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Tunable, High Stability, Microwave Oscillator*

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This paper describes a microwave oscillator which is phase stabilized to a high-order microwave harmonic from a stable frequency standard, and which may be conveniently tuned through any selected 200-Mc band in the microwave frequency range. One form of this oscillator has a stability of a few parts in 10^8 throughout the 200-Mc tuning range, while a slightly more complex form has a stability of a few parts in 10^9 through a reduced tuning range. While this oscillator has only been applied to a high resolution microwave spectrometer and to the spectrum analysis of stable cw microwave signals, it is also well adapted to gas beam maser spectroscopy.

THE advantages which are obtained by phase stabilizing a microwave oscillator, either a klystron or backward wave oscillator, are well known.[1] The method employed here has two distinct advantages over previously reported methods. (1) All microwave signal drift and instability is essentially controlled by *one* vhf oscillator whose stability in turn can be controlled by standard techniques, or increased by further application of phase stabilization techniques. (2) The stabilized microwave oscillator may be tuned over a 200-Mc range.

The principal sources of oscillator frequency instability are (1) thermal variations of the resonator cavity dimensions in klystrons, (2) sensitivity of the oscillator tuning electrode to acoustical vibrations, (3) sensitivity of the oscillator tuning to control element voltage variations, (4) sensitivity of the oscillator tuning to variations in load admittance, (5) presence of stray magnetic fields, and (6) sensitivity of the oscillator tuning to noise in the oscillator electron stream.[2] The first five instability causes can be greatly reduced by using acoustical and magnetic shielding, temperature regulation, power supply voltage regulation, and load isolation. However, all six instability sources can be compensated by the application of phase stabilization.

A number of phase stabilized microwave oscillators have been constructed at various laboratories.[1,3–8] However, these oscillators either lack the required stability or have only limited application due to a narrow tuning range. In contrast, the stabilization technique described here affords both high stability and a wide tuning range. These features make this oscillator very flexible not only in its present primary application to high resolution microwave spectroscopy, but also in microwave maser spectroscopy and in other applications such as microwave spectral density measurements on stable cw signals.

PHASE STABILIZATION CONTROL SYSTEM

The frequency control system operation can be outlined with the aid of the block diagram shown in Fig. 1. Four main components are used in the frequency control system. These are (1) a microwave oscillator, which may be either a klystron or a backward wave oscillator (BWO); (2) a crystal-controlled secondary frequency standard with an associated frequency multiplier chain to generate microwave harmonics; (3) a phase lock receiver which may be tuned from 50 to 260 Mc and which has a dual phase detector output; (4) a 60-cycle servo control system which includes modulator, amplifier, and motor to tune the oscillator mechanical frequency control element.[9]

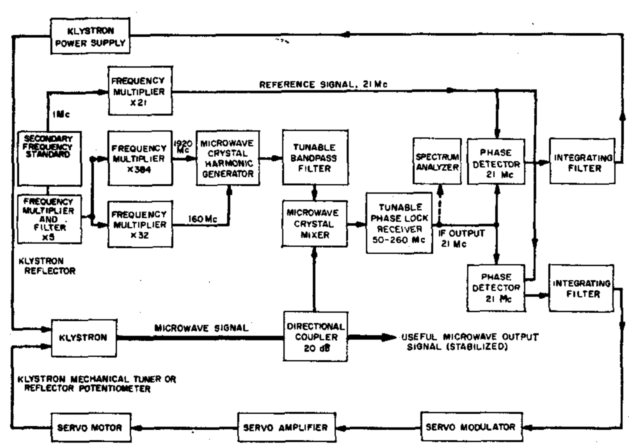

FIG. 1. Phase lock control system. This system includes a spectrum analyzer for monitoring the phase lock receiver performance.

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[1] M. Peter and M. W. P. Strandberg, Proc. Inst. Radio Engrs. **43**, 869 (1955).

[2] A discussion of this noise source for klystrons is given in Chap. 17 of *Klystrons and Microwave Triodes* by D. R. Hamilton, J. K. Knipp, and J. B. H. Kuper, MIT Radiation Laboratory Series (McGraw-Hill Book Company, Inc., New York, 1948), Vol. 7.

