinois).

Wullenweber Array Configurations

The Two-Screen Wullenweber Array

A plan and elevation view of the two-screen, two-band Wullenweber Array is shown on figure 5-1 and a perspective view of a segment of this array is shown in figure 5-3. This configuration comprises a conventional high-band array built as large in diameter as siting conditions, economic limits, or other requirements permit, inside which a low-band array is located. Two screens and two rings of elements are used. The high-band elements are located on the largest diameter in front of the high-band reflector screen, whereas the low-band elements are located on a smaller diameter in front of the much higher low-band screen. Thus the low-band array sees through the entire high-band array. The radial spacings of antenna elements and reflecting screens are critical and depend on the frequency range to be covered. It has been found that a practical limit of the frequency band of one array is about 3:1, so that the low-band and high-band arrays will cover a total frequency range of about 9:1.

The high-band array is designed as if the interior low-band array did not exist, since its performance is not influenced by the presence of the low-band array except at frequencies below its nominal range where the high-band screen does not act as a reflector. Care must be exercised to obtain suitable relations between the dimensions and radial spacing of the high-band elements and the height of the high-band screen, to avoid trapped surface wave propagation along the periodic structure of the high-band screen and pattern degradation.

The low-band array must be designed so that it can see through the high-band array. This requires proper proportioning of the high-band array, and of the spacing of the low-band elements from the high-band screen, this spacing being about 20% greater than the height of the high-band screen. It is possible to make the height of this screen so that it acts as a parasitic director for the low-band array just below the nominal cross-over frequency. This will decrease the elevation angle at the upper end of the low-band frequency range. The heights of the reflecting screens are about $\lambda/4$ at the low end of each band. Although two screens are required, the total amount of wire used in both screens and the cost of these is considerably lower than in the case of the single screen configuration where the height of the single screen is $\lambda/4$ of the low frequency in the low band, whereas the number of screen wires is determined by the highest frequency of the high-band. The number of elements used depends, of course, on the diameter of the array and the required frequency band. For a band ratio of 3:1, the number of elements in the high-band is three times as great as that in the low-band. For a typical case the number of elements is 40 and 120 respectively.

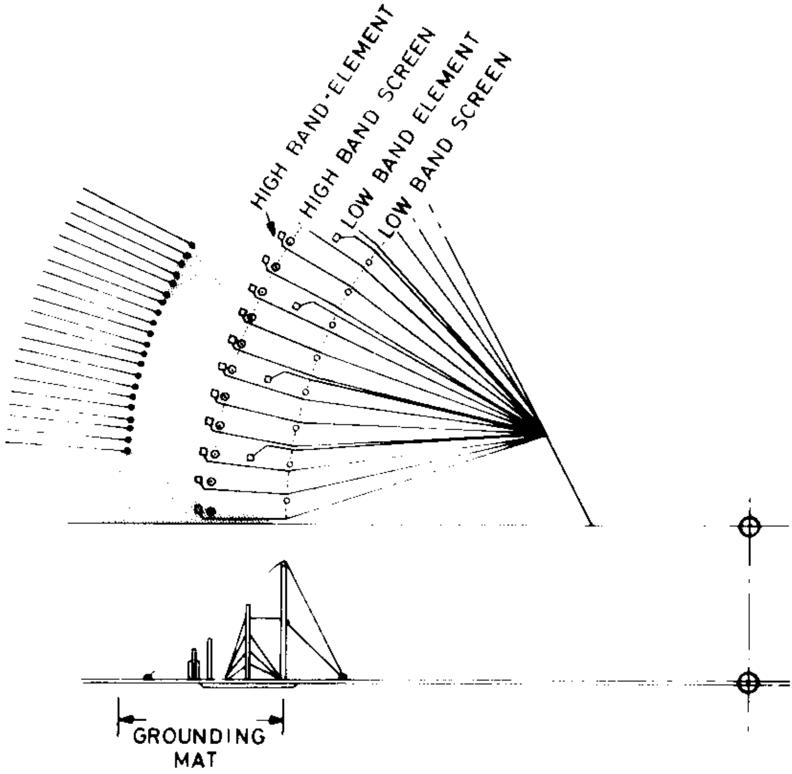

Fig. 5-1 Layout of Double Screen Array.

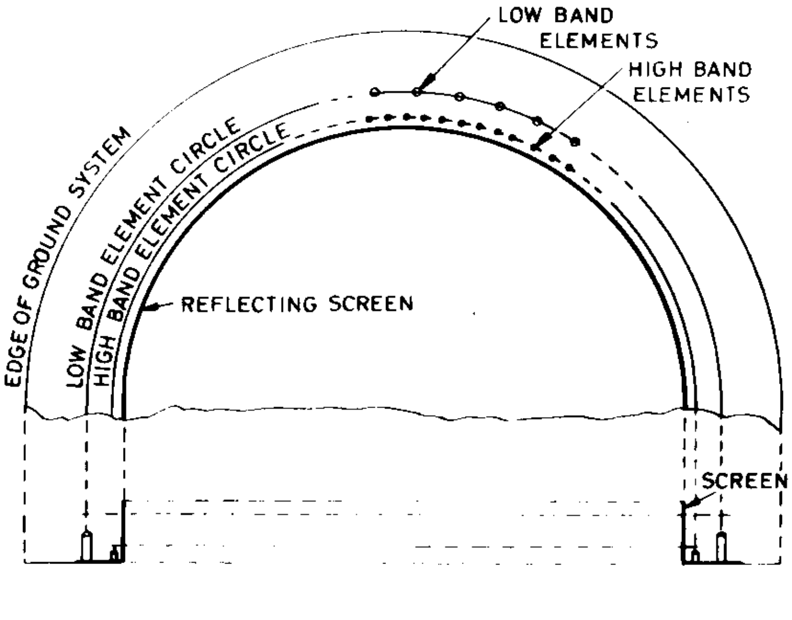

Fig. 5-2 Layout of Single Screen Array.

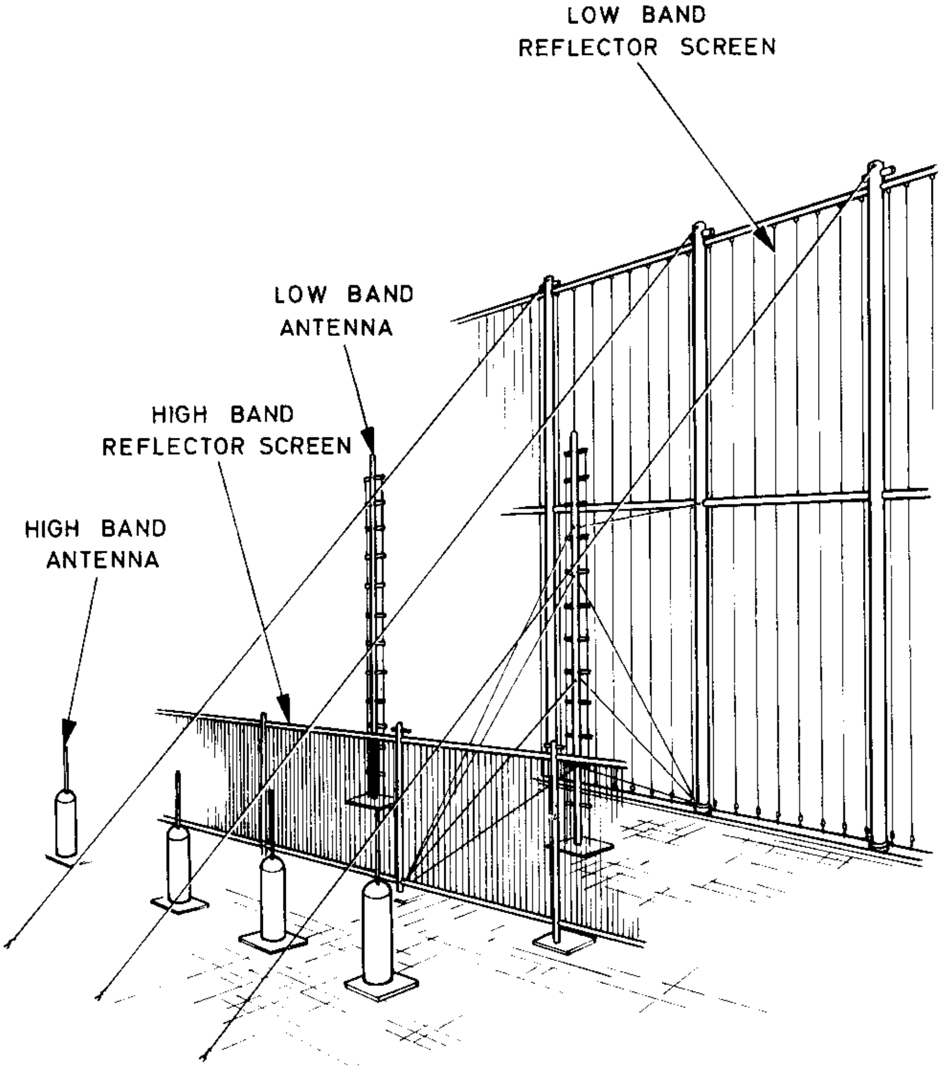

Fig. 5-3 Segment of Double Screen Array.

