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SURVEY OF METHODS FOR PRECISION FREQUENCY CONTROL

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SURVEY OF METHODS FOR PRECISION FREQUENCY CONTROL

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4 January 1950

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ABSTRACT

A survey of existing and proposed methods for precision frequency control of communications equipment is presented. Primary consideration has been given to the 200-400 Mc frequency range, and there is a discussion of the advantages and disadvantages of the methods described. A new system proposed would employ a wide-range oscillator and an electronic tuning device, and in operation would tend to overcome such weaknesses as spurious responses common to systems now in use.

PROBLEM STATUS

This is a final report on one phase of the problem; work is continuing on other phases.

AUTHORIZATION

NRL Problem R01-05D (BuShips Problem No. S767.1)
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SURVEY OF METHODS FOR PRECISION FREQUENCY CONTROL

INTRODUCTION

There exist many methods and schemes for precisely determining the operating frequency of communications receivers and transmitters; these methods range in complication from the simple L-C or crystal oscillator to the several "crystal-saver" schemes. Before setting a course of further research and development directed toward means for accurately setting the frequency of a communications link (the 200-400 Mc frequency range being of primary concern), it is well to review in some detail the methods now in use, and those which have been proposed. Consequently, this report presents a description of the known means for generating precision frequency control spectra; each method is discussed in the light of its attendant advantages and disadvantages.

FUNDAMENTAL CONSIDERATIONS

Inductance-Capacitance Oscillators

In the ordinary vacuum-tube oscillator (such as the Hartley, Colpitts, feed-back, etc.) the oscillation frequency is such that the voltage applied to the grid of the tube is of the proper phase and magnitude to allow the tube to supply its own input excitation. Thus the oscillation frequency, and hence its constancy, are determined by the tube electrode potentials and the coupled load impedance as well as by the tank-circuit constants (Ref. 1).

The effect of tube voltages on frequency can be minimized by the use of a tank circuit with high effective Q (low L-C) and by the insertion of suitable reactances in series with the plate and grid leads. Frequency changes due to variations in coupled load impedance can be minimized by coupling very lightly, by use of a "buffer amplifier" between oscillator and load, or by employing an electron-coupled oscillator circuit. The resonant frequency of the tank circuit itself can be stabilized to a degree: variations in inductance and capacitance with temperature and humidity variation can be combatted by hermetically sealing the tank circuit or by the use of temperature-compensating capacitors; variations in tube interelectrode capacitances with temperature or tube interchange can be partly masked by using a low L-C ratio. In general, the problem of oscillator compensation for fixed-frequency operation is relatively simple compared to the compensation of a variable-frequency oscillator because of the variation in temperature coefficients of circuit elements with frequency or setting.

In addition to stabilization and compensation of an oscillator, means must be provided for setting the frequency on any of the designated channel frequencies within a given band. This requires the use of calibrated dials or "detent" mechanisms; hence, the total possible error in oscillator frequency is increased by the inaccuracy of the dial or "detent." At present, it is estimated that the frequency error of an oscillator set by a "detent" mechanism could be held to less than 0.1 percent (Ref. 2).

Crystal Oscillators

1. Simple Crystal Oscillator

High frequency stability can be obtained by replacing the tuned circuit of an oscillator with a piezoelectric crystal element. Such crystals have the property of high-Q resonant circuits, the resonant frequency being determined by the orientation of the cut from the natural crystal and the physical dimensions of the plate. Generally, crystals have several possible resonant frequencies; hence, it is necessary, by grinding or mounting techniques, to discourage vibration in the unwanted modes. The crystal oscillator is by nature a fixed-frequency device; however, a small amount of frequency adjustment is possible by variation of circuit parameters external to the crystal. Due to mechanical strength considerations, crystals operating on their fundamental frequencies are seldom used above about 15 Mc.

Since, for a given cut of crystal, the resonance frequency is dependent on the dimensions of the plate, crystals exhibit frequency changes with variations in temperature. The temperature coefficient of frequency ranges from several parts per million per degree Centigrade down to practically zero, depending on the orientation of the cut from the natural crystal. To more nearly approach constancy of the frequency generated by a crystal oscillator, control of the operating temperature may be introduced. This is accomplished by placing the crystal element in a thermostatically controlled enclosure ("oven").

2. Frequency Multiplication and Division

Frequency-controlled sources are sometimes required with output frequencies well above the highest crystal oscillator frequency. For this purpose recourse is made to frequency multiplier, or harmonic generator, circuits. At present, multipliers with an output frequency up to about 1000 Mc may utilize triode doublers and triplers; for higher output frequencies klystron multipliers are used. The output of optimum design triode multipliers ranges from about 65 percent of normal class C output for a doubler to about 25 percent for a quintupler. Klystron multipliers produce output on the tenth harmonic of the input frequency with efficiencies of the order of 0.1 percent.

To obtain output at sub-multiples of a control frequency, use can be made of frequency dividers (Refs. 3, 4, and 5). Divider circuits include synchronized relaxation oscillators, synchronized regenerative oscillators, counting circuits, multivibrators, and regenerative modulator circuits. Of these only the last is suited for high-frequency operation (up to 30-50 Mc). A block diagram of the regenerative, modulator frequency divider is shown in Figure 1. Here, frequency division by n is accomplished by the use of a mixer circuit, a times (n - 1) multiplier, and a filter circuit tuned to the desired output frequency f/n. The input frequency is impressed on the suppressor grid of the mixer. The plate of the mixer is tuned to f/n and is coupled to the output of the divider and the input of a multiplier tuned to $\left(\frac{n-1}{n}\right)f$ which is in turn coupled to the control grid of the mixer tube. The beat between $\left(\frac{n-1}{n}\right)f$ and f is f/n, the desired [redacted]