[3] R. W. Zimmerer, Rev. Sci. Instr. **31**, 106 (1960).

[4] R. W. Zimmerer, Rev. Sci. Instr. **30**, 1052 (1960).

[5] E. F. Davis, External Publication No. 380, University of California Jet Propulsion Laboratory, June, 1957.

[6] M. C. Thompson and J. V. Cateora, Rev. Sci. Instr. **28**, 656 (1957).

[7] M. C. Thompson, M. J. Vetter, and D. M. Waters, Electronics **31**, 100 (April, 1958).

[8] A. Narath and W. D. Gwinn, Rev. Sci. Instr. **33**, 79 (1962).

[9] This element can be either the klystron mechanical tuning control or the reflector voltage control. The klystron reflector tuning mode is usually only broad enough to allow a limited frequency coverage in this latter method. However, for narrow frequency control ranges, 10–30 Mc, such a technique is very convenient. In the case of a BWO, the servo control can be applied to the helix voltage control in order to cover the entire frequency span of the tube.

A small sample of the microwave klystron output signal is obtained from a 20-dB directional coupler and is fed into a microwave crystal mixer. A second microwave signal is generated by high-order frequency multiplication from a very stable crystal-controlled 1-Mc oscillator and is also fed to the microwave crystal mixer. By filtering these microwave harmonics with a tunable bandpass filter a particular harmonic may be selected such that the heterodyne signal between this harmonic and the klystron will fall within the frequency range 50–260 Mc. The heterodyne signal which is detected in the microwave crystal mixer is applied to a wide range (50–260 Mc) phase lock superheterodyne receiver. A phase error signal is generated by comparing the receiver i.f. output signal with a stable 21-Mc reference signal. This phase error signal is fed to the voltage control tuning element of the microwave oscillator in such a way as to reduce the resultant error signal amplitude with respect to the local oscillator *in the receiver*. If the receiver 21-Mc reference signal is very stable (one cycle in 10^8 cycles or better), then the klystron frequency will be determined by the receiver local oscillator and not by the 21-Mc reference signal, as long as the klystron oscillator is within the proper control range. If the reference oscillator is not stable, then the klystron instability will be the sum of the local oscillator and reference oscillator instabilities.

In order to restrict tuning and residual error control to only the local oscillator the phase reference signal is derived by direct frequency multiplication from the master 1-Mc frequency standard controlling the frequency multiplier chain. In this way the only uncompensated signal is placed entirely in the receiver local oscillator. Because the over-all stability is limited only by the local oscillator, great care was taken to ensure that this oscillator was stable by providing adequate isolation, light loading, and thermal and electronic regulation.

If the system were operated with only electronic phase lock control, the microwave oscillator would "follow" the receiver until the system reached the end of the mode or the limit of its electronic control range. If either the receiver or the klystron were tuned beyond the control limit, the klystron frequency would no longer be controlled and would fall out of lock. To prevent this, the second phase detector output from the receiver is applied to a servomechanical system to correct the mechanical mistuning of the klystron (or BWO helix voltage control) to keep the electronic error control signal near zero and thereby keep the electronic frequency control system from reaching the control limit. Hence, the servomechanical control acts to extend the microwave oscillator electronic control range. By tuning the receiver, an "error" signal is created which will cause the servomechanical controller to "correct" the microwave oscillator mechanical tuning. This provides a method of tuning the microwave oscillator by tuning the receiver; the microwave tuning range is therefore the same as the receiver tuning range. A synchronous clock motor has been attached to the receiver tuning dial to provide a slow sweep drive of the microwave oscillator.

The phase detector which develops the electronic error signal for the klystron reflector electrode must be able to operate at a high voltage level, while the phase detector which develops the servomechanical control signal must work at a low voltage level. This problem is handled by feeding the receiver i.f. signal into two phase detectors, one of which is appropriately insulated for high voltage operation. Since each phase detector will generate the same error signal, a filter circuit is used in order to limit the audio frequency response band of the servomechanical control loop, which will not respond to voltage variations of a frequency greater than 4 cps. The servomechanical loop compensates for slow microwave oscillator frequency fluctuations and gives master tuning control to the receiver, while the electronic control loop corrects oscillator frequency fluctuations up to about 100 kc.