The antenna elements used in this two-screen array are the balanced terminated folded monopole for the low-band and the sleeve antenna for the high-band. Although the sleeve element has higher efficiency than the folded monopole it assumes large dimensions at the low frequency and consequently is more expensive than the latter. In the two-screen configuration the emphasis has been placed on optimum performance in the upper frequency band, dictated by R & D requirements. Since the high-band array has a larger aperture than the low-band array and the sleeve antenna element has high efficiency combined with moderate cost it is apparent that the performance at the high frequency band has been optimized. This has been borne out by extensive measurements on full scale arrays. It has been demonstrated that, when properly designed, the two frequency bands are fairly independent of each other with only very small interactions between bands.

The Single Reflecting Screen Wullenweber Array

A plan and elevation view of a single screen two-band Wullenweber Array (low-band and high-band) is shown in figure 5-2 and a perspective view of a segment of this array is shown in figure 5-4. This array was developed for RADC by Sylvania Electronic Systems. This configuration comprises a ring of low-band sleeve antenna elements on a circle with the largest diameter. The high-band sleeve antenna elements are arranged closer to the single reflecting screen which is supported by specifically designed steel towers. The low-band elements as well as the high-band elements are of similar design, and cover a frequency band of 3:1, so that the total frequency coverage is 9:1. For symmetry reasons the number of low-band elements is one-half of the number of high-band elements. A third array with high-band elements can be arranged concentrically with the two lower band arrays at a much smaller diameter, using horizontally polarized wide band elements of the bow-tie type. This array is completely independent of the two other arrays.

The screen height for this array is determined by the low frequency coverage limit and the wire spacing in the screen is governed by the high frequency coverage limit of the vertically polarized high-band elements. The diameter of the screen basically determines the aperture of the array and is chosen accordingly with due consideration of siting conditions, economic and other requirements. The radial distance of the elements from the reflecting screen is such that it is not greater than $3\lambda/8$ at the highest frequency of the corresponding band. Due to the inherent symmetry of the element arrangement (twice as many high-band elements as low-band elements) the scattering effects of the low-band elements on the high-band elements are eliminated and so is the occurrence of a trapped wave propagating along the reflecting screen, since this is always higher than a quarter wave.

The design emphasis of the single screen array is placed on the low frequency band, as is evident from the use of sleeve type antenna elements in the low-band, and from the large aperture of the array which is maximum in the low-band. Photographs of an array are shown in figures 5-5 and 5-6. Figure 5-5 shows two sets of sleeve elements in front of the single screen which is supported by steel towers. Figure 5-6 shows a view from inside the array through the single screen of the high-band and low-band elements, which are outside the high-band elements, as shown in figure 5-5. On the left side of figure 5-6 is shown a higher band array which is located concentrically inside the single low-band screen. Since it is horizontally polarized, it is not affected by the high screen and the sleeve elements which are vertically polarized.

