

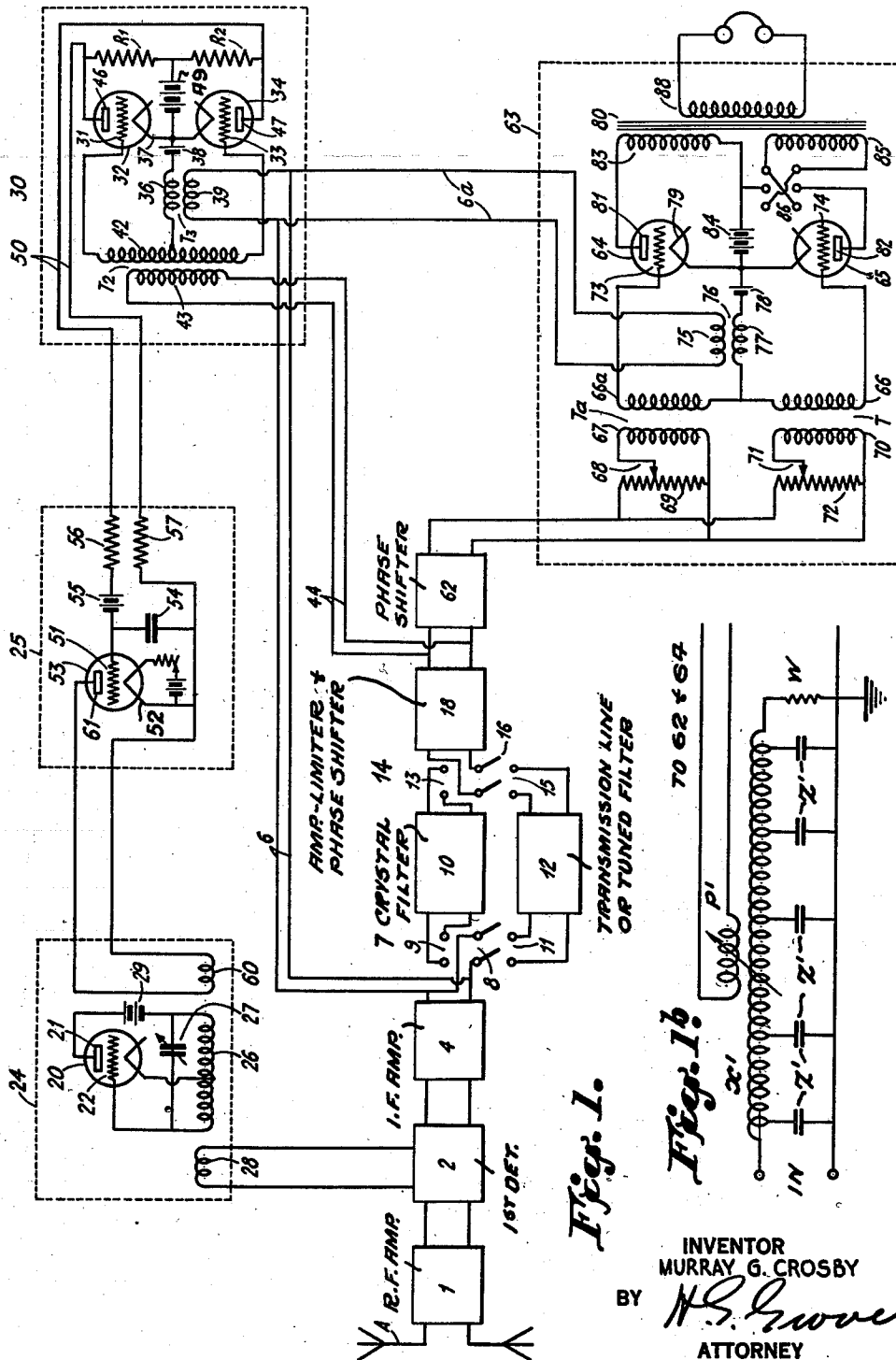
Dec. 29, 1936.

M. G. CROSBY
AUTOMATIC FREQUENCY CONTROL SYSTEM

2,065,565

Filed June 13, 1932

3 Sheets-Sheet 1



Dec. 29, 1936.

M. G. CROSBY

2,065,565

AUTOMATIC FREQUENCY CONTROL SYSTEM

Filed June 13, 1932

3 Sheets-Sheet 2

Fig. 2

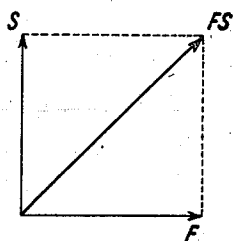


Fig. 3

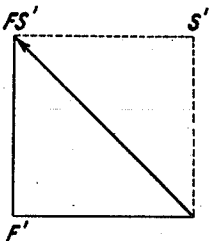


Fig. 4

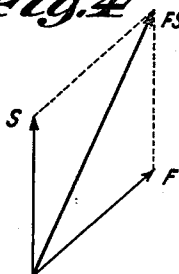


Fig. 5

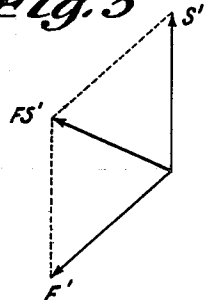


Fig. 6a

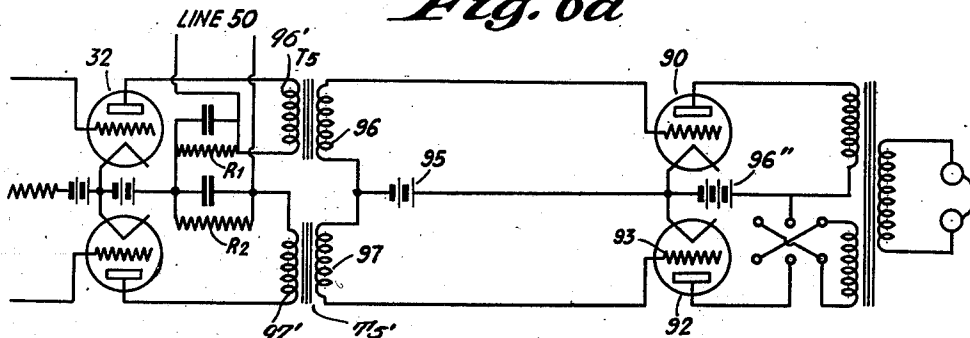


Fig. 7

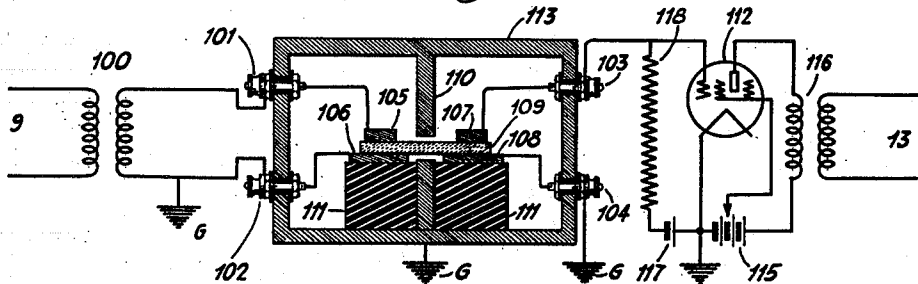
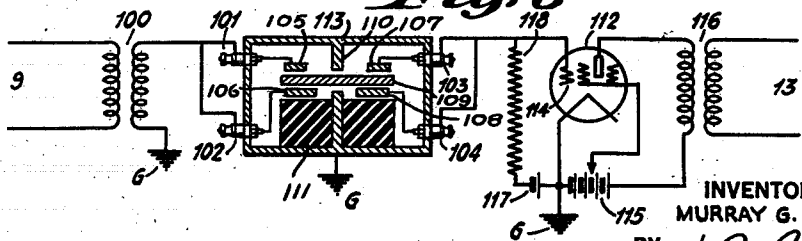


