A Single Sideband Musa Receiving System for Commercial Operation on Transatlantic Radio Telephone Circuits*

By F. A. POLKINGHORN

In the operation of short-wave radio telephone circuits selective fading is observed which is a result of the combination at the receiving antenna of waves which have arrived from the transmitter over paths of different lengths. The poor quality resulting from this fading may be mitigated by increasing the directivity of the receiving antenna in the vertical plane so as to favor the waves arriving at one angle to the exclusion of others. Friis and Feldman have described an experimental system designed to accomplish this end which they call a "Musa" receiving system. This system was found under certain transmission conditions to give an improvement in the grade of circuit which could be obtained. A commercial installation of this type has now been constructed for use on the single sideband circuits of the American Telephone and Telegraph Company from England. Two receivers have been provided for the operation of four radio telephone circuits.

The antenna system consists of a row of sixteen rhombic antennas two miles long, each antenna connected by a separate transmission line to receivers located near the center of the row of antennas. In each receiver the signals from the antennas are combined in the proper phase to permit simultaneous reception from three adjustable vertical angles. The three signals are then added through delay equalizing circuits or discretely selected on the basis of amplitude to obtain diversity reception. A fourth branch of the receiver has its vertical angle of reception continuously varying and is used to set automatically the angles of reception of the three diversity branches. The delay equalization is also automatically adjusted. A recorder is provided which continuously registers the relative carrier field strength with variation of vertical angle of reception, and the amount of delay equalization.

INTRODUCTION

In the operation of short-wave radio telephone circuits fading is observed which is caused by the combination at the receiving antenna of waves which arrive at different vertical angles and which have traveled from the transmitter over paths of different lengths. This fading may be mitigated by increasing the directivity of the receiving antenna in the vertical plane so as to favor the waves arriving over one path to the exclusion of the others.[1, 2] It is not

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* *Proc. I.R.E.*, April 1940.

[1] E. Bruce, "Developments in Short Wave Directive Antennas," *Proc. I.R.E.*, Vol. 19, pp. 1406–1433, August 1931.

[2] E. Bruce and A. C. Beck, "Experiments with Directivity Steering for Fading Reduction," *Proc. I.R.E.*, Vol. 23, pp. 357–371, April 1935.

possible, however, to increase this directivity to any great extent with an ordinary antenna system before it is found that the signal arrives outside the angular range of the antenna an appreciable part of the time. To overcome this difficulty Friis and Feldman experimented with a receiving system consisting of a number of antennas, each having moderate directivity and each connected by a separate transmission line to a receiver where the outputs are phased by a variable phase shifting system in such a manner as to give a system of high, variable directivity. A system of this kind, which they called a "musa" system from the initial letters of "multiple unit steerable antenna," was built and found to give under most transmission conditions an improvement in the grade of circuit which could be obtained.[3] Accordingly it was decided that a commercial system should be built for use on the circuits of the American Telephone and Telegraph Company from England. A corresponding system of modified design has been built by the British General Post Office.[4] The purpose of this paper is to review a few of the principles upon which a musa receiver operates, to describe the equipment which has been built in this country, and to discuss some of its operating characteristics.

The transmissions which are to be received are of the so-called twin single-sideband reduced-carrier type described by Oswald [5] and consist of two sidebands, representing two distinct speech channels, on opposite sides of a carrier which is 16 to 26 db below the maximum sideband amplitude. Under normal conditions one of the sidebands is adjacent to the carrier while the second is spaced by the width of one sideband from the carrier. A single sideband receiver for this type of transmission has been described by Roetken [6] and many of the features discussed by him were developed for use also in the musa receivers. These features include highly stable oscillators, crystal filters and automatic tuning circuits.

OUTLINE DESCRIPTION OF RECEIVERS

A block schematic of one channel of the commercial musa system is shown in Fig. 1. The sixteen rhombic antennas are placed in a line two miles long in the direction of the English transmitting station.

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[3] H. T. Friis and C. B. Feldman, "A Multiple Unit Steerable Antenna for Short-Wave Reception," *Proc. I.R.E.*, Vol. 25, pp. 841–917, July 1937; *B.S.T.J.*, Vol. XVI, No. 3, pp. 337–419, July 1937.

[4] A. J. Gill, Wireless Section, Chairman's Address, *Jour. I.E.E.*, Vol. 84, No. 506, pp. 248–260, February 1939.

[5] A. A. Oswald, "A Short-Wave Single Sideband Radio Telephone System," *Proc I.R.E.*, Vol. 26, No. 12, pp. 1431–54, December 1938.

[6] A. A. Roetken, "A Single Sideband Receiver for Short-Wave Telephone Service," *Proc. I.R.E.*, Vol. 26, No. 12, pp. 1455–65, December 1938.

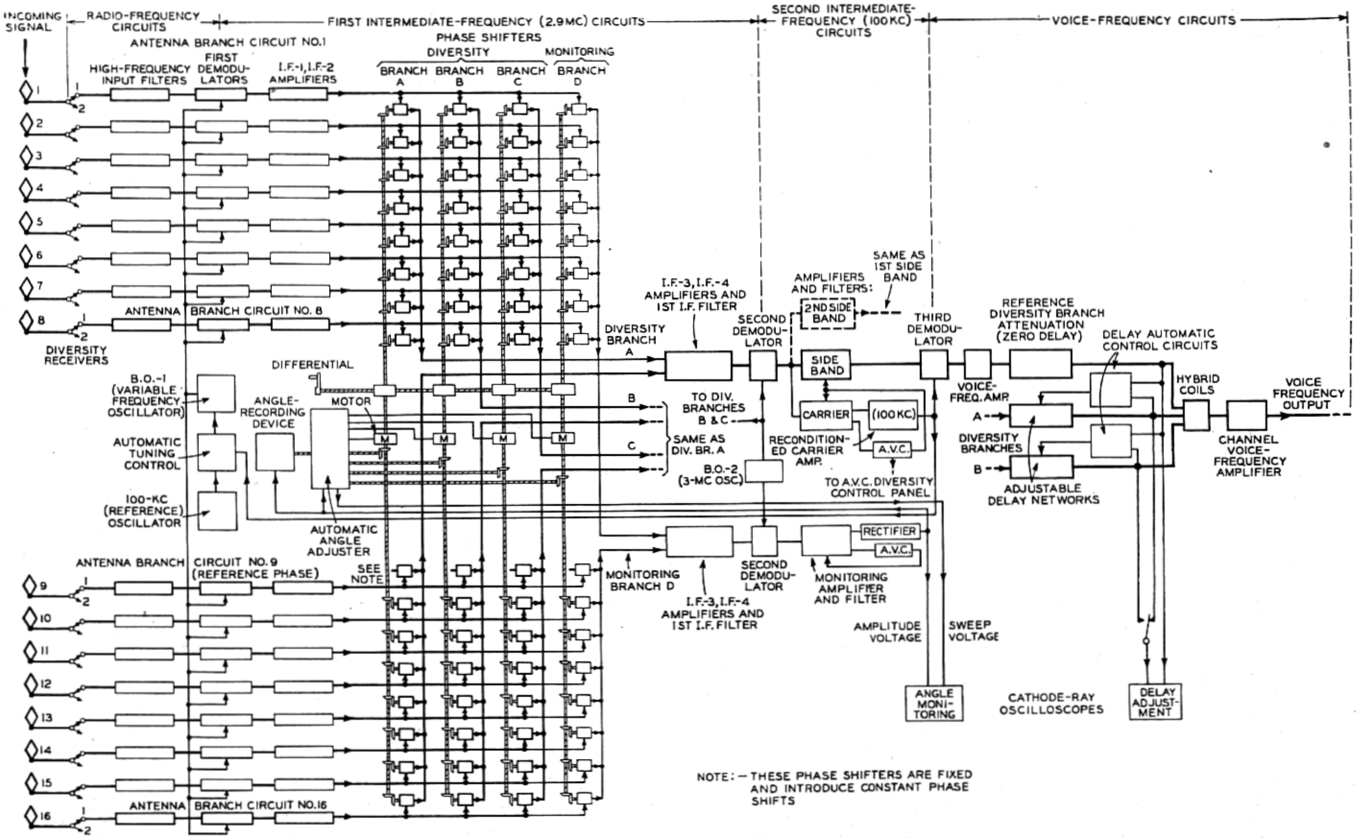

Fig. 1—Block schematic diagram of one musa receiver.

Separate transmission lines lead from each antenna to a building placed a little to one side of the rear of the ninth antenna. Two receivers, only one of which is shown in the figure, are connected in parallel to each transmission line. Each receiver is designed to receive five specific frequencies, ranging from 4,810 kc. to 18,620 kc., assigned to the corresponding transmitter in England.