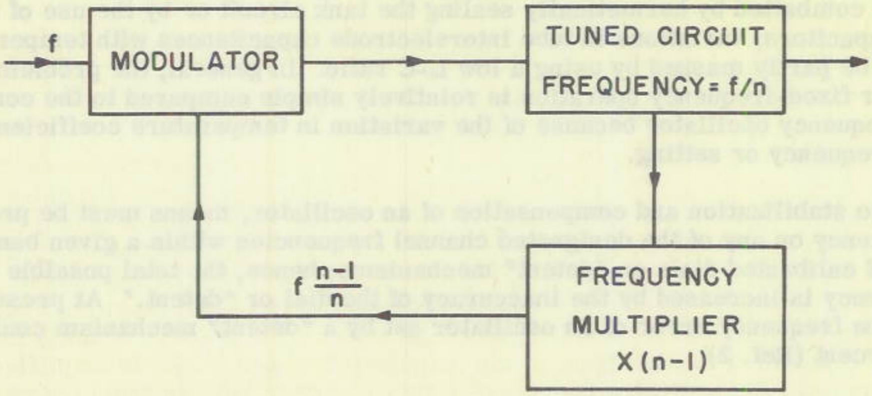

Figure 1

3. Overmode Operation of Crystals

By proper contouring and mounting of piezoelectric crystal elements, output can be obtained on frequencies well above the fundamental frequency of the crystal. These so-called overmodes are almost, but not exactly, at frequencies harmonically related to the fundamental frequency. The stability realized is about 0.005 percent over the temperature range of -55° to +90°C. The third, fifth, and seventh modes are utilized for outputs up to about 25, 50, and 100 Mc, respectively. The crystals operate as series resonant elements in a thickness-shear vibration.

Control Spectra

A control spectrum may be defined as radio-frequency energy or potential (at one or more frequencies) developed for disciplining the operating frequency of a radio device. The precision of the frequencies developed in the spectrum generator (usually called the frequency monitor) will then determine, in whole or in part, the operating frequency of the associated equipment. The generation of control spectra may be accomplished by combinations of oscillators, multipliers, dividers, mixers, and filters so interconnected as to produce the desired frequencies, as well as to suppress the unwanted frequencies.

Discussion

The primary function of a frequency monitor is to produce frequencies that are the operating frequencies or integral submultiples thereof. Monitors for multichannel wide-frequency range equipments, allowing selection of any of numerous channels, may be divided into two general classes: (1) those which directly compound operating frequencies (or submultiples); (2) those which generate a control spectrum used to discipline a locked oscillator by some type of automatic frequency control. Thus far, most of the effort expended has been on the development of systems falling into the second class.

MULTICHANNEL SYSTEMS (Refs. 6, 7, 8, and 9)

Variable I-F Systems

A system utilizing a variable i-f amplifier has been used to obtain multichannel operation with few crystals and still approximate crystal stability. Figure 2 is an example of this system (RT-67/GRC-5). The system employs two "detent" selector switches; the first switch selects in one-megacycle increments and the second selects 100-kc increments. A frequency of 27.9 Mc would be selected by turning selector switch one to position 27 and selector switch two to position 9.

The first selector switch accomplishes initial tuning by adjusting the r-f tuning capacitors, the first mixer circuits, the harmonic generator and also by selecting one of twelve crystals. The second selector switch, normally detented in 100-kc steps, operates the tuning of the variable i-f amplifier, the continuously variable self-excited oscillator, and, through a differential, further adjusts the r-f and first mixer tuning without disturbing the harmonic generator and associate circuits. If the "detents" are released from the second selector switch, continuous tuning between megacycle increments is provided. The operation of the system is best explained by tracing a signal. Assume a 27-Mc signal at the antenna terminals. This is amplified by the r-f amplifier and combined in the first mixer stage with a 22.55-Mc voltage from the harmonic generator. The variable frequency i-f amplifier is tuned to the difference frequency 4.45 Mc and amplifies the first mixer output; this signal combines with a 3.05-Mc voltage from the variable oscillator in the second mixer and the resulting heterodyne of 1.4 Mc is amplified by a fixed frequency, narrow band i-f amplifier. The output of this amplifier is fed to a f-m discriminator and the audio modulation is detected and then amplified and delivered to the head set. If the desired signal were 27.9 Mc the crystal harmonic frequency injected into the first mixer would remain unchanged, but the variable i-f amplifier would be tuned to 5.35 Mc and the variable

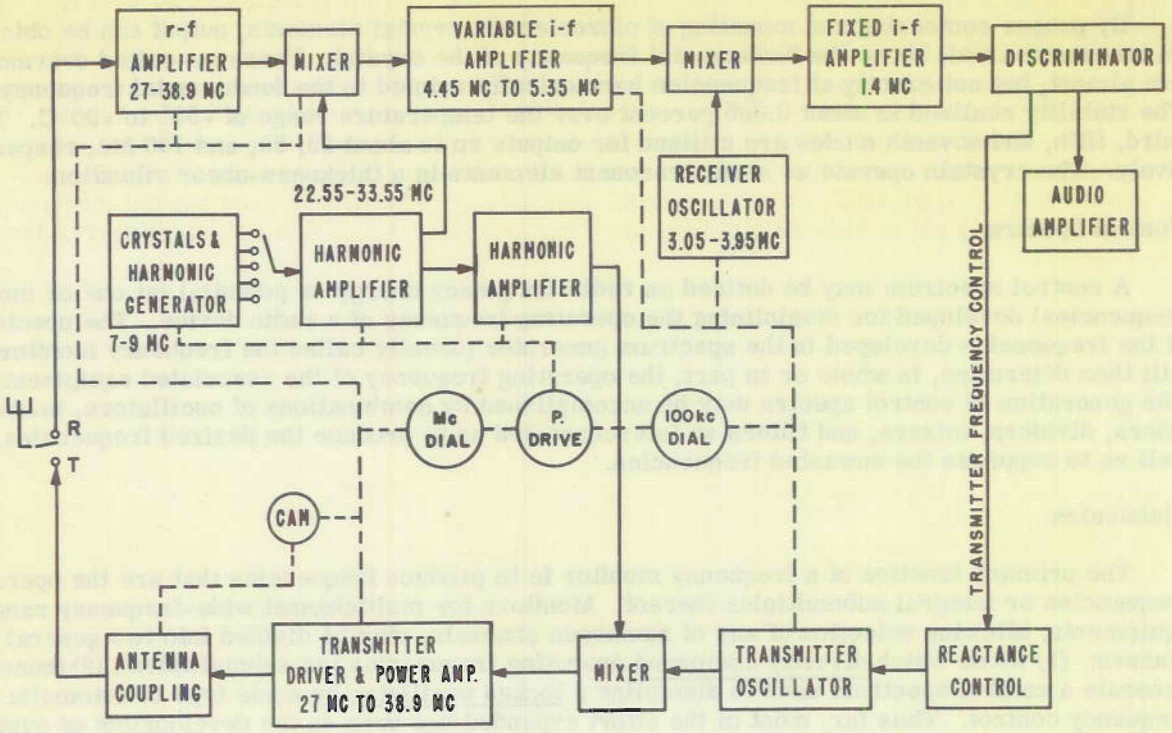

Figure 2

oscillator tuned to 3.95 Mc, again resulting in a 1.4-Mc heterodyne output frequency in the second mixer output which would be amplified, as before, by the fixed frequency i-f amplifier. Reception of signals higher in frequency than 28 Mc require a change in crystal and harmonic frequency injected into the first mixer.