A schematic diagram of the receiver double phase detector is given in Fig. 2. The circuit form chosen here permits balanced operation to ground as seen by the floating portion of the phase detector. The phase detector makes use of a single balanced transformer for the i.f. signal input. The reference signal is capacitively injected at the center tap of the balanced transformer. This method of reference signal injection eliminates the problem of designing and constructing a dual transformer for the phase detector in which physical dimensions and location are extremely critical for proper circuit operation. The floating portion of the phase detector is capacitively coupled to the transformer output terminals. A ground reference is established with a capacitor bypass to ground at the point X (see Fig. 2). The floating detector output signal is applied to a transistor amplifier which uses type 2N341 transistors in order to give an output signal amplitude of about ±60 V. This signal is sufficient to electronically lock the microwave oscillator over a range of about ±25 Mc which depends upon the voltage tuning sensitivity of the particular microwave oscillator in use. For optimum performance, the phase lock loop gain and

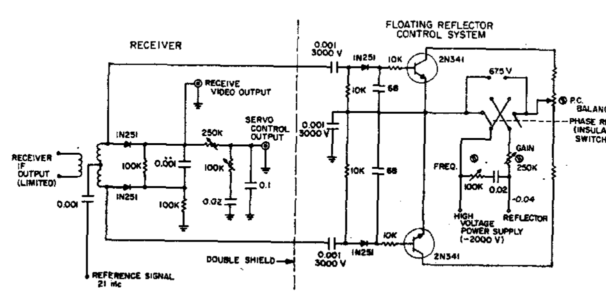

FIG. 2. Double phase detector.

frequency response controls were made adjustable, primarily because the voltage tuning sensitivity of a particular klystron will not be constant throughout the oscillator tuning range. For klystrons, the reflector tuning sensitivity may vary from 0.05 to 4 Mc/V; while for BWO's, tuning sensitivity is of the order of 10–20 Mc/V. Thus, the minimum klystron electronic lock range will be no less than 6 Mc. With a good lock the residual phase noise is restricted to a 500- to 1000-cps band centered at the microwave oscillator frequency. By careful adjustment of the lock loop response controls, this noise bandwidth can be further reduced to about 200 cps.

In the phase locked microwave oscillator control system described above, the residual FM is a few hundred cycles per second. To further decrease this instability, the receiver local oscillator may itself be phase stabilized with reference to a harmonic from a very stable low frequency VFO. A simplified block diagram of such a system is shown in Fig. 3. A modified Gertsch model AM-1 vhf interpolator was used for this purpose, and permitted the receiver local oscillator to be stabilized to about 20 cps at 200 Mc, or to one part in 10^7. However, the tuning range was reduced to a few megacycles. If a wider range stable VFO were available, then the tuning range could be extended. Because the receiver functions as a difference frequency detector, this local oscillator stability corresponds to a microwave oscillator stability of one cycle in 10^9 cycles, or 20 cycles at 20 000 Mc. If a considerably reduced tuning range were acceptable, even further stabilization could be achieved by extending this technique. Such stability was not required in the present study.

Except for the frequency multipliers and the tunable phase lock receiver with its associated phase detectors and integrating filters, all of the equipment used in this stabilization system is of standard commercial manufacture. The microwave frequency multipliers were adapted from equipment constructed at JPL for other applications. The phase lock receiver is a modified commercial FM telemetry receiver.

As constructed, the microwave oscillator control system amounts to a double conversion microwave superheterodyne receiver[10] with a variable first conversion frequency and a fixed, 21 Mc, second conversion frequency. A telemetering receiver was chosen for the first converter because greater image and spurious signal rejection could be obtained at detection frequencies above 100 Mc. The slight loss in receiver sensitivity arising from the rf amplifier noise figure is unimportant because the microwave multiplier harmonics are strong enough up to at least 40 000 Mc. Further, the use of a simple microwave superheterodyne receiver could produce severe interference problems with other test equipment due to local oscillator harmonic radiation into the waveguide. By using a vhf telemetering receiver, the internal rf amplifiers act as isolation amplifiers to keep down stray radiation.