After passing through selective input circuits the signals from each antenna are demodulated by a common oscillator to a band adjacent to a carrier frequency of 2,900 kc. The signals, after going through two stages of intermediate frequency amplification are then applied to the inputs of four phase shifter systems in parallel. In each of these phase shifter systems the signals from the sixteen antennas are combined so as to give reception from a particular vertical angle. This angle can be varied by a mechanical movement of a phase shifter drive shaft. Three of the phase shifter system outputs are used for a three-branch angular-diversity system in which the signals arriving over three separate paths are separately received and then either combined or individually selected for connection to the line, while the fourth branch is used for monitoring to determine where the phase shifters of the three diversity branches should be set in order to receive the best signals. From each phase shifter group the circuit continues through the first intermediate frequency filter and two further stages of amplification to the second demodulator where the 2,900 kc. carrier frequency is shifted to 100 kc. The carriers and sidebands of each diversity branch are then amplified separately and again combined in the final demodulators to give three distinct voice frequency outputs for each sideband. These three outputs are either combined after inserting variable delay in two of the branches or, optionally, the branch having the greatest signal at any instant is connected to the line. Both of these operations are performed automatically. The output of the monitoring phase shifter group is also heterodyned to 100 kc. and after amplifying the carrier only it is rectified and applied to an automatic system for adjusting the phase shifters of the three diversity branches.

A general view of the receivers is shown in Fig. 2. The principal parts of the two musa receivers occupy three rows of bays each about 25 feet long and 11½ feet high. The row shown on the right contains the input circuits and first demodulators for both receivers. The middle row contains the remaining equipment for one receiver and the left row that for the second receiver. In addition there are five bays of rectifiers and power control equipment located in a fourth row which is not shown.

Fig. 2—View of musa receivers.

GENERAL

When waves arriving over several paths from the same transmitter are demodulated in a simple receiver the severity of the resultant selective fading is dependent upon the relative amplitudes at the demodulator of the several path contributions, the differences in the times of transmission over the several paths, and the rates at which the path lengths are varying.[7] When the difference in the time of

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[7] R. K. Potter, "Transmission Characteristics of a Short-Wave Telephone Circuit," *Proc. I.R.E.*, Vol. 18, No. 4, pp. 581–648, April 1930.

transmission over two paths is t there are alternate maxima and minima in the frequency spectrum caused by these two components which are separated by $1/2t$. Continuous small changes in the lengths of the paths cause these maxima and minima to wander back and forth through the spectrum. By separating the waves arriving at distinctly different angles the musa receiver succeeds, for the most part, in separating those waves which have greatly different transmission times and thus widens the frequency interval between a maximum and an adjacent minimum. As the interval increases the fading appears less selective. The signal appearing to arrive at any one angle, however, is in reality composed of a bundle of waves, the components of which have traveled over slightly different paths and which might be expected to be nearly alike in amplitude and transmission time but not in phase. As a consequence it is to be expected that the general fading on a single-angle musa receiver will be greater than on an ordinary receiver and it is essential that some form of diversity be used to insure a satisfactory output amplitude at all times. Sudden shifts in the received angle of signals will also give general fading which will be greater the greater the angular discrimination of the musa system.

A musa receiver differs from an ordinary receiver in that there are a number of separate antenna branches, the outputs of which must be added in the proper phase over an appreciable band of frequencies.

When delay equalization is used between the various diversity branches, these branches must also have equal phase shifts if the audio-frequency outputs are to add properly. In both antenna and diversity branches the problem of keeping equal phase shifts is complicated by the action of the automatic volume control system which changes the operating condition of the vacuum tubes over a wide range. In designing these receivers a nominal overall value of non-uniformity of ± 10° was taken as acceptable and an effort made to keep the phase uniformity of individual elements to within one or two degrees wherever possible.

Within the receiving station all radio-frequency wiring is made with a flexible coaxial cable having rubber insulation. The various panels composing the receivers are placed on the racks with a view to operation and maintenance rather than ease of wiring and consequently long leads between panels are frequently necessary. For this purpose the circuit impedance is dropped to 70 ohms and at a number of points brought out to jack panels to facilitate testing.

Coaxial jacks are used which fit into the usual jack strips. Normalling jacks are not available and consequently it is necessary to have plugs in jacks during operation. In order to avoid cords, which would be in the way, the jacks to be connected regularly are mounted adjacent to each other and connected together by two plugs mounted in a shell similar to that commonly used for terminating resistances. Alternating current for cathode heating is supplied to conduit outlets near each panel. Flexible cords with plugs complete the circuit to the panels. All audio frequency, bias, and signal wiring is made into cables in the usual telephone manner. Wires having a potential of over 150 volts to ground are placed in conduit and safety switches are provided to remove the voltage from a panel when the panel cover is removed.

ANTENNA SYSTEM

The degree of vertical resolution and the signal-to-noise improvement of a musa antenna system are functions of the overall length and number of unit rhombic antennas used. The decision to build a sixteen-antenna system was based on experience with the six-antenna system and took into consideration the land necessary, the cost of antennas and transmission lines, and the complexity of the receiving equipment, as well as the resolution which it would be practical to use and still have it possible for the operator or automatic equipment to follow changes in the direction of signal arrival.

When the spacing between unit antennas of a musa system is several wave-lengths there will be more than one vertical angle at which the phase shifters will simultaneously phase the antenna outputs. The spacing between antennas is so chosen that the range traversed by the lowest of these angles will be the range covered by useful signals. Fortunately the angle of useful signals varies with frequency in such a manner as to permit a variation in frequency over the range desired with a fixed spacing. The unit rhombic antenna is designed to have a null at the position of the second phasing maximum and reception is thus confined essentially to the lowest phasing maximum.

Extensive study did not disclose a better unit rhombic antenna than the one used in the experimental system and consequently an antenna 590 feet (180 meters) long, 60 feet high, and having each side angle equal to 140 degrees was used. The spacing is 656 feet (200 meters) between corresponding parts of adjacent antennas.

A representative directive diagram of a unit rhombic and the 16-unit array in a vertical plane in the line of the antennas is shown plotted in rectangular coordinates in Fig. 3. A polar diagram of the major lobe in three different positions, corresponding to three possible angles of diversity reception, is shown on Fig. 4*a*. In this figure the

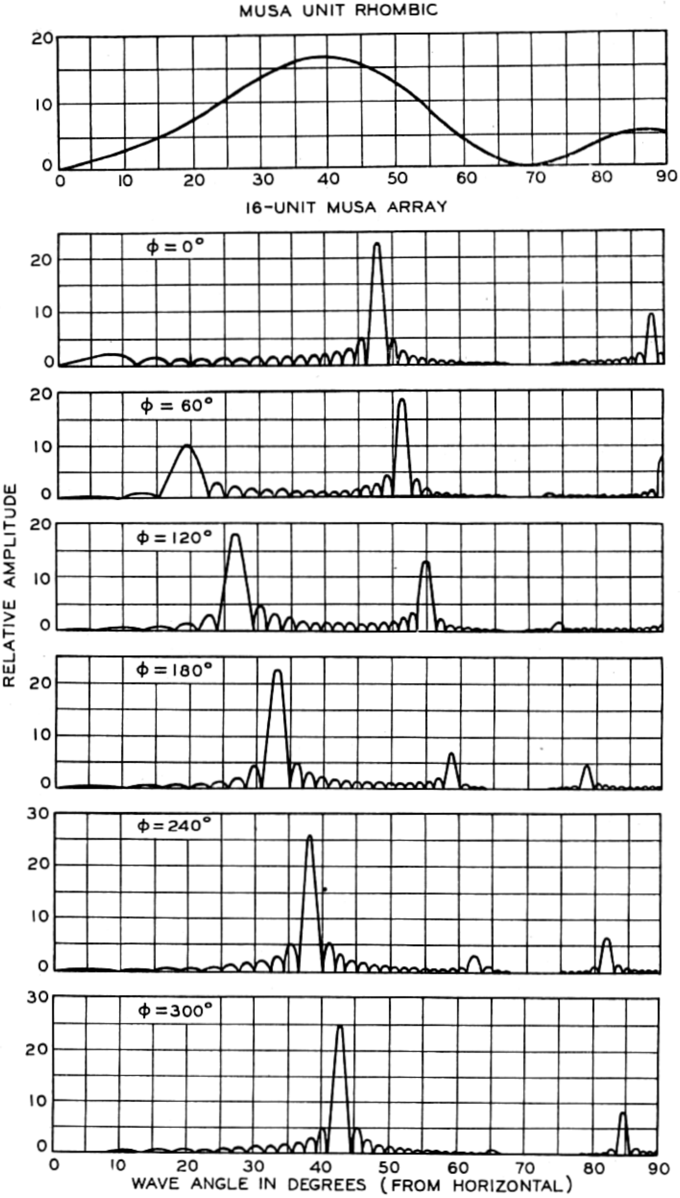

Fig. 3—Directive diagram in the vertical plane of a unit rhombic antenna and the 16 unit musa array. Frequency 4700 Kc. ϕ = phase shifter setting.

dotted outline is the diagram of the unit rhombic antenna characteristic enlarged 16 times. The complete diagram is of course a solid. Figure 4*b* is an attempt to show how the middle lobe of Fig. 4*a* looks when viewed from the ground plane at a horizontal angle of 45° from the line of the antennas. The contour lines on this leaf-shaped figure are lines of equal reception. All of these diagrams are for a frequency of 4,700 kc., near the low end of the range of received signals. At higher frequencies the lobes will be more slender and the angle of maximum reception will be lower. Fortunately the latter corresponds to the trend of the received signals.

