A Frequency-Modulation Station Monitor*

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Summary—*This paper describes the development, theory, and characteristics of a frequency-modulation station monitor developed in the general engineering laboratory of the General Electric Company. The monitor measures mean carrier frequency with and without modulation and the percentage of frequency modulation as a percentage of 75-kilocycle deviation. In addition, it provides a flasher and alarm circuit for overmodulation adjustable from 50 to 120 per cent and an audio-frequency fidelity monitoring circuit. The paper begins with a discussion of the requirements for frequency-modulation monitors and compares the problems involved with those involved in standard broadcast monitors. Several schemes which were examined for use as a frequency-modulation monitor are briefly described, including counter and frequency-division systems. The principles and design of the final monitor are discussed.*

The last part of the paper is devoted to a discussion of the salient development problems encountered, to a detailed description of the circuit, and to a discussion of the over-all specifications of the commercial sample.

REQUIREMENTS FOR FREQUENCY-MODULATION MONITORS

IT IS convenient to introduce the problems involved in a frequency-modulation station monitor by recalling what is required of standard broadcast monitors. The first of these to be considered is the frequency monitor, which is a relatively simple device designed to measure the frequency of the unmodulated carrier. Simplicity is achieved by virtue of the fact that in an amplitude-modulation broadcast transmitter the unmodulated carrier wave is always available for frequency measurement. The frequency of this unmodulated carrier may be measured independently in one part of the circuit while the same carrier is being modulated in another part of the circuit. The measured frequency of the unmodulated wave is the same as that of the carrier component of the radiated band of frequencies resulting from modulation.

In frequency modulation, however, as employed in the systems now in extensive use, no isolated unmodulated carrier component exists during the modulation process. In one system, frequency modulation is accomplished by means of a reactance tube which directly varies the frequency of the master oscillator. Thus, during modulation, there is obviously no isolated carrier component in this system which is available for frequency measurement. In another system, the frequency modulation is accomplished by using a balanced amplitude modulator and reinserting the carrier component after shifting its phase by 90 degrees. Since this system begins with an amplitude-modulation process in which the unmodulated carrier is readily available for frequency measurement, it might appear that no difficulty would exist in obtaining the frequency of the radiated carrier component of the frequency-modulated wave. However, the frequency-modulated wave which is obtained in this manner inherently must have a very small frequency swing for distortionless modulation. This condition is fulfilled by modulating at a lower frequency and subsequently employing frequency multipliers. In practice, these increase the frequency swing by more than two thousand times in order to produce the required standard swing of 75 kilocycles for 100 per cent modulation. This multiplication factor is so high that if it were applied directly to the initial frequency-modulated wave, it would produce a resultant frequency band far above the regular 42- to 50-megacycle band. Therefore, the multiplication is combined with a beating process in order to reduce the frequency of the modulated wave without reducing the swing. As a result of this beating process, the frequency of the final carrier component is a function not only of the frequency of the initial amplitude-modulated carrier but also of the frequency of the heterodyne oscillator.

Thus, in neither of the present widely used systems is the carrier component of the final frequency-modulated wave directly available for measurement. The carrier-frequency component must either be measured without modulation with a conventional frequency meter or it must be measured during modulation with a device which separates it from the side tones.

At present, the Federal Communications Commission requires only that the "center frequency," which is defined as the frequency of the carrier without modulation, be held within 2000 cycles of the assigned value in the high-frequency broadcasting band (42 to 50 megacycles). However, it is desirable that the frequency monitor be capable of indicating the frequency of the carrier component during modulation because it is especially during this time that it is important to keep the transmitter frequency within its tolerance since shifts of radiated signal band may easily cause adjacent-channel interference or receiver distortion. However, in a frequency-modulated wave, the carrier component is a very elusive thing; under some conditions of modulation it disappears entirely, and under fluctuations in level such as exist in normal programs, its amplitude is constantly varying so that in itself it may be regarded as an amplitude-modulated signal having a small band of frequencies which may be spaced even closer than the lowest audio modulating frequency. Thus, its direct separation from the rest of the components of the wave seems hopeless of accomplishment. A more useful quantity, and one which can be measured, is the mean frequency of the wave. The mean frequency is the continuous average of the instantaneous frequency taken over a time which is long compared with the period of the lowest modulating

