FREQUENCY CONTROLLED OSCILLATION SYSTEM

Filed March 19, 1954 3 Sheets-Sheet 1

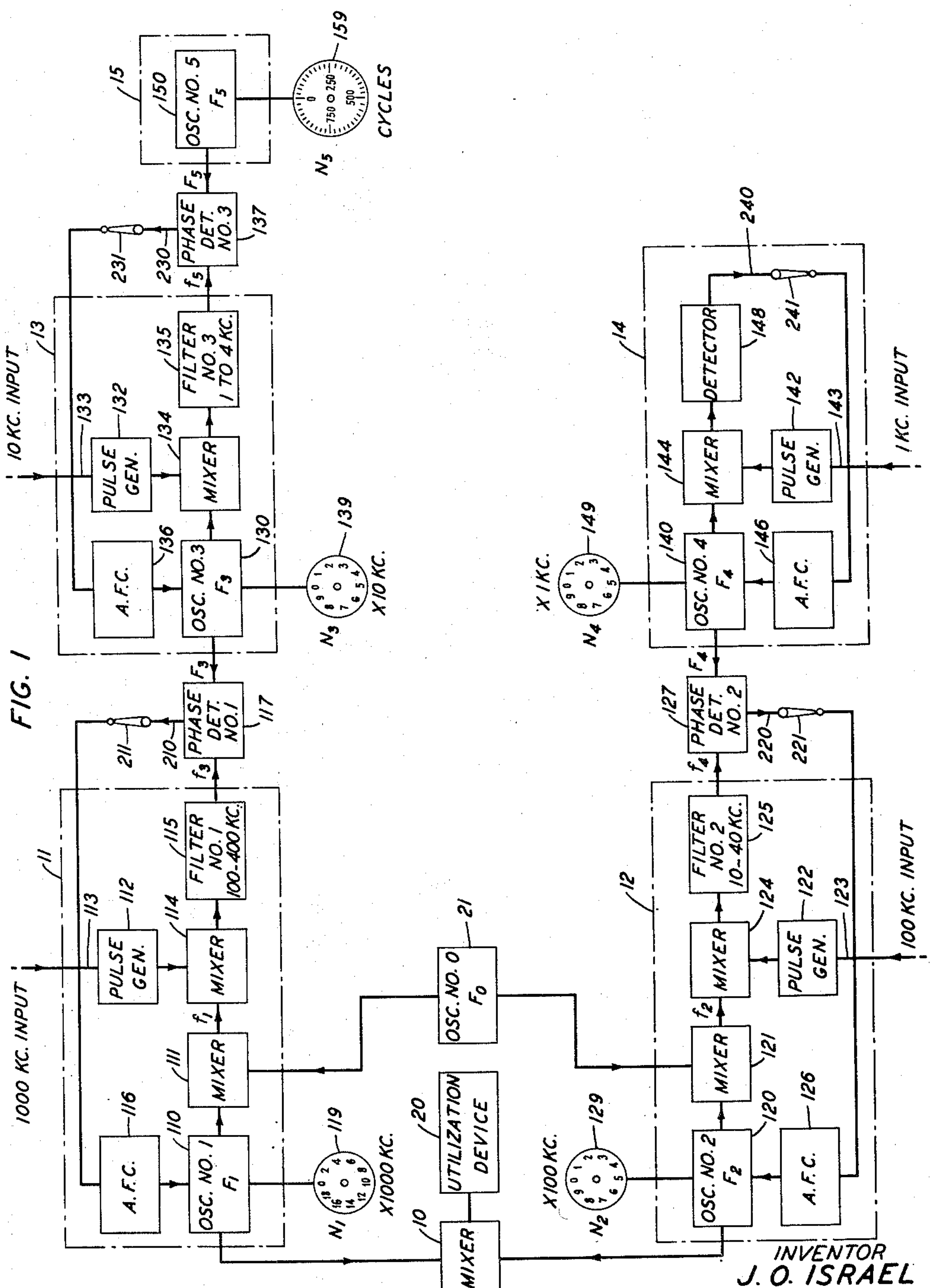

FIG. 1

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Dec. 25, 1956 J. O. ISRAEL 2,775,701

FREQUENCY CONTROLLED OSCILLATION SYSTEM

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FIG. 2

OSC. NO. 1	
NOMINALLY 90 TO 70 MC. BY 1 MC. STEPS	
STEP NO.	MEASURED FREQ.
0	90 MC.
1	89
2	88
3	87
4	86
5	85
6	84
-	-
19	71
20	70

FIG. 3

OSC. NO. 2	
NOMINALLY 90 TO 90.9 MC. BY 100 KC. STEPS	
STEP NO.	MEASURED FREQ.
0	90.0 MC.
1	90.1
2	90.2
3	90.3
4	90.4
5	90.5
6	90.6
7	90.7
8	90.8
9	90.9

FIG. 4

OSC. NO. 3	
NOMINALLY 232 TO 322 KC. BY 10 KC. STEPS	
STEP NO.	MEASURED FREQ.
0	232 KC.
1	242
2	252
3	262
4	272
5	282
6	292
7	302
8	312
9	322

FIG. 5

OSC. NO. 4	
32 TO 23 KC. BY 1 KC. STEPS	
STEP NO.	MEASURED FREQ.
0	32 KC.
1	31
2	30
3	29
4	28
5	27
6	26
7	25
8	24
9	23

FIG. 6

OSC. NO. 5	
2 TO 3 KC. CONTINUOUSLY CALIBRATED	
MARKED FREQ.	MEASURED FREQ.
0 C.P.S.	2000 C.P.S.
100	2100
200	2200
300	2300
400	2400
500	2500
600	2600
700	2700
800	2800
900	2900

FIG. 7

STEP NO.	NOMINAL RANGE OF f_1		
0	1232	TO	1323 KC.
1	2232		2323
2	3232		3323
3	4232		4323
4	5232		5323
5	6232		6323
6	7232		7323
7	8232		8323
-	—		—
19	20232		20323
20	21232		21323

FIG. 8

STEP NO.	NOMINAL RANGE OF f_2		
0	1232	TO	1223 KC.
1	1132		1123
2	1032		1023
3	932		923
4	832		823
5	732		723
6	632		623
7	532		523
8	432		423
9	332		323