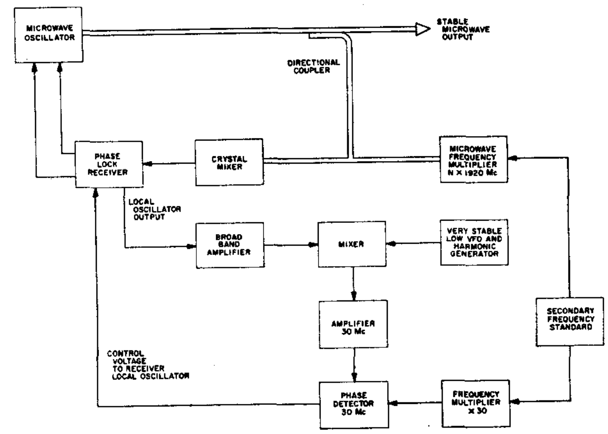

FIG. 3. Auxiliary stabilization of the phase lock receiver local oscillator.

NOISE AND STABILITY MEASURING SYSTEMS

A measuring system is required which will determine the microwave oscillator characteristics, noise bandwidth, stability, drift, and tunability. A description is given of two measuring systems which were used to determine the above parameters. For actual operation applications, a third, more convenient system was used even though this measuring system had the disadvantage that it would not see small deviations of the microwave oscillator from the control local oscillator; such deviations might occur if the phase lock system were incorrectly adjusted. The desired measurements were made with a spectrally pure crystal-controlled 1-Mc secondary frequency standard (Hewlett-Packard model 104AR quartz oscillator). The microwave frequency multiplier chain which was driven by this oscillator had a measured spectral power distribution of 3 cps for harmonics near 12 000 Mc.

A block diagram of the first measuring system is shown in Fig. 4(a). This system employs two adjacent 160-Mc harmonics from the main frequency multiplier chain. One of these 160-Mc harmonics is used for phase lock stabilization of the microwave oscillator. The stabilized klystron oscillator is tuned to 500 kc from the second 160-Mc harmonic to produce a heterodyne signal suitable for examination by a high resolution spectrum analyzer (Panoramic SB-12a). The power spectrum of the 160-Mc harmonics was measured and found to be 3 cps wide. Thus, negligible noise was introduced into the microwave oscillator from this source. Further, by using two adjacent 160-Mc harmonics the beat signal between the "stabilized" klystron and the 160-Mc standard harmonic would consist

[10] Standard microwave receivers are described in S. N. Van Voorhis, *Microwave Receivers* (McGraw-Hill Book Company, Inc., New York, 1948).