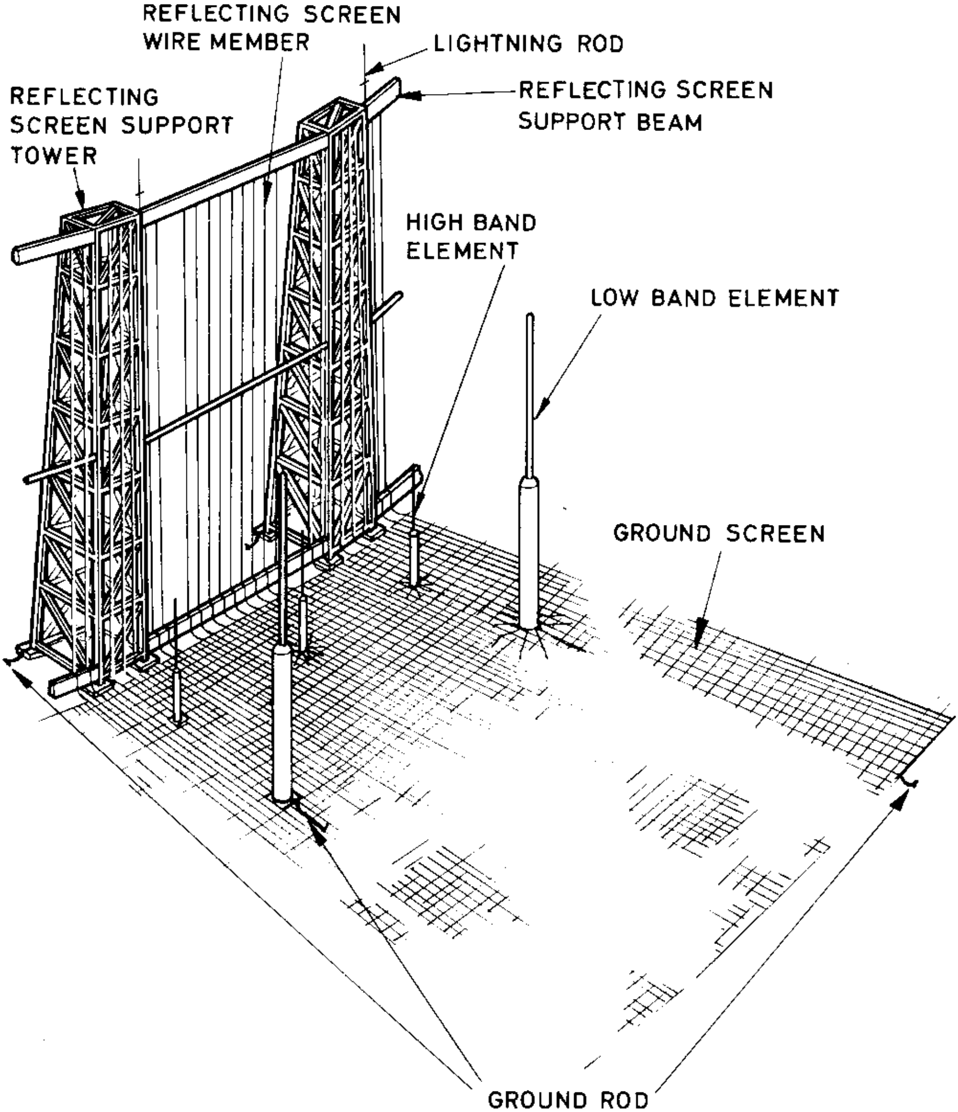

Fig. 5.4 Segment of Single Screen Array

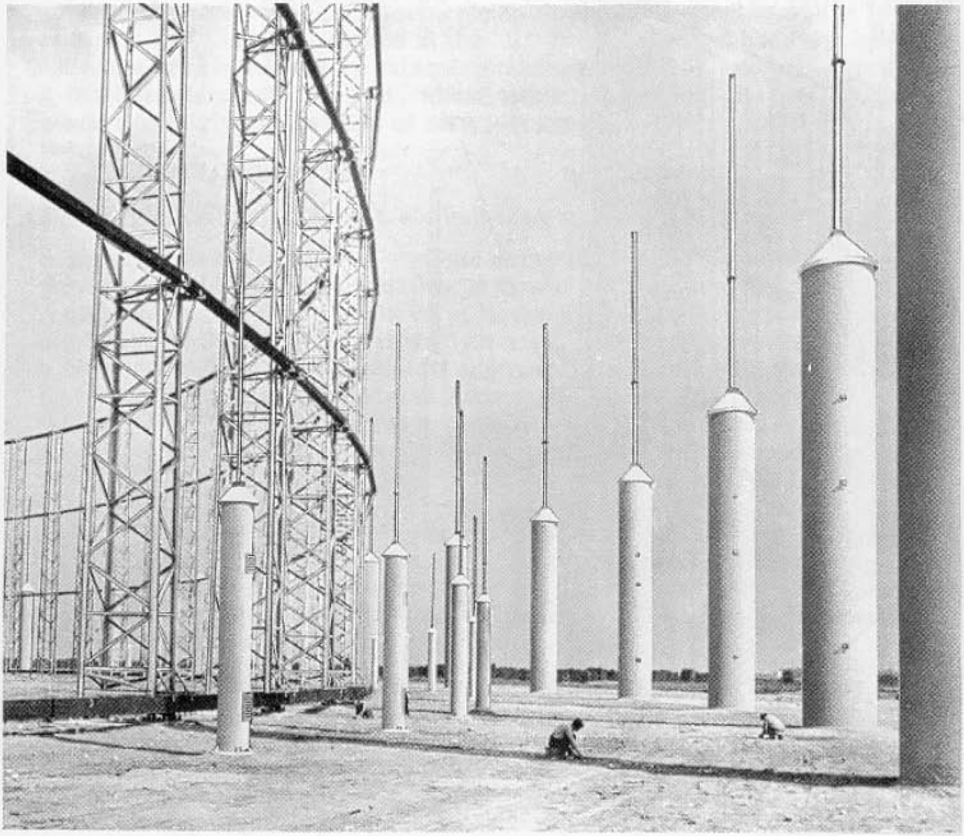

Fig. 5-5 Partial view of Single Screen Array

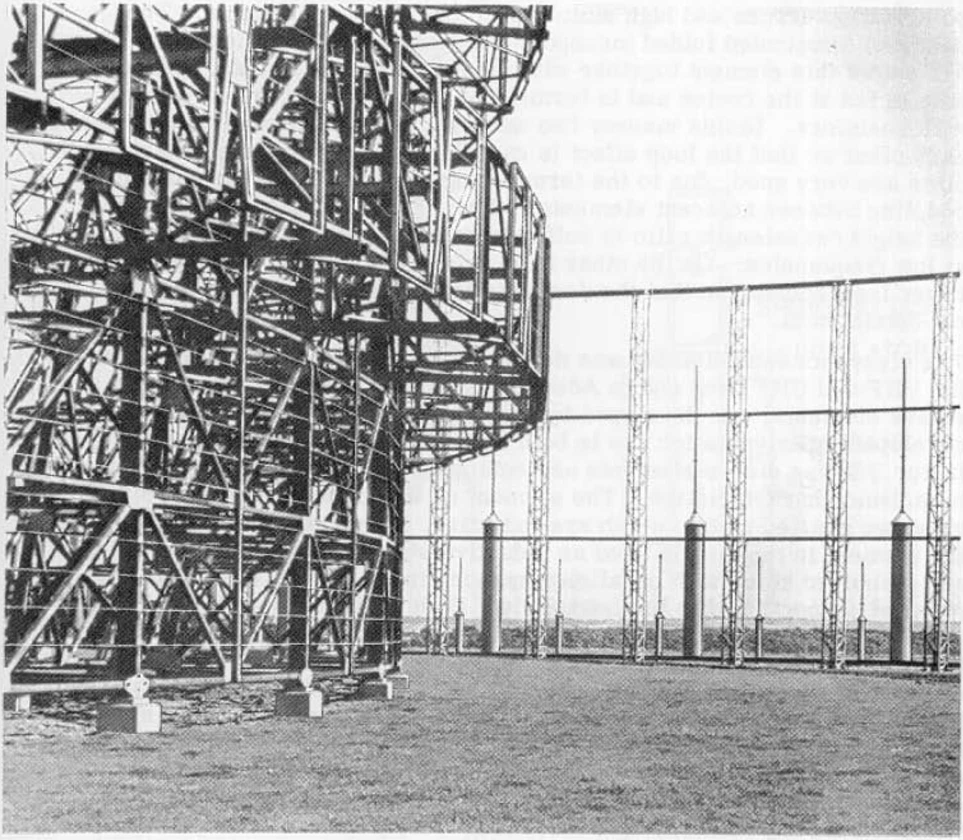

Fig. 5-6 Partial view of three Concentric Arrays

Components of Wullenweber Arrays

Antenna Elements

Considerable effort went into the development of a broadband antenna element with good efficiency. Both travelling wave type and standing wave type elements have been developed and are in use. Originally inverted V antenna elements terminated into a resistive load were used. This element has a larger bandwidth than the original cage antenna, but it exhibited polarization errors and high mutual coupling between elements. The balanced terminated folded monopole eliminated these deficiencies. Figure 5-7 shows this element together with sleeve antenna elements. The monopole is fed at the center and is terminated at the ends of the outer legs with resistors. In this manner two narrow loops are formed which balance each other so that the loop effect is cancelled. The impedance characteristics are very good, due to the terminating resistors, and the mutual coupling between adjacent elements is low. The efficiency is good when the height/wavelength ratio is sufficiently large but it drops considerably at low frequencies. On the other hand external noise increases at the lower frequencies, so that the decrease in efficiency in certain cases is not detrimental.

The sleeve antenna element was developed by NRL originally for use in the VHF and UHF band and in Adcock systems. Figure 5-7 shows two sleeve elements, one developed by NRL for use in the high-band and one developed by Sylvania for use in both bands with the appropriate scaling factor. These sleeve elements use compensating circuits to enhance their broadband characteristics. The element on the right-side in figure 5-7 uses two shorted stubs, which are inductive, in series connection whereas the element in the middle uses an inductive stub in series with the feed and a shorted stub, with parallel resonance in the middle of the band, in parallel connection with the feed cable. Both achieve a V.S.W.R. of better than 5:1 at the ends of the 3:1 band and a V.S.W.R. of better than 2.5:1 over 50% of the band. The proportioning of the various dimensions of the sleeve element is critical in order to accomplish good performance over the band. If not properly designed the current distribution along the antenna element may become inadequate with the center of gravity too high above ground. As a result of this the element pattern may break up, i. e., nulls in the elevation pattern may develop. However, with proper design good radiation pattern has been obtained over a 3:1 frequency band.

The Beamforming System

In the Wullenweber Array radiating elements are arrayed in a circle about a circular reflecting screen. Directive beams in a fixed direction are formed by combining the outputs of a group of elements from contiguous elements over a sector of the circle, typically 60° to 120° through delay networks such that reinforcement occurs for those signals having planar fronts normal to the desired space angle vector. In the combining process for a beam, the signal from each element is phase corrected for the curvature of the aperture, amplitude weighted to achieve the design sidelobe level, and vectorily summed in a combining network. Many such beams are formed simultaneously and independently of one another at differing azimuthal angles by employing each radiating element many times. This is accomplished by dividing the signal power from each radiating element. In this manner each element can be used a number of times in conjunction with other beam forming networks to provide beams at differing azimuthal angles. The beam forming networks are identical for all beams within a band. Differing beams are obtained by the selection of a different group of antenna elements.