When the outputs of several antennas are connected to a receiver and added in the proper phase the total signal can be made equal to the sum of the signal voltages. The set noise, however, adds at random phase with the result that there is an improvement in signal-to-noise ratio over a single antenna equal to the square-root of the number of antennas, or $10 \log_{10} n$ in decibels. The theoretical improvement of a 16-antenna system is, therefore, 12 decibels. On the assumption that received noise comes from a random direction with respect to the signal a similar result is obtained. At a particular time, however, the principal noise may be arriving from such a direction as to allow of no discrimination by the antenna system, or at another time to allow much more than 12 db discrimination.

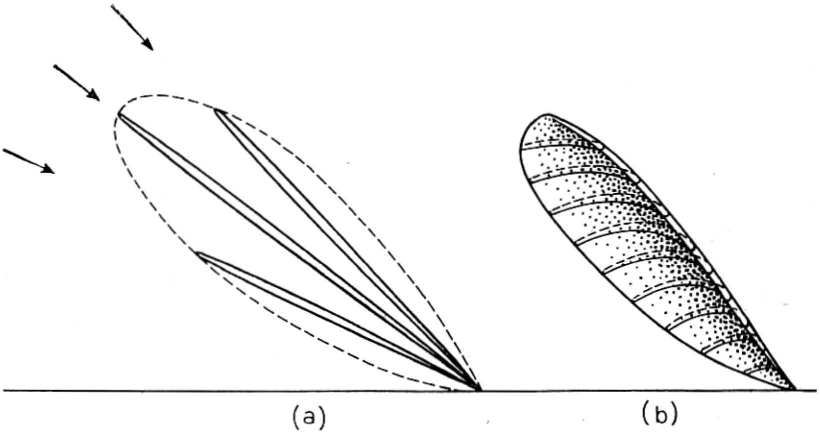

Fig. 4—Polar diagrams of musa antenna system. (*a*) Showing three possible locations of the major lobe. (*b*) Solid polar diagram of middle lobe shown in (*a*).

The received signal in an antenna is a result of both the direct wave, arriving from some angle above the horizon, and the same wave front reflected from the ground at a point ahead of the antenna. If the phase of the induced voltage is to progress uniformly from antenna to antenna it is essential that the ground be homogeneous and flat. For this and other reasons a flat marsh near Manahawkin, N. J. was chosen for the station site. The ground is level to within less than one foot, except where there are inlets, for the entire length of the antenna and for a considerable distance ahead.

As shown in Fig. 3, in addition to the major lobe caused by the phasing factor there are fourteen minor lobes. The amplitude of the first three starting from a major lobe are approximately $2/3\pi$, $2/5\pi$, $2/7\pi$ of the major lobe. However, when the major lobe is at a very low or very high angle it is greatly reduced in amplitude by the unit antenna directional characteristic while the adjacent minor lobes on one side may not be reduced to any such extent. Consequently the ratio of the amplitude of the major to minor lobes may be much less than the values given and signals from two or more angles might be received simultaneously with comparable amplitude on the same diversity branch and so defeat the purpose of the system.

It has been shown by John Stone Stone and others that if the amplitudes of the currents contributed by the various units of the antenna system are tapered in such a manner that the central units contribute more than the end units a reduction in the amplitude of the minor lobes can be obtained. However, this is accompanied by a widening of the major lobe and a reduction in the signal-to-noise improvement obtained. For antenna systems having only a few units there appears to be a net advantage in tapering but for the sixteen-unit system under discussion a large amount of tapering broadens the major lobe so that it extends over the normal first and possibly second minor lobes. Since the remaining lobes are already of a low enough amplitude to be comparable with those which might be produced by inescapable errors in phase and amplitude of the various unit contributions, there appears to be no particular advantage in much tapering in this system. Provision has, however, been made to obtain tapering should it ever be found desirable. Under normal conditions all antenna branch amplifiers are operated at the same gain so as to use only the small tapering caused by the losses in transmission lines.

The antennas are coupled to the transmission lines through metallic core transformers which pass a band from 4,000 kc. to over 20,000 kc. with a loss of less than 1 db. The transformers are equipped with lightning arrestors and arranged so that the total d.c. loop-resistance of the transmission line, antenna, transformer, and antenna terminating resistance can be checked from the station.

The transmission lines from the antennas to the receiver are of the coaxial type made of copper tubing $1\frac{1}{4}''$ in inside diameter surrounding a central conductor of $\frac{3}{8}''$ outside diameter. Ceramic insulators $\frac{1}{8}''$ thick are spaced every 16″ and a locking insulator is placed every 250 feet to prevent creeping of the inside pipe. The velocity of propagation of the line is 0.980 of that in space. The attenuation amounts to about 1 db per 1,000 feet at 20 megacycles.

The lines are buried to protect them from mechanical injury and to prevent phase errors due to differences in expansion. Bacterial growth in the marsh makes the soil extremely corrosive and it was necessary to protect the lines by coatings of tar and asbestos tape. The lines are kept under gas pressure at all times.

In a musa receiving system a saving of nearly one half of the transmission line can be made if the receiving equipment is located at the center of the antenna system rather than at one end. Furthermore, since the average length of transmission line will be cut in half, the diameter of the coaxial transmission line also could be cut in half and still maintain the same signal loss. The economic, and to a lesser extent the locational, advantages of the center position were so great that the equipment was so placed in spite of certain technical disadvantages.

THEORY OF PHASE SHIFTER SYSTEM WITH CENTER LOCATION OF RECEIVERS

At this point some of the theory of the musa phase shifting system will be reviewed and extension made to cover the situation of the receiver being located near the middle of the antenna system.

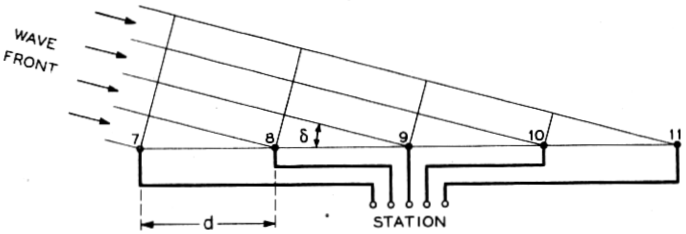

Fig. 5—Diagram of wave front approaching antenna.

Assume a plane wave front progressing toward the earth from the Kennelly-Heaviside layer at an angle δ with respect to the horizon and impinging upon the receiving antennas indicated as points 7, 8, 9, 10, 11, etc. (Fig. 5). Let the receiving station be located at antenna 9. Let the time of arrival at the receiving station of the voltages induced in the various antennas by this wave front be computed with respect to that of antenna 9. The wave front will arrive at antenna 9 at a time $\frac{1}{c}(d \cos \delta)$ later than at antenna 8. The voltage from antenna 8 will require a time $\frac{d}{v}$ to reach the receiving station over the transmission line, making the net time delay between the two outputs equal to

$$t_{9-8} = d\left(\frac{1}{v} - \frac{1}{c}\cos \delta\right), \tag{1}$$

where d is the horizontal distance between antennas
c is the velocity of transmission in space
v is the velocity of transmission in the transmission line

Similarly the difference in time of arrival of the voltages from antennas 9 and 7 will be:

$$t_{9-7} = 2d\left(\frac{1}{v} - \frac{1}{c}\cos \delta\right). \tag{2}$$

The voltages from all three antennas could be made to add in phase if a delay of

$$2d\left(\frac{1}{v} - \frac{1}{c}\cos \delta\right) \tag{3}$$

were added to the output from antenna 9, and half as much to the output of antenna 8. For a greater number of antennas these delays would have to be correspondingly increased.