Fig. 8



INVENTOR
MURRAY G. CROSBY

BY *H. S. Grover*
ATTORNEY

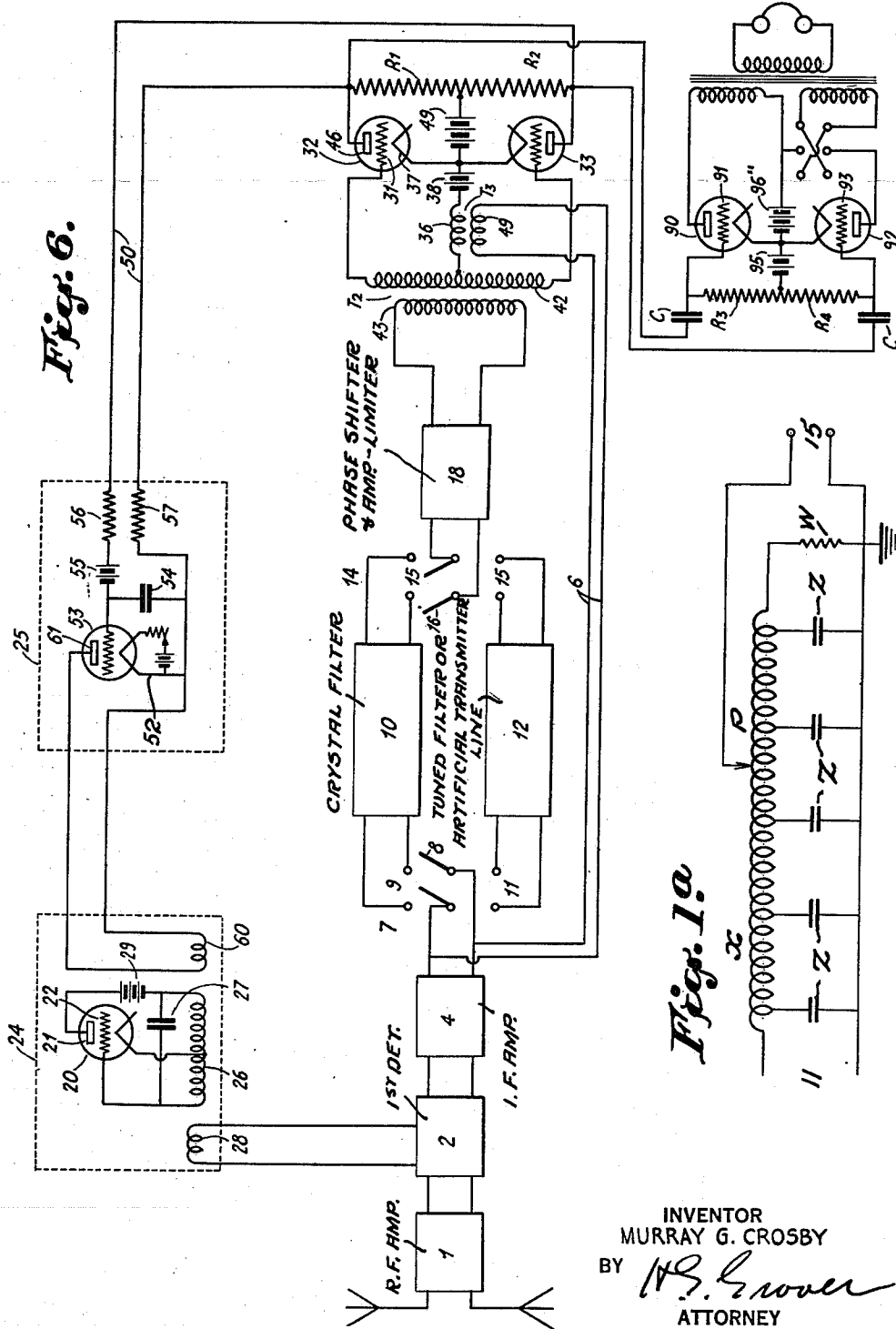
Dec. 29, 1936.

M. G. CROSBY
AUTOMATIC FREQUENCY CONTROL SYSTEM

2,065,565

Filed June 13, 1932

3 Sheets-Sheet 3



UNITED STATES PATENT OFFICE

2,065,565

AUTOMATIC FREQUENCY CONTROL
SYSTEMMurray G. Crosby, Riverhead, N. Y., assignor to
Radio Corporation of America, a corporation
of Delaware

Application June 13, 1932, Serial No. 616,803

30 Claims. (Cl. 250—20)

This invention relates to control means to be used with receivers of signal modulated oscillations.

More in detail, this invention relates to a novel receiver and novel automatic means for controlling the frequency to which a receiver of signal modulated oscillations is tuned. The automatic frequency control means of the present invention is applicable to receivers of frequency or phase or amplitude modulated oscillations. The automatic frequency control may be readily applied to new receivers or to receivers known heretofore in the art.

Frequency control means have been known heretofore in the art. The frequency control means known heretofore in the art have been used to some extent in frequency modulated signal receivers. Frequency control means have not been used heretofore in crystal filter receivers adapted to receive phase or amplitude modulated signals.

The filter circuits used in phase or frequency or amplitude modulated signal receivers in general used heretofore are relatively broad and therefore the frequency control means known heretofore were sufficiently efficient to maintain the tune of the receiver fairly close to the frequency of the signal and, since the filters were broad, operation of these receivers was comparatively satisfactory.

In the novel receiver of the present invention the carrier wave is filtered by means of a highly selective crystal filter such as disclosed more in detail in Hansell U. S. application #564,770 filed Sept. 24, 1931, now Patent No. 2,001,387, May 14, 1935 and in Hansell U. S. application #611,050 filed May 13, 1932, now Patent No. 1,999,902, April 30, 1935. Since this filter is crystal controlled and highly selective the band of frequencies which it will pass is very narrow and therefore frequency control means as known heretofore in the art will be useless to control the frequency of a receiver in which the crystal filter referred to above is incorporated.

The automatic frequency control of the present invention is sufficiently sensitive and accurate to maintain the tune of the signals constant, or approximately constant, so that they are at all times passed by the selective crystal control filter circuit.

Briefly, the novel receiver of the present invention and the frequency control therefore is arranged as follows:

The absorbed signals are fed to a first detector,

which is coupled with a high frequency generator. The intermediate frequency signals appearing in the output circuit of the first detector are fed by way of a crystal filter or of an artificial transmission line or wave filter to a limiter device, and from there to detecting means, from which the signals are utilized. The automatic frequency control means comprises a thermionic tube having its anode coupled to the frequency determining circuits of the oscillator and its input circuit connected with the output circuits of two thermionic detector tubes to utilize the differential currents resulting therein when the input circuit to the two detector tubes is fed by a combination of the filtered and unfiltered circuit to control the frequency of the high frequency oscillator of the superheterodyne arrangement. If phase or amplitude modulated signals are to be received the signals from the intermediate frequency amplifier are passed through the crystal filter circuit referred to above. If the signals to be received are frequency modulated the signals appearing in the output circuit of the intermediate frequency amplifier are passed through an artificial line or long transmission line or tuned filter circuit, of the type described more in detail in Crosby United States application No. 618,154 filed June 20, 1932.