The frequency stability of the system is based on three factors: the crystal oscillator, the variable frequency oscillator, and the reset accuracy of the detents used in conjunction with the variable oscillator. Reported accuracies are based on an operating frequency of 31.9 Mc and are as follows: detent mechanism ±0.6 kc; over-all drift with temperature variation from +18°C to -45°C, -4.5 kc and from +18°C to +65°C, -5.5 kc. This drift is attributed mostly to the variable oscillator. The variable oscillator drift with primary supply change from 11 to 15 volts was reported to be 4.6 kc. The frequency stability is not a function of operating frequency.

The system involves four groups of variable frequency elements all interconnected with the channel control. It is obvious that such a control is complex and delicate, and that reliability and maintenance as well as weight and size are adversely effected. The use of just a variable i-f amplifier without the following mixer and fixed frequency amplifier results in a much simpler system (RCA Model AN/ARC-2) but this gain is achieved by loss of selectivity.

Plug-in Crystals and Crystal Switching

Navy Model RED (experimental designation X-RED) is an example of a single channel system providing crystal stability in a frequency range of 225 to 400 Mc. The preselector and crystal multiplier circuits are ganged together and are continuously variable through the frequency range. Channel selection is accomplished by selecting and inserting the desired crystal and then tuning the ganged circuits. Each channel requires a crystal but some channels may have the same crystal and different multiplication. Continuous tuning is possible by replacing the crystal oscillator with a self-excited variable oscillator, but the stability is adversely affected.

The use of overmode type CR-9 crystals reduces the multiplication requirements and consequently lessens the spurious frequency interference. The equipment is light, simple, and small, and,by using four or five simultaneously, a number of frequencies may be monitored. The demand on crystals is severe, however, as about 750 crystals are required for 750 channels spaced 200 kc in the 225 to 400 Mc range. The over-all stability is good but the frequency accuracy is not as good as may be obtained when the same crystals are an integral part of the equipment.

By using crystal switching and autotune mechanisms ten preset channels can be made available. Navy model RDZ and TDZ equipments are examples of this system (Figure 3). The theory of operation is the same as the single crystal system except autotune drives select one of ten crystals and tune the multiplier chain and preselector circuits to the operating frequency. Channel selection is accomplished by changing crystals and preset tuning of the preselector-multiplier gang. Again every channel requires a crystal, and the transmitter requires a different crystal frequency than the receiver to operate on the same channel. Type CR-7 crystals are used and the over-all stability of the receiver is 0.007 percent under service conditions. The crystal frequencies required to cover the band are from 4.48 to 7.1 Mc. Crystal frequencies from 4.48 to 5.32 Mc and from 6.49 to 7.1 Mc are used with a multiplication of 48 and from 5.32 to 6.49 Mc with a multiplication of 64. This high multiplication results in severe spurious interference, both radiated and received. It is because of the spurious interference and the large number of crystals required for communication with this system that work was initiated on crystal-saving techniques.

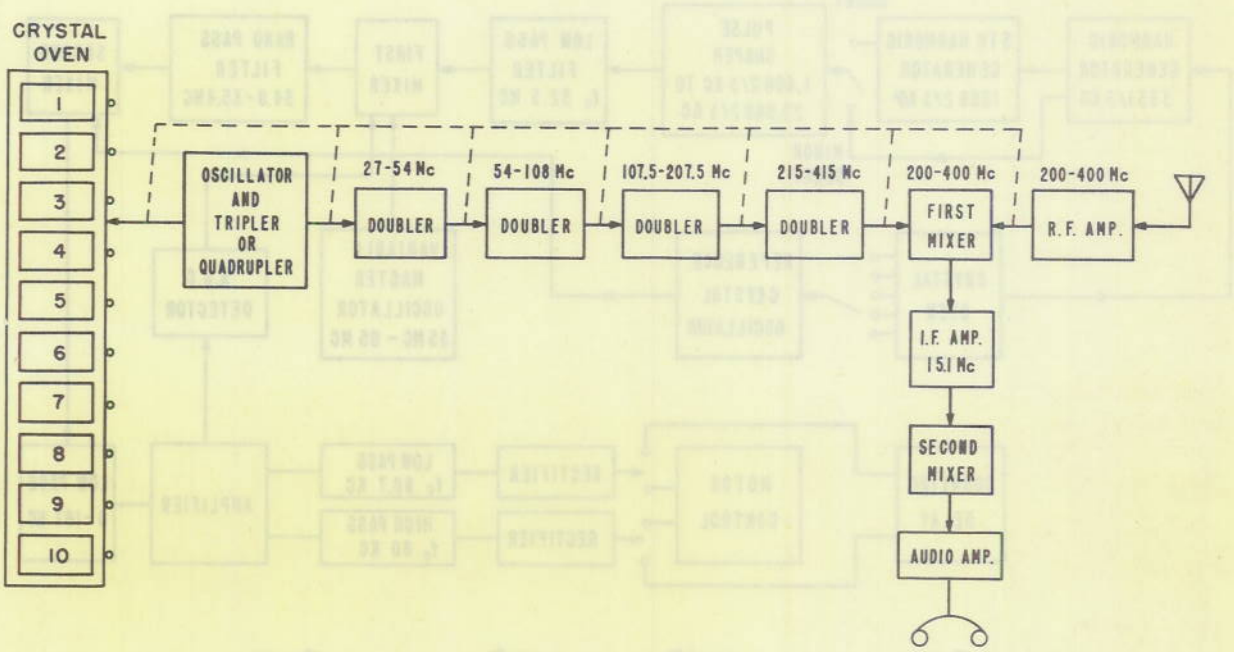

Figure 3

Crystal Savers (Refs. 10 and 11)

1. System Based on British TR1407 Equipment

By the use of novel circuits, substantially crystal stability is achieved in multichannel equipment employing only a few piezoelectric crystals as integral components. The first circuit to be developed was taken from the British TR1407 equipment. This type of monitor employs a master oscillator and a control spectrum. Pulses generated by beats between the master oscillator and control spectrum are counted by a stepping relay. Equipment with this type monitor are the AN/URC-3, AN/ARC-19 (XN-1), AN/ARC-19 (XN-2), and (XCU-1). These equipments provide rapid selection of any one of approximately 800 channels spaced 200 kc apart in the frequency range from 225 to 400 Mc. Figure 4 is a simplified block diagram of the monitor of the the (XCU-1) equipment.