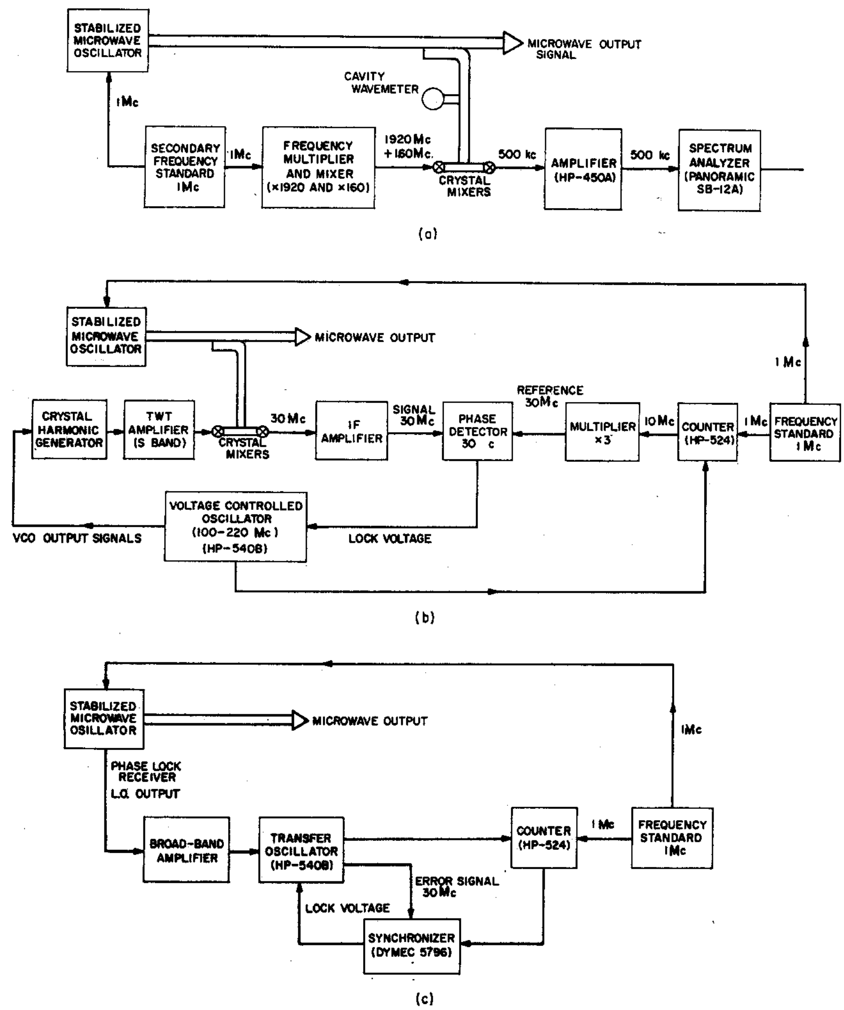

FIG. 4. Three systems used for measuring the microwave oscillator stability. The secondary frequency standard was stable to ±3 parts in 10^{10} at a frequency of 1 Mc.

of the noise spectrum of the klystron. Both absolute stability and drift could also be measured with this system.

A second system which is shown in Fig. 4(b) was used to measure stability, drift, and tuning characteristics at frequencies other than near one of the harmonics available from the frequency multiplier chain. S-band (2000 to 4000 Mc) harmonics from a 100–200-Mc oscillator (H-P model 540-B transfer oscillator) were amplified by a traveling wave tube amplifier (H-P model 491A) and applied to either a microwave crystal or a varactor harmonic generator. The 100–220 Mc oscillator could be tuned until the difference frequency between one of its harmonics and the stabilized klystron signal was 30 Mc. This difference frequency was amplified by a 30-Mc i.f. amplifier and fed to a Dymec model 5796 synchronizer. The dc control signal output from the synchronizer was used to phase lock the 540B transfer oscillator to the klystron signal. The 540B oscillator frequency was counted by an H-P model 524 counter which had its time base controlled by the master 1-Mc frequency standard. The counter actuated a digital printer with an analog output which could be used to provide an X-axis sweep on an X-Y recorder. With this system very precise measurements could be made of the over-all system stability and drift.

The third measuring system was much more convenient than the first two, but involved the assumption that the klystron was tightly locked to the control phase lock receiver local oscillator, so that the klystron noise and stability would closely approximate that of the local oscillator. If this were not the case, then additional noise and instability will appear which are more characteristic of the klystron than of the receiver local oscillator. Consequently, this system required occasional checks. A signal from a coupling loop in the vicinity of the receiver local oscillator was amplified by a wide band distributed amplifier (H-P-460A) and mixed in a crystal with a sample of the H-P 540B transfer oscillator signal to generate a 30-Mc beat signal. This beat signal was fed to a Dymec 5796 synchronizer, the output of which was used to lock the 540-B transfer oscillator to the receiver local oscillator. A sample signal from the transfer oscillator was counted by an electronic counter (H-P 524). This method was used in

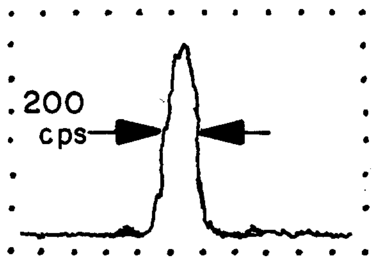

FIG. 5. Noise bandwidth of the stabilized klystron at 19 000 Mc. This signal was observed with measuring system (b) in Fig. 4.

order to (1) obtain an adequate drive signal for the counter, (2) prevent serious disturbance of the local oscillator stability, and (3) prevent coupling stray signals from the counter and the transfer oscillator into the receiver where they would interfere with the klystron control circuits.

The third frequency measuring method was used in actual applications of the stabilized microwave oscillator. However, the second measuring system was used for all measurements on the microwave oscillator stability and tunability because the use of this system involved no assumptions about the phase lock control of the microwave oscillator and allowed observation of the over-all stability, including that of the receiver.