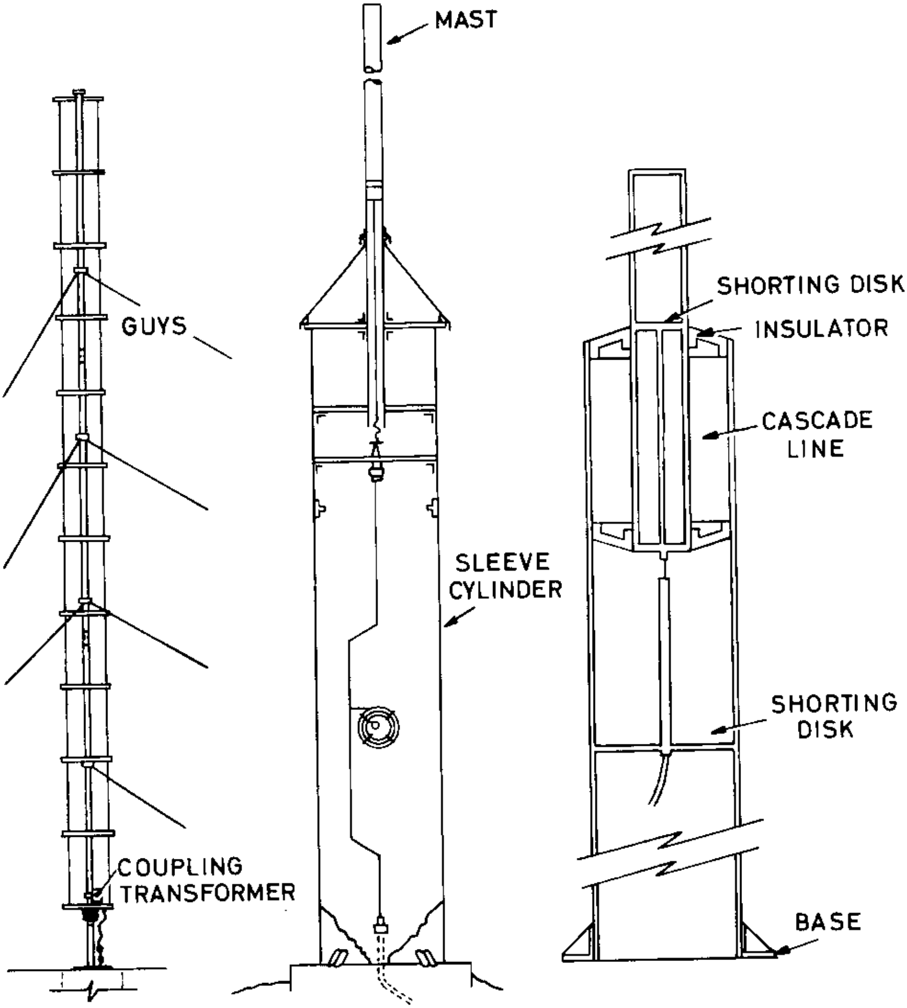

Fig. 5.7 Antenna Elements

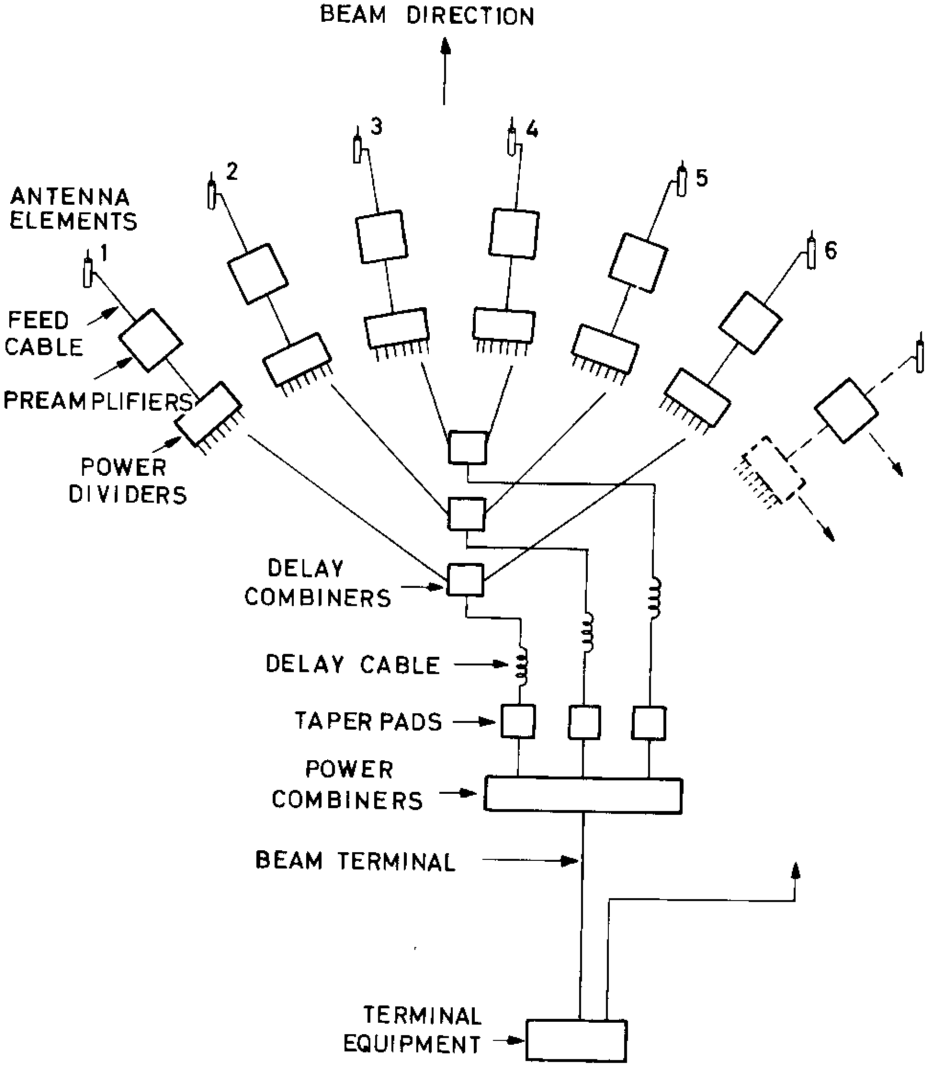

Fig. 5.8 Beam Forming System

The signal flow (Fig. 5-8) from each antenna element is transferred to an RF preamplifier through an underground feed cable to the center of the array where the beam forming electronics are housed. At the front and back of the preamplifier are directional couplers which sample the signal and feed it to the calibration and monitoring equipment. The output of each preamplifier is fed to a power divider to provide the required number of independent outputs. The symmetrically located outputs of the power dividers are combined in the delay combiners and then fed into the beam-forming network consisting of a number of coaxial delay cables of differing lengths to provide the required phase delays from each of the contributing elements. Taper pads follow the delay cables in each signal channel path to provide the required amplitude distribution across the array. The beam forming components are designed so that the maximum phase reinforcement is in a vertical angle of arrival appropriate for the frequency band of the array. All signals associated with a particular directional beam are vectorily summed in the power (or delay) combiner. At the output terminal of the power combiner a high-gain beam is available in a fixed direction. All beams are connected to the inputs of antenna multicouplers to provide inputs for other functions, such as an omnidirectional beam and sector beams (broader beams). An omnidirectional beam can be formed for each band by combining, through a hybrid tree, one high level output from each power divider.

Sector beams approximately 60° in azimuthal width can be formed by sector beam forming networks. These combine the outputs of adjacent high-gain beams to form a wider beam with a lower directivity.

The typical geometry of high-gain beam, sector and omnidirectional beams is illustrated in figure 5-9. The number of fixed beams is the same as the number of elements used in one band, and this in turn depends on the diameter of the array and so does the width of each beam. Thus for a typical two-screen system with 36 elements in the low-band and 72 elements in the high-band, 36 and 72 beams respectively are obtained in the two bands. Adding 6 sector beams and one omnidirectional beam in each band gives a total of 122 beams, all simultaneously available. In larger systems simultaneous coverage over 360° with up to 180 fixed high-gain beams have been obtained.

The basic characteristics of Wullenweber Arrays, i.e., radiation pattern directivity, beamwidth, sidelobe level, have been measured and were found to be in good agreement with theory. The directivity varies from 15 to 20 dB depending on frequency, and sidelobe levels are 15 to 20 dB below the beam maximum.

The RF Distribution System

Basically the Wullenweber Receiving Antenna system consists of a set of antenna elements with reflecting screens, beam forming components, and a set of multicouplers. The antenna array provides a large number of high-gain beams, sector and omnidirectional beams. In order to be useful, these beams must be conveniently available to the using receivers. This is the purpose of the RF distribution and signal processing system. The arrangement of components is determined by the number of beams implemented, the number of receivers used, and user requirements. The problem is to make the various beams available to a number of operators. The distribution system can be made very flexible depending on the particular requirements of the system. In most cases it will not be necessary to make all beams available to all operators, although this is possible. Often it will be sufficient to provide each operator access to a limited number of beams and making this limited number fully flexible via a patching arrangement so that each operator can be provided a separate set of beams adapted to his needs. Typically the distribution system consists of multicouplers to provide the required outputs, an antenna patch panel to provide flexibility in the use of the multicouplers, a console patch panel to provide an operator's position with a choice of beams, and switching units to provide an operator access to a selected beam from the choice made available by patching at the console patch panel.

Electronic Equipment Design

Beam Forming Components

Since the gain and the control of sidelobes are dependent on proper phase relations, the phase budget must be given careful consideration. The cables connecting elements to the central building, the delay line cables and the cables within the central building used to connect beam-forming equipment have to be carefully selected and tested. The primarily electrical length changes in performance with temperature, artificial aging (temperature cycling) and mechanical working were measured for several types. It was found that cables with a dielectric of foamed polyethylene have good phase linearity and superior phase stability. This dielectric type is therefore very suitable for connection of the antenna elements with the central building and for the delay cables themselves because of the phase stability. Standard cables are adequate for interconnecting cables on the basis of these tests. It was found desirable to pre-age all cables by temperature cycling before cutting to electrical length.

The cables between elements and the central building have to be measured and cut to electrical length after installation. Since this is a tedious and time-consuming trial and error procedure, an adjustable air dielectric delay line is used for the final adjustment of each cable.

Preamplifiers and Multicouplers

An antenna system for communications reception must be designed to degrade only minimally the signal/noise ratio which, at the input terminals of the antenna, is determined by the magnitude of the signal, by the magnitude of the external noise, and the spurious signals. National Bureau of Standards (NBS) noise predictions, together with the performance characteristics of the antenna elements, provide the information necessary to specify preamplifier and multicoupler performance. At HF, external noise is a strong function of frequency, siting, and direction; hence, a range of noise environments is encountered. NBS predictions indicate that over much of the frequency band, and antenna element characteristics, external noise power is considerably greater than the internal noise power under the best system design conditions. Economies can therefore be realized by reducing the preamplifier gain requirements below that required to establish the system noise figure practically as the noise figure of the first active element plus any defined system losses preceding it. The preamplifier gain can be set accordingly.

Intermodulation products in preamplifiers and multicouplers must be held for the best performance at low levels. Intermodulation distortion is generally defined in terms of distortion products generated by two equal signals not harmonically related. For good performance it is considered necessary that the second and third order distortion products are 70 dB or more below either of the two equal input signals when these signals have an amplitude of 0.10 Volt for preamplifiers, and 0.46 Volt for multicouplers.

A solid-state preamplifier built by Sylvania is now available with 22 dB gain

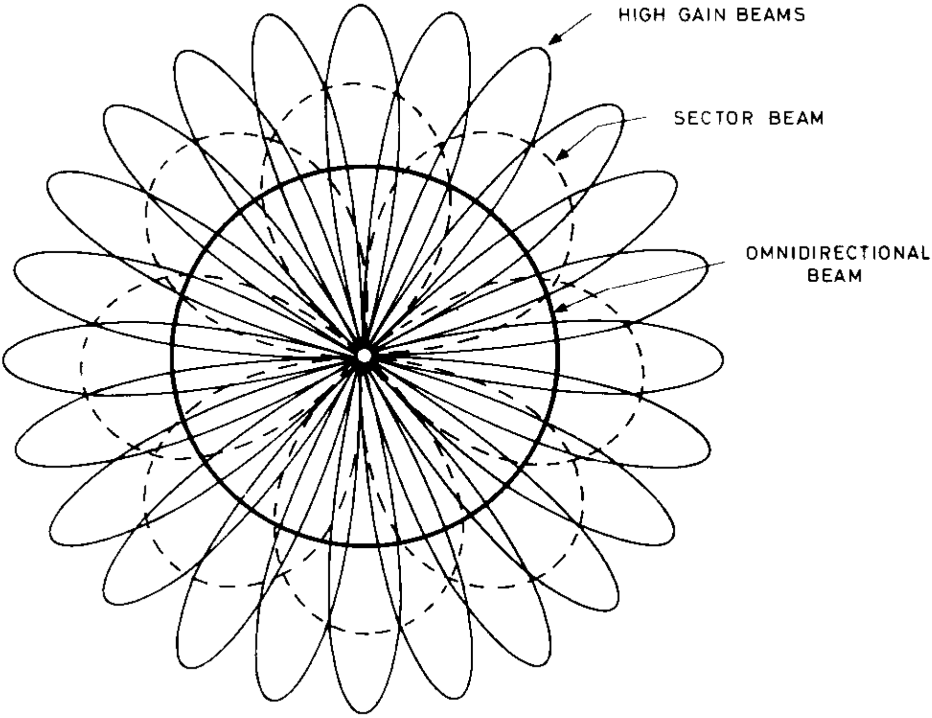

Fig. 5-9 Beam Geometry.