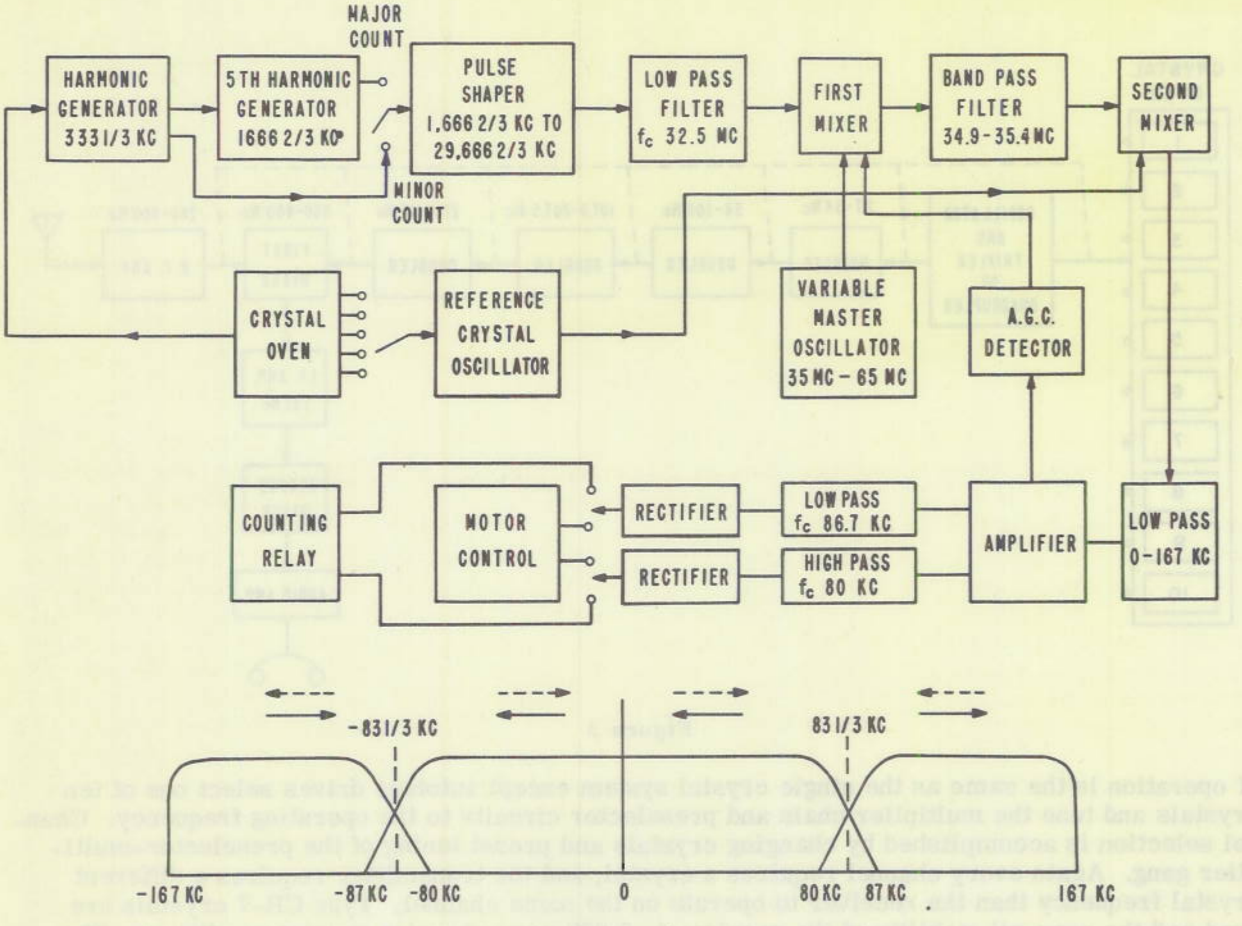

Figure 4

The monitor employs six crystals stabilized by a temperature controlled oven. One crystal, 333-1/3 kc, is used to generate the control spectrum, and the other five are "reference" crystals. The control spectrum is composed of products differing in frequency by 333-1/3 kc for minor counts and five times 333-1/3 kc, or 1,666-2/3 kc, for major counts.

The signal frequency of the system is six times that of the master oscillator so the change in signal frequency corresponding to one minor count is six times 333-1/3 kc, or 2 Mc, and the change of one major count is 10 Mc. The major-minor counting is used to lessen the requirements of the counting relay and to shorten the time required in counting large numbers of channels. Only the difference frequency derived from mixing the spectrum and master oscillator is selected and amplified by a narrow band pass amplifier, and this signal is mixed with the reference oscillator operating at the frequency of one of the reference crystals. Both sums and differences are selected by a low-pass filter.

The discriminator is formed by two filters with a common input connected to the low-pass filter. One leg of the discriminator consists of a low-pass filter of bandwidth 0-87 kc followed by a diode and d-c amplifier. A sensitive relay in the plate circuit of the d-c amplifier is actuated by changes in plate current, and the relay in turn controls the servo system tuning the master oscillator. The other leg of the discriminator is similar except for the high-pass filter and the relay action, which tunes the master oscillator in the opposite direction. The over-all response of the three filters of the discriminator is shown at the bottom of Figure 4. The negative sign represents a difference beat at the second mixer. The solid arrows indicate the direction the master oscillator is changed if the beat frequency lies in a given region. For the solid arrows the system will stabilize only at one beat frequency: -83-1/3 kc. This frequency change corresponds to a signal frequency change of one megacycle. Therefore, if the discriminator is used both forward and reversed with each of the five reference crystals, ten channels are available from only five reference crystals. Furthermore, since change of the cross-over frequency of the discriminator will change the master oscillator frequency, the transmit-receive change is accomplished by changing the cross-over frequency one-sixth of the i-f nominal frequency, or ten kc. Systems using high-frequency i-f amplifiers accomplish transmit-receive through a crystal controlled side-step oscillator.

