Modern Single-Sideband Equipment of the Netherlands Postals Telephone and Telegraph*

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Summary—**After an introduction, a short description is given of the equipment developed before 1940, followed by a survey of the principles of the modern equipment. The way in which the automatic tuning in the receiver is accomplished is described in detail. A summary is given of the advantages of the modern equipment with respect to the earlier art. In an appendix, some theoretical considerations are given with respect to the automatic tuning control; particularly, the conditions for a stable circuit are derived.**

INTRODUCTION

SINGLE-SIDEBAND TELEPHONY on the Netherlands long-distance radio transmissions started in 1933, preparatory work having been carried out in the years before. Owing to the initiative of the late N. Koomans and the late W. F. Einthoven, the Postal and Telecommunication Services of the Netherlands and the Netherlands East Indies were among those who first put to commercial use a four-channel single-sideband system on a commercial link. Apart from many modifications important from a practical point of view, the original scheme of the apparatus did not change until 1940. In 1938, Koomans gave a description of this equipment.[1]

After extensive experimental work, carried out during the occupation of the Netherlands and continued after the war, the construction of new single-sideband equipment was started. In preparation for commercial production, a few prototypes have been constructed at the PTT laboratories, these equipments being in operation on the U.S.A.–Netherlands link.

One of the outstanding features of this new equipment, in comparison with the former, is the introduction of carrier telephone equipment. Moreover, many improvements, made in the earlier days and suggested by the requirements of communication, have been included from the beginning in our design, thus leading to further simplicity and efficiency. An extensive use of crystals in filters and oscillators, the avoidance of switches in signal circuits, and a different way of accomplishing automatic tuning control in the receiver are some salient points in our new apparatus. Special attention has been paid to the stability of the first oscillators.

As to the transmitting part, we shall limit ourselves to the "premodulator." In the premodulator, the low-frequency telephone channels are transformed to a higher frequency level and are grouped together in their correct positions. At this point, the energy is still low, the actual amplification taking place in the "transmitter." At the transmitting center of Kootwijk, the premodulators are placed in a separate building, the "studio," at 1 kilometer from the transmitter buildings.

GENERAL ADVANTAGES OF THE SINGLE-SIDEBAND SYSTEM

The general advantages of the single-sideband system may be summarized as follows: In an AM system, the energy of the carrier forms a large part of the total radiated energy, whereas, in the single-sideband system, this carrier and one sideband are eliminated at the transmitter, a local carrier being added again in the receiver. Consequently, an energy reduction (or a more economical use of the energy), a reduction of the bandwidth, and, by applying a local carrier, a noticeable reduction of fading is obtained.

In view of the necessity to fix the channels relative to the local carriers in the receiver, a pilot frequency, which has a definite position with regard to the suppressed carriers, is transmitted simultaneously.

FORMER EQUIPMENT (KOOMANS)

In the premodulator, the low-frequency band of each channel is modulated on a definite carrier, different for each channel, after which selection of the upper or the lower band takes place by means of a filter network, varying in frequency for each channel. The *A* channel is modulated on 10 kc (or 7 kc); this modulation is followed by selection of the 7- to 10-kc band. The *B* channel is modulated on 10 kc (or 13 kc), after which selection of the 10- to 13-kc band takes place. Similarly, the modulation frequencies of the *C* and *D* channels are 14 and 20 kc, and the frequency bands 14 to 17 kc and 17 to 20 kc. (Fig. 1).

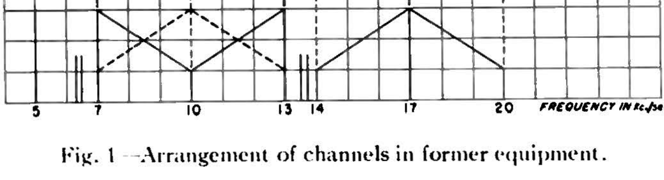

Fig. 1—Arrangement of channels in former equipment.

This arrangement of these four channels with a pilot frequency at 5 or 10 kc and with two channels for double-tone telegraphy (mark and space), covering in total the frequency band 5 to 20 kc, is characteristic for the "Indies link." This frequency band is converted

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[1] N. Koomans, "Single-sideband telephony applied to the radio link between the Netherlands and the Netherlands East Indies," PROC. I.R.E., vol. 26, pp. 182–207; February, 1938. Discussion, H. J. J. M. de Bellescize and N. Koomans, PROC. I.R.E., vol. 26, pp. 1299–1301; October, 1938.

successively to the band 65 to 80 kc and to the band 465 to 480 kc in two steps, the final frequency transformation and the amplification of the energy taking place in the transmitter.

Testing apparatus for observing the excitation of the transmitter, the mutual interference, and nonlinear distortion are provided for.

In the receiver, the high-frequency spectrum, by an analogous process, is converted to the frequency band 5 to 20 kc and, by means of oscillators of 7, 10, 13, 14, 20 kc, to the low-frequency *A*, *B*, *C*, and *D* channels.

In our original equipment, the automatic frequency control is substantially electric; in a discriminator, the frequency variations of the pilot frequency are converted into voltage variations (+ or − voltage); these voltage variations operate the second oscillator in the receiver. This second oscillator contains a reactance tube coupled to the oscillator tube.

MODERN EQUIPMENT

In the low- and medium-frequency parts of our modern equipment, carrier telephone equipment, as normally used by the Netherlands PTT Administration, has been applied.

Premodulator (*Block Diagram, Fig. 2*).

The low-frequency band of *each* channel is modulated on 60 kc and the upper band (60.3 to 63.4 kc) is selected. A low-pass filter, 0 to 2800 cps, confines the frequency range to the usual "3000-cps" band on radio links. This upper band is converted into a band having the frequency range of 266 to 286 kc by means of a (crystal) oscillator, unique for each channel (60+x oscillator).[2] After this second modulation process, the relative positions of the channels are such as are required for a particular correspondent (Fig. 8).