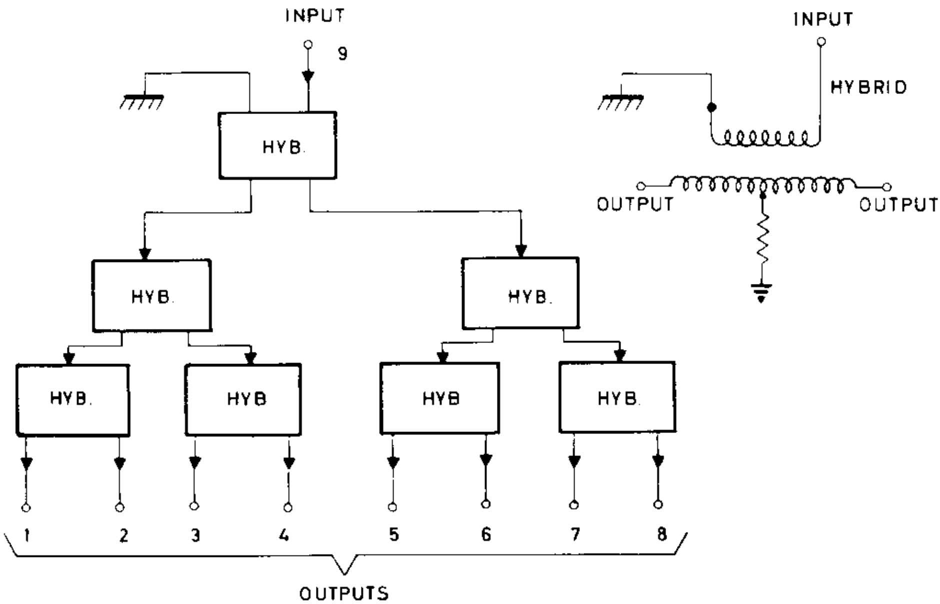

Fig. 5-10 1:8 Power Divider.

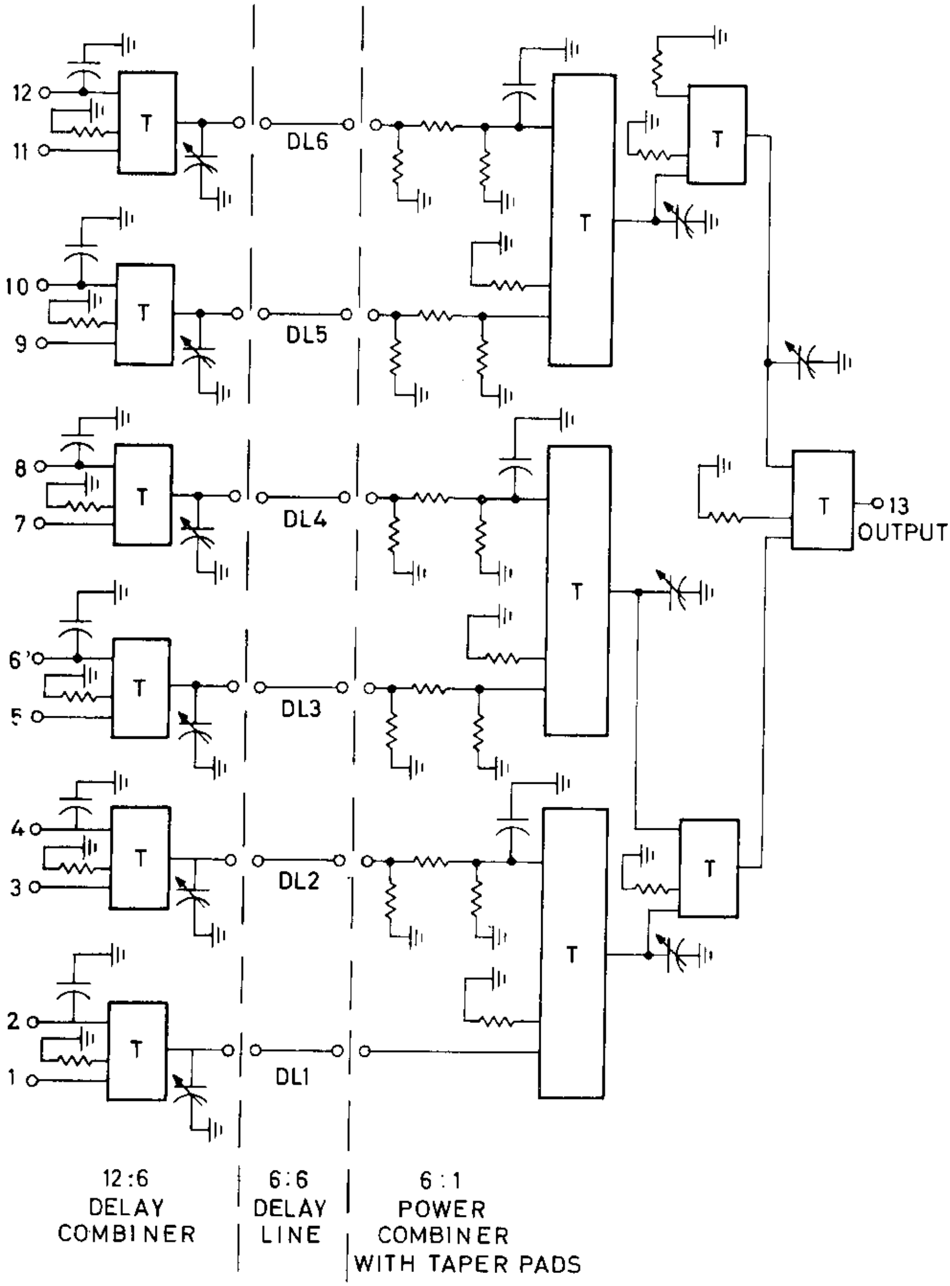

Fig. 5.11 Beamformer Circuitry

and 6 dB noise figure. This is a broadband amplifier covering the entire HF range with low intermodulation distortion as specified above.

The high-gain provided by the individual beams of a wide aperture Wullenweber array places stringent requirements on the multicouplers. In order that system performance is not seriously degraded by in-band spurious products from high-level signals, the linearity must be high. The noise figure must be low to allow reception of low-level signals when the system is not externally noise limited. The phase and amplitude must be controlled to provide satisfactory sector-beam performance. Multicouplers which are useable over the HF band and satisfying these requirements have been developed by Sylvania, and are in use. The performance characteristics are:

Gain 1 to 3 dB.

Noise figure 8 dB maximum.

Intermodulation distortion as defined above, better than -72 dB.

Amplitude Tracking ± 0.5 dB.

Phase Tracking ± 2 degrees.

Isolation 40 dB minimum.

v.s.w.r Input and Output 1.5: 1 maximum.

Power Dividers/Power Combiners

All of the power dividers and power combiners used in beamforming are composed of a binary tree of 1:2 wideband hybrid transformer power dividers with associated resistor-capacitor circuitry.

A block diagram of a 1:8 power divider is shown in figure 5-10. An RF signal applied to the input terminal of the first hybrid transformer appears at its output terminals with a phase difference of 180°, and attenuated by approximately 3 dB. The signals are then further divided in the following hybrid tree. The resulting 8 outputs are all of equal amplitude, attenuated by approximately 9 dB from the input signal. The outputs consist of two equiphase groups of signals (terminals 1, 3, 5, 7 and terminals 2, 4, 6, 8) with a 180° phase difference between the two groups.

Since the power divider is a passive device, it may be used bilaterally as a power combiner. In this instance, input signals with the appropriate 0° and 180° phase differences are applied to terminals 1 through 8, and the combined output is obtained at terminals 9.

Beamformer

The electrical schematic of a typical beamformer chassis is presented in figure 5-11. Twelve input signals from twelve adjacent antenna element power dividers are applied to terminals 1 through 12 of the 12:6 delay combiner. Terminals 11 and 12 are associated with the end elements while terminals 1 and 2 are associated with the center elements.

The 12:6 delay combiner consists of six independent 2:1 hybrid transformer power combiners. The signals are combined in each section of the delay combiner and connect to a precision delay line (DL1 through DL6). Each line is made from a special heat-treated flexible cable so that phase tolerances in the operating temperature range will be maintained. The signal out of delay line DL1 connects directly to one input of the 6:1 power combiner. The signals out of delay lines DL2 through DL6 connect to the other five inputs of the 6:1 power divider through the resistive PI network attenuator taper pads.

Taper Pads and Phase Tracking

On a circular array an untapered beam will have sidelobes in the order of 13 dB below the peak of the main lobe. A -15 dB to -20 dB sidelobe level is accomplished by tapering of the beam by inserting attenuator pads in the signal paths of all except the center elements contributing to a particular beam.