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frequency. In an ideal frequency-modulated wave, the mean frequency is the same as the carrier-component frequency. This follows from the definition of a frequency-modulated wave, the equation for which may be written as

$$e = A \sin \left\{ \omega_0 t - \frac{K\omega_0}{\rho} \sin \rho t \right\}.$$

In this equation $\omega_0/2\pi$ is the frequency of the carrier component and $\rho/2\pi$ is the frequency of the audio modulating wave and A and K are constants. The instantaneous frequency is defined as $1/2\pi$ times the rate of change of the phase angle

$$\left(\omega_0 t - \frac{K\omega_0}{\rho} \sin \rho t \right)$$

which is $(\omega_0/2\pi)(1 - K \cos \rho t)$. The mean value of the right-hand term of this quantity, taken over a long time compared with $2\pi/\rho$, approaches zero so that the mean frequency approaches $\omega_0/2\pi$ which is the frequency of the carrier component.

The monitor to be described in this paper measures the mean frequency of the frequency-modulated wave which, as shown above, is the same as the frequency of the carrier component when averaged over a period sufficiently long compared with the period of the lowest modulating frequency.

Returning to the comparison with amplitude-modulation monitoring practice, it will be recalled that a percentage-modulation monitor is also required in a standard broadcast station. This is usually a linear detector with an audio amplifier and peak-reading voltmeter. The percentage modulation is proportional to the ratio between the amplitude of the detected envelope of the carrier and the average carrier amplitude. In frequency modulation, however, the percentage modulation is defined by the Federal Communications Commission for high-frequency broadcasting stations as the percentage of a 75-kilocycle frequency swing or deviation above and below the carrier component which the instantaneous frequency undergoes during modulation. Thus, the measurement of percentage modulation is a measurement of the range of instantaneous frequency with 75 kilocycles as 100 per cent. It will be noted that a device which measures the sideband breadth is not suitable for this purpose since for high modulating frequencies the sidebands are considerably broader than the frequency deviation. The monitor described in this paper measures percentage of frequency modulation and also operates a warning flasher which may be adjusted to flash on peaks of modulation which exceed the value for which the flasher control is set. This value may be adjusted to any desired level between 50 and 120 per cent modulation.

In addition to performing these functions, the monitor also supplies an audio output for monitoring fidelity. In certain cases, this may also be found useful in estimating transmitter distortion and noise level. Thus, the unit monitors four essential characteristics of a frequency-modulated wave as follows: (1) mean frequency of carrier with and without modulation, (2) percentage of frequency modulation with (3) alarm indication for overmodulation, and (4) fidelity of the modulated signal.

General Description of the Monitor

Several schemes for the frequency monitor were considered. One of them was based on the principle of frequency division. When a frequency-modulated wave is passed through a series of frequency dividers, the ratio of sideband energy to carrier-component energy progressively decreases and when the frequency deviation becomes less than the lowest modulating frequency, practically all the energy resides in the subharmonic of the carrier component. The frequency of this component, which may be easily measured, is then equal to the frequency-modulation carrier component divided by the division factor. However, no sufficiently simple and economical means of accomplishing the large frequency division required was found which would justify the use of this principle in a monitor.

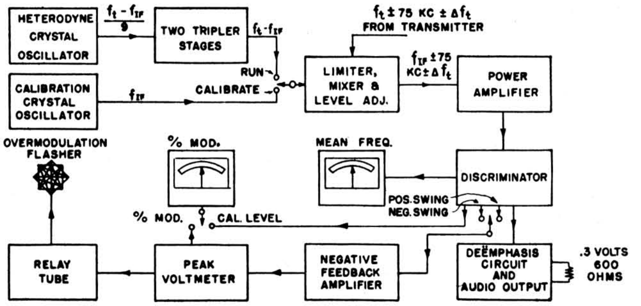

Fig. 1—Block diagram of frequency-modulation station monitor.