Counting is performed by paralleling the rectifier outputs and connecting one of the relays to a stepping relay. The stepping relay is preset by the setting of channel selector switches and is so connected as to anticipate the next to the last count. As the last count is made the discriminator is switched in and controls the motor drive.

The most serious fault of systems using the British TR1407 principle is infrequent and random improper channel selection. This mischannel occurs without any warning or evidence of error to the operator except in cases of complete failure to select a channel. Recent improvements in the monitor circuit have resulted in greatly improved channel selection reliability, but still there exists the possibility of channel selection error without evidence of the error to the operator. A major modification to the system has been proposed whereby the possibility of improper selection without warning of other error is reduced. The proposed plan is to have a sector switch on the master oscillator shaft and to eliminate counting the entire spectrum. A count is made at the beginning of each sector to establish a frequency reference and further counts are made, as required, to the selected channel. The system could not stabilize except when the oscillator stops in the proper sector, thus reducing the possibility of error without warning.

Another fault of the systems in use at present is spurious signals, both radiated and received, that are generated by the multipliers following the master oscillator. Although the multiplication is small, six to twelve times, the resulting interference is of major importance.

2. System Based on AN/ARC-19 (XA-1) Set

The AN/ARC-19 (XA-1) radio set is an example of a system utilizing a monitor that eliminates counting. This equipment provides 1751 channels spaced every 100 kc in the operating range of 225 to 400 Mc derived from 23 crystals. Figure 5 is a block diagram of the monitor unit.

A brief description of the monitor operation is as follows: Selection of a channel serves to switch the proper harmonic of the first crystal oscillator and the correct crystals in the second, third, and fourth crystal oscillators. The V.F.O. master oscillator is then caused to sweep the

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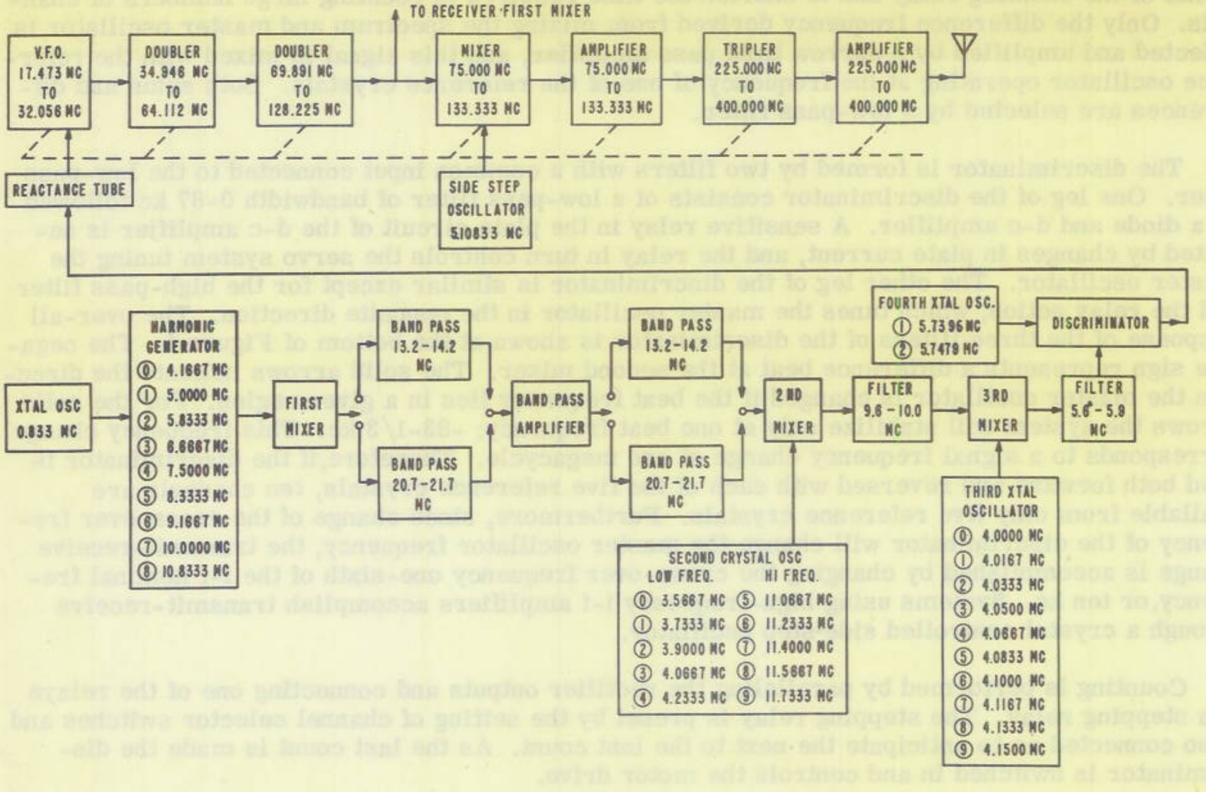

Figure 5

tuning range from the high frequency end to the low. As the master oscillator approaches the selected frequency, the heterodyne beat through the three mixers will approach the frequency of the discriminator crystal oscillator. The control of the tuning motor is then transferred to the discriminator. The reactance tube will pull the master oscillator "on frequency" but the motor continues to tune the oscillator until the error voltage from the discriminator falls between specified limits. The discriminator is both frequency and phase sensitive and will hold the master oscillator on frequency over a wide range. The circuit is stabilized by using a crystal oscillator to establish the discriminator center frequency. By using sector switches and proper choice of crystal frequencies, the system can stabilize at only one frequency, the selected master oscillator frequency. This is an important advantage of this monitor principal. There is virtually no possibility of improper channel selection without evidence to the operator of the error. Evaluation tests made on preproduction models of this radio set indicate the monitor performance to be very good under service conditions. The principal source of failure noted was hunting of the motor drive about the selected channel. Any system utilizing two types of control is subject to instability between the two controls, but it should be possible, by proper design, to eliminate the instability.