The rectifiers connected with the utilization circuit include means for connecting the anode circuits thereof in push-pull relation or in parallel so that phase or amplitude modulated signals may be detected. In a modification the rectifiers connected with the utilization circuit also serve to provide the differential currents which operate through the thermionic control tube to determine in part the frequency of the oscillations generated by the generator connected with the first detector.

The accomplishment of this phase synchronism enables the use of circuits where the filtered circuit is recombined with the signal in such a manner as to produce a more perfect detection of the signal wave as well as reduction of certain kinds of interference.

Another apparent advantage of this receiver is that the filtered carrier oscillations may be limited to a constant value so as to effect an automatic volume control in the present invention. The recombination of the filtered carrier with the unfiltered signal also cancels out the second harmonic square law detector distortion so that distortions due to fading are minimized.

Heretofore the reception of phase modulated oscillations is accomplished by means of a re-

ceiver of frequency modulated oscillations or signals which has in its output circuit amplitude correcting means. In some cases reception of phase modulated signals is also accomplished by means of a crystal filter receiver, the filter circuits of which are manually tuned. In the first mentioned phase modulated oscillation receiver in which the audio circuits included correction means the audio frequency correction increases the low frequency noise and interference. In the crystal filter receiver manual tuning of the crystal filter receiver is so critical that the use of this receiver is impractical. Consequently, the use of the receiver of the present invention, wherein automatic tuning means is included, eliminates these disadvantages, thereby making phase modulated oscillation signalling a more valuable signalling method.

The novelty in the type of frequency control, herein described, lies in the fact that phase detection of the signal is utilized to provide the controlling energy. The prior art includes systems in which differential voltages are obtained by frequency discriminating circuits for control purposes. No systems are known in the prior art in which the object of the filter is solely to produce a phase shift proportional to the frequency of the carrier. In reality this type of demodulation converts a frequency change in the carrier into a phase change in the resulting oscillations, which phase change is in turn converted into amplitude modulated oscillations characteristic of the original frequency modulated oscillations. By the use of this system of phase detection or demodulation of a frequency or phase modulated carrier oscillation a universal receiver may be designed in which changes in adjustment only are necessary to convert the receiver so that it will receive phase or frequency or amplitude modulated oscillations or waves.

The novel features of the present invention have been pointed out with particularity in the claims appended hereto.

The method of carrying out the present invention, the manner in which the present invention may be carried out, and the operation thereof, will be better understood by the following detailed description thereof, and therefrom when read in connection with the attached drawings throughout which like reference numerals indicate like parts, and in which:

Figure 1 illustrates an at present preferred novel arrangement for demodulating frequency, phase, or amplitude modulated signals, which arrangement includes frequency control means;

Figures 2, 3, 4, and 5 show charts illustrating graphically the relation of the currents impressed on the differential detectors producing the frequency control energy;

Figure 6 shows a modification of the arrangement of Figure 1;

Figures 1a and 1b illustrate details of filter circuits or artificial transmission lines and phase shifter circuits, respectively utilized in the receiver circuits of Figs. 1 and 6; while,

Figures 7 and 8 illustrate the at present preferred crystal filter to be included in the receivers of Figure 1.

Referring to the drawings, and in particular to Fig. 1 thereof, A indicates an absorption system connected with a radio frequency amplifier 1, the output of which feeds amplified energy to the first detector 2 of a superheterodyne receiver. The intermediate frequency produced by the combination of the radio frequency signals and

the local oscillations, the production of which will be described more in detail hereinafter, produces in the output circuit of the first detector 2 an intermediate frequency which is transmitted to the intermediate frequency amplifier 4. The details of the radio frequency amplifier and of the first detector, and of the intermediate frequency amplifier form no part of the present invention, and in order to reduce the length of the present specification such units will not be described in detail here. It will, however, be noted that the radio frequency amplifier, the first detector and the intermediate frequency amplifier may be of any of the types known in the art today.

The output circuit of the intermediate frequency amplifier 4 is connected with a line 6 and with the movable elements 8 of a double pole, double throw switch 7. Two of the terminals of this double pole, double throw switch are connected by leads 9 to the input of a crystal filter 10. This crystal filter 10 is of the type disclosed more in detail in Hansell United States application No. 611,050, filed May 13, 1932, and in United States application #564,770 filed Sept. 24, 1931.

A crystal filter, as used here and described in the aforesaid applications, utilizes the extreme selectivity afforded by the piezo-electric resonance of a crystal by exciting the crystal through one set of electrodes and obtaining the piezo-electric energy from another set. In this manner a selectivity is obtained which is sufficiently sharp to completely eliminate the side-bands from the modulated wave and to build up or pass readily the carrier frequency.

Preferably the crystal filter circuit included in unit 10 includes an arrangement as disclosed in Fig. 7. This circuit comprises a transformer 100 having its primary winding connected with the line 9 and its secondary winding connected as shown by way of a terminal 101 on shield 113 to a metal plate 105 and to ground G and by way of terminal 102 to a second metal plate 106. These metal plates 105 and 106 bear on a crystal 109 and are coupled therethrough to plates 107 and 108 respectively as shown. In order to insure that the only coupling between these plates is by way of the crystal partitions 110 are formed in the metal box 113 and extend from the walls thereof to approach the crystal 109 on both sides between the metal plates 105 and 107 and 106 and 108. The crystal 109 is mounted as shown on an insulating support 111.

The metal plate 107 is connected by way of terminal 103 to the control electrode 114 of a thermionic tube 112. The input circuit of tube 112 is completed by connecting the cathode thereof to ground and by connecting the plate 8 by way of terminal 104 to ground. All of the terminals 101, 102, 103, and 104 are insulated from the box 113. Charging potentials for the anode and screen grid electrode of tube 112 are supplied from a source 115. Biasing potential for the control grid 114 is supplied by way of resistance 118 from a source 117. The secondary winding of the transformer 116 having its primary winding connected as shown with the output electrodes of tube 112 may be connected as shown with the line 13 of Fig. 1. In the above arrangement the coupling between the circuits due to the crystal holder are shunted out. The only coupling between the circuits is by way of the crystal 109.

The crystal filter may take the form of the arrangement shown in Fig. 8. This arrangement

is somewhat similar to the arrangement of Fig. 7 and needs no description other than to note that the lower plates 106 and 108 are not grounded as in the arrangement of Figure 7, but are connected as shown to the high potential ends of the secondary of 100 and of resistance 118 respectively, as are the plates 105 and 107 respectively. Now we have the crystal 109 in a series circuit including the secondary of 100 and the impedance 118. The operation of the filter now depends on the magnitude of the impedance of the secondary of 100 and the impedance of 118. Here as in Figure 7, the shield 110 shields out the natural capacity of the crystal holders 105, 106, and 107, 108 to give the filter circuit a symmetrical characteristic.