Now consider the outputs of antenna 9, and those antennas which lie behind it. It will immediately be seen that the time between the arrival of the voltage caused by the wave front at antenna 9 and antenna 10 will be the sum of the times of transmission of the wave front from 9 to 10 in space and on the transmission line back from 10 to 9, which is similar to equation (1) except that the sign between the space and transmission line components is reversed. Similarly the equation for the delay between the outputs of antennas 9 and 11 is similar to that between 7 and 9 with the same sign reversed, and likewise with the other antennas.

Considering either the group of antennas ahead of the station or the group of antennas behind the station, and considering antenna 9 as a part of whichever group is being considered, it will be seen that the delay compensation which it is necessary to insert in the various antenna outputs to make the signal voltages add up in phase at the receiving station is always an integral multiple of either:

$$d\left(\frac{1}{v} - \frac{1}{c}\cos\delta\right) \tag{4}$$

or

$$d\left(\frac{1}{v} + \frac{1}{c}\cos\delta\right), \tag{5}$$

so that for either the front or the rear group the delay compensation could be adjusted by means of a single shaft geared to various individual delay compensators through gears having integral ratios.

Practically, the difficulty in building continuously variable delay circuits resulted in the use of continuously variable phase shifters. For any particular delay t there is a corresponding phase shift $\frac{2\pi ct}{\lambda}$ radians. Since this phase shift is a function of frequency, for a given phase shifter setting the frequencies in a wide band transmission will not all be in phase. The substitution of phase shifters for delay compensating circuits therefore results in a restriction of the band of simultaneous reception from a given angle. For the group of antennas ahead of the station the band restriction is small, since the space and transmission line paths give a partial delay compensation. For the antennas behind the station the net delay difference between antennas is large and the band is restricted to a much greater extent.

When using phase shifters it is possible to get minus as well as plus values of phase shift. This makes it possible to reverse the order in which delay compensation was assumed to be added in the above discussion so that no phase compensation is added to antenna 9, one negative unit is added to antenna 8, two to antenna 7, etc. In the equipment herein described the phase shifters were so designed.

Assume that the phase shifters of the front group are all set alike and then changed so as to receive from an angle δ. There will have been introduced a change of phase of

$$\phi = \frac{2\pi cd}{\lambda}\left(\frac{1}{v} - \frac{1}{c}\cos\delta\right) \tag{6}$$

between each of the antenna outputs.

Similarly if the phase shifters of the rear group were initially set alike, and similar to the initial condition of the front group, and then changed to receive from an angle δ the change of phase which would be required would be

$$\phi = -\frac{2\pi cd}{\lambda}\left(\frac{1}{v} + \frac{1}{c}\cos\delta\right). \tag{7}$$

The negative sign ahead of this equation takes account of the fact that an increase in the angle δ requires that more phase will have to be taken from line 8 while less phase will have to be subtracted from 10.

It will be noted that for a given change in δ, however, the amount of change of phase is the same absolute amount for the two groups. This indicates that it should be possible to connect the front and rear groups of phase shifters together and drive them as a single unit. To do this it will be necessary to connect the shafts together after they have been moved from their initial position by the amounts given in the above equations. The difference in phase is

$$\phi_{8-10} = \frac{4\pi d}{\lambda}\frac{c}{v}. \tag{8}$$

It will be noted that for a given installation this value is dependent upon the received frequency and will have to be changed when the received frequency is changed.

In the receivers herein described the phase shifters connected to antenna 9 are not driven. The phase shifters connected to antennas 1 to 8 are driven at ratios of 8 : 1, 7 : 1, 6 : 1, 5 : 1, 4 : 1, 3 : 1, 2 : 1 and 1 : 1 respectively. The phase shifters of antennas 10 to 16 are driven in the opposite direction at ratios of 1 : 1, 2 : 1, 3 : 1, 4 : 1, 5 : 1, 6 : 1, and 7 : 1 respectively. A differential gear mechanism is inserted between the two groups. Changing the position of the ring gear of the differential permits a mechanical shift equivalent to the phase shift given in equation (8) to be inserted between the two groups. This change may be made while the drive shafts are in motion. The ring gear drives of the differentials of the four groups of phase shifters are all connected by a common adjustment shaft so as to insure that the monitoring branch does not give a false indication of receiver performance by being set differently than the diversity branches.

A front view of the phase shifting system is shown on the left of Fig. 6. The vertical shafts drive the individual phase shifting condensers through spiral gears, of which there are eight inside each of the lower cast boxes and seven inside each of the upper cast boxes. The horizontal shafts connect to the cam switches used with the automatic adjustment feature. A rear view showing a few of the individual phase shifting condensers is given in Fig. 7. Each phase shifting condenser consists of four quadrantal stators each consisting of two plates between which revolves an eccentric circular plate. The rotor plates of the condensers in a horizontal row (see Figs. 1 and 7) are connected in parallel through the demountable brushes, and a wire which is behind the brush support, to the output of one of the antenna branch amplifiers. The corresponding stator plates of the condensers in a vertical row are connected together with coaxial wiring and to the four terminals of an artificial quarter-wave transmission line, which

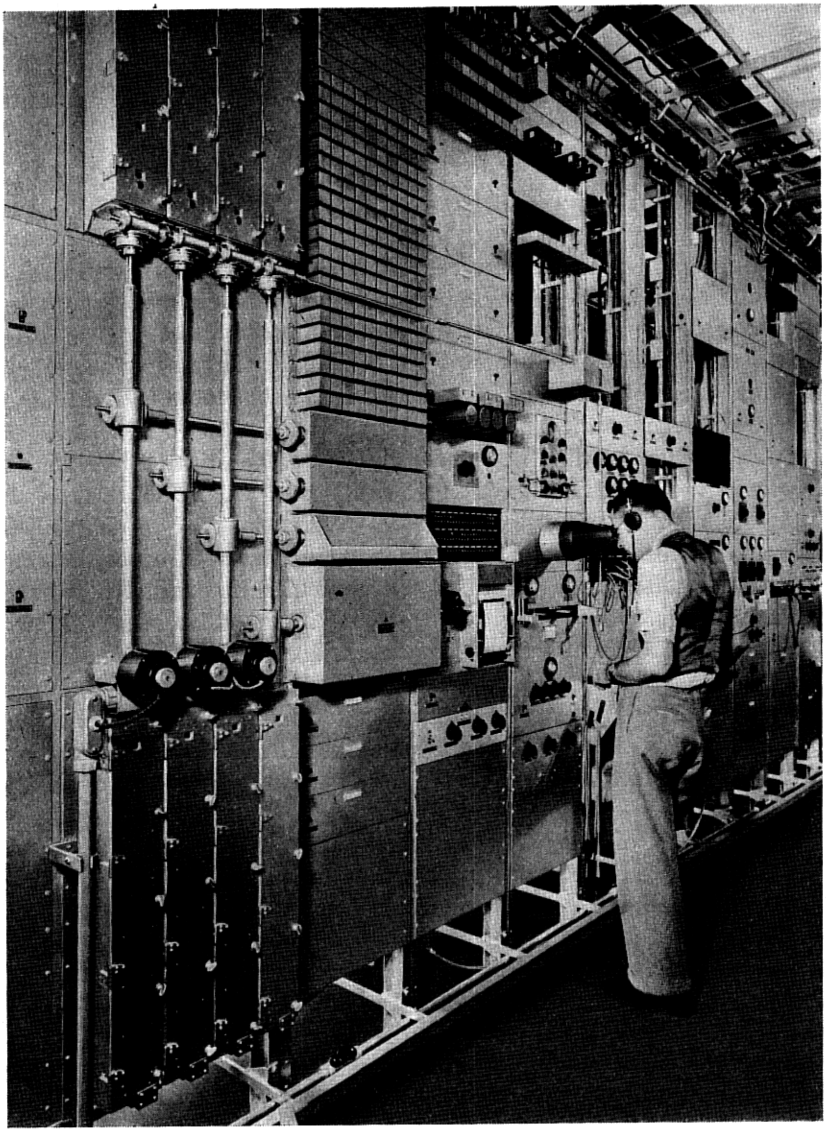

Fig. 6—View of second row of bays showing phase shifter drive system (left).