The use of a reactance tube forces a lower operating frequency for the system master oscillator which in turn requires a high multiplication to the final frequency and results in more spurious responses. The use of a rather large number of crystals (23) in the monitor presents a problem of isolating the monitor from the receiver to avoid more spurious responses or even blocked channels. There is a definite advantage to monitors that employ as few crystals as possible unless the monitor chassis may be adequately shielded from the receiver.

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Measurements of the number of channels blocked or impaired by heterodyne beats were made on systems using different monitors. The test consisted of tuning a test signal with no modulation and variable strength between 5 and 100 microvolts through every channel pass-band and noting any beats or irregularities. Radio Set AN/URC-3 employing six monitor crystals and a multiplication of six following the master oscillator had no interference on any of 824 available channels. Radio Set AN/ARC-19 (XN-2) employing eleven monitor crystals and a multiplication of six following the master oscillator had interference on 75 of 876 available channels. Radio Set AN/ARC-19 (XA-1), employing 23 monitor crystals and a multiplication of twelve following the master oscillator, had interference on 434 of 1751 channels available. It must be noted, however, that both the AN/ARC-19 (XN-2) and the AN/ARC-19 (XA-1) have continuously operating guard receivers which produce some of the blocked channels.

3. System Based on AN/ARC-27 Set

A third type of monitor (AN/ARC-27) is shown in Figure 6. Actually it is not a monitor but a system for multichannel operation. Almost four thousand channels, spaced fifty kc apart, in the frequency range of 200 to 400 Mc are available from thirty-one crystals. The system differs materially from types described above in that no master oscillator is employed. The incoming

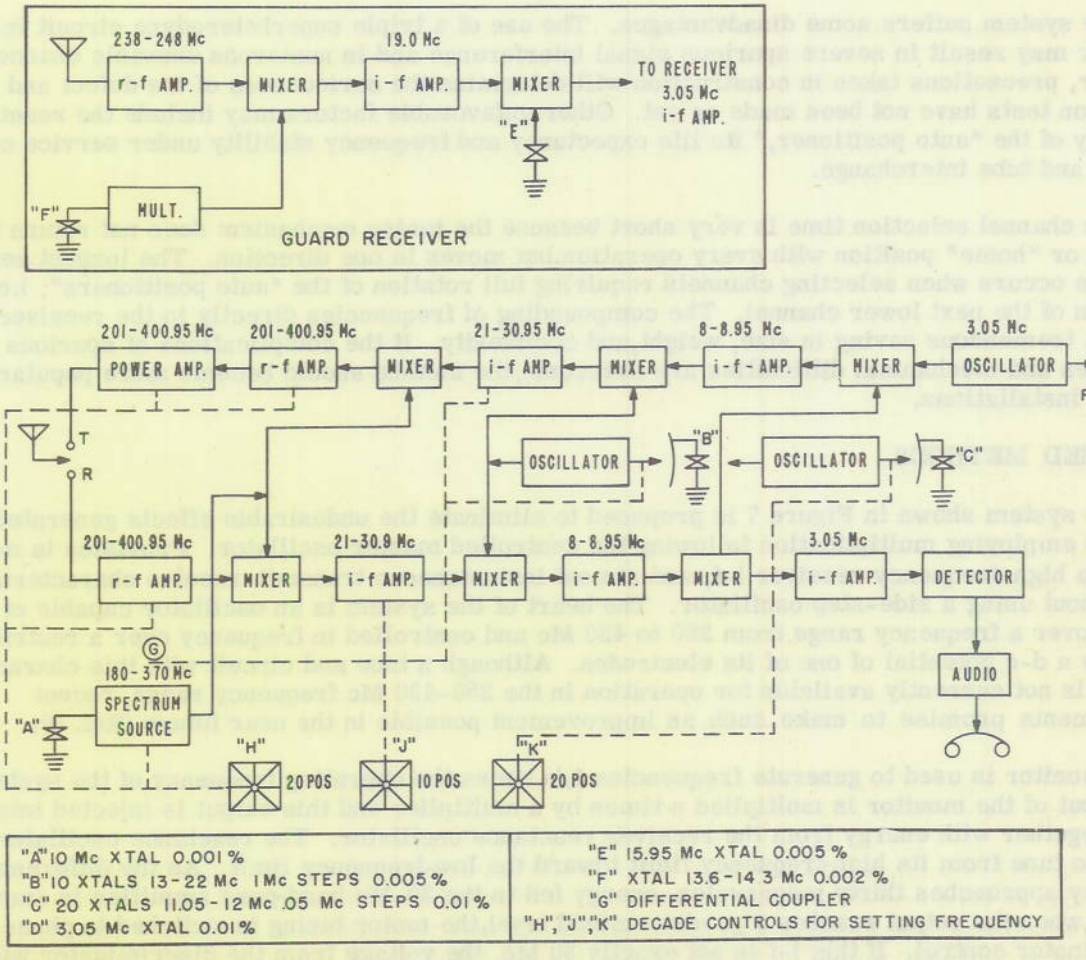

Figure 6

signal is amplified by an r-f amplifier and mixed with a selected harmonic from a ten-megacycle crystal oscillator. The output of the first mixer is amplified by a variable-frequency i-f amplifier with the tuning suitably ganged with the r-f circuits and within the frequency range of 21 to 30.9 Mc. The signal is mixed again with one of ten crystals of frequencies from 13 to 22 Mc in one-Mc steps. The output of the second mixer is selected and amplified by a band pass amplifier of frequency from 8 to 8.95 Mcs. and mixed with one of twenty crystals of frequencies from 11.05 to 12 Mc in 50 kc steps.

The output of the third mixer feeds the final i-f amplifier from which the audio output is derived after rectification. The transmitted signal is compounded in the same manner except the process is reversed starting with the 3.65-Mc crystal oscillator. In practice the "H" control causes an "auto positioner" to position the r-f tuned circuits in ten-Mc steps. The "J" control causes an "auto positioner" to select the proper crystal and position the r-f circuits in one-Mc steps; i.e., a vernier on the ten-Mc setting. It also sets the correct center frequency of the variable-frequency i-f amplifier. The "K" control selects one of twenty crystals which provide the 50-kc channel spacing. If fewer channels with wider channel spacing are desired, it is possible to provide them by employing only ten crystals of frequencies spaced 100 kc in the circuit operated by the "K" control.