The other pair of terminals of the double pole, double throw switch 7 are connected through leads 11 to the input of an artificial transmission line or tuned filter circuit 12 of the type disclosed more in detail in United States application No. 618,154, filed June 20, 1932. This transmission line or tuned filter circuit forms no part of the present invention and does not warrant a detailed description here. The circuit may, however, as shown in Fig. 1a, comprise series inductive reactances X and parallel capacitive reactances Z. The input of the line may comprise an inductance coupled to the output of the detector in 4. The line may terminate in an impedance W. Waves of the desired phase relative to the phase of the waves impressed at 11 may be selected in the line connected with 15 by means of a point P movable on the line. Other types of transmission lines or tuned filters may be utilized, and I do not propose to limit my invention to any particular type of artificial line, transmission line or tuned filter circuit. This artificial transmission line or tuned filter circuit is for use in receiving frequency modulated oscillations. The double throw, double pole switch 7 permits the intermediate frequency amplifier to be connected either to the crystal filter 10 or the artificial transmission line 12, for either phase and amplitude modulated wave reception or frequency modulated wave reception. The output circuit of the crystal filter unit 10 is connected with two terminals 13 of a double pole, double throw switch 14. The output circuit of the artificial transmission line 12 is connected to the other two terminals 15 of the double pole, double throw switch 14. The blade elements 16 of the double pole, double throw switch are connected with a limiter and phase shifter 18. The double pole, double throw switch 14 permits the amplitude limiter and phase shifter 18 to be connected either to the crystal filter circuit 10 or to the artificial transmission line 12, depending on the manner in which the carrier frequency to be received has been modulated. The amplitude limiter and phase shifter 18 contains means to maintain the filtered signal at a constant level, regardless of fading of the signal and phase shifting means, to regulate the phase of the carrier frequency.

The amplitude limiter per se forms no part of the present invention and may be of any known type, such as a thermionic tube operated at saturation so that variations in the amplitude of the input energy can cause no variations in the amplitude of the output energy, or the limiter may comprise a thermionic tube connected in an automatic volume control circuit.

Details of the phase shifter per se form no

part of the present invention and the phase shifter may be of any type known. For example, it may comprise, as illustrated in Fig. 1b, an artificial line of the type disclosed in detail in my U. S. appln. Ser. No. 618,154, filed June 20, 1932. Briefly, such a phase shifter may comprise series inductive reactances X' and parallel capacitive reactances Z'. The wave may be applied to one end of the line, the other end of which may be terminated by an impedance W. Wave energy of the desired phase relative to the phase of the applied energy may be selected from points, one of which is fixed on the low potential side of the line and the other of which is movable along the inductive reactance, as illustrated in Fig. 1c. As an alternative, an inductance P' may be movably coupled to the inductive reactance in the line and may be moved along the line to a position at which the current induced in the inductance is of the desired phase relative to the phase of the energy impressed on the line.

The local oscillations to be introduced into the first detector 2 for producing an intermediate frequency are produced by a unit 24 including a thermionic tube 20 having its anode 21 and control electrode 22 connected in a circuit for producing sustained oscillations comprising an inductance 26 shunted by a variable capacity 27 and a source of potential 29. The oscillations generated in the oscillation generator 20 are of a frequency determined to a major extent by the value of inductance 26 and of the tuning capacity 27. These oscillations are introduced into the first detector 2 by means of a coupling inductance 28 coupled with the inductance 26.

The novel means of the present invention for controlling the frequency of the oscillations produced by the local source in a manner characteristic of changes in frequency of the incoming signals, thereby maintaining the receiver apparatus in tune to the modulated signals, will now be described.

The automatic frequency control unit 30 comprises two thermionic rectifier tubes 32 and 34 having their control electrodes 31 and 33 fed cophasally with unfiltered signal energy through transformer secondary winding 36 connected between the control electrodes 31 and 33 of tubes 32 and 34 respectively and the cathode 37 of said tubes by way of a biasing source 38. Unfiltered signal is introduced into the secondary winding 36 from the primary winding 39, which is connected over the line 6 with the output of the intermediate frequency amplifier 4. The tubes 32 and 34 have their control electrodes fed in phase opposition by filtered and limited signals impressed on the secondary winding 42 from the primary winding 43, which is connected with the output circuit of the amplitude limiter and phase shifter over line 44. The anode electrodes 46 and 47 of tubes 32 and 34 respectively are connected through resistances R₁ and R₂. Charging potential for the anodes of these tubes is furnished by a source 49 connected between the resistances R₁ and R₂ and the cathode 37 of the tubes 32 and 34. The high potential terminals of resistance R₁, R₂ are connected over lines 50 to the control electrode 51 and cathode 52 of a control tube 53. The drop across the resistors R₁, R₂ acts as a biasing potential for the control tube 53. A condenser 54 connected in parallel with the input impedance of tube 53 regulates the time constants of the circuit composed of the resistors R₁, R₂, the direct cur-

rent biasing source 55, and the series resistances 56 and 57. An inductance 60, coupled to the inductance 26 in the oscillation circuit of generator 20, is connected between the anode 61 and cathode 52 of modulator tube 53.

In this manner, as will appear more in detail hereinafter, the frequency of the oscillations generated in 20, which are determined to a major extent by the values of the inductance 26 and capacity 27, are determined to a minor extent by the nature of the current flowing in the inductance 60 coupled to the inductance 26. In other words, variations in plate current of the tube 53 will act through inductance 60 to modulate the oscillations produced by 20.

The signals from the phase shifter and amplitude limiter 18 are fed to a second phase shifter unit 62 and from there to unit 63, by means of which the modulated carrier frequencies are converted into audio frequency. The phase shifter may be of any known type, such as for example of the type discussed hereinbefore in connection with the circuits in 18. The unit 63 contains a pair of thermionic detectors 64 and 65 having their control electrodes connected to inductances 66a and 66 which form the secondary windings of transformers Ta and T having primary windings 67 and 70. Primary winding 67 is connected by a tap 68 in parallel with a portion of a potentiometer resistance 69 connected with the output circuit of 62, and primary winding 70 is connected by a tap 71 in parallel with a potentiometer resistance 72 connected in parallel with the first potentiometer resistance 69. By this means filtered energy from the phase shifter 62 is impressed in phase opposition on the control electrodes 73 and 74 of tubes 64 and 65 respectively. The line 6, connected with the intermediate frequency amplifier output, is connected over line 6a to the primary winding 75 of a transformer 76 having a secondary winding 77 connected through a biasing source 78 between the control grids 73 and 74 and the cathodes 79 of tubes 64 and 65. In this manner unfiltered energy appearing in the output of the intermediate frequency amplifier 4 is impressed co-phasally on the control electrodes of the rectifier tubes 64, 65. Potentiometer resistances 69 and 72 regulate the amplitude of the filtered and limited carrier, which is fed to the detectors or rectifiers 64 and 65. The phase of this carrier is regulated by the phase shifter 62.

The detected or demodulated signals impressed on 64 and 65 produce audio frequency oscillations on the anodes 81 and 82 of tubes 64 and 65 respectively. The anode 81 of tube 64 is connected through a primary winding 83 of combining transformer 80 and an anode charging potential source 84 to the cathode of tube 64 while the anode 82 is connected through the primary winding 85 of transformer 80 and the source 84 to the cathode 79. A double pole, double throw reversing switch permits the transformer primary winding 85 to connect the anodes of tubes 64 and 65 in push-pull relation or in parallel. A secondary winding 86 of the transformer 80 is connected with any utilization circuit, as, for instance, an aural indicator.