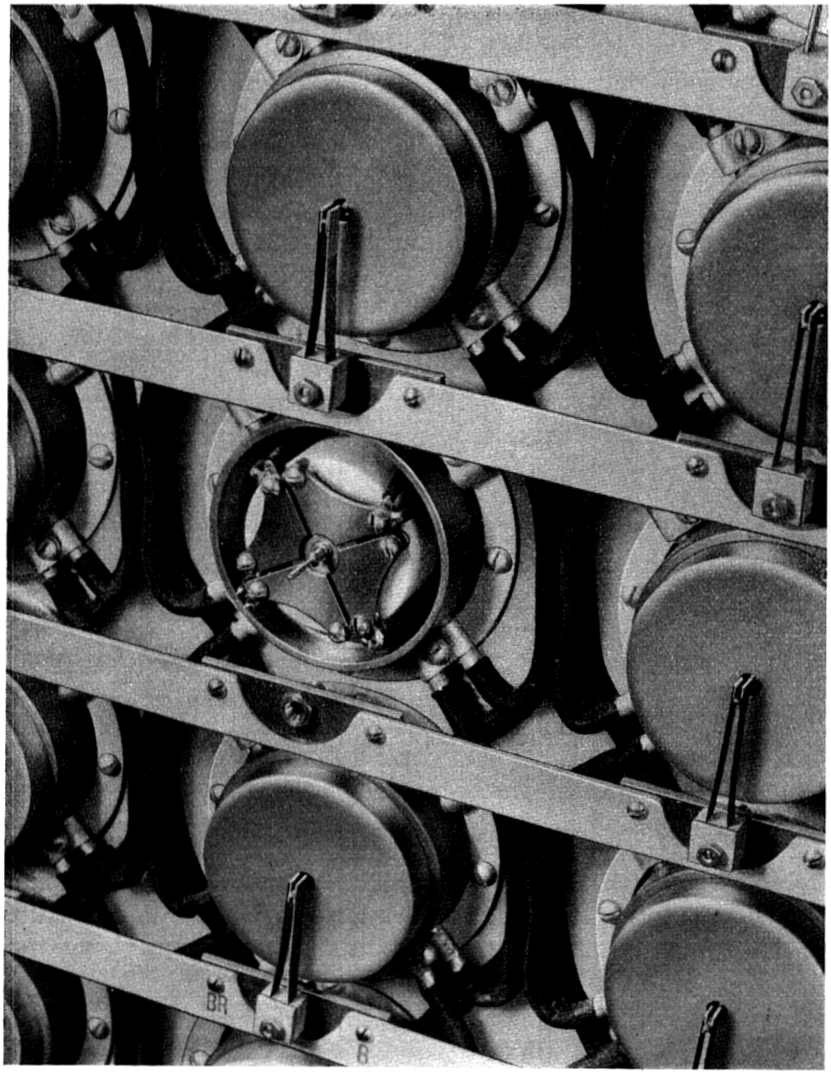

Fig. 7—Portion of a group of phase shifting condensers. Brush and cover removed from center condenser to show construction.

in turn is connected to the output amplifier. The quarter-wave line forms a combining network for the contributions of the various phase shifters. The two groups of eight phase shifters forming one diversity branch are each treated as units so as to facilitate isolating one group in case of trouble or the necessity of reducing the resolution of the antenna system.

There are two opportunities for undesirable interchanges of power in the parallel phase shifter system; there can be an interchange between antenna branches through condensers in the same diversity group, and an interchange between diversity branches through condensers in the same antenna branch. Both of these can be reduced to the required values by a proper proportioning of input and output impedances with respect to the condenser reactance. This results in a large loss, about 40 db, through the phase shifting system.

INPUT CIRCUITS AND FIRST DEMODULATORS

Obtaining uniformity of phase shift in the circuits preceding the first detectors is facilitated by reducing the number of circuit elements and selectivity to a minimum. No high-frequency amplification is used for this reason. The selectivity required to avoid image reception is materially lowered by the choice of a high operating frequency for the first intermediate frequency amplifiers. In addition to the usual requirement of high selectivity and high voltage transformation ratio, the input circuits must have uniformity in gain and phase, and must properly terminate the transmission lines so that multiple reflections will not shift the effective input amplitude or phase.

These factors seemed to preclude use of the usual variable tuned circuits on account of the time required to change from one frequency to another, and consequently fixed tuned circuits were used. Five input circuits are mounted on a panel and the switches for changing the input and output circuits of the two panels of each receiver which are mounted on a single bay are ganged. Each input circuit consists of two anti-resonant circuits capacity-coupled to each other and to the transmission line. It operates into the grids of the two first demodulator tubes which are paralleled. The first beating oscillator input is applied in push-pull between the cathodes of the tubes.

OSCILLATORS AND AUTOMATIC TUNING SYSTEM

Three highly stable oscillators are used in the receivers, one for beating the signal frequency down to 2,900 kc., the second for beating it down further to 100 kc., and the third for use as a reference frequency for the automatic tuning system, or it may be used in the final demodulator when the automatic branch selector is used.

The first beating oscillator is of the coil-and-condenser type and covers the range from 7,000 kc. to 17,000 kc. Automatic tuning is used to compensate for long-time variations in its frequency, as well as any variations in the transmitter frequency, but every effort has been made to keep short-time variations to a minimum. The oscillator is contained in a cast box mounted on rubber supports. The inductance coils have an extremely low temperature coefficient and are mounted on cast supports for rigidity. The condenser is also of rigid construction. A variation in plate voltage of one volt gives a frequency variation of about 6 cycles at 18,000 kc.

A buffer amplifier connects between this oscillator and a push-pull power amplifier which delivers ten watts of output. This output is delivered to a transformer located on the center bay of the row of first demodulator bays. Coaxial cables of equal length distribute it to the first demodulators on the adjacent bays. A vacuum tube voltmeter connected across this transformer gives an alarm if the voltage fails.

In the automatic tuning system the incoming carrier at approximately 100 kc. is beaten with the local 100 kc. oscillator. The phase of the beat frequency is then split and the resultant two-phase output applied to a motor which drives a condenser in the first beating oscillator circuit until the beat frequency is reduced to zero. In order to avoid interruption of control due to fading, all three diversity branch carriers are simultaneously connected to the circuit.

The second beating oscillator operates at 3,000 kc. and is a standard broadcast oscillator which has been slightly modified.

The 100 kc. oscillator is required to have the same frequency as the center of the pass band of the carrier filters. Since these are only 40 cycles wide both filters and oscillators are made with low temperature coefficient crystals. The oscillator is of the bridge type described by Meacham [8] but without temperature control.

AUTOMATIC VOLUME CONTROL AND FINAL DEMODULATORS

Only the carrier is rectified for automatic volume control purposes. In the 100 kc. amplifiers where the carrier and sideband are amplified separately, separate automatic volume control circuits are used. The time-constant of the carrier amplifier control is made 0.1 second, which is as fast as is practical with the narrow carrier filter used, and the time-constant of the sideband volume control is made variable but is generally set at a value of 1 second.

With the common automatic volume control used with diversity receivers the rectifiers are so connected as to give outputs which vary according to the square or first power of the branch input. The sum of the rectifier outputs is held substantially constant. If the combined signal output is also to be held constant, the final demodulators of the

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[8] L. A. Meacham, "The Bridge-Stabilized Oscillator," *Proc. I.R.E.*, Vol. 26, No. 10, p. 1278, October 1938; *B.S.T.J.*, Vol. XVII, No. 4, p. 574, October 1938.

branch circuits must follow the same law, i.e., if linear rectifiers are used, the final demodulators should be linear, and if square-law rectifiers are used, the final demodulators should be square-law. When linear demodulators are used the output noise is independent of the strength of the incoming carrier and since the gains of all branch amplifiers are the same the noise output of each branch will be the same, assuming that received noise does not vary with the vertical angle of reception. As a consequence the total noise will be equal to the product of a single branch noise and the number of branches regardless of the signal contributions of each branch. If square-law detectors are used, however, the noise output of a branch will go down when the carrier in the final demodulator of that branch goes down and consequently the total noise will be proportional to the total signal. In a three-branch diversity system a theoretical improvement in signal-to-noise ratio varying up to 4.77 db can be had by using square-law demodulators rather than linear. For this and other reasons square-law final demodulators have been used in this equipment.

When delay equalization is used between the various diversity branches it is essential that the received carrier be used in the final demodulation process. Small changes in the lengths of the paths in space traversed by the sidebands being received by the various diversity branches make the phases at random and if all branches were demodulated by a common carrier the audio outputs would not add in phase. By using the carrier arriving over each path for the demodulation of the accompanying sideband the random relation disappears and the audio outputs can be added in phase.