The system suffers some disadvantages. The use of a triple superheterodyne circuit in the receiver may result in severe spurious signal interference and in numerous unusable channels. However, precautions taken in construction will determine the seriousness of the defect and evaluation tests have not been made as yet. Other unfavorable factors may include the reset accuracy of the "auto positioner," its life expectancy and frequency stability under service conditions, and tube interchange.

The channel selection time is very short because the tuning mechanism does not return to a starting or "home" position with every operation, but moves in one direction. The longest selection time occurs when selecting channels requiring full rotation of the "auto positioners"; i.e., selection of the next lower channel. The compounding of frequencies directly in the receiver allows a tremendous saving in size, weight, and complexity. If the complications of spurious responses and mechanical difficulties are overcome, the method should become more popular in aircraft installations.

PROPOSED METHODS

The system shown in Figure 7 is proposed to eliminate the undesirable effects generated in systems employing multiplication following the controlled master oscillator. Provision is made to have a high-frequency receiver i-f, and almost instantaneous transmit-receive characteristics without using a side-step oscillator. The heart of the system is an oscillator capable of operation over a frequency range from 250 to 430 Mc and controlled in frequency over a restricted range by a d-c potential of one of its electrodes. Although a tube and circuit with this characteristic is not currently available for operation in the 250-430 Mc frequency range, recent developments promise to make such an improvement possible in the near future (Ref. 9).

A monitor is used to generate frequencies 1/n times the operating frequency of the system. The output of the monitor is multiplied n times by a multiplier and this output is injected into a mixer together with energy from the receiver reactance oscillator. The reactance oscillator is caused to tune from its high-frequency limit toward the low-frequency limit. As the difference frequency approaches thirty megacycles, energy fed to the 30-Mc band-pass amplifier is amplified; and, when the output reaches a predetermined level, the motor tuning is switched to phase discriminator control. If this i-f is not exactly 30 Mc, the voltage from the discriminator will tune the reactance oscillator until the beat is 30 Mc. In addition, the amplitude of the error voltage from the discriminator is used in controlling the motor to tune the oscillator in the event of long time drifts beyond the range of the electronic tuning. The operation of the phase discriminator is similar to the operation of the Foster-Seely discriminator used in f-m receivers except

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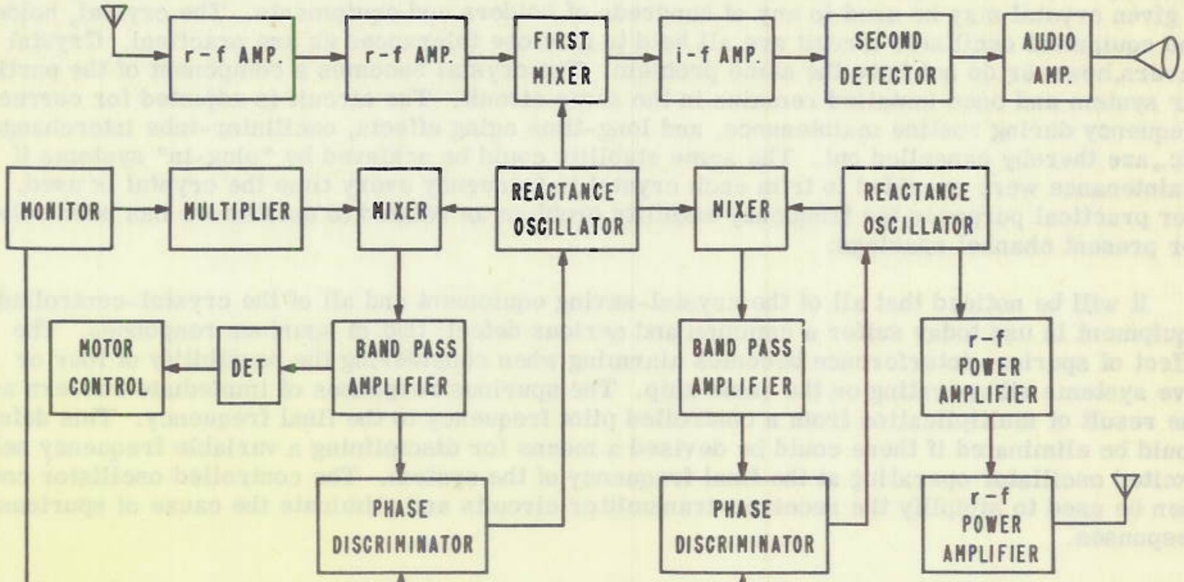

Figure 7

that the center frequency, instead of being determined by the tuning of the secondary of the circuit, is determined by a frequency supplied from a crystal oscillator, in this case operating at 30 Mc. When the frequency of the i-f is exactly 90° out of phase with the 30-Mc crystal oscillator frequency, the discriminator output will be zero. If the i-f deviates from the 90° out of phase condition, a positive or negative voltage will be produced at the discriminator output, depending upon whether the change was to make the i-f leading or lagging. As the i-f approaches exactly 30 Mc, the frequencies will pass in and out of phase at a rate determined by the beat difference between them. This "instantaneous" in-phase condition will produce an output from the discriminator which will tune the reactance oscillator to bring it on frequency.

The transmitter excitation is derived from a reactance oscillator similar to that used for the receiver local oscillator. The two reactance oscillators are ganged together and tracking is assumed to be good enough to adjust the transmitter oscillator within ±2 megacycles of the desired frequency. Since the receiver oscillator is stabilized it may be used as the reference for the transmitter. When the system is switched to transmit, the transmitter oscillator is energized and the difference beat of 30 Mc ± 2 Mc between the transmitter and receiver oscillators is amplified by a 30-Mc amplifier and fed to a phase discriminator. Electronic tuning brings the transmitter on frequency. The phase discriminator is stabilized by the same crystal oscillator as used with the receiver discriminator.

An outstanding feature of the proposed system is the elimination of spurious interference, both radiated and received. The transmitter does not have any multipliers and is just a cascade of voltage and power amplifiers all operating at the system output frequencies. The receiver is a simple superheterodyne circuit with a high intermediate-frequency to secure image rejection and with a simple self-excited local oscillator operating at the system frequency.