The principle of the operation of the filtered carrier receiver as a phase and amplitude modulation receiver has been known to the art of some time. However, the problem of maintaining synchronism of the signal and crystal filter has been an unsolved problem. Heretofore the manual tuning required on the crystal filter receiver has

made the receiver impractical due to the necessity of constant retuning. In the receiver herein described, part of the crystal filtered energy is made use of to effect a constant retuning of the high frequency oscillator and maintain synchronism. In the arrangement of Fig. 1 the filtered and limited carrier is fed to the automatic frequency control detectors in phase opposition through transformer T₂. Vectorially these two voltages to the two detectors would be represented by F and F¹ of Figs. 2 and 3. The unfiltered signal is fed to the detectors cophasally by transformer T₃ as represented by vectors S and S¹ in Figs. 2 and 3. These relative phase relations of the filtered and unfiltered signal are obtained by means of the phase shifter in unit 18. Hence, the resultant voltages presented to the two detectors are as portrayed by vectors FS and FS¹. These conditions are obtained when the signal (i. e. in the intermediate frequency amplifier) is tuned to the peak of the crystal filter.

When the frequency of the signal, or the high frequency oscillator, varies, the output of the crystal filter changes very rapidly, with frequency, not only in amplitude, but also in phase. The amplitude variations of the crystal filter output, with frequency, are removed in the limiter included in unit 18, but the phase variations remain; hence, at a slightly different frequency the conditions portrayed by Figs. 4 and 5 exist. Thus, the filtered output rotates in phase so that the amplitudes of the resultant voltages are no longer equal, but have changed in opposite directions. A change of frequency in the opposite direction reverses the phase change of the crystal filter output so that differential voltages are presented to the two detectors to give differential currents through resistors R₁ and R₂. The voltage drop across these two resistors will have a magnitude depending upon how far off tune the signal is from the filter and a direction depending upon which side of the filter peak the signal is on.

This differential voltage across the resistors R₁ and R₂ is used to serve as biasing potential for the control electrode of the modulator tube 53. Consequently the differential voltage operates to vary the anode to cathode impedance of the modulator tube. The effect of varying the anode impedance of tube 53 is to vary the frequency of the oscillator circuit through the coupling coil 60. Thus, as soon as the signal starts to fall out of the crystal filter, the frequency of the high frequency oscillator is changed an amount sufficient to bring the frequency of the intermediate frequency wave coil to the frequency of the crystal filter. In this manner an automatic frequency control is effected which maintains the signal constantly in tune with the crystal filter.

In order that the control will hold over during a complete or partial fade-out of the signal, the time constant of the circuit consisting of condenser 54 and resistors 56, 57, R₁, and R₂ is adjusted so that the condenser will remain charged a sufficient length of time to hold the biasing effect due to drop through R₁ R₂ on the modulator tube 53 near enough to the proper point until the signal returns.

The filtered carrier is combined with the unfiltered signal for detection in unit 63. For phase and amplitude modulation signals the drops across the resistors R₁ and R₂ may be utilized for the audio output but to make the receiver more flexible and universal, and to improve the

detection of amplitude modulation, a separate set of detectors are used. With this separate detection the amplitude and phase of the carrier may be regulated at will for the proper combination with the unfiltered signal.

To adjust the receiver for reception of frequency modulation, the crystal filter 10 is switched out and the artificial line or tuned circuit filter 12 switched in. The purpose of this line or filter is to produce a phase change in a frequency modulated wave proportional to the frequency of said wave. Thus, if the electrical length of the line or filter remains constant with frequency, the phase of its output will change with frequency. If this output is then combined with the unfiltered signal, a change in frequency will produce a change in phase of combination of the two voltages and consequently vary the resultant amplitude, as set forth more in detail in United States application No. 618,154 filed June 20, 1932. This variation in amplitude is utilized in the automatic frequency control detectors to hold the receiver in tune, and in the audio frequency detectors, to detect the modulation.

The operation theory of this type of phase detection when applied to frequency modulation proceeds as follows:

The frequency modulated wave is given by:

$$(1) \quad e = Em \sin (wt + B - fd/fm \cos (\phi t + \alpha))$$

where w is the radiation angular velocity, B is the arbitrary phase angle of the carrier wave; fd is the frequency deviation with modulation; fm is the modulation frequency; ϕ is the modulation angular velocity and α is the arbitrary phase angle of the modulation frequency. The initial conditions are: $B = \alpha = 0$ when $t = 0$. The frequency of the wave given by (1) differentiates to:

$$(2) \quad f = fc + fd \sin (\phi t + \alpha) \quad (fc = \text{carrier frequency})$$

In the demodulating circuit of the receiver, the unfiltered wave given by (1) is combined with a wave passed through a device whose output phase is proportional to the frequency so that the output phase is given by:

$$(3) \quad \theta = Kf$$

substituting (2) in (3) gives the phase angle added to the wave emitted from the output of the device or:

$$(4) \quad \theta = Kfc + Kfd \sin (\phi t + \alpha)$$

Adding this phase angle to the phase angle of the wave given by (1) or the input to the artificial line or phase multiplying device, gives the wave emitted at the output or:

$$(5) \quad e = Em \sin (wt + B - fd/fm \cos (\phi t + \alpha) + Kfc + Kfd \sin (\phi t + \alpha))$$

The input of one of the differential detector tubes receives the resultant of (5) plus (1) and the other tube the resultant of (5) minus (1). Taking this sum or difference, and squaring to get the direct current and audio frequency output:

$$(6) \quad e^2 = [Em \sin (wt + B - fd/fm \cos (\phi t + \alpha) + Kfc + Kfd \sin (\phi t + \alpha)) \pm E'm \sin (wt + B - fd/fm \cos (\phi t + \alpha))]^2$$

gives as the direct current terms:

$$(7) \quad e_{dc} = \frac{E^2 m}{2} + \frac{E'^2 m}{2} Em E' m Jo(Kfd) \cos (Kfc)$$

and as the audio frequency terms:

$$(8) \quad e_{af} = \pm 2Em E' m [J_1(Kfd) \sin (\phi t + \alpha) + J_3(Kfd) \sin 3(\phi t + \alpha) + J_5 \dots] \sin (Kfc) \pm 2Em E' m [J_2(Kfd) \cos 2(\phi t + \alpha) + J_4(Kfd) \cos 4(\phi t + \alpha) + J_6 \dots] \cos (Kfc)$$

The operating conditions make the angle (Kfc) equal to 90, 270, 450, etc., degrees so that when the signal is in tune, the direct current differential currents are equal to

$$\frac{E^2 m}{2} + \frac{E'^2 m}{2}$$

As soon as the signal falls out of tune, $\cos (Kfc)$ becomes appreciable and one detector plate current is given by:

$$(9) \quad \frac{E^2 m}{2} + \frac{E'^2 m}{2} + Em E' m Jo(Kfd) \cos (Kfc)$$

And the other by:

$$(10) \quad \frac{E^2 m}{2} + \frac{E'^2 m}{2} - Em E' m Jo(Kfd) \cos (Kfc)$$

These two equations portray how the plate current of one detector increases when the frequency is changed (due to the change in the quantity (Kfc)), and the other decreases. The quantity $Jo (Kfd)$ is equal to unity for zero modulation and decreases with modulation. Hence the frequency control operated by these differential currents is decreased in sensitivity as the modulation is increased. However, the limit of modulation would be reached before the frequency control lost control.