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FIG. 9

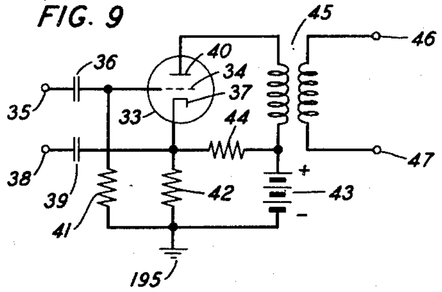


FIG. 11

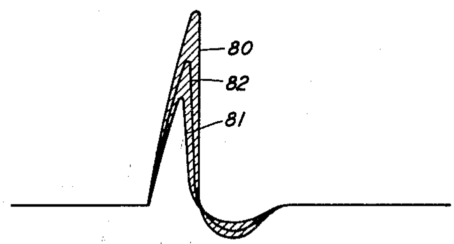


FIG. 10

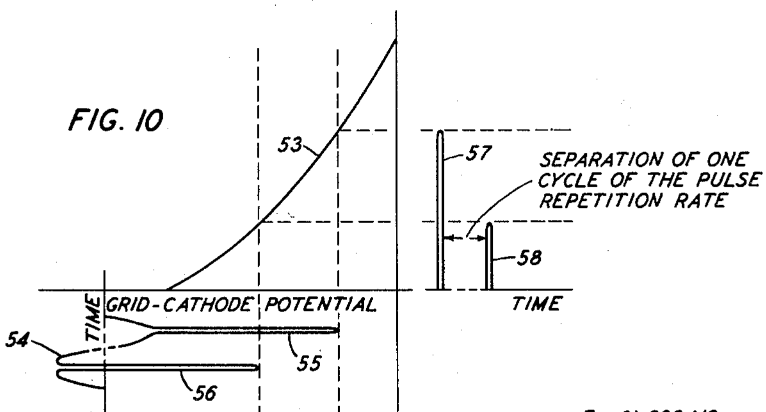
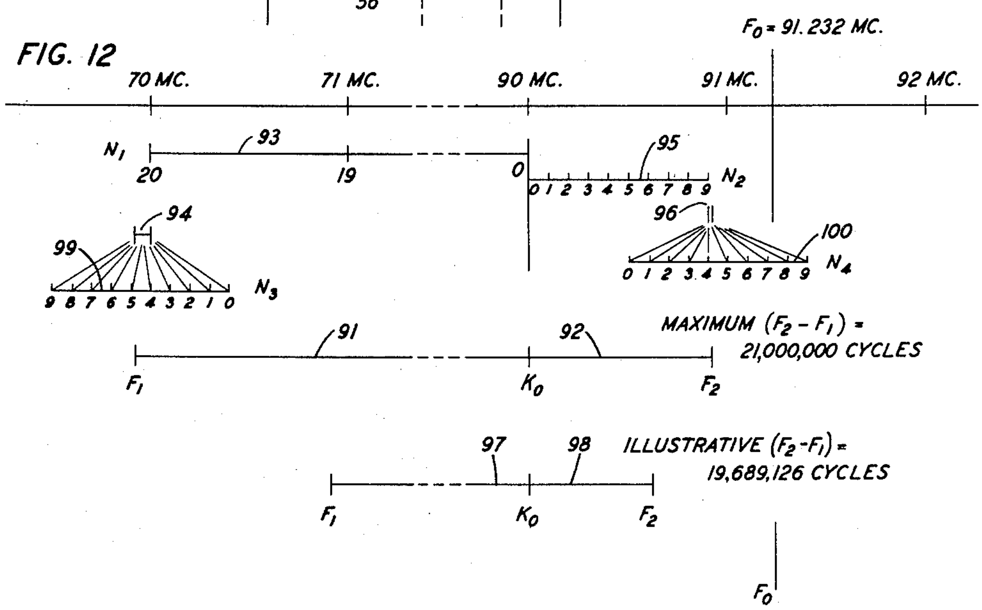


FIG. 12



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FREQUENCY CONTROLLED OSCILLATION SYSTEM

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4 Claims. (Cl. 250—36)

This invention relates to highly precise means and methods for setting up and maintaining a wave the frequency of which is automatically locked in with the frequencies of a plurality of standard reference sources.

An object of the invention is to set up any desired output frequency with such accuracy that the frequency shall depart from the desired value by an amount no greater than the sum of the maximum errors of a plurality of standard frequency sources, including the maximum error of an interpolation oscillator for obtaining frequencies between adjacent harmonics of the lowest frequency standard source.

Another object is to reduce the stringency of frequency discrimination requirements upon certain of the elements of such a system.

A further object is to insure that for every setting of the frequency determining dials of the system there shall be but one final output frequency possible and to insure that the final output frequency shall without fail correspond exactly with the desired frequency within the limits of error aforesaid.

A feature of the invention is an increase in the number of standard frequency sources and auxiliary oscillators employed compared with certain prior art systems, with the result that less precise calibrations are required for the auxiliary oscillators and the total cost of the frequency locking arrangements may be reduced accordingly, while the over-all accuracy of settings obtainable is preserved.

Another feature is the use of a band pass filter to eliminate ambiguity as to the ordinal number of the harmonic with which a given auxiliary oscillator is locked.

A further feature of the invention is the choice of a suitable set of offset frequencies for the respective auxiliary oscillators according to a scheme whereby the frequency offsets cancel out in the process of synthesizing the desired output frequency.

In the drawings:

Fig. 1 is a block schematic diagram of an illustrative embodiment of the invention;

Figs. 2 through 6 are tabular representations of the relationship of scale readings to measured frequencies in the several variable oscillators comprised in the system shown in Fig. 1;

Figs. 7 and 8 are tabular representations of the frequency ranges over which the waves vary, at certain points in the system shown in Fig. 1;

Fig. 9 is a schematic circuit diagram of a mixer suitable for use in one of the units of the system shown in Fig. 1;

Fig. 10 is a diagram useful in explaining the operation of the mixer shown in Fig. 9;

Fig. 11 is a sketch of pulse forms produced in the mixer shown in Fig. 1; and

Fig. 12 is a graphical representation of certain frequencies occurring in the system shown in Fig. 1.

In the system of Fig. 1, two trains of major units are shown connected through a mixer **10** to any desired utilization device **20**. The upper train as shown in the figure

comprises three odd-numbered units **11**, **13**, and **15**, although either more or fewer units may be employed as desired. The lower train in the figure comprises two even-numbered units **12** and **14**, although again the number of units in the train may be varied as desired. The units are numbered in numerical order beginning with unit **11** in the upper train as disposed in the figure and continuing alternately with unit **12** in the lower train, unit **13** in the upper train, etc.

In both the upper train and the lower train each major unit except the last one at the right-hand end of each train as disposed in the figure is essentially an auxiliary oscillator which is automatically controlled as to frequency in conventional manner by means of a phase-sensitive detector under the control of a standard frequency source individual to the unit in question. The first unit at the left-hand end of each train as illustrated in the figure may be special and is so shown in the figure, the special feature being that the oscillator is of the heterodyne type comprising the combination of a mixer and two simple, i. e., nonheterodyne, oscillators, one of which is shown outside the unit. More specifically, units **11** and **12** are shown as each including an individual oscillator which may be nonheterodyne, the two units together employing a common beating oscillator **21**. Unit **13** is a typical unit involving a single oscillator which may be nonheterodyne. Additional units essentially like unit **13** may be added as intermediate units in either the upper or the lower train in any desired number, or even substituted for heterodyne units **11** and **12**. Units **14** and **15** are special terminal units. Either train may be terminated at the right-hand end either by a unit like unit **14** or by one like unit **15**. Units like unit **14** may be used to terminate both trains if desired, whereas it will not usually be advantageous to use units like unit **15** to terminate both trains. Where a terminal unit of the type of unit **15** is used it will preferably be the unit with the largest ordinal number regardless of which train contains the unit with that ordinal number.

Assuming that it is desired that the system cover all frequencies from some lower limit such as 50 kilocycles or less, up to say 20 megacycles, the standard reference frequencies may conveniently constitute a decade or decimal system, namely 1, 10, 100, and 1000 kilocycles as shown in Fig. 1 together with an interpolation oscillator (Oscillator No. 5) covering a band of frequencies one kilocycle wide. Oscillators Nos. 0 and 1, and a mixer **111** form together a heterodyne source, covering a frequency band 20 megacycles wide with a suitable offset frequency of 1232 kilocycles, determined as hereinafter explained. Oscillator No. 1 may produce a band of frequencies 20 megacycles wide extending actually from say 90 megacycles to 70 megacycles. The dial **119** associated with Oscillator No. 1 may have a scale marked in steps nominally one megacycle each, step zero being at a measured frequency of 90 megacycles, step one at a measured frequency 89 megacycles, etc., down to step twenty at a measured frequency of 70 megacycles. Fig. 2 shows in tabular form such an allocation of the measured frequencies to the steps on dial **119**.