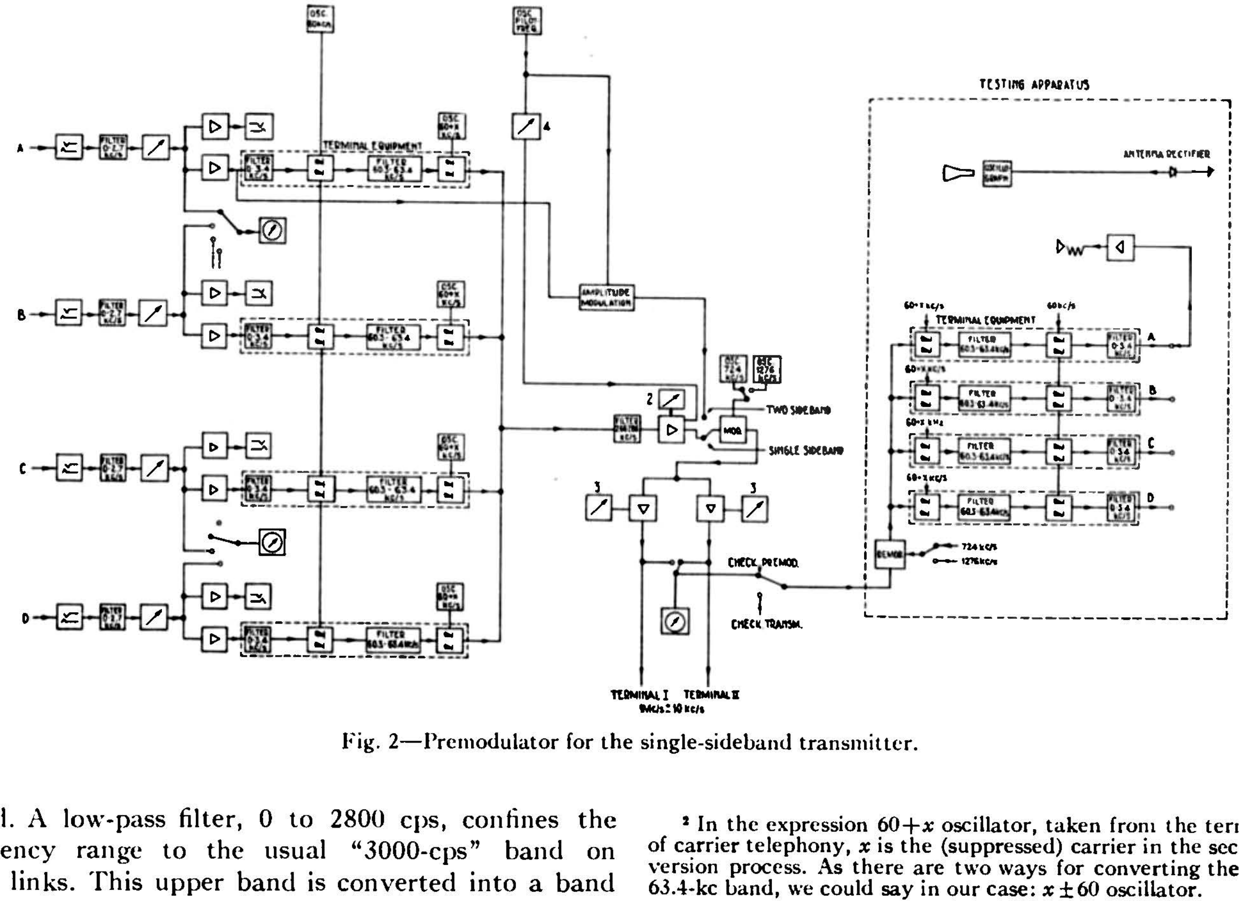

Fig. 2—Premodulator for the single-sideband transmitter.

By choosing the frequencies of the oscillators properly, we can, in a simple way, obtain frequency arrangements required by the different correspondents. In our first equipment, a change in the relative position of the channels necessitated a change of filters.

A band-pass filter 266 to 286 kc, with high attenua-

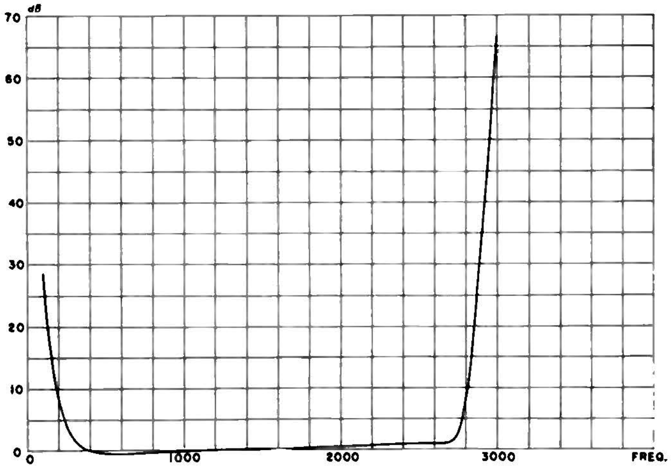

Fig. 3—Attenuation curve of a telephone channel in the premodulator.

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[2] In the expression 60+x oscillator, taken from the terminology of carrier telephony, x is the (suppressed) carrier in the second conversion process. As there are two ways for converting the 60.3- to 63.4-kc band, we could say in our case: $x \pm 60$ oscillator.

tion, prevents radiation of modulation products outside this range.

Practice has proved the necessity of transmitting a given channel band, as formed in the second process (266 to 286 kc), both in the "right" position, in which the sequence of the channels as transmitted in sense of increasing frequency does not change, and in the "inverted" position, in which this sequence is inverted, as well.

The output terminals of the premodulator are provided, so that two transmitters can be operated simultaneously (the maximum output voltage is 10 volts and the impedance of the cable from premodulator to transmitter is 130 ohms).

In view of correspondents using a different channel arrangement, a number of $60+x$ oscillators are available; the description of our receiver contains a table of these oscillators.