PERFORMANCE AND RESULTS

Using the two measuring systems described above, the following results were obtained. The phase stabilized microwave oscillator exhibited a noise bandwidth of 200 cps (see Fig. 5). The microwave oscillator drift was observed to be the same as the receiver local oscillator drift which is about 1 kc/h as measured by the second system. Long time stability was also of the same magnitude.

Tuning the receiver produced a decrease in stability, as shown in Fig. 6. A rapid tuning rate of 100 kc/min was accompanied by a decreased stability of 2.0 kc/min. Slower tuning rates were less affected; at a tuning rate of 25.5 kc/min, the oscillator instability was about 0.5 kc/min. The limiting case of no tuning showed a stability of 1.0 kc/h.

When the receiver local oscillator was phase stabilized, the above performance was improved by about one order of magnitude, a factor which depended upon the quality of the reference oscillator. The over-all microwave oscillator noise bandwidth was reduced to approximately 20 cps. However, the stability and drift were reduced to between 20–50 cycles/h.

The main application of this stabilized oscillator is in "high resolution" microwave spectroscopy. Figure 7 shows a recording of the $\Delta J=0$, $J=10$ transition between l-type doublet levels in HCN. The stronger absorption peak occurs at 24 660.338 Mc. The lines are separated by 134 kc, and have half-widths of 120 kc. This absorption

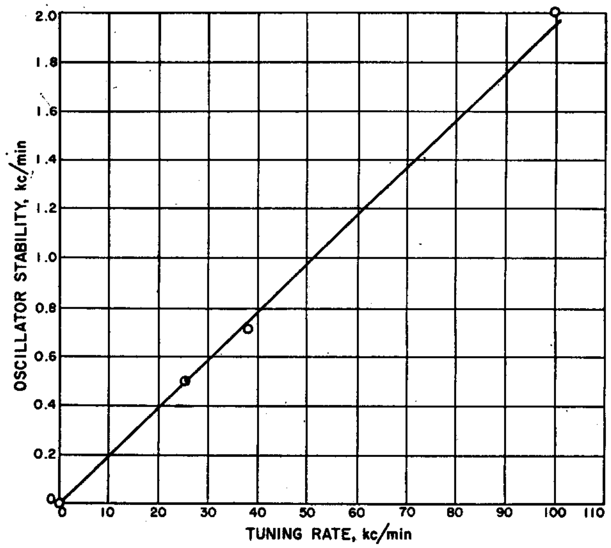

FIG. 6. Microwave oscillator stability dependence upon tuning rate. This curve represents the inherent instability of the phase lock receiver local oscillator transferred to microwave frequencies.

spectrum was observed at a gas pressure of 4 μ, a square wave Stark modulation field of 700 V/cm, a modulation frequency of 10 kc, and a sweep speed of 38 kc/min with a time constant of 2 sec.

The stabilized microwave oscillator has been used in several other applications. It has been used to examine the power spectral distribution of high-order harmonics from crystal controlled frequency multiplier chains. An example of this application is shown in Fig. 8, which shows the spectrum of the 410th harmonic of a 32-Mc crystal controlled oscillator at 13 120 Mc. The observed width of this spectrum (3000 cps) appears to be caused by both

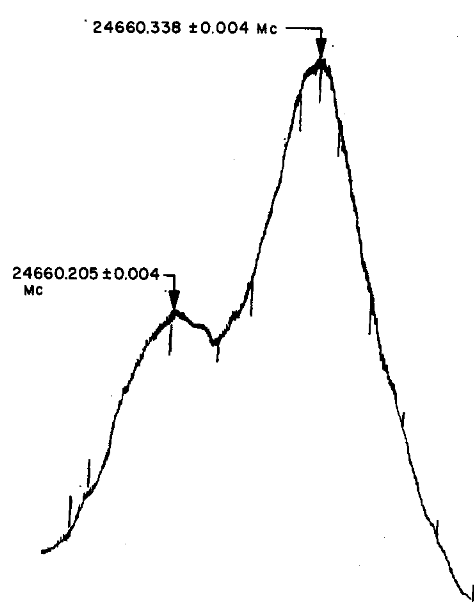

FIG. 7. HCN absorption line at 24 660 Mc.