Oscillator No. 0 is set to 90 megacycles plus the desired offset frequency, a total of 91,232 kilocycles. This oscillator is not adjusted during normal operation. The frequency F_0 which it supplies is used as a comparison frequency with which all other frequencies used in the system are compared. As only frequency differences are relied upon, the absolute value of F_0 need not be known with great precision nor need the frequency stability of Oscillator No. 0 be exceedingly great, nor is any automatic frequency control required therefor.

The frequency f_1 developed at the output of the mixer **111** is the difference between F_0 and F_1 and covers a range substantially 20 megacycles wide which is offset from zero frequency by the predetermined offset frequency, 1232 kilocycles.

It is advantageous to use two oscillators such as No. 0 and No. 1 and a mixer **111** to supply the frequency controlled wave rather than a single oscillator, in that the limits of the frequency range of the calibrated oscillator (Oscillator No. 1) may be placed in a favorable portion of the frequency spectrum in accordance with well known practice. A single oscillator tunable over a range from say 10,000 to 20,000,000 cycles per second is more difficult to build and to calibrate precisely than one, for example tunable from 70 megacycles to 90 megacycles per second. Use of the heterodyne principle also avoids appearance of spurious harmonics as a result of the automatic frequency control because harmonics of Oscillator No. 1 which may result from frequency control are well removed from the useful frequency band of that oscillator.

Referring now particularly to unit **11** in Fig. 1, Oscillator No. 1, further identified by reference numeral **110** has its output connected along with an output from Oscillator No. 0, to the input of the mixer **111** which may be of conventional design. A pulse generator **112**, also of conventional design is arranged to be supplied with an input wave of standard reference frequency, e. g. 1000 kilocycles, through an input path **113**. A second mixer **114** has its input circuits connected respectively to the output of the mixer **111** and the output of the pulse generator **112**. The output wave from the mixer **114** is arranged to be passed through a band pass filter **115**, designated Filter No. 1, to constitute one of two outputs from the unit **11**. The second output from the unit **11** constitutes the output from the oscillator **110** to the mixer **10**. The oscillator is provided with an automatic frequency control unit **116** of any suitable known type.

Unit **12** is similar to unit **11** but is supplied with an input of a standard frequency, e. g., 100 kilocycles, differing in frequency by one decade from the standard frequency input supplied to unit **11**. The oscillator, designated Oscillator No. 2, is indicated by reference numeral **120**, and has its output connected to the input of a mixer **121** along with a connection from the oscillator **21**. The pulse generator **122** is supplied with a 100-kilocycle input wave over an input path **123**. Output waves from the mixer **121** and the pulse generator **122** are combined in a mixer **124**, the output from which in turn is supplied to a filter **125**, designated Filter No. 2. An automatic frequency control unit **126** is provided to control the oscillator **120**.

Unit **13** comprises an oscillator **130**, designated Oscillator No. 3, connected to a mixer **134** together with a wave from a pulse generator **132**. A wave of standard frequency, e. g., 10 kilocycles, is supplied to the input of the pulse generator **132** over an input path **133**. The output of the mixer **134** is supplied to a filter **135**, designated Filter No. 3. An automatic frequency control **136** is provided to control the oscillator **130**.

Unit **14** comprises an oscillator **140**, designated Oscillator No. 4, connected to a mixer **144** together with the output of a pulse generator **142**, which latter is supplied with a standard frequency, e. g., one kilocycle, over an input path **143**. An automatic frequency control unit **146** is provided to control the oscillator **140**. The output of the mixer **144** is supplied to a detector **148**, the output of which is supplied in turn to the control unit **146**.

Unit **15** comprises an oscillator **150**, designated Oscillator No. 5, which covers, for example, a frequency band one kilocycle in width and may be calibrated continuously to any desired fineness of scale division. Oscillator No. 5 functions as an interpolation oscillator, interpolating between frequency controlled cardinal points on the scale of Oscillator No. 4.

Between each pair of immediately adjacent units in each train there is provided a phase-sensitive detector to the input of which is supplied a wave from the filter of the unit on the left in the figure and a wave from the output of the oscillator of the unit on the right. The output of each phase detector is connected to the input of the automatic frequency control in the unit to the left through a control path which may include a switch. The phase-sensitive detectors **117**, **127**, and **137** are designated Phase Detectors No. 1, No. 2, and No. 3 respectively. Each may be of any suitable type, such as a phase-sensitive rectifier disclosed in the book entitled "Principles of Radar" by members of the staff of the Radar School, Massachusetts Institute of Technology, third edition, McGraw-Hill Book Company, 1952, pages 314–315 and Fig. 35, or United States Patent No. 2,288,025, issued June 30, 1942, to A. F. Pomeroy. The respective control paths are designated **210**, **220**, and **230**, with individual switches **211**, **221**, and **231**.

Each oscillator is provided with a manual setting means such as a dial having an index and a calibrated scale, except that Oscillator No. 0 need not be so provided as it operates at a single, fixed frequency. The dials for Oscillators Nos. 1, 2, 3, 4, and 5 are designated **119**, **129**, **139**, **149**, and **159**, respectively. The scales of Oscillators Nos. 2, 3, and 4 are preferably provided with ten equal scale divisions numbered from 0 to 9, inclusive, conforming to a decimal system. The scale of Oscillator No. 1 may also have ten scale divisions, or it may have any other desired number, e. g., twenty divisions. To avoid crowding in the drawing only the even numbered divisions of a 20-division scale are shown on dial **119**. The scale of Oscillator No. 5 is preferably finely divided and may have a continuous scale covering a range from 0 to 1000.

In mixer **114**, the substantially single-frequency wave of frequency f_1 from mixer **111** beats with pulses of 1000 kilocycle repetition rate from pulse generator **112**, producing a plurality of beat frequencies, a single one of which is selected in Filter No. 1. Provided the frequency f_1 differs from the nearest harmonic of 1000 kilocycles by an amount in the range from 100 kilocycles to 400 kilocycles there will be a wave passing through Filter No. 1 at the difference frequency. The designation f_3 is assigned to represent the frequency of such a wave and is indicated in the drawing at the filter output.

Amplification may be employed, if needed, preferably following each filter, to bring the amplitude of the wave from the preceding mixer to a suitable value for application to the next following phase-sensitive detector.

Oscillator No. 3 provides a plurality of frequency steps at intervals of ten killocycles each, which lie within the pass band of Filter No. 1. Step 0 on dial **139** of Oscillator No. 3 corresponds to a measured frequency of 232 kilocycles, step 1, 242 kilocycles, etc., up to step 9 at 322 kilocycles. The correlation between these steps and the measured frequency of Oscillator No. 3 is shown in tabular form in Fig. 4.

Phase Detector No. 1 compares the phase of the substantially single frequency sinusoidal wave of frequency f_3 from Filter No. 1 with the phase of a substantially single frequency sinusoidal wave of comparable frequency F_3 from Oscillator No. 3. The automatic frequency control action establishes a frequency difference between f_1 and the next lower harmonic of 1000 kilocycles of such value that f_3 becomes equal to F_3. Any departure from a predetermined standard phase relationship between these two sinusoidal waves results in the production of a control wave which is applied to the automatic frequency control **116** to change the frequency F_1 in the proper sense to establish or restore the said predetermined standard phase relationship.