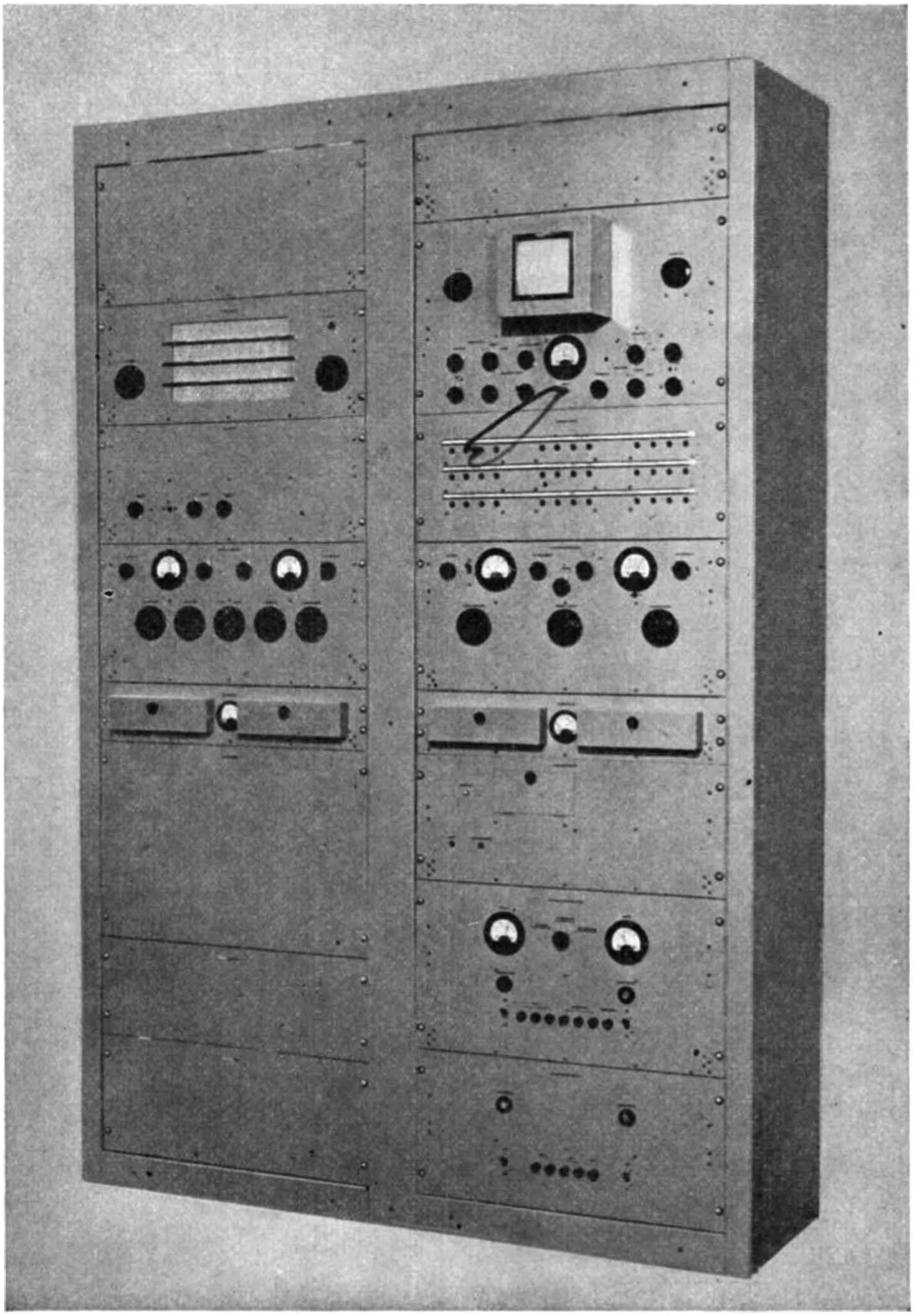


Fig. 4—Front view of the premodulator.

In a third converter stage, the frequency band is raised to 1 Mc ± 10 kc. In view of the foregoing, there are two crystal oscillators, 724 kc and 1276 kc corresponding with the "right" and the "inverted" position.

Fig. 3 shows the frequency characteristic of one channel; this curve is determined by the band-pass filter, 60.3 to 63.4 kc, the low-pass filter, 0 to 2800 cps, and a couple of correction elements compensating the attenuation in the lower frequencies. Between 300 and 2700 cps, such variations are slight. At full modulation of a channel, the "suppression" of the 60-kc carrier, achieved in the filter and the balanced modulator (ring-type modulator), amounts to at least 60 db. The attenuation of the 266- to 286-kc filter at the frequency of the $60+x$ oscillators is better than 85 db. This high order of attenuation is necessary for an adequate suppression of the $60+x$ frequencies in the radiated spectrum.

The possibility of using normal double-sideband transmissions (AM) is provided for. A frequency of 276 kc (in single-sideband transmissions used as a pilot) is modulated by the Heising method. The frequency spectrum, 273 to 279 kc, is further raised to 1 Mc by mixing with 724 kc.

The testing apparatus, forming an important part of the premodulator, permits observation of the linear and nonlinear distortion of every channel, the degree of modulation, and the mutual interference of the channels; deficiencies of premodulator and transmitter can be measured separately.

The following devices are used:

1. *A test "receiver"*; in order to observe the mutual interference and distortion, the spectrum of all channels can be separated again in this receiver, using the $60+x$ oscillators and a set of 60.3- to 63.4-kc filters.

(a) For checking the premodulator, the 1-Mc band is converted to 276±10 kc. Applying the $60+x$ oscillators already available, each of the set of channels is converted to 60.3 to 63.4 kc and, after applying 60 kc, the low frequencies are again obtained.

(b) For checking the transmitter, the high-frequency band is converted to the 1-Mc band and passed to the studio. The separation of the channels takes place as in (a).

2. *An oscillograph with dc amplifier* (cutoff frequency, 1 Mc) measures the rectified antenna current; for this purpose the transmitter contains a rectifier, the output of which is fed to the oscillograph. This arrangement permits a supervision of the excitation of the final stage. The oscillograph can also be used for a visual observation of the signal in the different stages of the premodulator. The time-base frequency can be varied over a range covering frequencies up to 100 kc.

3. *Low-frequency amplifier (with loudspeaker)*. For an over-all check, the equipment contains a low-frequency amplifier with loudspeaker; using the arrangement 1(a) or 1(b), the quality of each channel at the input and at the output terminals of the premodulator and of the transmitter can be checked.

4. *Vacuum-tube voltmeters* for measuring peak voltages indicate input and output voltages of the premodulator. An important device, not described in detail, is a wave analyzer for the 1-Mc band, provided with a crystal filter for 100 kc (bandwidth 100 cps), bringing about the separation of the frequencies in the 1-Mc band. This instrument, useful for laboratory tests in the studio, is not a part of the premodulator. A schematic diagram of the premodulator is given in Fig. 2. Transformation of a channel from the low-frequency band to a band in the 266- to 286-kc range takes place in the normal "carrier-terminal equipment." The carrier-terminal apparatus, containing no tubes, comprises a low-pass filter, a ring-type modulator (for 60-kc modulating frequency), a band-pass filter 60.3 to 63.4 kc, and a second modulator ($60+x$ kc modulating frequency); the absence of tubes permits the use of carrier terminal equipment in both directions (the "receiver" direction being used in 1). All four carrier-terminal sets are connected to the band-pass filter 266 to 286 kc.