Phase tracking between similar units is a requirement of all beam forming equipment including active units and interconnecting cables. It is necessary, therefore, to give very careful consideration to control of both phase and amplitude response in designing all beam forming components. This leads quite naturally to smooth, slowly-changing frequency responses having a 3 dB bandwidth considerably broader than the nominal band limits.

Calibration – Monitoring System

In a system such as the Wullenweber Array which is made up of a large number of components, both passive and active, interconnected in a multi-terminal matrix there is a severe alignment and maintenance problem. All components must have their transfer functions aligned and maintained within tight tolerances of the no-error design value to realize the design performance level of the array. This function is performed by the calibration and monitoring system. Figure 5-12 shows a block diagram of a semi-automatic monitoring system which is used in some of the arrays. Directional couplers are placed in each of the N element channels, and in each of the M-beams. The RF generator supplies a suitable measurement signal at frequencies in the band of interest. An input distribution section supplies a signal of constant phase and amplitude to the input of the component or channel being measured. The output RF collection system samples the signal at the output of the channel being measured and routes it into the signal processing equipment. The result is displayed on an oscilloscope and printed out.

Some typical measurements are:-

Mode 1

Preamplifier measurement. The test signal is fed in sequence to directional coupler 1 and extracted at directional coupler 3 of each element channel. The average over N preamplifiers is taken.

Mode 2

Beam Measurement. The test signal is fed in sequence to the L directional couplers 1, 1a, 1b.... belonging to one beam. The signal is extracted at directional coupler 4 of the beam being measured. The average over a beam is taken. Complementary time delay and attenuation circuitry is used for compensation of the beamforming transfer function.

Mode 3

Measurement of Antenna Elements. The test signal is fed into directional coupler 2 of one antenna element and extracted at directional coupler 3' of the adjacent element. This is a check on antenna elements by sensing mutual coupling. Although this is not an absolute measurement it has been found very useful and effective in determining changes in antenna element characteristics.

In all modes the print-out indicates the defective channel number, the appropriate phase and amplitude averages, the deviations from the mean, and the degree of tolerance variation in faulty channels. The system works

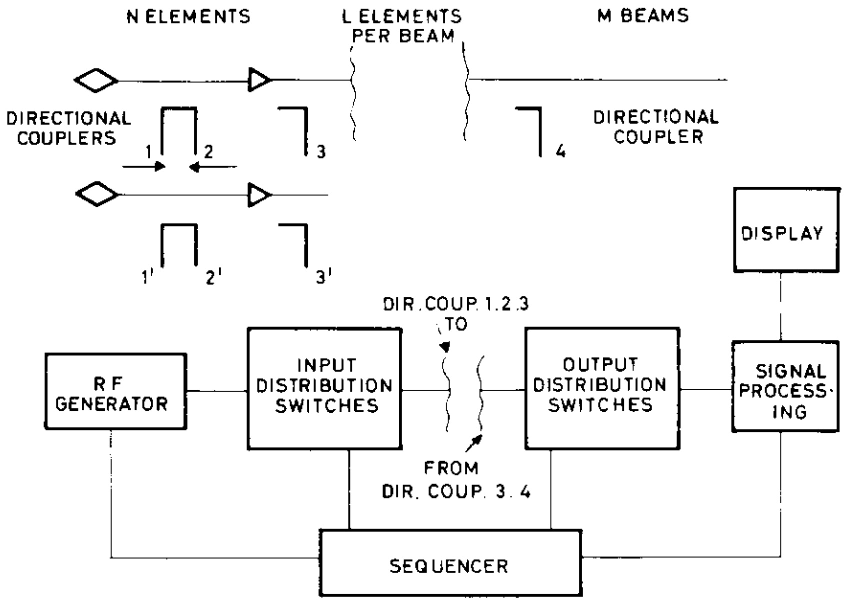

Fig. 5-12 Calibration and Monitoring system.

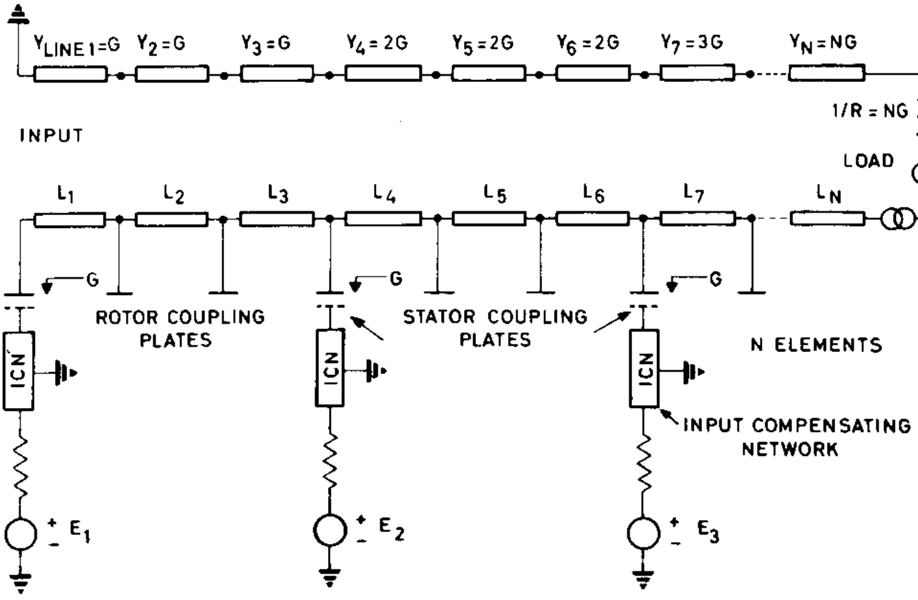

Fig. 5-13 Tapped tapered Series Delay Line.

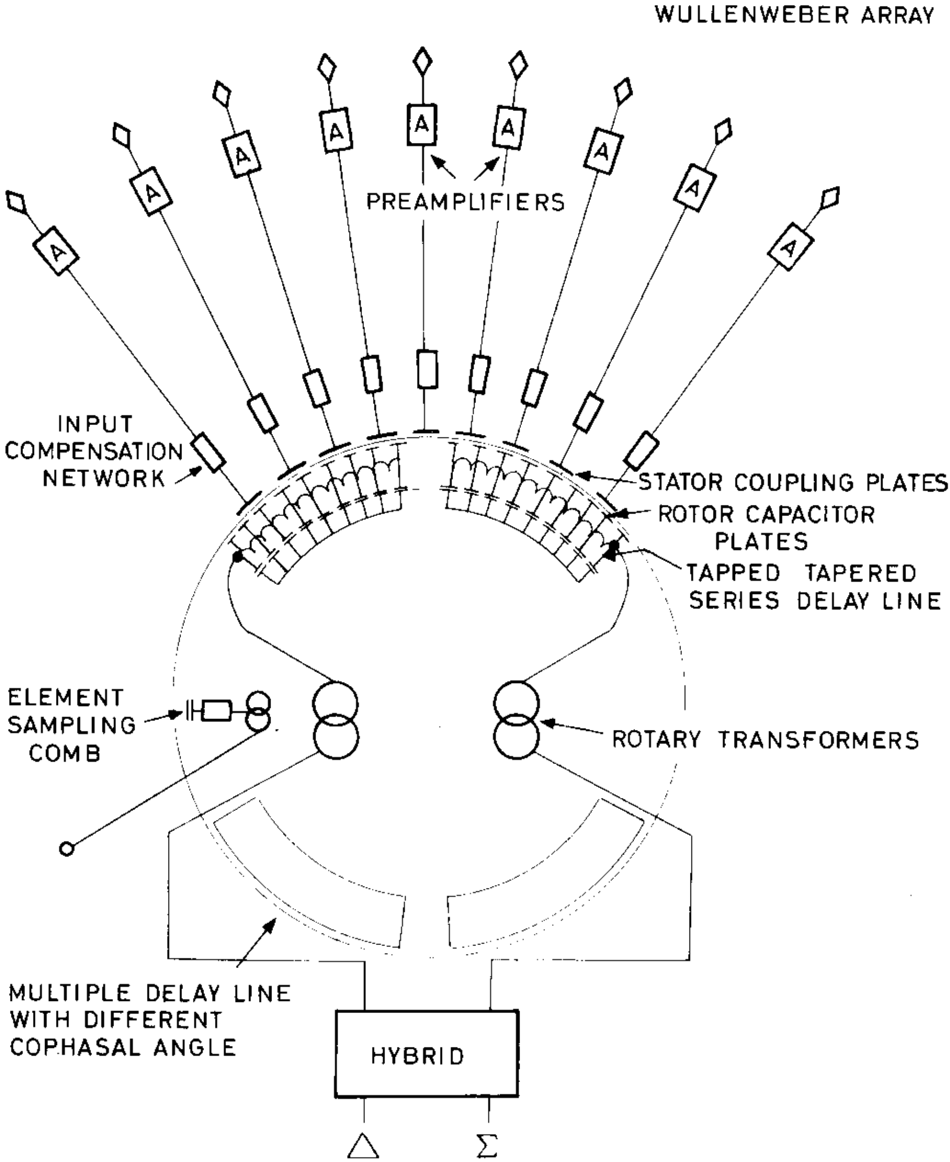

Fig. 5.14 Diagram of Goniometer

on a noninterfering basis with the operational effectiveness of the antenna system. Measurements, which ordinarily would take considerable time to perform, can be made frequently or continuously without loss of operational time. Thus continuous calibration and monitoring of the system characteristics is accomplished.