In the mixer **114**, the wave of frequency f_1 beats with harmonics of the 1000 kilocycle reference frequency from the pulse generator **112**, to produce a plurality of beat frequencies one and only one of which lies within the pass band of Filter No. 1. The action of Phase Detector No. 1 wherein the selected beat frequency wave is compared in phase with the wave of frequency F_3 from Oscillator No. 3 energizes the automatic frequency control **116** which in turn acts to lock Oscillator No. 1 at a point below the frequency F_0 of Oscillator No. 0 by a suitable frequency interval.

A generally similar operation centers about the Phase Detector No. 3 wherein the phase of a wave of frequency f_5 from Filter No. 3 is compared with the phase of a wave of frequency F_5 from Oscillator No. 5 to actuate the automatic frequency control **136** to readjust Oscillator No. 3 until f_5 becomes equal to F_5.

Oscillator No. 5, which is the interpolation oscillator, has an offset of two kilocycles and the frequency range covered is from two to three kilocycles. The scale on its dial **159** is marked with 0 at a measured frequency of 2000 cycles and marked as 1000 cycles at a measured frequency of 3000 cycles. Fig. 6 shows in tabular form the relationship between a few of the dial settings of the interpolation oscillator and the corresponding measured frequencies.

In unit **13**, the frequency F_3 from Oscillator No. 3, beats with a plurality of harmonics of 10 kilocycles from pulse generator **132** to produce a plurality of beat frequencies, one and only one of which passes through Filter No. 3 and beats with the wave of frequency F_5 from Oscillator No. 5 in Phase Detector No. 3, thereby actuating the automatic frequency control **136** to change the frequency F_3 by a suitable amount. When this adjustment is completed, F_3 continues to beat with harmonics of 10 kilocycles in mixer **134** to produce a wave of frequency f_5, which now is equal in frequency to F_5.

The change in F_3 upsets the phase balance in Phase Detector No. 1, requiring a further downward adjustment of F_1 by control **116**.

The correlation of dial steps with measured frequencies of Oscillator No. 2 is shown in tabular form in Fig. 3. A similar correlation of dial steps with measured frequencies of Oscillator No. 4 is shown in tabular form in Fig. 5.

In unit **12**, frequency F_2 beats with F_0 to produce f_2. This beats with a plurality of harmonics of the 100 kilocycle reference source to produce a plurality of beat frequencies, one and only one of which, f_4, lies in the pass band of Filter No. 2. In Phase Detector No. 2, the wave of frequency f_4, combines with the wave of frequency F_4, to actuate control **126** to raise the frequency F_2 by a suitable amount.

Unit **14** maintains the frequency F_4 in synchronism with a harmonic of one kilocycle. This control is effected by beating the output wave from Oscillator No. 4 in mixer **144** with pulses of one kilocycle repetition frequency from the pulse generator **142** to produce a control wave which energizes detector **148** to actuate automatic frequency control **146** through a control path **240** which may include a switch **241**.

The final useful output frequency is obtained in mixer **10** by beating F_1 with F_2. It will be found at this point that all the offset frequencies have cancelled out in the process of synthesizing the desired final output frequency, as will be explained hereinafter.

It will be evident that f_1 and f_2 both vary during normal operation of the system of Fig. 1, f_1 having a range 91 kilocycles wide and f_2 having a range nine kilocycles wide, according to the illustrative frequency allocation recited. The frequency limits of the range of f_1 depend upon the step selected on dial **119** and are listed in tabular form in Fig. 7. The frequency limits of the range of f_2 depend upon the step selected on dial **129** and are listed in tabular form in Fig. 8. The range of f_1 is necessitated by the dependence of the frequency F_1 upon the settings of Oscillators Nos. 3 and 5, that is, in general, all oscillators to the right of Oscillator No. 1 in Fig. 1, in the present example a maximum of 90 kilocycles variation of Oscillator No. 3, plus a maximum of one kilocycle variation of Oscillator No. 5. Similarly, the range of f_2 is necessitated by the dependence of F_2 upon the setting of Oscillator No. 4, that is, in general, all oscillators to the right of Oscillator No. 2 in Fig. 1, a maximum of nine kilocycles variation.

Considering unit **14** in more detail, Oscillator No. 4 is locked in to the standard frequency source of one kilocycle base frequency by any suitable means such as the mixer **144**, the detector **148**, and the automatic frequency control unit **146**. In the mixer **144**, pulses of repetition frequency one kilocycle are combined with a sinusoidal wave from the output of Oscillator No. 4 to produce in the output of the mixer new pulses which are of constant amplitude as long as the original pulses occur in fixed phase relationship to the sinusoidal wave. If any change in relative phase occurs the amplitude of the new pulses varies, the variations being detected by the detector **148** and applied as a control to actuate the automatic frequency control.

Various mixing circuits suitable for mixer **144** are known in the art, one being selected for illustration in detail in Fig. 9 comprising a triode tube **33** with one input applied to the control grid **34** between ground **195** and an input terminal **35** through a coupling condenser **36**. The other input is applied to the cathode **37** between ground **195** and an input terminal **38** through a coupling condenser **39**. A grid leak **41**, a cathode load resistor **42**, and an anode potential supply source **43** are provided in conventional manner. A cathode bias is provided through a grid bias regulating resistor **44** as shown. An output transformer **45** is connected with its primary winding between the anode **40** and the positive terminal of the anode potential supply source **43**. The secondary winding of the transformer **45** is connected to a pair of output terminals **46** and **47**.

Fig. 10 helps to explain a preferred method of operating the mixer of Fig. 9 whereby the sinusoidal input wave is suppressed in the output. The curve **53** illustrates the anode current vs. grid-cathode potential characteristic of the tube **33**. It is assumed that by means of proper proportioning of the resistors **42** and **44** in Fig. 9 the grid-cathode circuit is biased beyond cut-off, and sufficiently so that the impressed sinusoidal wave, represented by curve **54**, produces no anode current in the absence of pulses. The pulses, when applied, are superimposed upon the signal current and may occur in general at any phase of the signal wave, as for example as shown at **55** and **56**, respectively, the former being shown arising from a positive peak and the latter from a negative peak of the signal wave. The resulting anode current comprises pulses **57** and **58**, respectively, which are essentially free from any component of the signal wave **54**. In actual practice, the pulses **55**, **56** are spaced apart at time intervals equal to full cycles of the standard frequency, one kilocycle in the case of unit **14**. Whether a given pulse is superimposed upon a positive peak, a negative peak, or upon some other portion of the signal wave depends upon the phase relationship between the pulse train and the signal wave. While pulses **55** and **56** are shown adjacent in Fig. 10, for economy of space, in practice the succeeding pulses will be spaced apart by one or more, up to 32 cycles of the signal wave in the illustrative embodiment shown in Fig. 1, broken lines being used in the figure to indicate an interval or intervals between pulses. The output pulses will always occur with the repetition rate of the standard frequency, here one kilocycle, whatever the frequency of the sinusoidal wave.

While the particular form of mixer shown in Fig. 9 operated as shown in Fig. 10 illustrates very clearly the independence of the mixer output wave with respect to the particular harmonic which is closest to the frequency of the signal wave, it may also be shown that a control wave having such independence is present as a component part of the output wave from other sorts of mixers and by other methods of mixer operation. In any form of mixing device in which modulation occurs, such a control wave is present and may be selected and utilized.