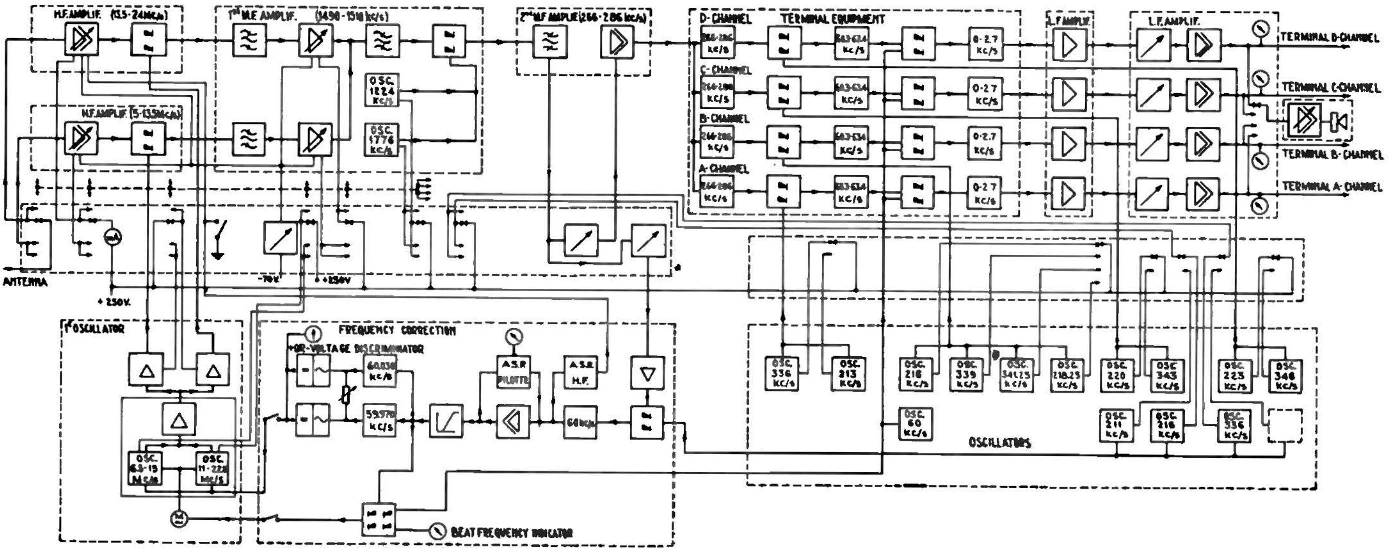


Fig. 5—Block schematic wiring diagram of the receiver with carrier mixing.

Volume Controls. (*See Block Diagram, Fig. 2 and Front View, Fig. 4.*)

For an adjustment of the level of each channel, the equipment is provided with four volume controls *1*, the level of the channel band being adjusted with a volume control *2*. Independently of *2*, volume control *4* controls the amplitude of the pilot frequency, and *3* controls the output voltages to the transmitters.

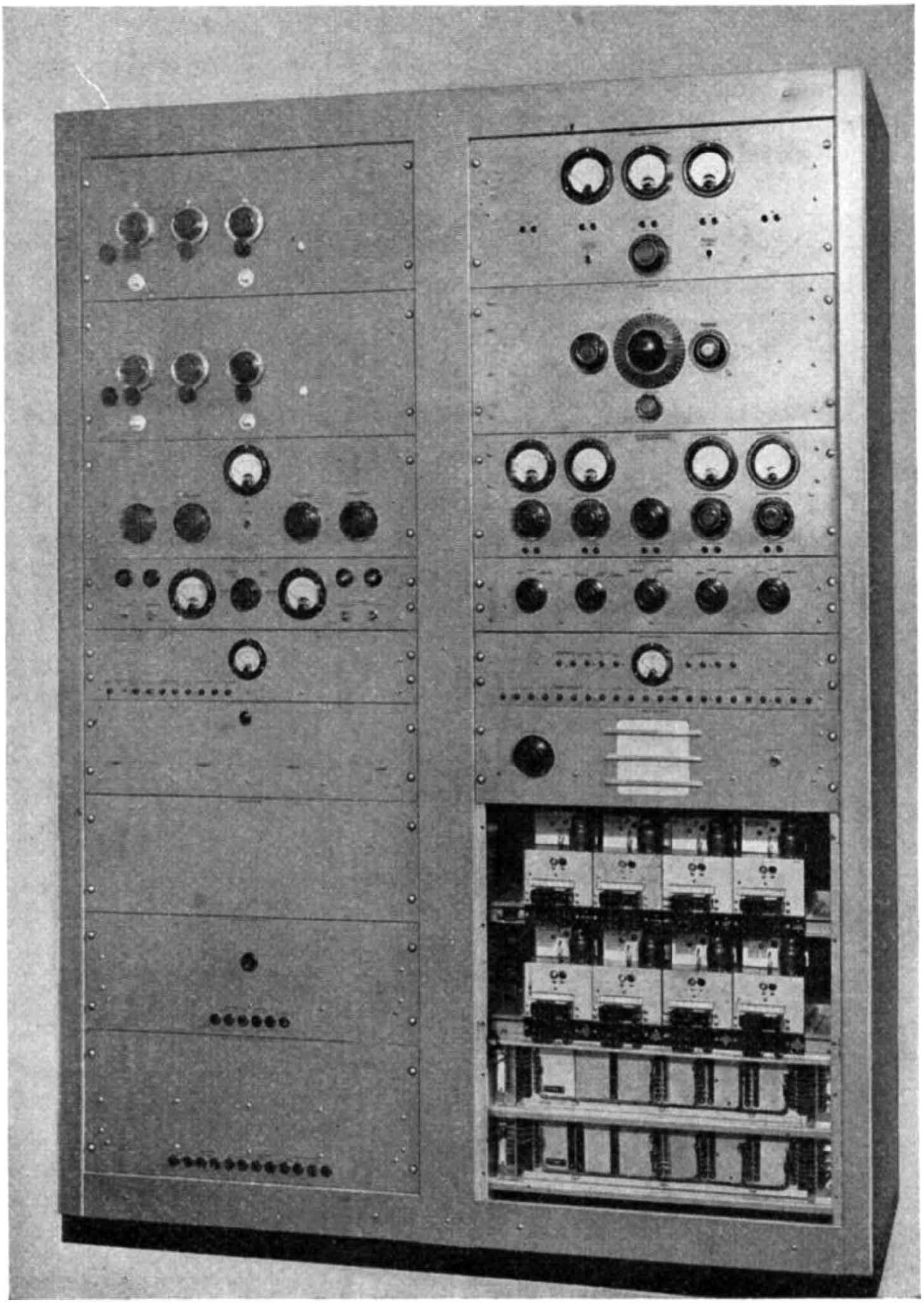


Fig. 6—Front view of the single-sideband receiver.

Receiver. (*Block Diagram, Fig. 5, and Front View, Fig. 6.*)

The receiver consists of a high-frequency, a medium-frequency, and a low-frequency part. In contrast with the older types of equipment, automatic tuning control takes place in the first oscillators, these being the only variable oscillators. All other oscillators are crystal oscillators. The frequency range 5 to 23.5 Mc is split into a range of 5 to 13 Mc and 13 to 23.5 Mc. For each range, the receiver is provided with a high-frequency amplifier. In the lower range, the frequency of the first oscillator is *above*, and in the higher range it is *below* the signal frequency. In both frequency ranges, the second-oscillator frequency can be taken higher or lower than the first medium frequency; thus one can receive a certain channel in the "right" or in the "inverted" arrangement. In this connection, we refer to what was said of the premodulator.

The first medium frequency is 1.5 Mc; the bandwidth of the first medium-frequency amplifier is 20 kc. In the following mixer stage, conversion to the second medium-frequency band, 276±10 kc, takes place after modulation with 1500−276 or 1500+276 kc (second-oscillator frequencies). Here, each channel, after modulation with a $60+x$ oscillator, characteristic for this channel (Table I), is converted to 60.3 to 63.4 kc and after modulation with 60 kc to the low-frequency bands; a low-pass filter limits this band to 2800 cps. These last demodulation processes are carried out in the "carrier-terminal equipment" consisting of a ring-type demodulator ($60+x$ kc), a band-pass filter 60.3 to 63.4 kc, a ring-type demodulator (60 kc) and a low-pass filter. In order to eliminate mutual interference between the channels, it is necessary to place a band-pass filter, 266 to 286 kc, before each carrier-terminal set. The input terminals of these filters are connected together (see Fig. 5).