A counter system was examined whereby a large number of individual frequency-modulation carrier cycles would be counted during accurately timed intervals. The indicated number of counted cycles during the intervals would be proportional to mean frequency. This, again, was far too complicated and expensive a system to be practicable.

Due to the multiplicity of sidetones in wide-band frequency modulation and the ever-changing amplitude of the carrier component itself, no means of identifying and measuring the frequency of this component directly was found.

The method finally adopted measures the average of the instantaneous carrier frequency using a circuit which in principle is a modified precision frequency-modulation receiver. A general account of this will be given followed by a more detailed discussion of the problems encountered in the development.

Referring to Fig. 1, the theory of operation is as follows: The frequency-modulated wave $f_t \pm 75$ kc $\pm \Delta f_t$ is fed into the monitor from the transmitter. It is immediately limited and converted to an intermediate frequency of approximately 5 megacycles in the mixer tube. The beat oscillator frequency is derived from a crystal oscillator and multiplier which has an output frequency of $f_t - f_{IF}$. The frequency-modulated intermediate frequency $f_{IF} \pm 75$ kc $\pm \Delta f_t$ is then fed to a frequency-discriminator circuit through a buffer-amplifier stage. The discriminator circuit is designed to deliver a current which is proportional to the instantaneous deviation of the carrier from its assigned value, being zero at the assigned value. The zero-output-current point of the discriminator may be calibrated when necessary by a separate precision crystal oscillator which has a frequency of f_{IF}. The discriminator output current is averaged over the audio cycle and the resultant direct current is proportional to the shift of the mean frequency from its assigned value. A zero-center, direct-current instrument with a linear scale marked from -2000 to $+2000$ cycles indicates the difference between the mean carrier frequency and its assigned value.

The alternating-current component of the output of the discriminator circuit has the form of the modulating wave because of the linear relation between current and frequency in the discriminator. Since the peak value of the signal is proportional to the peak frequency deviation, the per cent modulation is indicated by a peak voltmeter. This is operated by the discriminator audio output after amplification and it is so calibrated that 100 per cent modulation is indicated when the instantaneous peak frequency deviation is 75 kilocycles. A gas tetrode 2051 tube is arranged with the peak rectifier output applied to its grid so that when the modulation peaks exceed some preset value, which is under the control of the operator, the tube is "fired." Since the plate supply voltage for the gas tube is 60 cycles alternating current, the plate is negative every 1/60 of a second with respect to the cathode. This allows the grid to regain control of the plate current every 1/60 of a second. The "firing" of the tube causes a red flasher lamp to light and also closes a relay circuit which may be connected to an external alarm device or to a counter to record the number of peaks of modulation which exceed the value for which the control is set.

Audio quality monitoring has been provided in this monitor. Since it is standard practice in frequency-modulation broadcasting to pre-emphasize the high frequencies of the audio modulating signal according to a standard frequency characteristic, a de-emphasis is necessary in recovering the original audio signal. In the monitor, as in standard frequency-modulation receivers, this de-emphasis circuit has an impedance function which is the inverse of that of the pre-emphasis circuit in the transmitter. The output of the discriminator is passed through this circuit and thence into a low-distortion output tube designed to feed an external 600-ohm audio system.

DEVELOPMENT PROBLEMS

At the outset of the development, it was realized that an averaging circuit, if linear, would deliver a direct output current proportional to mean frequency but it was not evident that such a circuit could be made to maintain sufficiently precise alignment or stability to give a reliable output indication. The circuit must have output-current response which is strictly proportional to frequency over a range greater than 150 kilocycles in order to follow faithfully the full excursion of the instantaneous frequency. However, the total range of the mean frequency indication is only 4 kilocycles.