From Equation (8) it can be seen that when (Kfc) is equal to 90, 270, 450, etc., degrees, the audio outputs are given by:

$$(11) \quad e_{af} = \pm 2Em E' m [J_1(Kfd) \sin (\phi t + \alpha) + J_3(Kfd) \sin 3(\phi t + \alpha) + J_5(Kfd) \sin 5(\phi t + \alpha) \dots]$$

and no even harmonics are present in either detector output. Even harmonics only appear when (Kfc) is other than 90, 270, 450, etc., degrees. Since the automatic frequency control holds the value of (Kfc) at 90, 270, 450, etc., degrees, second harmonic distortion is absent from the receivers output. Odd harmonic distortion is present but only to a degree given by the Bessel function of the order of the harmonic; hence, at full modulation the third harmonic distortion is less than 10 per cent.

When the receiver is adjusted for phase modulation the crystal filter employed is selective enough to completely remove the modulation so that a synchronized carrier is available. This carrier is combined with the unfiltered carrier wave with a 90 degree phase displacement; the direct current outputs are used for frequency control, and the audio frequency output is the received modulation. The detector outputs are given by:

$$(12) \quad e = [Em \sin (wt + B) \pm E'm \sin (wt + P \sin (\phi t + \alpha))]^2 \quad (P = \text{phase deviation})$$

From (12) the direct current outputs are found to be:

$$(13) \quad \frac{E^2 m}{2} + \frac{E'^2 m}{2} \pm Em E' m Jo(P) \cos B$$

Hence the same type of currents are obtained as in the case of frequency modulation given by (9) and (10) and the same considerations with regard to the value of B and P apply as in the case of (Kfc) and (Kfd) , respectively.

$$(14) \pm 2EmE'm[(J_1(P) \sin(\phi t + \alpha) + J_3(P) \sin 3(\phi t + \alpha) + J_5 \dots) \sin B + (J_2(P) \cos 2(\phi t + \alpha) + J_4(P) \cos 4(\phi t + \alpha) + J_6 \dots \cos B)]$$
$$(15) \quad \pm 2EmE'm[J_1(P) \sin(\phi t + \alpha) + J_3(P) \sin 3(\phi t + \alpha) \dots]$$

The reception of amplitude modulation is similar to that of phase modulation in that the crystal filter removes the modulation to make a synchronized carrier available. In amplitude modulation, however, this synchronized carrier is combined with the unfiltered signal either in or out of phase with the unfiltered signal. In order to reverse the fundamental modulation so that balanced detection may be used, the synchronized carrier is combined with the signal at one of the detector inputs so that the resultant carrier is of opposite polarity to that present in the unfiltered signal. For such a balanced detector scheme the input of one detector is given by the unfiltered signal or:

35 and the input to the other detector by the combination of the unfiltered signal and synchronized carrier given by:

40 The audio output of a square-law detector fed by (16) is well known to be:

while (17) squared gives as the audio frequency
45 components:

50 and by adjusting the amplitude of the synchro-
nized carrier so that

the output is given by:

60 In the balanced detector outputs, (19) and (20) are added so that the fundamental components add and the second harmonics cancel. The output is then given by:

and no harmonics are present.

As mentioned in the operation theory, for frequency and phase modulation reception, the automatic frequency control detectors 32 and 34 of Fig. 1 may be used also as the audio frequency

Detectors 32 and 33 now perform the dual function of producing differential currents for the automatic frequency control to be fed to tube 53, and audio frequency currents corresponding to the signal to be fed to amplifiers 90 and 92. Since the inputs to both types of detectors are the same, one set may be utilized to produce both the control and signal currents.

In practice the primary windings 96' and 97' 35 of transformers T₅ and T₅' may be inserted in series with the resistances R₁, R₂ of Figures 1 and 6, as indicated in Fig. 6a. The secondary windings 96 and 97 of these transformers then may be utilized to energize the input electrodes of the 40

My frequency control system is not limited to use with the circuit shown. The frequency control means of the present invention may be used with any circuit wherein a frequency change may be produced by a direct current change. For instance, my control means may be applied to the dynatron frequency modulator, described in detail in United States application No. 608,383, filed April 30, 1932 or the two tube type, of the dynatron frequency modulation, described in United States application No. 621,569 filed July 9, 1932, now Patent No. 2,032,403, March 3, 1936. Capacity in the oscillator circuit is varied by the differential currents in R_1 and R_2 .

Having thus described my invention and the operation thereof what I claim is:

1. The combination with a beat frequency receiver including a local source of oscillations 75

and a demodulator connected therewith, said demodulator having an output circuit, of a crystal filter having an input circuit connected with the output circuit of said demodulator, said crystal filter having an output circuit, and means for controlling the frequency of said oscillations and thereby controlling the beat frequency supplied from said demodulator to said filter, connected by a first circuit between said crystal filter output circuit and said local source of oscillations and by a second circuit between said demodulator output circuit and said source of local oscillations.

2. The combination with a beat frequency receiver including a local source of oscillations and a demodulator coupled thereto, said demodulator having an output circuit, of a crystal filter having an input circuit connected with the output circuit of said demodulator, said crystal filter having an output circuit, rectifying means having an input circuit connected with the output circuit of said filter, said rectifying means having an output circuit, a circuit connecting the input circuit of said rectifying means to the output circuit of said demodulator and frequency control means connecting the output circuit of said rectifying means to said local source of oscillations.

3. A phase modulated signal wave receiver including circuits having variable tuning means comprising, a crystal filter connected with the output of said receiver, and circuits connected to said receiver output and to said crystal filter output on the one hand and to said tuning means on the other hand and responsive to unfiltered signal wave energy from said receiver and filtered signal wave energy from said filter for controlling said tuning means.

4. A signal modulated wave receiving means comprising signal modulated wave responsive means having an output, a demodulator having an input and an output the input of said demodulator being coupled to the output of said signal wave responsive means, an oscillator connected with said demodulator, wave filtering means having an input connected with the output of said demodulator, said filtering means having an output, rectifying means having an input connected with the output of said demodulator, said rectifying means having an output, a separate circuit connecting the input of said rectifying means to the output of said filter, and a connection between the output of said rectifying means and said oscillator.

5. Phase modulated signal demodulating means comprising a receiver of the heterodyne type including a local oscillation circuit having a frequency determining reactance and a demodulator having an input circuit coupled to said oscillation circuit, said demodulator having an output circuit, a pair of thermionic tubes each having an anode and a control electrode, said tubes having their anodes connected in push-pull relation, a circuit coupling the anodes of said tubes to said reactance in said oscillation circuit, a circuit connecting the control electrodes of said tube to the output circuit of said demodulator for energizing said electrodes cophasally by energy from the output of said demodulator, and a circuit including a filter connecting the output circuit of said demodulator to the control electrodes of said tubes for energizing the control electrodes of said tubes in phase opposition by filtered energy from the output of said demodulator.