TABLE I

FREQUENCIES OF THE CHANNELS AND THEIR CHARACTERISTIC $60+x$ OSCILLATORS IN MC

A-band	*B*-band	*B*-band (displaced)	*C*-band	*D*-band
(273–276)	(276–279)	(278.25–281.25)	(280–283)	(283–286)
273 −60 =213	276 −60 =216	278.25 −60 =218.25	280 −60 =220	283 −60 =223
276 +60 =336	279 +60 =339	281.25 +60 =341.25	283 +60 =343	286 +60 =346

Fig. 7 shows a low-frequency attenuation curve of a channel; the variation between 300 and 2700 cps being negligible. The image discrimination for frequencies >325 kc is better than 60 db; the attenuation of the lower frequencies in the transmission band, caused by the band-pass filter 60.3 to 63.4 kc, is compensated by correction elements.

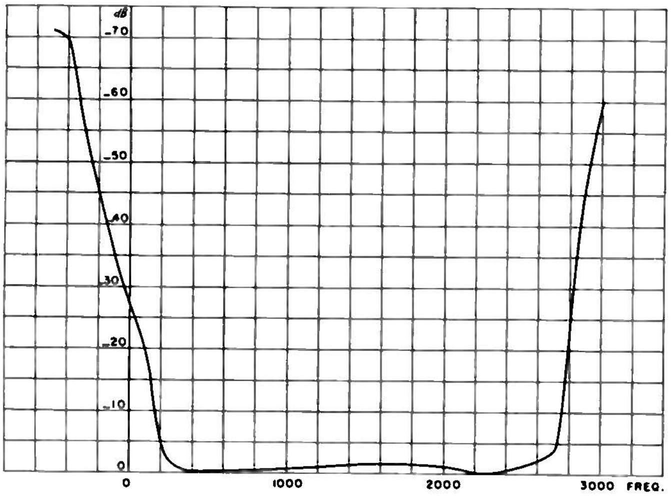


Fig. 7—Attenuation curve of the terminal equipment plus line repeater with wide-band corrector in the receiver.

As mentioned before, the receiver and the premodulator are provided with a number of $60+x$ oscillators; a special set of these oscillators being available for each correspondent.

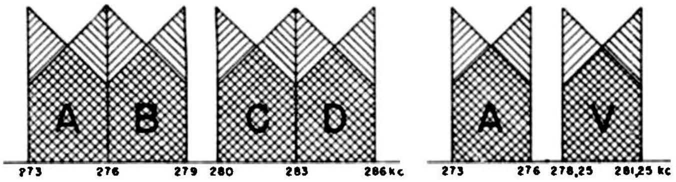
The different volume controls permit an adjustment of the high frequency, of the first and second medium frequencies, of the low-frequency amplification, and of the pilot-frequency amplification. The receiver contains an amplifier and a loudspeaker for monitoring purposes.

Automatic Tuning Control

The automatic tuning control forms an important part of the receiver. The purpose of an automatic tuning control is to keep the pilot frequency, and with it the band of channel frequencies, accurately in their appointed positions in the 266- to 286-kc band.

A transmitted "pilot frequency," having a fixed relative position to the channels, controls the frequency of the first oscillator. If a change in the pilot frequency takes place, caused by the transmitter or during its transmission, the frequency of the first oscillator is automatically changed in such a way that the medium frequencies are maintained.

An electric automatic tuning system, as used in our older equipment, is quite satisfactory for rapid frequency variations; such a device is not suitable for a slow variation in one direction. These variations may not only occur in the transmitter and because of the ionosphere, but also by temperature changes in the first oscillator of the receiver. In an electrical system, a regulating voltage (+ or − voltage) produced by the deviation of the pilot frequency from the correct frequency (in the 266- to 286-kc band), accomplishes the necessary correction of the first oscillator (or second oscillator in our older equipment). The frequency deviation of the first oscillator is only maintained as long as the regulating voltage is present; fading in reception may cause an interruption. Furthermore, the frequency adjustment is not complete; a certain difference has to be maintained for producing the necessary regulating voltage. These effects will be more pronounced as the oscillator is detuned more by the regulating voltage.



(a) (b)

Fig. 8—(a) The position of the channels on the Indies link; (b) the position of the channels in the so-called "displaced-band" configuration. The different shadings apply to both possibilities with regard to the position of a specific channel.

An electromechanical system produces a change in frequency by a modification of the mechanical arrangement (self-induction, or capacitance) of the oscillator; the oscillator obtaining a new equilibrium. A short sur-

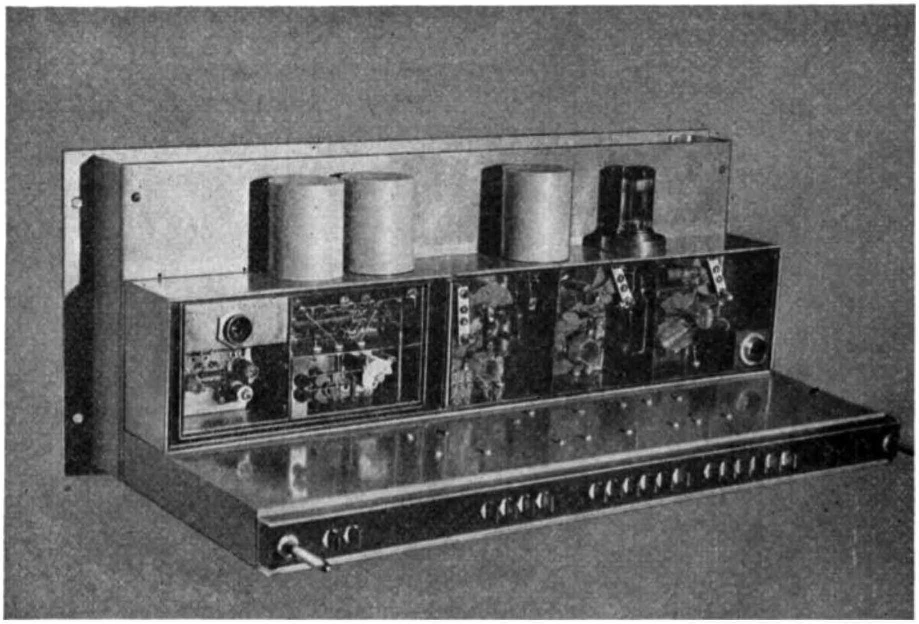


Fig. 9—High-frequency repeater (rear side opened).

vey of the automatic tuning devices in the receiver is given in the following paragraphs (Fig. 5).