When using an automatic branch selector which discretely chooses one branch at a time for connection to the line it is no longer necessary to consider phases in the diversity branches and a local carrier is used because it reduces output amplitude variations. With only one diversity branch connected to the output, only the corresponding volume control rectifier should be contributing to the automatic volume control voltage if the output volume is to be held as constant as possible. This result is obtained by putting a rectifier in the d.c. output lead of each branch volume control rectifier so that only the volume control rectifier having the highest amplitude will supply current to the load resistance.

DELAY CIRCUITS AND SWITCHES

On account of the fact that waves arriving at different vertical angles have taken different times in transit it is necessary to insert delay compensation in two of the three diversity branches when they are all connected to the output at once so that the audio outputs will add in phase. The branch receiving the waves at the highest angle, which are always the waves which have traversed the greatest distance, does not contain a delay circuit. The other two branches contain variable delay circuits having a maximum of 2,768 microseconds delay in steps of 31 microseconds. The band covered by the delay circuits is 6,000 cycles, the same as the width of the filter in the last intermediate frequency amplifier. The delay steps were made small enough so that it would be technically possible to phase properly over the entire band within less than a quarter cycle provided that the phase distortions of the transmission path, and the other parts of the receiver made it practical to do so.

The delay circuits each consist of 8 units having a delay of 31 microseconds and 9 units having a delay of 280 microseconds. Hand operated switches are provided to vary the delay in the usual decade switch manner. A motor driven switch is also provided which is arranged with two shafts connected by an intermittent movement so that when the eight small units of delay have been added a continued movement of the shaft removes these units from the circuit and simultaneously connects one of the large units, which is equivalent to nine small units. Further movement in the same direction successively adds in the smaller units again.

AUTOMATIC DELAY ADJUSTING CIRCUITS

A block schematic of the automatic delay adjusting apparatus as well as the automatic angle adjusting and recording equipment is shown in Fig. 8.

The proper delay compensation to phase the output of two diversity branches can be determined by connecting the outputs of the two branches to the two pairs of plates of a cathode ray oscilloscope and varying the delay in the lower angle path until a straight line pattern is obtained on the oscilloscope screen. This adjustment is facilitated by the restriction of the band in each branch at the oscilloscope to about an octave. If only a single frequency were used for this adjustment several positions of the delay adjustment might be found to give a straight line on the oscilloscope, the number of positions depending upon the frequency. In order that there may be only one position when the maximum delay is 2,768 microseconds the phase shift caused by this delay must be less than 180°, and consequently the frequency of operation must be less than 180 cycles. Where a band of frequencies a few hundred cycles wide is used, however, this difficulty is not encountered and there is only one adjustment of the delay which gives a straight line on the oscilloscope.

With the cathode ray oscilloscope there is no indication as to whether the delay in the circuit is too small or too great, but only that it is either correct or incorrect. A direct indication of whether the delay should be increased or decreased can be obtained by connecting one diversity branch to the push-pull input of a balanced modulator and another diversity branch to the parallel input of the same modulator, after having shifted the phase between the two branches by 90°. When the two receiver branch outputs are in the same phase the two modulator input voltages will add in quadrature and the currents in the plate circuits of the two modulators will be the same, but when the phases are not the same the current in one plate circuit will be greater and the other less than in the in-phase case, the sense of the unbalance depending upon whether too little or too much delay is in the circuit. A center-zero meter in a bridge connection in the plate circuits therefore can be made to indicate the sense of the necessary correction. By substituting a voltmeter relay for the indicating meter a motor drive of the variable delay circuit can be operated in such a manner as to adjust the delay to the correct value.

This automatic equipment must operate satisfactorily with circuits having types of privacy in which the energy bearing components of speech are shifted from their normal position in the frequency spectrum. The equipment is made, therefore, to operate on a band of frequencies from 250 to 750 cycles. Volume limiters are provided which keep the input to the automatic equipment from this band substantially constant. If the delay is never incorrect by more than 1,000 microseconds, which has been found to be true under all conditions of normal operation, the automatic equipment will bring it to the correct value. For greater errors the equipment tries to set the delay at values about 2,000 microseconds higher or lower than the correct value.

Since the delay adjustment operates on speech, the relay operation will be intermittent at a syllabic rate and the motor drive relay system must incorporate a suitable hangover circuit to keep the motor operation as constant as possible when the delay is far from the proper value, and still not cause an over-run when the proper adjustment is reached. Freedom from over-run caused by motor inertia is obtained by using a motor having a multiple-pole permanent magnet armature with a speed of 75 r.p.m., which under no load will brake itself in about twenty degrees of armature travel.

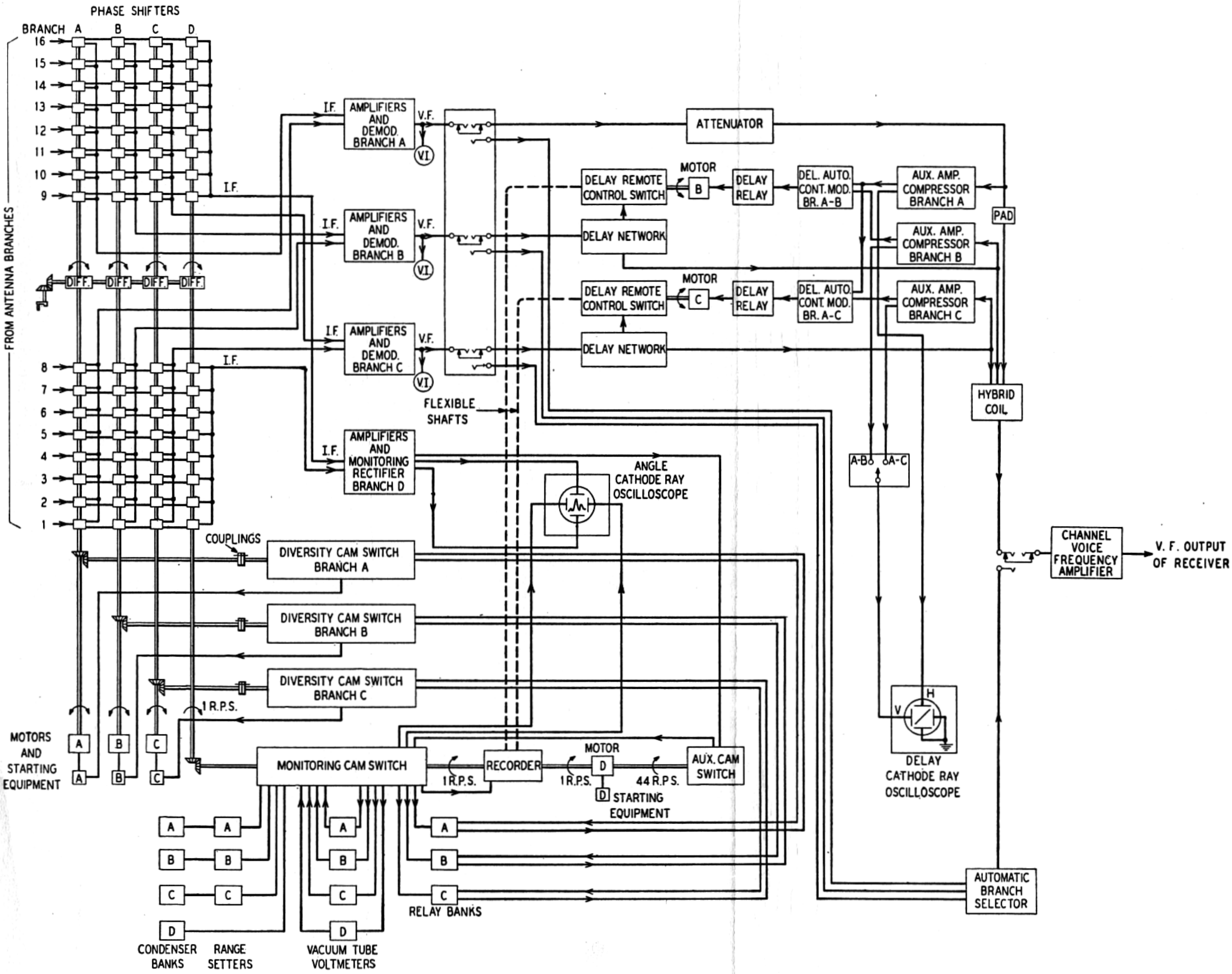

Fig. 8—Block schematic diagram of automatic adjusting circuits.

Automatic Branch Selector

As an alternative to the combination of the outputs of the diversity branches after delay equalization it is possible to use a system which discretely chooses one branch for connection to the line. Equipment to do this has been provided.