6. The combination of a heterodyne receiver including a local oscillator having an input circuit including frequency determining means and

an output circuit, a demodulator having an input circuit coupled to the output circuit of said local oscillator, said demodulator having an output circuit, phase changing means having an input circuit connected with the output circuit of said demodulator, said phase changing means having an output circuit, frequency control means having an output circuit coupled to the frequency determining means in the input circuit of said oscillator, said frequency control means having an input circuit, a circuit connecting the input circuit of said frequency control means to the output circuit of said phase changing means, and a separate circuit connecting the input circuit of said frequency control means to the output circuit of said demodulator.

7. In signal modulated wave receiving means, signal absorption means, signal amplifying means having an input circuit connected to said absorbing means, said amplifying means having an output circuit, a local oscillator including frequency determining means, a circuit connecting said oscillator to the output circuit of said amplifying means, a demodulator having an input circuit connected to said amplifying means, said demodulator having an output circuit, a selective filter circuit having an input connected to the output of said demodulator, said filter circuit having an output circuit and being tuned to pass a limited frequency band, a second signal demodulating circuit having an input connected with the output of said filter circuit and connected by a separate circuit with the output circuit of said first demodulator, means in one of said last named circuits for shifting the phase of the energy passed thereby relative to the phase of the energy in the other of said circuits, and a connection between the output of said second demodulating circuit and the frequency determining means of said oscillator.

8. In a signal modulated wave receiving means, signal amplifying and demodulating means having an output, a local oscillation producing circuit having a frequency determining reactance, a circuit coupling said oscillation producing circuit to said amplifying and demodulating means, a selective bandpass filter having an input connected with the output of said amplifying and demodulating means, said filter having an output, rectifying means having an input connected by a first circuit with the output of said amplifying and demodulating means and by a separate circuit with the output of said bandpass filter, a second rectifying means having an input connected by a third circuit with the output of said amplifying and demodulating means and by an additional separate circuit with the output of said bandpass filter, said second rectifying means having an output, a thermionic tube having an input circuit and an output circuit, means coupling the output circuit of said tube to the frequency determining reactance of said oscillation producing circuit, and means coupling the input circuit of said tube to the output of said second rectifying means.

9. The combination with a signal receiving means including a tuning reactance, said receiving means having an input circuit on which signals may be impressed and an output circuit, of a phase shifting circuit having an output and having an input coupled to said receiving means, said phase shifting means being adapted to produce a substantially 90° shift in the energy passed thereby, a pair of electron discharge tubes each having a control grid and an anode, a circuit cou-

pling the anodes of said tubes to said tuning reactance, a circuit coupling the output circuit of said receiving means to the control grids of said tubes, and a circuit coupling the output circuit of said phase shifting means to the control grids of said tubes.

10. The combination with a signal receiving means, of frequency determining means and frequency reducing means connected with said receiving means, said frequency reducing means having an output circuit, phase shifting means connected at its input with the output of said frequency reducing means, said phase shifting means having an output circuit and being adapted to produce a phase shift in the energy passed thereby, signal demodulating means having an input circuit connected to said receiving means and also connected by a separate circuit to said phase shifting means, said demodulating means having an output circuit, and a control circuit connecting the output circuit of said demodulating means to said frequency determining means.

11. The combination of a heterodyne receiver including a tunable local oscillator having an output circuit, a first detector having an input circuit connected with the output circuit of said local oscillator, said first detector having an output circuit, a filter having an input circuit connected to the output circuit of said first detector, said filter having an output circuit, phase changing means having an input circuit connected with the output circuit of said filter, frequency control means having an output circuit connected with said tunable local oscillator, said frequency control means having an input circuit, and separate circuits connecting the input circuit of said frequency control means to the output circuit of said phase changing means and to the output circuit of said demodulator.

12. A receiving means as recited in claim 8 in which phase shifting means is connected in a circuit common to a portion of said separate circuit and said additional separate circuit.

13. Means for signalling with phase modulated waves comprising a beat frequency receiver including, a local oscillator and a demodulator, a phase shifting circuit connected with said demodulator, a pair of thermionic tubes having their anodes connected in push-pull relation and to said source of local oscillations, a circuit coupled between said demodulator and the control electrodes of said tubes for energizing the control electrodes of said tubes co-phasally by energy from said demodulator, and a circuit coupled between said phase shifting circuit and the control electrodes of said tubes for energizing the control electrodes of said tubes in phase opposition by phase shifted energy from said receiver.

14. The method of receiving phase or frequency or amplitude modulated oscillatory energy including the steps of, beating said modulated oscillatory energy with oscillations from a local source to produce modulated oscillatory energy of a beat frequency, filtering a portion of said oscillatory energy of beat frequency to substantially remove the modulation frequencies therefrom, combining said filter energy with unfiltered oscillatory energy of beat frequency and utilizing the resultant produced by said combination to control the frequency of the oscillations from said local source to thereby control the frequency of said oscillatory energy of beat frequency.

15. The method of receiving phase or frequency

or amplitude modulated signals comprising, beating said signals with oscillations from a local source to produce a beat frequency, selectively filtering said beat frequency to obtain substantially pure carrier wave energy shifting the phase of said substantially pure carrier wave energy, combining said filtered and phase shifted wave energy with unfiltered energy and demodulating said combined energy and utilizing the resultant thereof to determine the frequency of the oscillations from the local source to thereby maintain the beat frequency at a value which may be selectively filtered.

16. The method of automatically controlling the tune of a frequency modulated wave receiver which includes the step of receiving signal wave energy, altering the frequency of said signal wave energy, filtering a portion of the energy of the altered frequency, combining filtered energy with unfiltered energy of the altered frequency, and utilizing said combined energy to control the tune of the receiving means.

17. The method of automatically determining the frequency to which a beat frequency receiver is tuned which includes the steps of, producing local oscillations, beating said oscillations with the incoming signal to produce a beat note, filtering said beat note, combining said filtered beat note with an unfiltered beat note, utilizing said combined energy to produce differential direct current pulsations, and utilizing said differential direct current pulsations to determine the frequency of the oscillations produced.

18. A device for receiving, amplifying and demodulating signals modulated in phase or amplitude or in frequency comprising, a signal wave responsive device, a demodulator coupled to said device, a source of local oscillations comprising a thermionic tube having its input and output electrodes connected by oscillation producing circuits including an inductance, a coupling between said inductance and said demodulator, a selective filter circuit including a crystal, an artificial transmission line, switching means for coupling the input of said filter or the input of said artificial line to the output of said demodulator, a phase shifting circuit, switching means for coupling the input of said phase shifting circuit to the output of said crystal filter circuit or to the output of said artificial line, and means for maintaining said receiver in tune comprising, a pair of thermionic tubes each having an anode and a control grid, a circuit coupling the control grids of said tubes in phase opposition to the output of said phase shifting circuit, a circuit connecting the control grids of said tubes in phase to the output of said demodulator, a pair of resistances connected between the anodes of said tubes, a coupling tube having its input electrodes connected to said resistances by way of a time constant device, an inductance connected between the output electrodes of said coupling tube and a coupling between said last named inductance and the inductance in said oscillation generator.