A simple example will illustrate the point. Suppose that the transmitter is operating at its assigned frequency and is modulated with a square wave (50 per cent pulse width) at full ±75-kilocycle deviation. During the positive half cycles of the square-wave modulation, the discriminator output current is a steady positive current of $+75$ units, assuming 1 current unit per kilocycle to be the discriminator slope. If the discriminator characteristic is linear, then during the negative half cycles of the square-wave modulation, the discriminator output current is -75 units, and the average current, which indicates the mean frequency, is zero. Now suppose that the discriminator characteristic is not strictly linear in such a way that $+75$ current units flow during the positive modulation intervals but only -74 instead of -75 current units flow during the negative intervals, a nonlinearity of only 1.3 per cent; then the average current is $+1$ unit instead of zero and the indicated mean frequency is 1000 cycles above the actual value, an error of one half of full scale due to only 1.3 per cent nonlinearity.

It must be realized, of course, that with ordinary complex modulation waveforms small deviations from linearity of the discriminator characteristic are not as serious as would seem from the above example since the average current is obtained from an integration of current over the whole discriminator characteristic rather than from two isolated points as is the case for square-wave modulation.

The first major question to be answered in the development, then, was whether or not a sufficiently linear response could be obtained economically in the frequency-discriminator circuit. Rather than find the answer to this question by mathematical analysis of the complicated discriminator circuit, the circuit was set up and adjusted for best linearity of response between output current and input frequency. Holding constant input amplitude, it was found that the characteristic did not deviate from a straight line by more than about 1/2 of 1 per cent and this was the order of accuracy of the output current measurement and of the constancy of the input amplitude.

This result seemed to justify an experimental test of the stability of the output indication of mean frequency since this was the next questionable characteristic of this type of circuit for use in a precision monitor. It was found, for example, that in a typical discriminator circuit a change in secondary capacitance of only 52 parts per million caused a 200-cycle change in indicated frequency out of the possible full-scale indication of 2000 cycles. It was previously mentioned that the discriminator may be instantly calibrated by throwing a switch. This applies a signal from a precision crystal oscillator whose frequency is equal to the crossover frequency of the discriminator. The output indication at this frequency can be adjusted to zero by a vernier secondary trimmer capacitance on the discriminator. Nevertheless, in order that this calibration process be required as infrequently as possible, it is desirable to have as high a stability as possible. For stability of 200 cycles in the output indication of mean frequency, the requirement for secondary discriminator inductance and capacitance is a stability of 0.005 per cent. This requirement was met by using special precautions in the design and manufacture of the coil form and winding and by employing suitable negative-temperature-coefficient tuning capacitors to supply compensation for the positive temperature coefficient of the inductances. With these precautions it has been found possible to omit the temperature control of the discriminator transformer employed in the earlier samples without loss of accuracy in the frequency indication.

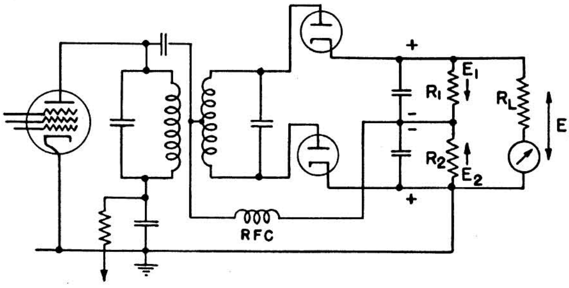

Fig. 2—Conventional frequency-discriminator circuit.

The author would like to acknowledge at this juncture that it was largely due to E. D. Cook of the General Electric Company that this type of monitor circuit was investigated at all. It was generally believed that the linearity and stability requirements would be too severe for such a circuit to be practicable for use in a precision mean-frequency monitor. However, once having established by test that the discriminator could be made to have the required characteristics, the decision to concentrate on such a design was easily made and the monitor circuit, as previously described and as illustrated in Fig. 1, was developed.