Following the second frequency conversion (266 to 286 kc), the pilot frequency is converted to 60 kc, by the use of $60+x$ oscillators. If, as is usual now, the pilot frequency is 276 kc, these oscillators are 216 or 336 kc, for the "right" or "inverted" channel arrangement, respectively.

In accordance with the position of the pilot on the former Indies link on four channels (Fig. 1), an oscillator of 211 kc is provided. The 60-kc pilot, after selection in a crystal filter (bandwidth 100 cps), amplification and limitation, operates a discriminator, converting the frequency deviations from 60 kc into voltage variations (+ or −), these voltages operating a first-oscillator suppressor grid (Fig. 10). This design was developed by Prins, engaged in laboratory work at the Radio Laboratory of the PTT.

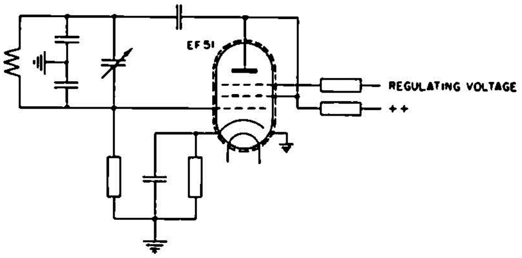


Fig. 10—Block schematic of the first oscillator.

The discriminator contains two crystals (60 kc ± 20 cps). A change in suppressor-grid potential causes a change in space charge and, accordingly, a frequency change. Between the discriminator and the suppressor grid an RC network is fitted for the purpose of stabilizing the electrical frequency-adjustment circuit, preventing, at the same time, a rapid fall of the voltage during fading.

Our mechanical frequency adjustment is essentially that of the Western Electric single-sideband receiver.[3,4] The 60-kc pilot and a 60-kc stabilized frequency (crystal oscillator) are applied to the grids of four tubes (two pairs), and each pair is balanced with regard to one of these frequencies; with regard to the other frequency, these pairs are shifted 90 degrees. The plate current of each tube flows through the windings of one of four stator poles of a motor; a frequency difference produces a rotating field in a direction depending on the sense of frequency deviation. As the four grids are biased, the four poles are in fact magnetized in turn. The rotor consists of a magnetic wheel provided with a number of teeth (11), not being a multiple of the number of poles; a magnetized pole will turn the rotor in a position most suitable to the magnetic flux. The successive magnetization of the poles produces a rotation of the rotor; a trimmer coupled with the axis of the motor varies the frequency of the first oscillator.

To avoid large differences in trimmer frequency variation over the frequency range of one oscillator, coupling of trimmer and tank capacitances is by means of a network.

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[3] F. A. Polkinghorn and N. F. Schlaack, "A single sideband short-wave system for transatlantic telephony," Proc. I.R.E., vol. 23, pp. 701–718; July, 1935.

[4] A. A. Roetken, "A single sideband receiver for short-wave telephone service," Proc. I.R.E., vol. 26, pp. 1455–1465; December, 1938.

The tuning capacitors and the trimmer of both oscillators are of the twin type. Thus one tuning knob and one motor are sufficient for both first oscillators and both frequency ranges. In this equipment, the electric tuning control is designed for control of rapid frequency variations and the mechanical for the slower variations. (This does not mean that a mechanical correction is essentially "slow.")

Frequency difference of the pilot and the 60-kc standard causes a rotation of the motor and a change of the first-oscillator frequency through the trimmer capacitor. In contrast with an electrical frequency adjustment, the frequency difference is completely neutralized.

Stability and Instability in Automatic Tuning Systems

In a system for automatic frequency adjustment, as in any feedback circuit, stability or instability may exist.

The conditions for stability, which must be fulfilled in the receiver, will be deduced in the theoretical part of this paper.

For the purpose of a stabilization of the electrical fre-

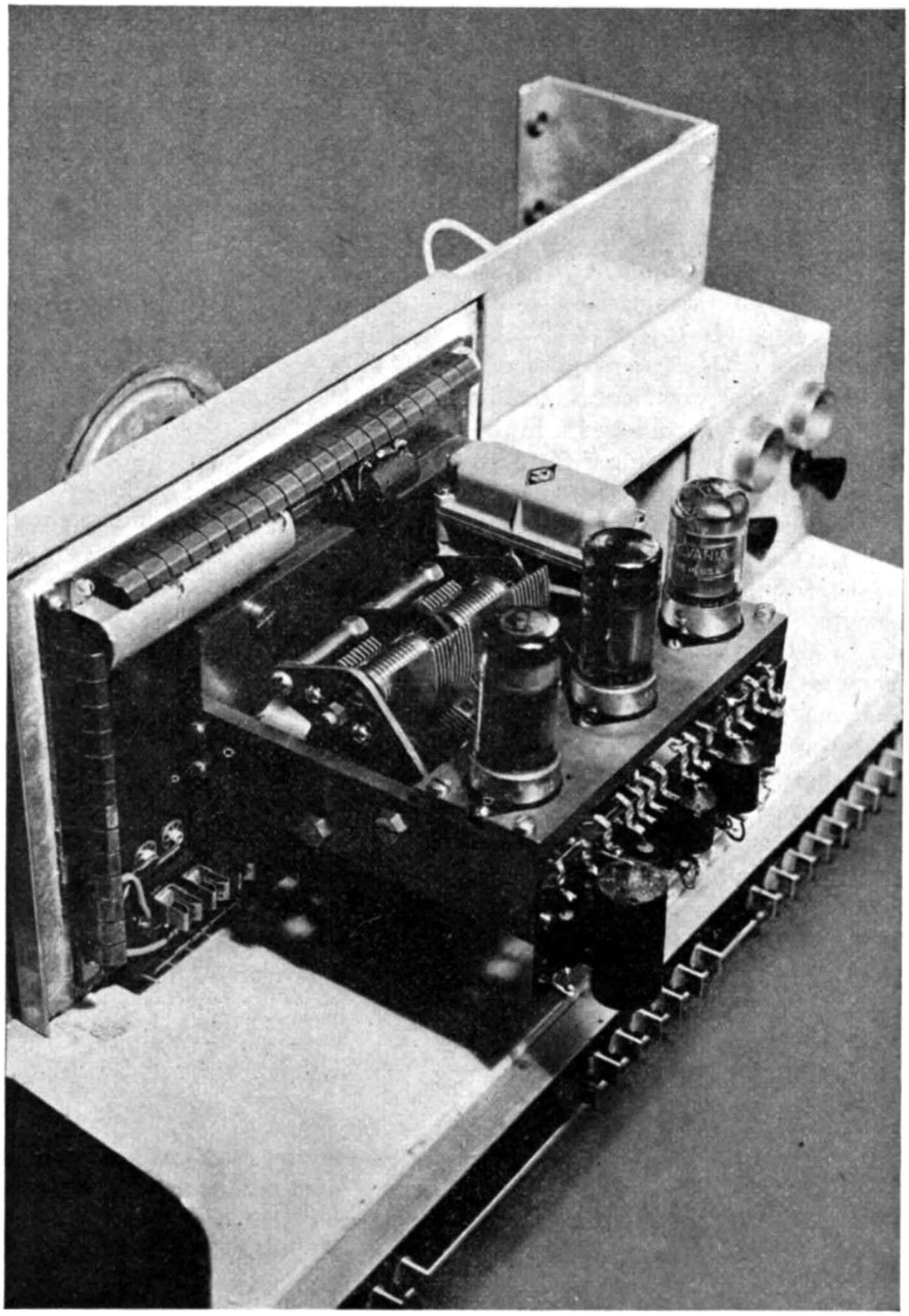

Fig. 11—Rear view of the first oscillator with thermostat and double screening removed.

quency adjustment, an *RC* network is inserted between the discriminator and the oscillator.