19. A device for receiving, amplifying and modulating signals modulated in phase or amplitude or in frequency comprising, a signal wave responsive device, a demodulator coupled to said device, a source of local oscillations comprising a thermionic tube having its input and output electrodes connected by oscillation producing circuits including an inductance, a coupling between said inductance and said demodulator, a selective filter circuit including a crystal, an artificial transmission line, switching means for coupling the input

of said filter or the input of said artificial line to the output of said demodulator, a phase shifting circuit, switching means for coupling the input of said phase shifting circuit to the output of said crystal filter circuit or to the output of said artificial line, a signal rectifying device comprising, a pair of thermionic tubes each having a control electrode and an output electrode, circuits coupling the output of said phase shifter in phase opposition to the control electrodes in said tubes, a circuit connecting the output of said demodulator in phase to the control electrodes of said tubes, an indicating circuit, and means for connecting said indicating circuit in parallel relation or in pushpull relation with the output electrodes of said tubes, and means for maintaining said receiver in tune comprising, an additional pair of thermionic tubes each having a control grid and an anode, a circuit coupling the control grids of said last pair of tubes in phase opposition to the output of said phase shifting circuit, a circuit for connecting the control grids of said last tubes in phase to the output of said demodulator, a pair of resistances connected between the anodes of said last named pair of tubes, and a coupling including a time constant device between the anode electrodes of said last named pair of tubes and the inductance in said oscillation generator.

20. The method of receiving signal modulated wave energy which includes the steps of, reducing the frequency of said wave energy, filtering the wave energy of reduced frequency to remove therefrom sideband frequencies, shifting the phase of the filtered wave energy of reduced frequency, producing potential variations of unlike sign characteristic of said wave energy of reduced frequency, producing potential variations of like sign characteristic of said wave energy of reduced frequency, combining the potentials of like sign in phase quadrature with the potentials of opposite sign to produce resultant energy, producing indications characteristic of said resultant energy, and controlling the frequency to which said signal modulated wave energy is reduced in accordance with the character of said resultant energy.

21. The method of receiving signal modulated wave energy which includes the steps of, reducing the frequency of said wave energy, filtering the wave energy of reduced frequency to remove therefrom sideband frequencies, shifting the phase of the filtered wave energy of reduced frequency, producing potential variations of opposite sign characteristic of said phase shifted wave energy of reduced frequency, producing potential variations of like sign characteristic of unfiltered wave energy of reduced frequency, combining the potentials of like sign in phase quadrature with the potentials of opposite sign to produce resultant energy, and controlling the frequency to which said signal modulated wave energy is reduced in accordance with said resultant energy.

22. The method of receiving signal modulated wave energy which includes the steps of producing local oscillations of a frequency which differs from the frequency of said wave energy by an intermediate frequency, beating said local oscillations with said received wave energy to produce a heat note of said intermediate frequency, separating the energy of said beat note into two portions, filtering the energy of one of said portions to obtain therefrom a filtered wave the frequency of which is equal to said intermediate frequency, shifting the phase of the energy of said filtered wave, producing potential variations of opposite

sign characteristic of said filtered and phase shifted wave energy, producing potential variations of like sign characteristic of the wave energy in said other portion, combining the potential variations of like sign in phase quadrature with the potential variations of unlike sign to produce resultant energy characteristic of the phase relation of said combined energies, combining said last obtained resultant energies to produce controlling impulses, and controlling the frequency of the oscillations of said local source by means of said controlling impulses.

23. The method of receiving signal modulated wave energy which includes the steps of producing local oscillations of a frequency which differs from the frequency of said wave energy by an intermediate frequency, beating said local oscillations with said received wave energy to produce a beat note of said intermediate frequency, separating the energy of said beat note into two portions, filtering the energy of one of said portions to obtain therefrom a filtered wave the frequency of which is equal to said intermediate frequency, shifting the phase of the energy of said filtered wave, limiting the amplitude of the energy of said shifted and filtered wave, producing potential variations of opposite sign characteristic of said shifted and amplitude limited energy, producing potential variations of like sign characteristic of the energy in said other portion, combining the potential variations of like sign in phase quadrature with the potential variations of unlike sign to produce resultant energy characteristic of the phase relation of said combined energies, producing indications characteristic of said resultant energy and controlling the frequency of said produced local oscillator in accordance with said resultant energy.

24. The method of receiving signal modulated wave energy which includes the steps of producing local oscillations of a frequency which differs from the frequency of said wave energy by an intermediate frequency, beating said local oscillations with said received wave energy to produce a beat note of said intermediate frequency, separating the energy of said beat note into two portions, filtering the energy of one of said portions to obtain therefrom a filtered wave the frequency of which is equal to said intermediate frequency, shifting the phase of the energy of said filtered wave, limiting the amplitude of the energy of said shifted and filtered wave, producing potential variations of opposite sign characteristic of said filtered, phase shifted and amplitude limited wave energy, producing potential variations of like sign in phase quadrature with the potential variations of unlike sign to produce resultant energy characteristic of the phase relation of said combined energies, and controlling the frequency of the oscillations of said local source by means of said resultant energy and producing indications characteristic of said resultant energy.

25. The method of demodulating ultra high frequency oscillatory energy which has been modulated in phase in accordance with signals which includes the steps of reducing the frequency of said oscillatory energy without reducing the degree of modulation thereon, dividing said oscillatory energy into two portions, producing a phase shift in the energy of one of said portions such that there is a phase quadrature relation between the energies in said respective portions, and differentially combining the energies to render the signal.

26. The combination with a beat frequency receiver including a local source of oscillations and a demodulator connected therewith, said demodulator having an output circuit, of a filter having an input circuit connected with the output circuit of said demodulator, said filter having an output circuit, and means, for controlling the frequency of said oscillations and thereby controlling the beat frequency supplied from said demodulator to said filter, connected by a first circuit between said filter output circuit and said local source of oscillations and by a second circuit between said demodulator output circuit and said source of local oscillations.
27. In a phase modulated signal wave receiver having a circuit including a variable tuning means, said receiver having an output circuit, a filter circuit having an input connected with the output circuit of said receiver, a circuit having an input connected to said receiver output circuit, said circuit having an output connected to said tuning means and being responsive to unfiltered signal wave energy from said receiver, a separate circuit having an input connected to the output of said filter circuit and an output connected to said tuning means, said separate circuit being responsive to filtered energy which cooperates with the unfiltered energy of said first circuit for controlling said tuning means.
28. The method of demodulating ultra-high frequency oscillatory energy which has been modulated in phase in accordance with signals which includes the steps of, reducing the frequency of said oscillatory energy without reducing the degree of modulation of said energy, dividing said oscillatory energy into two portions, producing a

relative phase shift in the energies of said portions such that there is a phase quadrature relation between the energies in said respective portions, differentially combining the energies, producing signal indications characteristic of said combined energies and controlling the frequency to which said oscillations are reduced in accordance with said combined energies.

29. The method of demodulating high frequency oscillatory energy which has been modulated in phase in accordance with signals which includes the steps of, producing oscillatory energy characteristic of said phase modulated energy, dividing said produced oscillatory energy into two portions, producing relative phase shift in the energies of said portions such that there is a phase quadrature relation between the energies in said respective portions, differentially combining the energies of said portions, producing indications characteristic of the combined energies and controlling the frequency of the produced characteristic oscillatory energy in accordance with said combined energies.

30. In a radio receiver, a source of signal energy, a radio frequency amplifier coupled to said source, means for producing an intermediate frequency energy from the energy derived from said amplifier, a detector circuit, a path extending from the output of said means to the input of said detector arranged to pass both the carrier and its associated sidebands, and means in circuit with said path including a piezo-electric crystal tuned to the carrier for amplifying the carrier independently of the sidebands.

MURRAY G. CROSBY.