The intermediate frequency is a function of the frequency of both the beat oscillator and the incoming wave to be monitored. For this reason the highest quality, temperature-controlled crystal available is used in the oscillator-multiplier circuit. The converter has been designed to provide amplitude limiting of the incoming wave from the transmitter in order to reduce to an acceptable degree any amplitude modulation which may be caused by maladjustment of the transmitter or by nonuniformity in the frequency response of the cable used to introduce the transmitter signal into the monitor. Amplitude modulation of this type is synchronous with the frequency modulation; that is, as the instantaneous frequency changes following the modulating wave so does the amplitude of the output change at a rate controlled by the modulating wave and the shape of the frequency response. If such a frequency- and amplitude-modulated wave is supplied to the discriminator, an incorrect mean-frequency indication will in general result because the current output of the discriminator is proportional to amplitude as well as to frequency of the signal supplied to it.

Design of Discriminator

As the development progressed, a problem of sensitivity soon presented itself in regard to obtaining sufficient current from the discriminator for mean-frequency indication. The conventional discriminator circuit illustrated in Fig. 2, as used in receiver applications, is designed primarily to have a high voltage sensitivity; that is, to deliver an audio voltage as large as possible for a given swing in frequency. This is applied to the loudspeaker through a suitable amplifier. In the monitor, however, it is also required that the direct output current, which is proportional to variation of the mean frequency, be available at a useful level. The range of mean-frequency variation is 4000 cycles whereas the range of the instantaneous frequency is 150,000 cycles so that the amplitude of the mean-frequency indicating signal is only 4/150, or 2.7 per cent of the amplitude of the audio signal from the discriminator. Furthermore, the mean-frequency indication is a slowly varying direct-current signal, and a stable direct-current amplifier is not easy to build. These considerations led to the development of a modified discriminator circuit, illustrated in Fig. 3, which is especially adapted to giving a high current sensitivity rather than a high voltage sensitivity. Moreover, this modified discriminator is balanced to ground and allows an audio signal of either polarity to be obtained from it. Thus, indication of either positive or negative

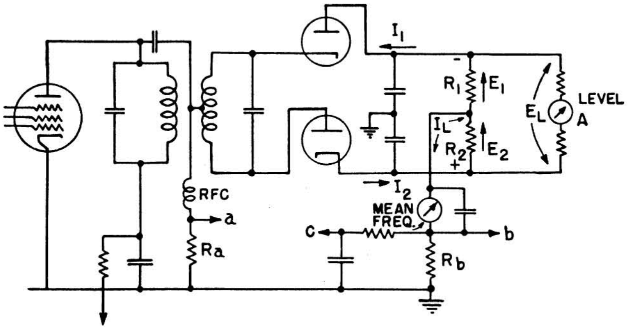

Fig. 3—Current-sensitive frequency-discriminator circuit.

percentage modulation is available. A direct-current instrument which is by-passed for audio frequencies has been provided to indicate the average output current directly from the discriminator and direct-current amplification is therefore not required.

In the conventional discriminator (see Fig. 2) E_1 and E_2 are equal and opposite direct voltages when the center frequency is applied to the discriminator. The sum of these voltages E_L is zero. As the frequency deviates to one side of center frequency E_1 increases and E_2 decreases so that E_L becomes positive; on the other side of center frequency, E_L becomes negative. A direct-current instrument to measure mean frequency must be be placed in series with R_L across R_1 and R_2, and R_L must be large compared with R_1 and R_2. This results in relatively low current sensitivity through R_L.

In the current-sensitive discriminator circuit (see Fig. 3), on the other hand, the diode voltages E_1 and E_2 are in the same direction and proportional to I_1 and I_2, respectively. The difference current I_L between I_1 and I_2 flows through the center-frequency instrument through a small resistor to ground, and back up to the secondary coil of the discriminator through another resistor and a radio-frequency choke. At center frequency, $I_1 = I_2$ and $I_L = 0$. At frequencies above and below center frequency, I_L has positive and negative values, respectively, and follows a linear characteristic with frequency as does the voltage E_L in a conventional discriminator circuit. The resistors R_a and R_b are inserted to give peak voltages proportional to positive and negative frequency swing during modulation. Voltages from these resistors supply the modulation-monitor circuits.