The output wave of the mixer **144** is applied with or without accompanying amplification to detector **148** where it is converted into a control wave for the automatic frequency control unit **146**. The control wave should be phase-sensitive, depending usually upon the value of cos θ, where θ is the phase difference.

It can be shown that stable frequency locking is obtainable over a certain range of values of phase difference θ while instability occurs over the remaining range. Assume first that a locked in condition exists with a phase difference of 90 degrees. Suppose then that the oscillator being controlled lowers its frequency slightly. This causes the phase difference θ to increase, giving cos θ a negative value and decreasing the height of the resultant pulses. If the connections of the automatic frequency control are such that decreasing the pulse height causes the automatic frequency control to lower the oscillator frequency still further, the system is evidently unstable. On the other hand, if decreasing the pulse height results in raising the oscillator frequency, stable operation is had. Assuming next that a locked in condition exists with θ equal to 270 degrees, then a lowering of the oscillator frequency causes cos θ to take on a positive value, increasing the pulse height. Stable operation at this value of θ is had if increasing the pulse height raises the oscillator frequency. Depending upon the internal arrangements of the automatic frequency control, stable operation will occur in the range of value of θ either from 0 to 180 degrees or from 180 degrees to 360 degrees, but not both. When θ reaches zero or 180 degrees, synchronism is lost momentarily and the system jumps abruptly to the next adjacent harmonic.

Since cos θ can range in value between plus one and minus one, the new pulse can range between a maximum positive value and a maximum negative value. However, the new pulse is superimposed upon the orginal pulse which may be larger than the new pulse in which case the two are directly in phase with each other and generally similar in shape. Hence, the resultant pulse varies in height as illustrated in Fig. 11 between two positive values as long as frequency locking has not been accomplished. Curve **80** represents the pulse of maximum height and curve **81** the pulse of minimum height. The pulse varies in height at a rate equal to the frequency difference between the sinusoidal wave and the nearest harmonic component of the pulse. In an oscilloscope a solid pattern appears between curves **80** and **81** as indicated by cross hatching in Fig. 11. When frequency locking occurs the pulse height ceases to vary but assumes a value dependent upon cos θ, which in turn depends upon the phase difference between the locked components. Curve **82** of Fig. 11 illustrates the pulse when locking has occurred. The wave forms of Fig. 11 are representative of the output of the mixer of Fig. 9 as well as of mixers in general.

The operation of the system of Fig. 9 is the same regardless of which harmonic the sinusoidal wave most nearly approaches in frequency.

The operation of the system shown in Fig. 1 may be explained in more general terms by reference to the following analysis.

Let N_1, N_2, N_3, N_4, and N_5 be scale readings which are indicated on the dials of the respective units.

Let F_{10}, F_{20}, F_{30}, F_{40}, and F_{50} be the frequencies produced by the respective Oscillators Nos. 1, 2, 3, 4, and 5 when their dials are set to scale readings N_1, N_2, N_3, N_4, and N_5, respectively, assuming for the time being that the automatic frequency controls are ineffective to change the frequencies produced.

Also, let f_{10} and f_{20} be the frequencies appearing at the outputs of mixers **111** and **121**, respectively, when Oscillators No. 1 and No. 2 produce F_{10} and F_{20}, respectively.

The analysis that follows is applicable whether f_{10} and f_{20} are produced by heterodyning as in the system of Fig. 1, or by single oscillators without heterodyning. In either case, the scale readings N_1 and N_2 are to be understood as referring to the dials by means of which f_{10} and f_{20} may be varied.

It is desired to synthesize a final output frequency F_D in such a manner that

$$F_D=N_1+N_2+N_3+N_4+N_5 \tag{1}$$

To obtain the final output frequency of 19,689,126 cycles per second for example, it is desired merely to set the dials to the following scale readings:

$$\begin{aligned} N_1&=19{,}000{,}000\\ N_2&=600{,}000\\ N_3&=80{,}000\\ N_4&=9{,}000\\ N_5&=126 \end{aligned} \tag{2}$$

in cycles per second, in terms of readings of dials **119**, **129**, **139**, **149**, and **159**, respectively.

The maximum error by which the final output frequency departs from its value as indicated by the scale readings is evidently no greater than the sum of the maximum errors of the standard frequency sources supplying the respective units plus the maximum error of the calibration of the interpolation oscillator, since when the frequency control operates each unit but the last has its frequency locked in to a harmonic of a standard frequency source.

Fig. 12 shows graphically how, in accordance with the invention the frequency increments making up F_1 and F_2 are arranged on both sides of an arbitrarily chosen offset frequency K_0 illustrated as 90 megacycles. Line segment **91** extending from K_0 down to F_1 represents the minimum value of F_1, that is, for the case of the highest F_D provided, namely 21 megacycles in the example illustrated.

Line segment **92** extending from K_0 up to F_2 represents the maximum value of F_2, that is, when F_D is 21 megacycles.

Segment **91** is made up of three parts, of which the two longer parts are depicted in the upper portion of Fig. 12 by segments **93** and **94**, and the third part is too short to be represented on the same scale and for clarity is omitted. Segment **93** is 20 megacycles in extent, from 90 megacycles down to 70 megacycles. Segment **94** is 90 kilocycles in extent, from 70,000 kilocycles down to 69,910 kilocycles. The third part (not shown) is one kilocycle in extent, from 69,910 kilocycles down to 69,909 kilocycles.

Segment **92** is made up to two parts **95** and **96**, of which part **95** is 900 kilocycles in extent, from 90,000 kilocycles up to 90,900 kilocycles, and part **96** is nine kilocycles in extent, from 90,900 kilocycles up to 90,909 kilocycles.

The difference between F_2 and F_1 is

$$90{,}909-69{,}909=21{,}000 \text{ kilocycles} \tag{3}$$

As an example of a desired frequency less than 21,000 kilocycles, the illustrative example of 19,689,126 cycles is shown in graphic form by line segments **97** and **98**.

Segment **97** extends from 90,000,000 cycles down to 70,919,874 cycles made up of three parts, the first extending from 90,000,000 cycles down to 71,000,000 cycles, contributing 19,000,000 cycles; the second from 71,000,000 cycles down to 70,920,000 cycles, contributing 80,000 cycles; and the third from 70,920,000 cycles down to 70,919,874 cycles, contributing 126 cycles; making a total of 19,080,126 cycles.

Segment **98** extends from 90,000,000 cycles up to 90,609,000 cycles, made up of two parts, the first extending from 90,000,000 cycles up to 90,600,000 cycles, contributing 600,000 cycles, and the second extending from 90,600,000 cycles up to 90,609,000 cycles, contributing 9,000 cycles; making a total of 609,000 cycles.

The difference between F_2 and F_1 in this example is

$$90{,}609{,}000-70{,}919{,}874=19{,}689{,}126 \text{ cycles} \quad (4)$$

Because of space considerations the segments **91**, **93**, and **97** in Fig. 12 are shown broken away between **71** megacycles and 90 megacycles, it being impractical to show magnitudes differing so widely as 20,000 kilocycles and one kilocycle.