CONCLUSIONS AND SUMMARY

The techniques of precision frequency control have advanced rapidly since the introduction of crystal-saving techniques and overmode crystals. The operating over-all frequency stability

[redacted]

of crystal-saving systems is better than systems employing plug-in crystals. This is because the plug-in crystal is generally tuned for maximum activity rather than for correct frequency. A given crystal may be used in any of hundreds of holders and equipments. The crystal, holder, and equipment oscillator circuit are all held to as close tolerances as are practical. Crystal savers, however, do not have the same problem. The crystal becomes a component of the particular system and once installed remains in the same circuit. The circuit is adjusted for correct frequency during routine maintenance, and long-time aging effects, oscillator-tube interchange, etc., are thereby cancelled out. The same stability could be achieved by "plug-in" systems if maintenance were provided to trim each crystal to frequency every time the crystal is used. For practical purposes, the frequency-stability problem as related to oscillators has been solved for present channel spacings.

It will be noticed that all of the crystal-saving equipment and all of the crystal-controlled equipment in use today suffer a common and serious defect: that of spurious responses. The effect of spurious interference becomes alarming when considering the possibility of four or five systems all operating on the same ship. The spurious responses of immediate concern are the result of multiplication from a controlled pilot frequency to the final frequency. This defect could be eliminated if there could be devised a means for disciplining a variable frequency self-excited oscillator operating at the final frequency of the system. The controlled oscillator could then be used to simplify the receiver-transmitter circuits and eliminate the cause of spurious responses.

The characteristics of frequency-control systems in order of importance are: channel selection reliability, frequency accuracy, channel selection time, number of spurious signals generated which may adversely affect the receiver-transmitter performance, size, weight and complication. The emphasis to date has been placed on developing a good receiver and good transmitter. More attention should be given the frequency-determining element, its reliability, and its effect on the receiver-transmitter performance. The history of the development of crystal savers indicates that there is a practical limit to the number of crystals that may be eliminated without sacrificing performance and complication. Both AN/ARC-19 radio sets were originally designed to operate with less than six crystals. In practical operation it was discovered that the addition of a few more crystals simplified operation and increased reliability. Further work is needed to reduce the size, weight, and complexity of the systems, or at least to achieve better performance from existing equipment.

Tabulated below are some of the characteristics of communication equipment operating in the 225-400 Mc frequency band. The data are taken from evaluation reports on preproduction models of the subject equipment (Refs. 10 and 11). The spurious response data were measured with the receivers tuned to approximately 370 Mc and the signal generator was tuned with full output from 225 to 400 Mc. The strength of the spurious response is measured relative to the desired signal. The receiver sensitivity is for ten decibels signal plus noise to noise ratio. The tests were not conducted under identical conditions and the data are used to indicate a trend rather than an exact comparison.

	RDZ	AN/URC-3	AN/ARC-19 (XN-2)	AN/ARC-19 (XA-1)
No. of Channels	875	824	876	1751
No. of Clear Channels	825	824	847	1661
Channel Spacing	200kc	200kc	200kc	100kc
No. of Crystals	875	6	11	23
Spurious Responses, 80 db	13	3	5	17
Receiver Sensitivity	3-20μv	2-6μv	1-4μv	1-4μv
Channel Selection Time	0.5-3sec	4.5-8sec	1 1/2-5 1/2sec	4.5-8sec
Frequency Accuracy	± 16kc	± 30kc	± 8kc	± 4kc
Multiplication to Operating Frequency	64	6	6	12

[redacted]

A clear channel, as used in this table, is defined as a receiver channel which is free of heterodyne beats and blocking due to any internally generated signals or a combination of the desired signal and internally-generated signals.

Considerably more information is available on spurious interference in the RDZ receiver than the other systems. Complete system analysis may be found in an NRL report by A. W. Walters, "Analysis of Channel Interference on Communication Systems," Report R-3059 (Confidential), 1 August 1947 (Ref. 12). The data in the table are taken from an NRL evaluation report on RDZ-1 by W. E. W. Howe, NRL Report R-2929 (Restricted), 19 August 1946. The data in Mr. Howe's report were taken under approximately the same conditions as that of the other systems. The more extensive survey by Mr. Walters indicated an average of twelve spurious responses per receiver channel.

From the table it is noted that the RDZ system requires a crystal for every channel, has a very large multiplication to final frequency, a large number of spurious responses, a fair sensitivity, and moderate frequency stability. The AN/URC-3 and the AN/ARC-19 (XN-2), both based on the TR1407 principal, exhibit an improvement in spurious response and receiver sensitivity. The large frequency deviation noted for the AN/URC-3 is caused by an error in uncontrolled master oscillator drift adjustment and is believed to be peculiar to the equipment measured and not inherent in the system. The AN/ARC-19 (XA-1) radio set has a marked improvement in frequency stability. The improvement was made at the cost of spurious responses and blocked channels. Since this equipment is made for aircraft where size and weight are all-important, it may be expected that a similar system could be made with more adequate monitor shielding and fewer spurious responses.

Not shown on the table, but very important, is channel selection reliability. In cases where the equipment makes a distinct mischannel, a table could be compiled of misses vs correct, but the systems suffer other faults which render them useless even when the channel selection is correct. The most common fault other than a complete mischannel is "hunting" of the control system about the desired channel. The AN/ARC-19 (XA-1) system had practically no complete mischannels noted during six months of testing. The complete mischannels occurred only during failure of parts. The system, however, was susceptible to hunting. If hunting occurred when a channel was first set up, it would continue to hunt regardless of the number of times the equipment was recycled. The equipment would not necessarily hunt on all channels nor on adjacent channels. During the hunting condition the equipment is rendered useless, but a tone is heard by the operator and he is made aware of the improper operation. The AN/ARC-19 (XN-2) system was susceptible to infrequent mischannels during the same test period. The mischannels were random in nature and, except for component failure, the correct channel would be set up if the equipment were recycled. There is little choice between the two faults. If the one system hunts on a given channel, the operator is aware of it but helpless to correct it. If the other system mischannels, the operator is not aware of it. If he should recycle the equipment, the probability is good that the correct channel would be set up.

RECOMMENDATIONS

It is recommended that:

1. Future work on multichannel communication equipment be directed toward increasing channel selection reliability.

2. The channel selecting circuit be isolated from the receiver-transmitter so as to eliminate all sources of blocked channels, spurious responses, and spurious radiations.

3. A development program be initiated to devise and develop a wide-range oscillator having an electronic tuning range of ± 4 Mc throughout the entire continuous tuning range as specified for the receiver.

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†References are cited particularly for material on Reactance-Variation Circuits.

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