The system is also of great practical value as an alignment tool and for trouble finding during installation when thousands of connections must be made and misconnections are practically unavoidable.

Direction Finding Instrumentation

The multiplicity of available high-gain beams makes the Wullenweber Array well suited for direction finding. DF was actually the original application of the Wullenweber antenna. Both scanning and nonscanning techniques are available for use with the Wullenweber Array. In particular, considerable progress was made in the development of a rotating goniometer and the twin channel phase monopulse interferometer system.

The Goniometer System

In the goniometer system the high insertion loss was one of the main deficiencies which limited the sensitivity of this device. As a result of an intensive investigation of the goniometer problem, Dr. Curtis while at Hermes (now with Adams-Russell Co., Waltham, Mass., U.S.A.) developed a rotating goniometer with an insertion loss of less than 2 dB.

A schematic of the goniometer developed by Hermes/Adams-Russell is shown in figure 5-14. From the antenna elements the signal flows through the preamplifiers to input compensating networks, one for each channel, which are directly connected with the stator coupling plates of the goniometer. Energy is capacitively coupled to the rotor capacitor plates which are connected to the beam-forming networks, which consist of multiple tapped delay lines. There are two pairs of delay lines with different cophasal angles located on the rotor. One pair is designed to provide maximum phase reinforcement for signals arriving at a shallow vertical angle, while the other is designed for a steeper vertical angle. Each pair provides two symmetrical beams which rotate in azimuth as the rotor moves and which are coupled through rotary transformers to hybrids which provide sum and difference outputs.

The characteristic features of this goniometer are:

(a) The impedance matched multitapped admittance tapered delay line.

(b) The incorporation of the input coupling capacity into compensating networks optimized for the frequency band (3:1)

(c) The use of multiple delay lines for various cophasal vertical angles and provision of single couplers for element checking.

(d) Utilization of modern low loss ferrites for hybrids and rotary transformers.

The principle of the multitapped admittance tapered delay line is shown in figure 5-13. The line consists of a large number (M) of sections, M being several times greater than the number of elements (N) from which one of the symmetrical beam pair is formed. A pair of these delay lines, which are mounted on the rotor, forms a pair of beams. Each segment of the line is connected to a rotor coupling plate. The antenna elements are connected through the input compensation network to the stator coupling plates, whose number is smaller (for instance 1/3) than the number of the rotor coupling plates. In figure 5-13 antenna elements E_1, E_2, E_3 are coupled through the input compensating networks and the coupling capacitors to sections L_1, L_4, L_7 of the delay line. The coupling capacity is part of the input compensating network which is so designed that the admittance (G) at the rotor coupling plates is practically purely conductive and constant over the frequency band. The N antenna elements which form one of the beam pair produce voltages which have different phases according to the direction of the incoming plane wave and these voltages are connected in parallel to various tap points of the series delay line. If a plane wave arrives in the bore-sight direction there will be a certain delay in each element such that the element coupled to the beginning of the line at the left end has the smallest delay and M subsequent elements have increasing delays. The delay line is designed to compensate these delays so that in this case all voltages add up in phase at the load end of the line and to provide optimum power transfer from the elements to the load.

The solution to the matching problem can be readily recognized by considering the transmission case. The source is then at the right end of the line as indicated, and has the internal impedance $Z = R$. The loading of each rotor element that is fully coupled to a stator element is G. The characteristic admittances of the line sections L_1, L_2, L_3 between the tap points of elements E_1 and E_2 are equal to the load conductance G: $Y_1 = Y_2 = Y_3 = G$, so that no reflections occur. Between the following tap points of elements E_2 and E_3, the line admittance $Y_L = 2G = Y_4 = Y_5 = Y_6$, since 2 antenna elements appear in parallel. At the transmitting source N elements appear in parallel, hence the characteristic admittance of the last sections is $Y_N = NG$. The internal resistance of the source, or in the receiving case, the load resistance, is matched to NG. Optimum energy transfer is obtained if in addition the delays of the sections of the delay line are adjusted to compensate for the delays of the N element voltages so that all voltages add up in phase at the load. This case is realized if a plane wave arrives in the bore-sight direction. For other directions of arrival the phases of the element voltages will be different and a partial or total cancellation of the voltages transferred to the load will occur.

A schematic layout of the delay line together with the input compensating network and hybrid is shown in figure 5-15. The delay line consists of a large number of PI sections with appropriate characteristic impedances and delays. The input network on the stator is designed to compensate the input coupling capacity and provides an optimized, practically ohmic, impedance over the band.

Smooth commutation is accomplished by providing a sufficiently large number of delay line elements whose characteristic impedance is changed in small steps. Each delay line section is connected to a rotor plate so that the number of rotor plates is considerably larger than the number of stator plates.

The performance of the goniometer with the admittance tapered series delay line has been very successful in practical use. The measured insertion loss has been found to be less than 2 dB, and DF accuracies of better than one degree have been obtained.

The Interferometer System

The interferometer technique for direction finding is also very well suited for use with a Wullenweber Array. With a twin-channel phase monopulse system, the wide antenna aperture available from a large Wullenweber Array can be fully utilized to obtain high sensitivity. Two basic problems are encountered with such a system. The accuracy of phase comparison is affected by the accuracy of phase tracking through hybrid transformers,

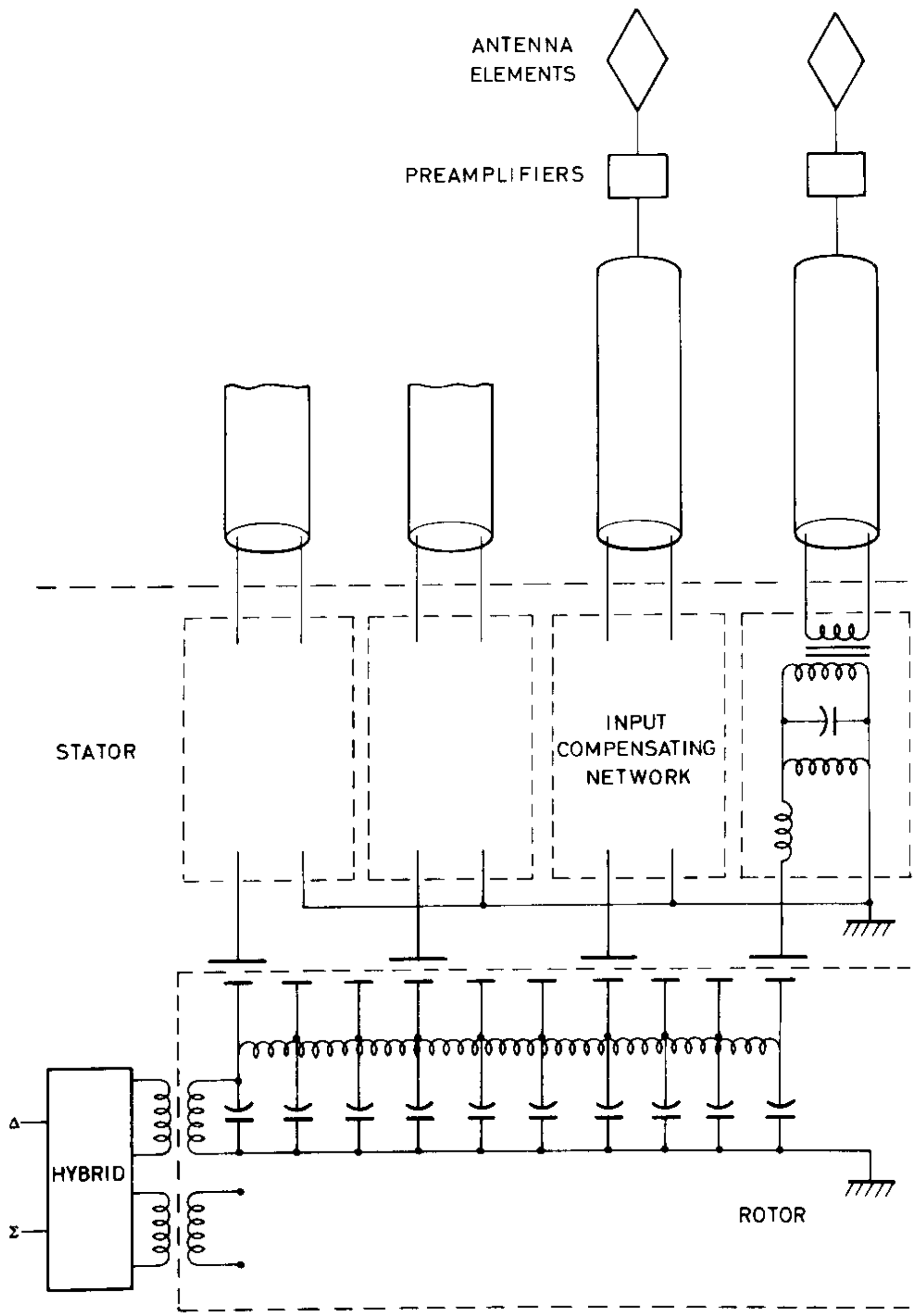

Fig. 5-15 Delay Line and Input Compensating Network.