Steps of one megacycle each are marked along segment **93**, corresponding to values of N_1. Because of the break in segment **93**, only marks 0, 19, and 20 appear. Steps of 100 kilocycles each, corresponding to values of N_2 are marked to scale along segment **95**. Steps of 10 kilocycles each along segment **94** and corresponding to values of N_3 are indicated diagrammatically by an expanded scale **99** which in actuality should be compressed within the length of segment **94**, which is too short to accommodate such a scale. Steps of one kilocycle each corresponding to values of N_4 are indicated by an expanded scale **100** which should be compressed within the length of segment **96**. Values of N_5 add on beyond segment **94** toward the left but are relatively so small that no attempt is made to indicate them in the figure.

In order that the ranges of variation of the respective variable oscillators may be located in favorable portions of the available frequency spectrum and in order that desired final output frequencies down to very low frequencies or even zero frequency may be obtained, each source is given a suitable frequency offset.

Let the offsets employed with the frequencies f_{10}, f_{20}, F_{30}, F_{40}, and F_{50}, respectively, be designated according to the following scheme:

$$\begin{array}{l} K_5+K_4+K_3+K_2 \\ K_5+K_4+K_3+K_2 \\ K_5+K_4+K_3 \\ K_5+K_4, \text{ and} \\ K_5 \end{array} \quad (5)$$

In what follows it will appear that the respective offsets are necessarily cumulative from unit to unit, as indicated by the compound expressions exhibited in the scheme of offsets. That is, the offset for the source of F_{40} is the offset for the source of F_{50} plus a further offset K_4; the offset for the source F_{30} is the offset for the source F_{40} plus a further offset K_3; and the offset for the source of f_{20} is the offset for the source F_{30} plus a further offset K_2. The scheme of synthesis requires that the offset for the source of f_{10} is the same as the offset for the source of f_{20}.

Of the frequencies f_{10}, f_{20}, F_{30}, F_{40}, and F_{50}, each equals its frequency offset plus or minus the frequency as read from the scale on the dial by which the frequency can be varied. In accordance with the invention, the scale readings are applied alternately plus and minus the successive units of the train, a suitable arrangement being consistent with that illustrated in Fig. 12, and expressible as follows:

$$\begin{array}{l} f_{10}=K_5+K_4+K_3+K_2+N_1 \\ f_{20}=K_5+K_4+K_3+K_2-N_2 \\ F_{30}=K_5+K_4+K_3+N_3 \\ F_{40}=K_5+K_4-N_4 \\ F_{50}=K_5+N_5 \end{array} \quad (6)$$

The automatic frequency controls produce frequency increments comprising departures from the frequencies set up by manipulation of the dials of the respective units. The notations f_1, f_2, F_3, F_4, F_5, as well as F_1 and F_2, will be assigned to represent the frequency of the respective source after the automatic frequency controls have produced the necessary frequency increments.

It is desired that the automatic frequency controls operate to supply such increments for the respective frequencies f_{10}, f_{20}, and F_{30} as are necessary to synthesize a correct set of frequency components for the desired final output frequency. The last two units in the illustrative embodiment do not vary in frequency in the course of the synthesis. From what follows it will appear that a suitable set of values for the respective frequencies after the frequency control has been completed is

$$\begin{array}{l} f_1=K_5+K_4+K_3+K_2+N_1+N_3+N_5 \\ f_2=K_5+K_4+K_3+K_2-N_2-N_4 \\ F_3=K_5+K_4+K_3+N_3+N_5 \\ F_4=K_5+K_4-N_4=F_{40} \\ F_5=K_5+N_5=F_{50} \end{array} \quad (7)$$

again consistent with the arrangements shown in Fig. 12.

The desired final output frequency is obtainable as

$$f_1-f_2=N_1+N_2+N_3+N_4+N_5$$

which will be recognized as the sum of the dial readings, all the offset frequencies having been cancelled out. In case heterodyning is used to produce f_1 and f_2, the desired final output frequency is also obtainable as F_1-F_2. It will be evident that

$$F_1-F_2=f_1-f_2 \quad (8)$$

where the same local oscillator frequency F_0 is employed in heterodyning F_1 to f_1 as in heterodyning F_2 to f_2. Fig. 12 brings out the relationships between F_1, F_2, and F_0 in graphic manner.

The operation of the automatic frequency controls in effecting the synthesis of the desired output frequency will now be described in greater detail than hereinbefore, after a general discussion of the means by which the respective controls are energized.

In each of the units **11**, **12**, and **13**, a wave of nominal frequency f_{10}, f_{20}, F_{30}, respectively, beats in a mixer with harmonics of the standard frequency supplied to the respective units through a pulse generator. In each unit, a plurality of beat frequencies result, and in each unit, a single one of the beat frequencies is selected by the respective Filter No. 1, No. 2, or No. 3. The selected beat frequencies have been designated f_3, f_4, and f_5, respectively.

The automatic frequency controls of the respective units **11**, **12**, and **13** are actuated by the outputs of Phase Detectors Nos. 1, 2, and 3, as hereinbefore noted. Each of these phase detectors is located between two units and compares phases of a beat frequency from the preceding unit and the oscillator frequency from the succeeding unit.

Starting with the action of Phase Detector No. 3, Oscillator No. 3 is controlled by automatic frequency control **136** to adjust F_3 away from the manually set value F_{30} until as a result of the adjustment the frequency f_5 passed by Filter No. 3 is made equal to F_5. The frequency f_5 results from beating F_3 with a harmonic H_{10} of the base frequency 10 kilocycles comprised in the output of the pulse generator **132**. The beat frequency may be expressed as

$$\begin{aligned} F_3-H_{10}&=K_5+K_4+K_3+N_3+N_5-H_{10} \\ &=(K_5+N_5)+(K_4+K_3+N_3)-H_{10} \quad (9) \\ &=F_5+(K_4+K_3+N_3)-H_{10} \end{aligned}$$

In order that the beat frequency may be F_5, it is necessary that

$$K_4+K_3+N_3=H_{10} \quad (10)$$

As H_{10} and N_3 are each harmonics of 10 kilocycles, K_4+K_3 must be a harmonic of 10 kilocycles.

Through the action of Phase Detector No. 1, Oscillator No. 1 is controlled by automatic frequency control **116** to adjust f_1 away from the initially set value f_{10} until as a result of the adjustment the frequency f_3 passed by Filter No. 1 is made equal to F_3. The frequency f_3 results from beating f_1 with a harmonic H_{1000} of the base frequency 1000 kilocycles comprised in the output of the pulse generator **112**. The beat frequency may be expressed as

$$\begin{aligned} f_1-H_{1000} &= K_5+K_4+K_3+K_2+N_1+N_3+N_5-H_{1000} \\ &= (K_5+K_4+K_3+N_3+N_5)+(K_2+N_1)-H_{1000} \\ &= F_3+(K_2+N_1)-H_{1000} \end{aligned} \quad (11)$$

In order that the beat frequency may be F_3, it is necessary that

$$K_2+N_1=H_{1000} \quad (12)$$

or in other words, if N_1 is a harmonic of 1000 kilocycles, K_2 also must be a harmonic of 1000 kilocycles.

Through the action of Phase Detector No. 2, Oscillator No. 2 is controlled by automatic frequency control **126** to adjust f_2 away from the initially set value f_{20} until as a result of the adjustment the frequency f_4 passed by Filter No. 2 is made equal to F_4. The frequency f_4 results from beating f_2 with a harmonic H_{100} of the base frequency 100 kilocycles comprised in the output of the pulse generator **122**.