The common automatic volume control which is used with both systems operates on the carrier and if the carrier and sideband fade alike the output volume is held substantially constant. To the extent that the received noise on the various branches is the same, the branch having the highest output volume will be the most desirable to use. In the equipment used part of the audio output of each of the three diversity branches is rectified and applied differentially to three polar relays in such a manner that the relay corresponding to the branch having the highest amplitude is operated. This relay reduces the bias of an amplifier which connects between that branch and the output line from a high to a normal value, and thus permits voice frequency signals to flow through that branch to the output. The noticeable effects of switching are eliminated by several expedients. Push-pull amplifiers with feedback are used so as to balance out the low-frequency thump. The variation of biasing takes place with a time-constant of 0.01 seconds in order to aid in this matter as well as to render unnoticeable the instantaneous differences in the two channels. A biasing winding on each relay insures that once a contact is broken the relay moves to the opposite contact in a fixed time, which permits the selection of time-constants for the suppression and build-up which are as nearly complementary as possible, and so keeps the volume constant.

A difference in volume of 1 to 2 db is required to cause a switch. During the switching period, which lasts about 20 milliseconds, the output varies about ± 1 db. When no speech is being transmitted the relays remain inoperative and consequently the line may not be connected to the branch which at the next instant may deliver the highest volume. It might be expected that clipping of the succeeding initial syllable would be intolerable. To reduce selective fading to an unnoticeable amount it is only necessary to suppress the unwanted branches by 12 to 15 db. With the equipment adjusted to give this suppression it is found that there is always sufficient signal transmitted through one or more of the branches to practically eliminate noticeable clipping.

The use of the automatic branch selector has the disadvantage that the effect of having more than one diversity branch contribute to the output at any one time is lost. This is estimated to be equivalent to not more than an increase of one decibel of transmitted power. To offset this there must be considered the possibility of the delay being out of adjustment for brief periods when changes in angle require sudden changes in delay equalization. The necessity for close phase uniformity between the various carrier and sideband amplifiers over a wide range of automatic volume control voltage is also eliminated when the automatic branch selector is used. Further, it is no longer necessary to use the received carriers for demodulation of the various branch outputs and a locally generated carrier of uniform amplitude can be used with a resultant increased stability of output volume. The practicability of trying to phase branch outputs by delay equalization over a range of more than 3,000 cycles from the carrier has not been demonstrated and consequently the use of automatic branch selection with the channel whose sideband is spaced by one sideband width from the carrier is to be recommended. The use of the branch selector also permits simpler operation of the automatic angle adjusting equipment as will be explained later. For all of these reasons it is to be expected that the automatic branch selector may eventually be used to the exclusion of the delay compensating equipment.

Automatic Angle Adjusting Equipment

In the experimental musa receiver the rectified carrier output of the monitoring branch was connected to one set of deflection plates of a cathode ray oscilloscope and a sweep circuit mounted on the monitoring phase shifter shaft connected to the other set of deflection plates. The oscilloscope screen displayed a graph of the amplitude of signal received for each phase shifter setting. The pattern frequently changed rapidly from moment to moment so that only by constantly observing the screen was it possible to determine at what phase shifter settings the best signals were being received and to set the diversity phase shifters accordingly.

The attention necessary to operate satisfactorily the equipment in this manner was believed to be too great for commercial operation, particularly since it might vary widely from hour to hour. With a mind to the fact that improper adjustment might give poorer reception than would be obtained with ordinary receivers it was decided to make the settings of the phase shifters of the diversity branches automatic.

In Fig. 8 the motors *A*, *B*, *C* and *D* drive the phase shifters of the corresponding branches through the vertical shafts. Motor *D* operates continuously so as to vary the phase shifting system through its complete range once a second, while motors *A*, *B* and *C* operate only when a change in the angle of reception is required. Connected to the vertical drive shafts by the horizontal shafts are the three diversity cam switches and the monitoring cam switch.

The incoming carrier in the monitoring branch D is amplified in such a manner as to keep the average peak amplitude constant. It is then rectified, and applied to the vertical deflection plates of a cathode ray oscilloscope in the same manner as in the experimental equipment, the monitoring cam switch being provided with a set of contacts and resistances which act as a sweep circuit for the horizontal plates of the oscilloscope.

The rectified signal from the monitoring rectifier is also connected through the auxiliary cam switch, the monitoring cam switch, a high resistance, and the range setters, to three separate banks of condensers, each consisting of 44 four-microfarad condensers. The condensers in each bank are connected successively to the rectifier circuit once each second for a short period by the cam switch so that each is charged at a rate depending upon the amplitude of the received signal for a particular phase shifter position. A vacuum tube voltmeter is connected successively across each condenser of a bank. When one condenser becomes charged to one-half volt or more during the preceding second the vacuum tube voltmeter operates a relay. With the Branch A, B, and C voltmeters this results in a relay corresponding to that particular condenser being locked up and all the condensers in that particular bank being discharged. The operation of the second relay causes the motor of the corresponding diversity branch to start and turn in the right direction so that the branch phase shifters are adjusted with the least movement to the position corresponding to the relay, at which point a contact in the diversity cam switch trips the relay and stops the motion.

If no further control were provided all the diversity branch circuits would be set in the same position and consequently no diversity action would be obtained. To prevent this the range setters, A, B, and C, have been provided which are operated manually to limit the angular range of operation of each diversity branch. These switches merely short-circuit the condensers of a particular branch in the range which it is not desired to use. Since the short-circuited condensers do not acquire a charge the automatic adjusting equipment will never move the phase shifters to a position corresponding to a short-circuited condenser in that particular branch.

In setting the range switches when using delay equalization it is necessary to know what the condenser position is which corresponds to the highest angle which it is possible to receive at the particular frequency being used. The short circuit will then be removed from this condenser and from the condensers representing successively lower angles in Branch *A* until it seems probable from the recorder or cathode ray oscilloscope pattern that a good signal will be received in that branch. The remaining condensers in that branch are left short-circuited. The short-circuits are then removed in a like manner from part of the remaining range for Branch *B* and in the remainder of the range for Branch *C*, the best division line being determined from the cathode ray oscilloscope or recorder pattern. This procedure is necessary inasmuch as branch *A* is used for a reference in adjusting the audio frequency delay compensation and must always have a satisfactory signal if that equipment is to operate.

When using the automatic branch selector other settings of the range switches are possible. One arrangement is to allow one branch to stop on even numbered contacts for a part of the range and another branch to stop on the remainder of the even numbered contacts. The third branch may then stop on any odd numbered contact. This permits two diversity branches to be set in the range of maximum signal. A difference of one contact has been found sufficient to give satisfactory diversity action in most cases and the recorder pattern always shows that the signal is more than one contact wide. The third branch is free to follow a signal in another part of the range, which may grow to be the strongest at any moment.

In order to improve the accuracy of this equipment and reduce the maintenance of the monitoring cam switch an auxiliary high speed cam switch is used which operates 44 times faster than the main switch, closes just after each contact of the monitoring switch, and opens just before each contact opens. The charging time for all condensers in a given bank is thus determined by the same cam and set of contacts.

To prevent over-running on the diversity branches from mechanical inertia a special motor is used. This motor is similar to the one used for automatic delay adjusting equipment.

At times there may be only one angle at which a satisfactory signal may be arriving. It is possible to get diversity action at these times by setting the diversity branches on opposite sides of the average angle of best reception. Provision is made for doing this with the automatic equipment by allowing one bank of condensers and one voltmeter relay to control all three diversity branches and then mechanically off-setting the phase shifters of two branches by means of adjustable couplings in the diversity cam switch drives.

It will be seen that to obtain accurate operation of the automatic angle adjusting equipment it is necessary that the charging voltage should be large as compared with the final voltage on any condenser and that the final voltage must be the sum of a number of charges. The time necessary for a condenser to reach the final voltage can be varied from 8 to 45 seconds or longer and successive movements of a diversity branch phase shifter drive will not be oftener than this. Once the motor has started, however, it will move the phase shifter shaft through an angle of 180°, the maximum which would ever be necessary, in 6 seconds.

Recorder

In order properly to set the phase shifters manually or to set the range adjusters of the automatic angle adjusting equipment it is necessary to know the phase shifter positions corresponding to the angles at which signals are arriving. The angle monitoring cathode ray oscilloscope shows how the signal amplitude *vs.* phase shifter position varies from second to second. By using a retentive screen on the oscilloscope it is possible to see the traces for the previous few seconds at the same time as the most recent trace. The traces, however, normally vary appreciably in position of maximum amplitude and it is somewhat difficult to form an opinion from looking at the oscilloscope as to just where to set the diversity branches. By integrating the value of received signal over a number of seconds a better conception can be obtained.