With regard to stability, the lowest value of *RC* is determined by the amplification in the circuit and the delay of the 60-kc filter, the stability of the mechanical adjustment being given by the frequency variation of the motor for one rotation.

Temperature Control of the First Oscillator (Fig. 11)

In order to minimize the influence of the temperature on the frequency, the first oscillators, together with a coupling tube, are placed in a thermostatically controlled oven.

Résumé

The advantages of the newest equipment in comparison with the older one may be summarized as follows:

1. The introduction of normal cable carrier equipment results, in addition to sharing all experiences already gained in the development of such equipment, in the application of one uniform type of filter (60.3 to 63.4 kc) for the formation of the single sideband. A change in the relative positions of the channels only involves a change of the $60+x$ frequencies.
2. The first and second medium-frequency filters may be comparatively simple. (In a receiver of the older type, the filter 465 to 480 kc is a derived type of filter (with frequency of ∞ attenuation) for a sufficient suppression of image response below 455 kc).
3. By applying electrical and mechanical adjustment, we take advantage of both systems.
4. The use of crystals in the pilot-frequency network and in the discriminators makes routine checks of these important parts superfluous.
5. The first oscillators are stable from an electrical and a mechanical point of view and are placed in thermostatically controlled ovens.

APPENDIX

SOME THEORETICAL CONSIDERATIONS ABOUT FREQUENCY ADJUSTMENT

I. *Electrical Adjustment*

ω_i = input frequency
ω_0 = oscillator frequency
ω_u = output frequency
Δ_ω = deviation of these magnitudes.

The frequency adjustment may be shown diagramatically according to Fig. 12.

M = modulator. *O* = oscillator. *D* = discriminator.

$$\omega_u = \omega_i - \omega_0 \qquad \Delta\omega_u = \Delta\omega_i - \Delta\omega_0. \tag{1}$$

With ω_i variable, ω_u will have to remain as constant as possible. The operation of the adjusting mechanism may be represented by

$$\Delta\omega_0 = m\Delta\omega_u. \tag{2}$$

From (1) and (2), and because $m \gg 1$, it follows that

$$\Delta\omega_u = \frac{\Delta\omega_0}{m+1} \approx \frac{\Delta\omega_0}{m}\cdot \tag{3}$$

Equation (3) gives the degree of control; i.e., the deviation of ω_u as a result of the deviation of ω_0. The adjusting mechanism has been considered as being static; this system, however, which is closed in itself, can, under certain circumstances, be in an unstable condition. The conditions for stability and unstability will now be considered.

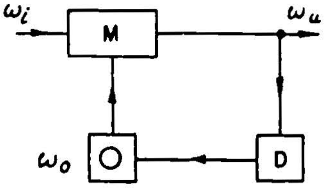

Fig. 12

Stability. The circuit for the adjustment is again shown in diagram in Fig. 13, with the addition of the pilot-frequency filter *F* and an *RC* network. These elements play an essential part when considering the frequency fluctuations which can occur in this circuit. It is supposed that these frequency fluctuations are small and remain limited to the frequency area of the filter *F*; the effect of *F* on the transmission of these "frequency waves" is given by a "time delay" τ. This time delay is determined by $d\phi/d\omega$ in the passing range, wherein ϕ = phase angle between the input and output voltages; the value of τ will be estimated.

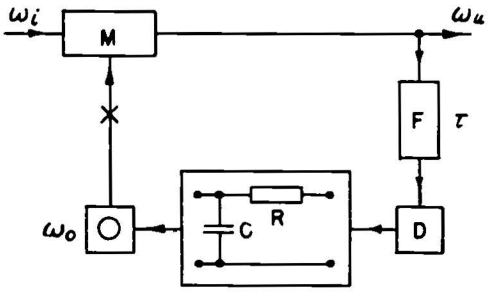

Fig. 13

By applying the Nyquist theorem,[5] a stability condition may be obtained in a simple way.

For that, we disconnect the circuit at *x* and trace the

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[5] R. E. Graham, "Linear servo theory," *Bell Sys. Tech. Jour.*, vol. 25, pp. 616–651; October, 1946.

variations of ω_0, while ω_i is periodically varied with a frequency ω.

From the following equations,

$$\Delta\omega_u = \Delta\omega_i - \Delta\omega_0 \tag{1}$$

$$\Delta\omega_0 = \frac{m}{\sqrt{(\omega CR)^2+1}} e^{-i(\omega\tau + \operatorname{arctg} \omega CR)} \Delta\omega_u \tag{3a}$$

where in (3a) the argument is determined by τ and RC and the modulus by RC, it follows

$$\frac{\Delta\omega_0}{\Delta\omega_u} = \frac{m}{\sqrt{(\omega CR)^2+1}} e^{-i(\omega\tau + \operatorname{arctg} \omega CR)}. \tag{4}$$

According to Nyquist, (4) will not contain the point -1, if plotted in the complex plane as $f(\omega)$ for a stable situation.

We can limit ourselves to positive values of ω; since the modulus of the function concerned decreases as ω increases, the Nyquist condition may be formulated thus:
If

$$\omega\tau + \operatorname{arctg} \omega CR = \pi, \tag{5}$$

then

$$\frac{m}{\sqrt{(\omega CR)^2+1}} < 1. \tag{6}$$

Because $m \gg I$, it follows from (5) and (6): $\omega CR \gg 1$ and $\omega\tau = \pi/2$ and, in connection with (6), the stability condition is

$$\boxed{\frac{m\tau}{RC} < \frac{\pi}{2}}. \tag{7}$$

This condition can also be obtained from the oscillation equation of the adjustment circuit in Fig. 13.

Supposing that ω_i = constant, it follows that $\Delta\omega_i = 0$ and, according to (1), $\Delta\omega_u = -\Delta\omega_0$.

In Fig. 14 the RC network is shown; U_i and U_u are the input and output voltages, respectively.