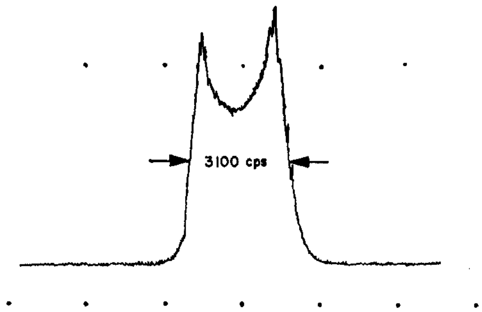

FIG. 8. Power spectral distribution of a test 32-Mc crystal controlled frequency multiplier chain at 13 120 Mc, as observed with the stabilized klystron and a spectrum analyzer.

noise and 60-cycle frequency modulation introduced in the frequency multiplication process. The observed width of the 32-Mc oscillator spectrum is 3 cps. The symmetric form of the spectrum is that characteristic of a frequency modulated cw signal. Further, the 32-Mc oscillator drifted by 2200 cps over a period of one hour.

TABLE I. Comparison of stabilization methods.

References	Stability: Observed in original reference	Stability: Measured[a] here	Stabilization method	Tuning range[b]
c	1000 cps	10 000 cps	AFC, cavity	200 Mc
d	10 000	10 000	AFC, cavity	20
e	2000 ?	4000	AFC, crystal harmonic	15
f	2000 ?	2000	Phase lock	100
g	2000 noise 10 000 drift	1000	Phase lock	6
h	?	500	Phase lock	0
	··· (a)	200	Phase lock	200
i	(b)	20	Phase lock	2

[a] These comparison measurements were made at 19 840 Mc, using crystal multiplier harmonics from a 1-Mc secondary standard (± 3 cps in 10^{10} cps), and a Panoramic SB-12a spectrum analyzer. The method is described in the text.
[b] Basic tuning range was estimated for system which was continuously tunable without any instrumental changes. All quoted values (except work done here) were taken from original reference.
[c] See reference 11.
[d] See reference 12.
[e] S. Geschwind, Ann. N. Y. Acad. Sci. **55**, 751 (1952); R. White, J. Chem. Phys. **23**, 249 (1955).
[f] See reference 8.
[g] See reference 3.
[h] See reference 5.
[i] This work. (a) Receiver local oscillator not phase stabilized. (b) Receiver local oscillator phase locked to stable low frequency tunable oscillator.

DISCUSSION

A comparison was made of the various reported stabilization schemes. For comparing the stabilization scheme performance, the microwave oscillator which was stabilized by the particular scheme under examination was used to measure the difference frequency between two adjacent harmonics from the frequency standard. These adjacent harmonics are separated by exactly 160 Mc so that the control phase lock receiver could be used to "tune in" the frequency standard harmonic adjacent to the harmonic which was being used for oscillator control. This receiver could be used for either the phase lock control systems or the more conventional automatic frequency control systems which utilized frequency standard harmonics for operation. For Pound[11,12] stabilization systems which are based upon the use of a control microwave cavity, the required microwave hybrid tee and cavity were mounted on a separate arm of the microwave output waveguide. Changes in the control system then involved only the transfer of the receiver input to the appropriate crystal detector mount, or the removal of the receiver input antenna signal and the substitution of a microwave crystal mixer for the receiver local oscillator, mixer and rf amplifier. The i.f. detection frequency remained at 21 Mc, which should have no affect upon the validity of the comparisons.

The results of these comparisons are presented in Table I, which also includes from the original papers an effective tuning range which was not observed here only because time was not available to set up the instrumentation for broadband operation. As can be seen, the stabilization systems fall into roughly three categories: moderate stability, high stability, and extremely high stability. The difference between the high stability and the extremely high stability stabilization systems appears to confirm that the use of uncontrolled oscillators prevents phase lock stabilization systems from realizing the greatest possible stability compatible with their tuning range.

[11] R. V. Pound, in C. G. Montgomery, *Techniques of Microwave Measurements* (McGraw-Hill Book Company, Inc., New York, 1947), pp. 58–78.
[12] L. Essen, Proc. Inst. Elec. Eng. (London), Pt. B, **100**, 19 (1953).