The beat frequency may be expressed as

$$\begin{aligned} f_2-H_{100} &= K_5+K_4+K_3+K_2-N_4-N_2-H_{100} \\ &= (K_5+K_4-N_4)+K_3+K_2-N_2)-H_{100} \\ &= F_4+(K_3+K_2-N_2)-H_{100} \end{aligned} \quad (13)$$

In order that the beat frequency may be F_4 it is necessary that

$$K_3+K_2-N_2=H_{100} \quad (14)$$

or in other words, if N_2 is a harmonic of 100 kilocycles, (K_3+K_2) also must be a harmonic of 100 kilocycles. Since K_2 must be a harmonic of 1000 kilocycles and hence of 100 kilocycles, K_3 also must be a harmonic of 100 kilocycles.

Since K_3 must be a harmonic of 100 kilocycles and hence a harmonic of 10 kilocycles, K_4 also must be a harmonic of 10 kilocycles.

Oscillator No. 4 is not controlled as to frequency by any unit other than unit **14** of which the oscillator is a part. The oscillator is controlled, however, by automatic frequency control **146** to synchronize F_4 with a harmonic H_1 of one kilocycle comprised in the output of the pulse generator **142**. The beat frequency may be expressed as

$$F_4-H_1=K_5+K_4-N_4-H_1 \quad (15)$$

In order to obtain a zero beat, it is necessary that

$$K_5+K_4-N_4=H_1 \quad (16)$$

or in other words, if N_4 is a harmonic of one kilocycle, (K_5+K_4) also must be a harmonic of one kilocycle. Since K_4 is a harmonic of 10 kilocycles and hence of one kilocycle, K_5 also must be a harmonic of one kilocycle.

Recapitulating the results of investigating the beat frequencies, it is found that in the illustrative embodiment of Fig. 1, K_5 is required to be a harmonic of one kilocycle; K_4 a harmonic of 10 kilocycles; K_3 a harmonic of 100 kilocycles; and K_2 a harmonic of 1000 kilocycles.

As noted above, the filter in a typical unit is employed to select from a plurality of beat frequencies one single beat frequency. By providing the filter with a single pass band of less than half the base frequency F supplied to the unit, the filter will pass only the beat frequency resulting from the impressed wave beating with the nearest harmonic of the standard frequency.

The filters may, for example, pass the band from 0.1F to 0.4F of the respective unit. It is evident that a beat frequency between an impressed wave and the second nearest harmonic will lie in the range from 0.5F to 1.0F, and hence lies outside the pass band.

By limiting the input frequencies applied to the mixer to those closer to the next higher harmonic or to those closer to the next lower harmonic as the particular case may require, it is feasible to insure that the beat frequency is produced only by the action of the one harmonic or the other, thereby preventing the alternative harmonic from introducing ambiguity.

Such limitation of input frequency range is effected by suitable choice of offsets.

In the embodiment illustrated the filter pass bands used are 100 to 400 kilocycles for Filter No. 1; 10 to 40 kilocycles for Filter No. 2; and 1 to 4 kilocycles for Filter No. 3.

We are now in a position to select particular offset frequencies which will cancel out and will center or approximately center the beat frequencies f_3, f_4, and f_5 within the pass bands of Filters No. 1, No. 2, and No. 3, respectively. Starting with f_5, it will be noted that normally f_5 equals F_5. The center of the pass band of Filter No. 3 is 2.5 kilocycles. When N_5 is varied, F_5 varies over a range one kilocycle wide. Hence to be centered in the band, F_5 variation should run from two to three kilocycles. Since

$$F_5=K_5+N_5 \quad (17)$$

and K_5 has been found to be limited to harmonics of one kilocycle, K_5 should be chosen as two kilocycles. In other words, two kilocycles is the preferred offset for Oscillator No. 5.

Turning now to f_4 which normally equals F_4, the range of variation should be approximately centered in the pass band of Filter No. 2, which band centers about 25 kilocycles. We have

$$F_4=K_5+K_4-N_4 \quad (18)$$

and N_4 varies over a range nine kilocycles wide. Hence, it would be desirable to assign to F_4 the range 20.5 to 29.5 kilocycles, giving Oscillator No. 4 an offset of 29.5 kilocycles. However, the choice of the offset is limited to values of (K_5+K_4) and K_5 has already been assigned the value two kilocycles. Furthermore, K_4 has been shown to be limited to harmonics of 10 kilocycles. Hence, the best choice of offset that remains is 2+30 or 32 kilocycles offset for Oscillator No. 4. Accordingly, F_4 varies from 32 to 23 kilocycles.

We next consider

$$F_3=K_5+K_4+K_3+N_3+N_5 \quad (19)$$

N_5 varies over a range one kilocycle wide and N_3 over a range 90 kilocycles wide. Hence, F_3 varies over a range 91 kilocycles wide. The center of the pass band of Filter No. 1 lies at 250 kilocycles. The most central range for F_3 is thus from 204.5 to 295.5 kilocycles, suggesting an optimum offset of 204.5 kilocycles. However, (K_5+K_4) has already been set at 32 kilocycles and K_3 has been shown to be limited to harmonics of 100 kilocycles. Hence, the best remaining choice of offset is 2+30+200 or 232 kilocycles offset for Oscillator No. 3. Accordingly, F_3 varies between 232 and 323 kilocycles.

The sources of the frequencies f_1 and f_2 are advantageously given offsets, although not because of filter pass band limits. Since

$$f_2=K_5+K_4+K_3+K_2-N_2-N_4 \quad (20)$$

f_2 varies on account of N_2 over a range 900 kilocycles wide, and over a range nine kilocycles wide due to N_4. The total range of variation of f_2 is therefore 909 kilocycles. The source of f_2 must have enough frequency offset so that f_2 can vary downward by 909 kilocycles without reaching zero. Since $(K_5+K_4+K_3)$ is 232 kilocycles and K_2 is limited to harmonics of 1000 kilocycles (which could include zero), the lowest permissible value of K_2 is evidently 1000 kilocycles, making the frequency offset for f_2 total 1232 kilocycles. Accordingly, f_2 varies from 1232 kilocycles to 323 kilocycles.

The source of frequency f_1 requires an offset exactly equal to that of f_2 in order that (f_1-f_2) shall give the desired final output frequency and all offsets shall be cancelled out. Since f_1 varies upward in frequency from the offset value, no need arises for frequency clearance for f_1 to prevent it from reaching zero. Hence, an offset that is sufficient for f_2 is likewise sufficient for f_1. Accordingly, 1232 kilocycles is the frequency offset to be assigned to the source of frequency f_1, and f_1 varies from 1232 kilocycles up to any desired upper limit. In the illustrative embodiment, the variation due to N_1 is 20,000 kilocycles; that due to N_3 is 90 kilocycles; and that due to N_5 is one kilocycle; making a total of 20,091 kilocycles, reaching an upper limit of 21,323 kilocycles.