In addition to the cathode ray oscilloscope it also seemed desirable to have a record available to the operator of the variation of signal intensity with phase shifter position as it changes from minute to minute so that he would not continuously have to observe the oscilloscope to determine whether the range adjusting switches were set properly. This required one more variable to be considered than the ordinary recorder is designed to register and it was consequently necessary to devise a new type of device.

The scheme of recording operates in a somewhat similar manner to the automatic angle adjusting equipment. A set of 44 condensers is charged by the incoming signal through the monitoring switch. Each condenser corresponds to a particular position of the phase shifters and consequently with a particular vertical angle of arrival at a particular frequency. A vacuum tube voltmeter is successively connected to the condensers until one is found which has acquired a predetermined potential in the order of two volts. A relay in the plate circuit of the voltmeter then operates, causing only that particular condenser to be discharged and making a record on a paper strip.

The recorder consists of a mechanism for driving a paper strip 5″ wide at a constant speed over a drum having a spiral wire on its periphery. Above the drum and paper are a typewriter ribbon and a thin bar which may be made to come down on the ribbon, paper tape, and spiral wire, by the action of an electromagnet. The action of this striker bar is to cause a dot to be made on the paper strip at the position where the striker bar and spiral wire intersect. The drum carrying the spiral wire revolves in synchronism with the phase shifters and there is consequently a lateral position on the paper corresponding to each one of the 44 condensers previously mentioned. When each condenser is discharged by the action of the vacuum tube voltmeter a dot is made in a particular lateral position on the paper strip and successive dots caused by the discharge of the same condenser fall in the same longitudinal line on the strip. The frequency of dots in a particular longitudinal line is, therefore, proportional to the relative field strength at a vertical angle corresponding to that line. As a result of the action of the automatic volume control on the monitoring branch amplifier, the maximum frequency of dots along a longitudinal line is kept approximately constant regardless of the absolute value of signal received so that the device does not record the variation of signal at a fixed angle from minute to minute.

A sample of a section of a record is shown on Fig. 9, together with a scale showing the angles corresponding to the rows of dots for a particular received frequency. The angle record is contained in the section above the "Phase Shifter Position" scale.

In order to have a check on, and a record of, the operation of the automatic angle adjusting equipment, provision has been made so that three longitudinal lines are drawn on the paper corresponding to the three angular positions of the diversity branches.

A record of the operation of the automatic delay adjusting device is also made by the recorder. This was done by inserting a mechanism which uses the margins of the paper on either side of the main record. The delay recording device consists of two drums mounted concentrically with the main recorder drive shaft which are similar in nature to the tens and units drums of an ordinary counter. Flexible shafts extend from the delay adjusting switches to the recorder where they drive the drums on each end of the shaft. The two drums on one end are connected together with an intermittent movement so that one revolution of the small units drum causes the large units drum to move forward one step.

With the paper tape normally running at only $\frac{1}{4}''$ per minute it is impractical to stamp numbers on the paper since the delay adjustment varies several times in a minute and thus would cause the numbers to record on top of one another. Recourse was accordingly taken to a mark in a definite lateral position to indicate the magnitude of the delay. The drums have segmental ridges on their periphery which are displaced in various lateral positions. Cam operated hammers descend on the typewriter ribbon above the drums and paper once each second leaving a mark in a lateral position corresponding to the segmental ridge which is beneath and consequently to the delay setting. Two reference lines are used to facilitate the reading of the delay values.

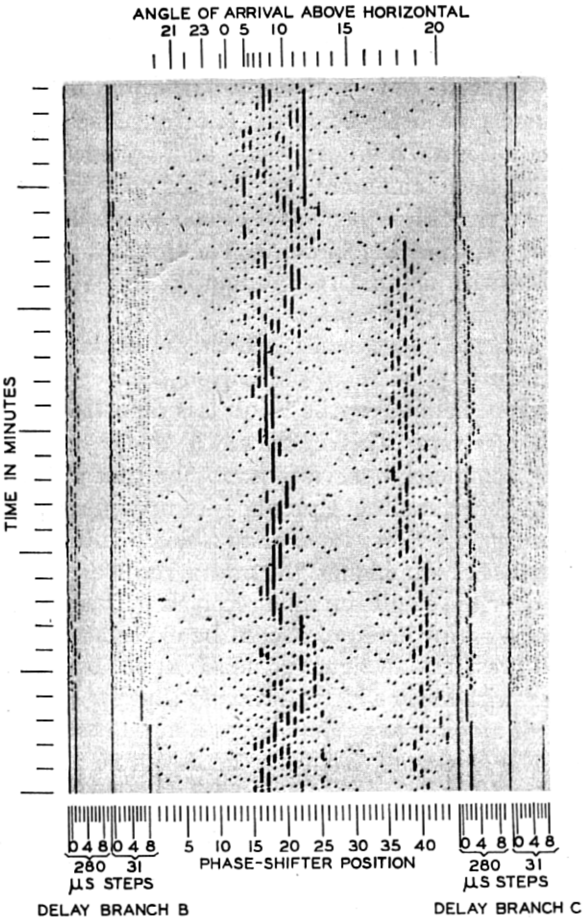

Fig. 9—Sample of musa recorder chart. Station GAW. Freq. 18,200 Kc.

Operation and Performance

The musa system can be expected to give an improvement in signal-to-noise ratio and in selective fading over a receiver using only a single antenna. The improvement in signal-to-noise ratio caused by the use of 16 antennas should average 12 db, but instantaneous improvements might vary from large negative values, if the equipment were not kept properly adjusted, to values of 25 or 30 db, which might be expected when the noise came from the direction of a null in the musa antenna directive diagram.

In the operation of radio telephone circuits there is a minimum signal-to-noise ratio below which commercial service cannot be given. As the signal-to-noise ratio is increased a value is reached where further increases give little benefit. The range between these two values is about 25 db. Transmitters and receivers generally are designed so that their maximum signal-to-set-noise ratio is somewhat greater than the maximum beneficial circuit value in order that set-noise shall not degrade the circuit. The maximum signal-to-noise ratio obtainable with a musa receiver and a single-antenna receiver should be approximately the same.

The 12 db average improvement which the musa receivers should give should make it possible to obtain, on the average, commercial circuits with signal field strengths 12 db less than those usable with a single-antenna receiver. This in turn will decrease the amount of time in which commercial service cannot be given.[9] On the other hand the musa receiver should produce its maximum signal-to-noise ratio for field strengths 12 db lower than a single-antenna receiver and at field strengths 12 db higher the musa receiver would show no improvement over the single-antenna receiver. The net improvement in signal-to-noise ratio therefore should be expected to average from 12 db at the lowest usable signal-to-noise ratios to 0 db at fields 25 or 30 db higher, with fairly wide variations with time from the average.

The results of a comparison between the musa system and a single sideband receiver operating from one of the same antennas confirm the theoretical expectations to a fair degree. The fraction of the time that given improvements in decibels are obtained follows approximately a normal probability curve.

The reduction in selective fading effected by the musa receivers is difficult to state numerically. Most of the objectionable selective fading is removed. There are times when waves that have traveled over distinctly different paths arrive at so nearly the same angle that they cannot be resolved. Fortunately these times are fairly rare. When waves of closely adjacent angle are present the monitoring system does not give a true indication of reception angles, as can be

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[9] R. K. Potter and A. C. Peterson, Jr., "Reliability of Short-Wave Radio Telephone Circuits," *Bell Sys. Tech. Jour.*, Vol. XV, pp. 181–196, April 1936.

shown by theory. It is a fairly common occurrence for a wave group which has apparently traveled over a single general path to have components which vary in transmission times by 100 or 200 microseconds from others of the same group. The fading caused by such small delay differences is not distinctly selective in effect and its chief detriment is in causing volume variations which must be overcome by the use of special devices.

During some severe magnetic storms successive traces on the angle monitoring cathode ray oscilloscope show little relation to each other. It has been reasoned that a reduction in resolution might be beneficial at such times but sufficient experience to prove this has not been obtained. A reduction in resolution can be obtained easily by switching off the amplifiers associated with one group of eight antennas. It has been found that fading on the front group of antennas is generally at random to that on the rear group so that the two groups can be used in space diversity if desired. No particular advantage has been found to this arrangement.

The use of delay compensation between the diversity branches does not seem to have any advantage over the use of the automatic branch selector. The output volume variations are slightly greater with delay compensation because of the use of reconditioned carrier for demodulation. On the other hand the use of the automatic branch selector promises materially to reduce maintenance by eliminating the necessity for keeping the phases of the various carrier and sideband amplifiers alike.

It has been amply demonstrated that the automatic adjusting features provided are essential to the efficient operation of the equipment.