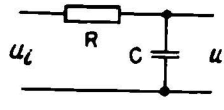

Fig. 14

From the following equations (Fig. 13),

$$U_{i_t} = \kappa\Delta\omega_{u_{t-\tau}} = -\kappa\Delta\omega_{0_{t-\tau}} \tag{8}$$

$$U_{u_t} = \lambda\Delta\omega_{0_t} \quad \text{where in} \quad \frac{\kappa}{\lambda} = m \quad \text{and} \tag{9}$$

$$U_u = U_i - RC\frac{dU_u}{dt}, \tag{10}$$

the oscillation equation follows as

$$\Delta\omega_{0_t} = -m\Delta\omega_{0_{t-\tau}} - RC\left\{\frac{d\Delta\omega_0}{dt}\right\}_t. \tag{11}$$

Substituting

$$\Delta\omega_0 = e^{\gamma t} \tag{12}$$

$$\gamma = \alpha + j\beta \tag{12a}$$

into (11), the two equations (13) will be obtained, after splitting up into real and imaginary parts, as follows:

$$1 + \alpha RC = -me^{-\alpha\tau} \cos \beta\tau \tag{13a}$$

$$me^{-\alpha\tau} \sin \beta\tau = \beta RC. \tag{13b}$$

The limit of stability, the transition from oscillations with increasing amplitude to those with decreasing amplitude, is given by $\alpha = 0$; because of $m \gg I$, it follows from (13a): $\beta\tau \approx \pi/2$ and, after substitution into (13b), the stability condition is obtained.

This result was found in 1932; a solution of the transcendent equations (13) by graphical methods is given in considerations by de Cock Buning,[6] which have not been made public. In these, the condition for a nonperiodical oscillation equation is also laid down. The deduction of this condition will be indicated briefly.

Substitution of (13b) into (13a) leads to the equation

$$1 + \frac{RC}{\tau}\left[\frac{\beta\tau}{\operatorname{tg}\beta\tau} - \ln\frac{RC}{m\tau}\frac{\beta\tau}{\sin\beta\tau}\right] = 0 \tag{14}$$

and because RC/τ is usually big, the following equation is obtained:

$$\frac{\beta\tau}{\operatorname{tg}\beta\tau} - \ln\frac{\beta\tau}{\sin\beta\tau} = \ln\frac{RC}{m\tau}\cdot \tag{15}$$

From equation (15) the various solutions for $\beta\tau$ can be obtained. It appears that for $ln(RC/m\tau) > 1$ no solution for $\beta\tau$ between 0 and 2π is possible. (Since the solutions for values of $\beta\tau > 2\pi$ imply a large attenuation, we can limit ourselves to the cases where $\beta\tau < 2\pi$.)

The condition for a nonperiodical solution is evidently more stringent than the condition for an oscillation with a decreasing amplitude and is, therefore,

$$\ln\frac{m\tau}{RC} < -1 \quad \text{or} \quad \frac{m\tau}{RC} < e^{-1}.$$

In the newest single-sideband receiver, $m \approx 200$ and $\tau \approx 50$ milliseconds and $RC = 35$.

II. *Mechanical Adjustment*

A schematic wiring diagram of the mechanical adjustment is shown in Fig. 15.

$S.M.$ = motor for the frequency adjustment
θ_d = angle of rotating field in motor
θ_r = angle of rotor in motor.

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[6] Unpublished data.

The following relations exist:

$$\Delta\omega_u = \Delta\omega_i - \Delta\omega_0 \tag{16}$$

$$\frac{d\theta_d}{dt} = \Delta\omega_u \tag{17}$$

$$\frac{d\Delta\omega_0}{dt} = m\frac{d\theta_r}{dt}, \tag{18}$$

while the differential equation of the motor is as follows:

$$I\frac{d^2\theta_r}{dt^2} + R\frac{d\theta_r}{dt} + A(\theta_r - \theta_d) = 0 \tag{19}$$

I = mass momentum of inertia of the motor
R = coefficient of resistance
A = force of rotating field on the rotor.

For a motor with negligible mass and resistance, $\theta_r = \theta_d$.

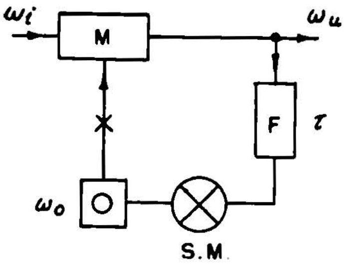

Fig. 15

Stability. When interrupting the circuit at x, it follows, as in the previous case, from equations (16), (17), and (18) for a motor without mass and resistance

$$\frac{\Delta\omega_0}{\Delta\omega_u} = \frac{m}{\omega}e^{-i(\omega\tau+\pi/2)}. \tag{20}$$

Application of the Nyquist theorem, as has been done in *I*, gives us the stability condition:

$$\frac{m}{\omega} < 1 \qquad \omega\tau + \frac{\pi}{2} = \pi \quad \text{or}$$

$$\boxed{m\tau < \frac{\pi}{2}}. \tag{21}$$

In the general case, it follows from (16)–(19) instead of (20):

$$\frac{\Delta\omega_0}{\Delta\omega_u} = \frac{m}{\omega^2\sqrt{R^2+(\omega I - A/\omega)^2}}e^{-i(\omega\tau+\pi+\text{arctg}\,[(\omega I-A/\omega)/R])} \tag{22}$$

(for $I = R = 0$, equation (22) changes into equation (20).

If $R^2 > AI$, in other words, if the resistance element is sufficiently big to make the motor "nonperiodical," the modulus of (22) will decrease with ω increasing. The stability condition may then be derived from

$$\omega\tau + \pi + \text{arctg}\frac{\omega I - A/\omega}{R} = \pi \quad \text{or}$$

$$\text{tg}\,\omega\tau = \frac{A/\omega - \omega I}{R} \tag{23}$$

and

$$\frac{m}{\omega^2\sqrt{R^2 + (\omega I - A/\omega)^2}} < 1. \tag{24}$$

From (23) and (24) it follows that

$$m\tau < \frac{R}{A}\,\frac{\omega^2\tau}{\cos\omega\tau}\cdot \tag{25}$$

From (23) it also follows that

$$0 < \omega\tau < \frac{\pi}{2}, \cdots \tag{26}$$

and if, in (23), ωI is small with regard to A/ω, $tg\omega\tau = A/\omega R$ and (25) changes into

$$m\tau < \frac{\omega\tau}{\sin\omega\tau}$$

and because of (26),

$$\boxed{m\tau < 1}. \tag{27}$$

Although reliable tests have not yet been carried out, it seems likely that the suppositions on which equation (27) is based are fulfilled.

In our case, $m \approx 10$ and $\tau \approx 50$ milliseconds.

CONCLUSION

With the exception of a part of the carrier equipment, the receiver as well as the premodulator have been constructed as prototypes at the Radio Laboratories of the Netherlands PTT.

With regard to the carrier equipment, the Transmission Laboratories of the PTT have been very helpful in the design, as well as during the construction.

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