Use of heterodyne sources for f_1 and f_2 enables the variation ranges of the variable oscillators to be raised to any desired portion of the available frequency spectrum as hereinbefore noted. In the illustrative embodiment, F_1 ranges downward from an arbitrary frequency K_0 herein set at 90,000 kilocycles as an illustrative value. F_1 ranges from 90,000 kilocycles down to 69,909 kilocycles and F_2 ranges from 90,000 kilocycles up to 90,909 kilocycles. That is,

$$F_1=K_0-N_1-N_3-N_5 \qquad (21)$$
$$F_2=K_0+N_2+N_4$$

Oscillator No. 0, which serves as beating oscillator common to Oscillators No. 1 and No. 2, may be assigned a frequency F_0 which is either higher than the highest other frequency in the system or lower than the lowest, as desired. In the first case, which is illustrated in Fig. 12,

$$F_0=F_1+f_1=F_2+f_2 \qquad (22)$$

We have seen that in order to come out with a final output frequency that is free from all offsets, F_1 and F_2 must be applied on opposite sides of some arbitrary frequency which has been designated K_0. Substituting values of f_1 and f_2 from Expression 7 and values of F_1 and F_2 from Expression 21 into Expression 22 gives

$$F_0=K_0+K_2+K_3+K_4+K_5 \qquad (23)$$

In the illustrative embodiment, F_0 is 91,232 kilocycles.

Alternating the decades as between the respective upper and lower trains of the system of Fig. 1, has the added advantage that it assures that the frequency increments introduced by the automatic frequency controls are always less than 0.1F, that is, one-tenth the frequency interval between harmonics in the unit in question. This is a feature which is important in removing ambiguity in the synthesis of the desired final output frequency. By virtue of this arrangement, the frequency of any component oscillator never departs far enough from the value required to beat with the proper harmonic to cause any possibility that a beat with another harmonic will lie within the filter pass band. For example, if N_1 is 19,000,000 cycles, and N_3 has its maximum value of 90,000 cycles, and N_5 its maximum value of one kilocycle, the sum $N_1+N_3+N_5$ will not exceed 19,091,000 cycles, which differs from 19,000,000 cycles by less than 10 percent of the 1000 kilocycle interval between harmonics in unit **11**. The 10 percent increment will not be sufficient to move the desired beat frequency out of the pass band of Filter No. 1, or to move an undesired beat frequency into the pass band.

Similarly, for any value of N_2, the maximum value of N_4 is nine kilocycles, which is less than 10 percent of the 100 kilocycle interval between harmonics in unit **12**.

Also, for any value of N_3, the maximum value of N_5 is one kilocycle, which is still only 10 percent of the 10 kilocycle interval between harmonics in unit **13**.

If the oscillators are accurately calibrated and precisely set, the filter bands may be restricted to cover only barely the range of variation expected of the frequencies to be impressed. For example, Filter No. 1 in the illustrative embodiment requires a minimum pass band extending from 232 kilocycles to 323 kilocycles; Filter No. 2, from 23 kilocycles to 32 kilocycles; and Filter No. 3 from two kilocycles to three kilocycles. Any inaccuracy of calibration or any lack of precision in setting may cause the desired frequency components to lie outside limits of the minimum pass band, requiring that the pass band be widened. The wider the pass band, the greater the tolerance in the calibration and setting of the oscillators. As noted hereinabove, a limit on extension of the bandwidth is imposed by the consideration of excluding a beat frequency involving a harmonic of wrong ordinal number. The illustrative band limits of 0.1F and 0.4F permit about the maximum safe tolerance without danger of introducing ambiguity. Accordingly, it is necessary only that the oscillator settings be accurate within about ±0.1F. For example, dial setting N_1 should be accurate within ±100 kilocycles. Each automatic frequency control should, of course, be arranged so that it is capable of catching, synchronizing and holding any frequency component that lies within the filter pass band, considerations which are well known to those skilled in the art of frequency locking.

A frequency allocation wherein F_0 is lower than any other frequency in the system may readily be worked out using the principles hereinbefore discussed.

Any of the control paths **210**, **220**, **230**, **240**, may be opened, as by means of the switches **211**, **221**, **231**, **241**, respectively, thereby enabling the oscillator ordinarily controlled by the respective control path to be swept continuously over its frequency range instead of being locked to discrete steps. In this way, any desired portion of the available frequency spectrum may be scanned for purposes of exploration, as for example to discover a frequency of special interest.

It is to be understood that the above described arrangements are illustrative of the principles of the invention and are not to be taken as limiting.

What is claimed is:

1. A decimal system of frequency synthesis comprising first generating means providing an array of frequency components uniformly spaced in frequency, second generating means providing an array of frequency components uniformly spaced in frequency at intervals each one-tenth the frequency interval provided by said first generating means, third generating means providing an array of frequency components uniformly spaced in frequency at intervals each one-hundredth the frequency interval provided by said first generating means, a first auxiliary oscillator, automatic frequency control means connected to and actuated jointly by said first and third generating means to control the frequency of the auxiliary oscillator, a second auxiliary oscillator, automatic frequency control means connected to and actuated by said second generating means to control the frequency of said second auxiliary oscillator, and mixing means connected to both said auxiliary oscillators to derive therefrom an output wave controlled as to frequency by all three said generating means.

2. A frequency synthesizing system comprising first generating means providing an array of frequency components at equal frequency intervals, second generating means providing an array of frequency components spaced at equal frequency intervals that are a fraction of said first frequency intervals, continuously variable generating means covering a range of frequencies equal in number to the frequency differential of said second interval, a first auxiliary oscillator, automatic frequency control means connected to and actuated jointly by said first generating means and by said continuously variable generating means to control the frequency of the auxiliary oscillator, a second auxiliary oscillator, automatic frequency control means connected to and actuated by said second generating means to control the frequency of said second auxiliary oscillator, and mixing means connected to both said auxiliary oscillators to derive therefrom an output wave controlled as to frequency over a continuous frequency range determined by all three said generating means.

3. A wave synthesizer comprising a plurality of reference sources the respective frequencies of which form a series of integral powers of a given base frequency differing by one power from one member of the series to

the next, a plurality of oscillatory stages associated in two groups, the typical stage in one group being connected to one of said reference sources and to the output of another stage in the same group wherein the connected reference source frequency is two powers smaller, the typical stage in the other group being connected to a reference source the frequency of which is one power different from one of the typical stages in the first mentioned group and to the output of another stage in the same group wherein the connected reference source frequency is two powers smaller, automatic frequency control means individual to each typical stage in each group whereby the output frequency of the stage depends upon the output frequency of another stage in the same group and upon the frequency of a respective one of the reference sources, first and second additional oscillatory stages, the typical stage of lowest said power in each group being connected to a respective one of said additional oscillatory stages in lieu of another typical stage, and mixing means combining output waves from a stage in one group and a stage in the other group for which stages the said respective powers differ by one.

4. A wave synthesizer comprising a plurality of control stages including at least first, second, and third control stages each comprising two wave sources, said control stages also comprising at least first, second, and third mixers respectively, each combining waves from the two wave sources in the respective stage, said control stages also comprising at least first, second, and third automatic frequency control means respectively, each controlling the frequency of one of the wave sources in the respective stage, a like plurality of phase detectors including at least first, second, and third phase detectors each responsive to a change in the phase relationship between two waves impressed thereon, first and second additional wave sources, means impressing upon the first phase detector a wave from the first mixer and a wave from the first additional wave source, means impressing upon the second phase detector a wave from the second mixer and a wave from the second additional wave source, means impressing upon each nth phase detector, where n is at least three, a wave from the nth mixer and a wave from the frequency controlled wave source of the $(n-2)$nd control stage, the output of the nth phase detector being connected to the nth frequency control means for each stage, the phase detectors thereby serving to connect the said additional wave sources and control stages into two trains, each train beginning with one of the said additional wave sources, and ending with a final control stage which includes a frequency controlled wave source, an additional mixer common to both trains, and means connecting the output of the respective frequency controlled wave source in the final control stage of each train to the input of said additional mixer.

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