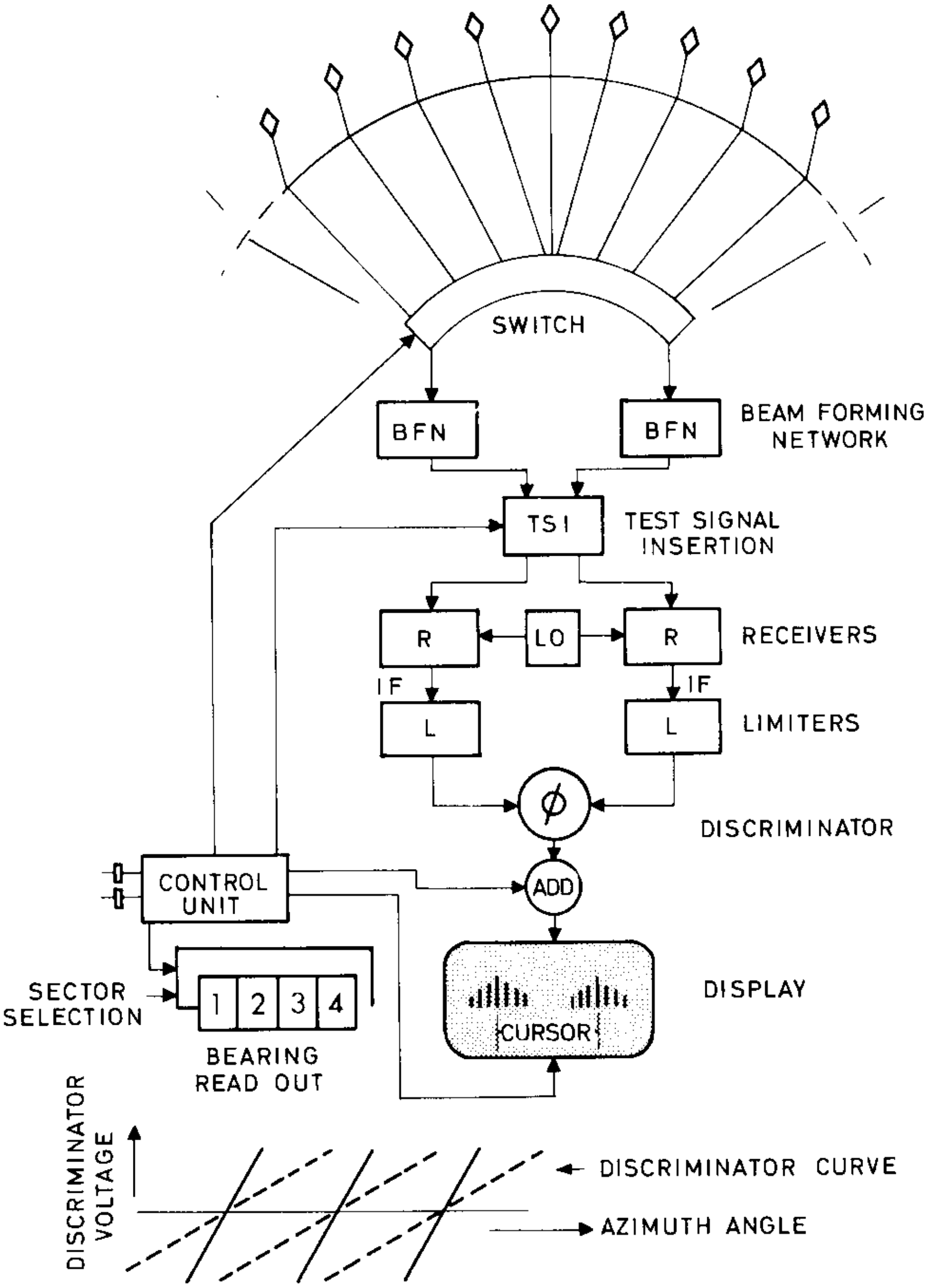

Fig. 5.16 Interferometer

delay lines and receivers. This problem can be solved by inserting a calibrate signal early in the signal paths so that these errors can be calibrated out. The second problem arises from the fact that the measured phase difference is a function of both azimuth angle of arrival and vertical angle of arrival. By alternately sampling adjacent sectors it is possible to derive a simple expression which eliminates the elevation error.

The interferometer provides a nonscanning technique with visual display. Figure 5-16 shows a block diagram of an interferometer. The interferometer consists of a pair of parallel beams which can be positioned in discrete steps, according to element spacing, over 360°. A number of antenna elements are connected by a switch to a pair of beam forming networks. The signals are fed into a two-channel receiver. Phase preservation in the two channels is obtained by using tracked receivers with a common local oscillator. After passing a limiter the signals are fed into the discriminator whose output voltage, for small deviations from the boresight, is proportional to the phase difference of the beam pair which is being measured, and hence proportional to the angle of arrival of the incoming wave. The slope of the discriminator curve depends on the elevation angle. To eliminate the elevation angle dependence, a measurement is made with the nearest adjacent beam pair which is possible if the angle between adjacent bore-sight positions is smaller than the beamwidth of a pattern lobe. Figure 5-16 shows 3 discriminator curves for the borepositions θ_1, θ_2, θ_3. Since all discriminator curves for the same elevation angle are approximately parallel and cross the axis at the bore-sight positions θ_1, θ_2, θ_3, one can eliminate the slope of the discriminator curve using the relation:

$$\tan \alpha = \frac{V_1}{\theta - \theta_1} = \frac{V_2}{\theta_2 - \theta} = \frac{V_2}{\theta_1 + \Delta\theta - \theta}$$

from which the bearing angle:

$$\theta = \theta_1 + \frac{V_1}{V_1 + V_2}\,\Delta\theta = \theta_2 - \frac{V_2}{V_1 + V_2}\,\Delta\theta$$

is obtained.

The measurements from two adjacent beam pairs are indicated on the display unit as a horizontal displacement from an arbitrary reference position. The vertical displacement is proportional to the signal amplitude.

A reference signal is inserted at the input to the receivers in the signal flow to provide a cursor which is compensated for all phase errors following the insertion point. This signal is derived from the sum output of the beam pair and is applied to both interferometer channels so that no phase difference exists at the point of insertion.

From the inserted reference signal, two cursors, one for each beam pair, are derived which are displayed as single vertical lines, one under each set of measurement lines. The position of the cursors is determined by the phase of the reference signal which is controlled from controls in the control unit. The four signals derived from the discriminator and from the reference signals are displayed in time sharing sequence. To take a bearing the cursors are manually moved until each is properly placed with respect to its associated distribution of measurement lines. The position of the cursors is a measure of the bearing deviation from the bore-sight angle of the appropriate beam. The analog voltage which is determined from the cursor control knobs is converted to digital form, added to the digital representation of the bore-sight position and visually displayed.

The interferometer technique offers certain advantages with respect to sensitivity because of lower scanning loss, reduced bandwidth, low modulation errors and good adaptability to antenna readout. With this system very good instrumentation accuracies of better than one degree have been achieved. However, there may be some difficulties in the manual operation of the system in the case of badly perturbed signals. A prototype interferometer with visual display, which has been demonstrated, requires the manual setting of two cursors. While this is readily done if the incoming signals are steady, it requires the operator in the case of strongly fluctuating signals to perform an averaging process which can only be as good as the operators short memory. Improvement is possible by the use of automatic instrumentation to which the interferometer technique is well suited. The averaging process and long term accuracy can be improved if the averaging is done in a simple computer in which the results of many bearings taken over a short and controllable time are processed to obtain long term and short term statistics. Some additional research and development is being accomplished to automate the interferometer function.

Conclusion

Two configurations of Wullenweber Arrays have been examined and described. Both the double reflector screen and the single reflector screen configurations have been developed, built and tested in the U.S. With these arrays a frequency range of 9:1 is readily obtained which by the use of a third array with horizontal polarization can be extended by another factor of 2. Some characteristic features of these Wullenweber Arrays are summarized below.

The antenna provides a multiplicity of fixed high-gain beams, low-gain sector beams, and omnidirectional beams, covering 360° in azimuth and giving broad elevation coverage, encompassing all elevation angles with half power points between 60° and 6°, enabling reception of waves over distances from 100 miles to over 1000 miles. By the use of a suitable beam forming system, multicouplers, and an elaborate RF distribution system with patch panels and switches, a receiving system with multiple access for a large number of receivers which can be attached to any combination of beams is obtained. High overall performance with respect to angular accuracy and sidelobe control requires high phase and amplitude stability of all equipment. Equipment has been developed providing excellent phase stability better than 5° and amplitude stability better than 1/2 dB. This is sufficient to assure a -15 dB to -20 dB sidelobe level. Preamplifiers and multicouplers are available with broad dynamic range and highly suppressed intermodulation products.

Great progress has been made in direction finding instrumentation. A rotating goniometer has been developed with a very low insertion loss. The phase interferometer technique has been developed to utilize the wide aperture of the array to obtain high sensitivity and accuracy.

Through advances in the development of high performance components with high stability it has been possible to create a versatile antenna receiving system which on a comparatively small area gives greatly improved performance particularly with respect to pattern and sidelobe control, directivity and gain, compared to conventional antenna systems.