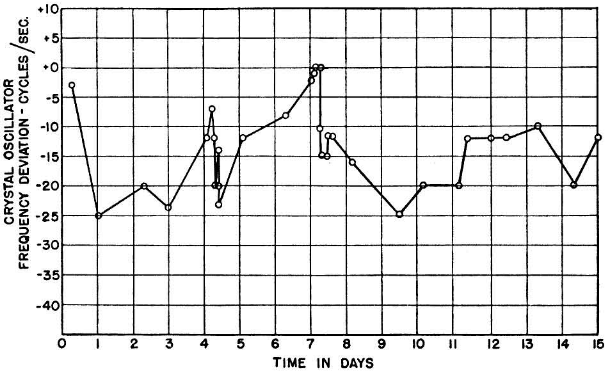

Fig. 4—Frequency-modulation station monitor crystal-oscillator frequency deviation taken during a 15-day continuous run.

Since the center-frequency indication is a function of both frequency and amplitude of the signal at the discriminator, it is required that a particular signal level exist there for correct indication. This may be indicated conveniently by a high-resistance direct-current instrument connected across R_1 and R_2. For any frequency in the pass band, E_1 is as much greater than its value at center frequency as E_2 is less than its value at center frequency. Thus, the sum of E_1 and E_2 is constant over the pass-band and E_L is a direct voltage even during modulation. Provision has been made to employ the percentage-modulation instrument for this purpose. It may be inserted in the level-measuring circuit by means of a front-of-panel push button when calibration is desired.

The de-emphasis circuit employed in this monitor is a resistance and capacitance network having the standard time constant. It is shown between R_b and point C in Fig. 3. This feeds the audio-output tube which delivers approximately 0.3 volt audio in 600 ohms at 100 per cent, 100-cycle modulation with very low distortion.

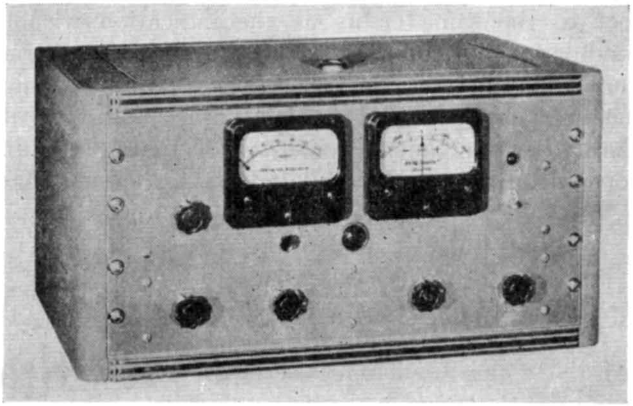

Fig. 5—Frequency-modulation station monitor complete with cabinet.

The amplifier which raises the level across R_a or R_b to a value sufficient for percentage-modulation indication is highly stabilized by negative feedback; the gain of this amplifier is only one thirtieth of what it would be without the feedback. This results in a calibration of the percentage-modulation instrument which is virtually independent of aging or changing of the percentage-modulation-circuit tubes.

No calibration of the monitor beyond adjusting for level and center frequency, as described previously, is necessary. This results from the inherent stability of the slope of the discriminator. Since a given change in the discriminator constants produces about one hundredth as much effect on the slope as it produces on the crossover point and since the stability with respect to crossover point is already on the order of 200 cycles, it is apparent that the stability of the slope of the curve is more than adequate.

OVER-ALL ACCURACY

The over-all accuracy of the center-frequency indication without modulation is mainly dependent on the accuracy of the local oscillator. During a 15-day continuous test run, one of these oscillators held within 25 cycles of its proper frequency. The error produced in center-frequency indication from this cause was a maximum of 225 cycles because of the ninefold multiplication of this frequency preceding the beating process. It should be noted, however, that a 25-cycle error in the calibration oscillator produces only 25 cycles error in the calibration of the discriminator center frequency because this operation is carried out at the fundamental frequency of the calibration oscillator. Rigorous tests have proved that accuracy is well within the 1000-cycle tolerance required by the Federal Communications Commission for frequency-modulation monitors.

The accuracy of the mean-frequency indication during modulation is more difficult to evaluate. It is subject to the same errors as the indication without modulation but, in addition, it is affected by the accuracy of the averaging process. One method which has been used to measure this accuracy is to separate the carrier component from the side tones. In a distortionless frequency-modulated wave the side tones are symmetrically placed about the carrier and the mean frequency of the wave is identical with the carrier-frequency component. When a high modulating frequency is used, the side tones nearest to the carrier are separated from it by frequency intervals equal to this high modulating frequency. Thus, for such a condition, it is easy to separate the carrier-frequency component and to measure its frequency. A test of this kind on the monitor showed that the accuracy of the indicated mean frequency with modulation was within 150 cycles of the accuracy of the measurement of carrier frequency without modulation. This was for 100 per cent, 10-kilocycle modulation. However, a sufficient condition for the accuracy of indication is that the over-all discriminator output be a linear function of the input frequency.

The Service Area of Medium-Power Broadcast Stations*

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Summary—*According to modern standards for amplitude-modulated transmission in the band from 500 to 1500 kilocycles, the field intensities required to provide a good service in urban, residential, and rural areas are 25, 5, and 0.5 millivolts per meter, respectively. It is useful to be able to make a rapid preliminary assessment of the service area that will be obtained from a station in the considered band, for various values of power, frequency, and conductivity. Families of curves are given to show these relationships for the powers 1/5, 1, 5, and 25 kilowatts and for the three field intensities 25, 5, and 0.5 millivolts per meter. When the distribution of population in an area is known, it is then easy to find the station site which will give the most efficient coverage.*

The main factors and principles affecting the coverage of a station are discussed, and methods of dealing with practical problems are detailed.

I. INTRODUCTION

THE problem of coverage from a medium-power broadcast transmitter in the band from 500 to 1500 kilocycles, is of interest to a large number of radio engineers. Although few are called upon to do detailed design and test work, there are many who have to deal with the preliminary design of stations in this band. Furthermore a clear understanding of the factors and principles involved is of value to all radio engineers.

The subject has, of course, received considerable attention and many excellent papers have been written on specific problems. However the field is wide and certain aspects are very complex. An attempt will be made, therefore, to gather together and present logically the results of available theoretical and practical investigations.

The method of approach to this synthesis of facts has been based on the fundamental idea that the ratio between two quantities is more important than their numerical difference. A simple illustration should suffice to make the meaning clear.

The power of a transmitter is doubled from 25 to 50 kilowatts. The field intensity received by any listener then increases by about 40 per cent. Thus the actual audio signal from the listerner's loudspeaker increases by the same percentage. The increase in power at any rate is quite impressive. However the listener's ear, which is the instrument that really matters, works according to Weber's law. This law says that the perceptible increase in stimulus is proportional to the stimulus already existing. This means that any change heard by the listener must be measured in terms of ratios and not in terms of absolute magnitudes. Fortunately engineers are already accustomed to express ratios logarithmically in terms of decibels. In this case an increase in power from 25 to 50 kilowatts gives an increase of 3 decibels. It can easily be proved in any control room that a change of 3 decibels in the level of speech or music is of small account. Therefore a twofold increase in power may have a certain publicity value, but the listener will scarcely notice the change.

If the question of coverage is approached with a clear understanding of the importance of the idea of ratios, it will be much simpler to obtain a picture in true perspective.

II. POWER

A variation of 1 decibel in an audible pure tone is just noticeable, but for speech or music the variation must be some 3 decibels, and about 6 decibels before it is really effective. The effect of power variation in

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† South African Broadcasting Corporation, Grahamstown, South Africa.