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INVESTIGATIONS OF PRECISION FREQUENCY CONTROL TECHNIQUES

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By
EDWARD G. HOLMES and DONALD W. FRASER

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PLACED BY THE U. S. ARMY
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III. CONFERENCES

Representatives of the Signal Corps and Mr. E. G. Holmes of Georgia Tech met in conference at the Squier Signal Laboratory, Fort Monmouth, New Jersey, on March 25, 1955. In this conference, suggested topics for investigations involving needs of the Signal Corps were outlined in some detail. It was decided that the topics listed herein as items (a) and (b) of section I, Purpose, would be undertaken and that experimental work thereon would be initiated on April 1, 1955, the effective date of the contract. New topics were suggested and were made subjects of exploratory investigations.

Following this conference, the latter topics were studied by personnel of this project, and another conference was then held at Squier Signal Laboratory on May 5, 1955. At this conference, consideration was given to various suggested investigations with particular emphasis on available facilities, experience of personnel and probabilities of completing the proposed topics within the period of the contract. It was then mutually agreed that the topics listed herein as item (c) of section I should comprise a basis of investigation.

The 9th Annual Frequency Control Symposium held at Asbury Park, New Jersey, during May 23, 24 and 25, 1955, was attended by E. G. Holmes of this Project. A paper entitled "Frequency Control Above 500 mc," by D. W. Fraser and E. G. Holmes, was presented.

During this conference some of the problems involved in connection with the above-mentioned investigations were discussed with members of the Signal Corps and personnel from other activities who were engaged in related work.
I. PURPOSE

The purpose of this project is threefold: (a) to investigate methods by which temperature-insensitive coaxial cavities may be produced, (b) to obtain long-term stability data, over a period of several months, of a cavity-controlled oscillator which has rendered good short-term performance, (c) to investigate methods by which very short-term stability measurements, in the order of 0.1 to 1.0 second, may be made with an accuracy not exceeding 1 part in $10^9$ and (d) to investigate other related topics as may be mutually agreed upon by the Contracting Officer and Georgia Institute of Technology during the course of this project.
II. ABSTRACT

A conference with representatives of the Signal Corps during this quarter resulted in a decision to concentrate upon three phases of experimental work during the year. These three phases are, respectively: (1) measurement of the long-term frequency characteristics of oscillators already constructed under a previous contract, (2) continuation of development of temperature-insensitive cavities by utilization of materials with small expansivity and (3) development of methods for determining the short-term frequency variations of oscillators of stable mean frequency.

Long-term frequency measurements are to be conducted on a 600-mc oscillator employing an Invar coaxial cavity as the frequency-sensitive element and using a series-capacitor circuit arrangement for improving frequency stability. This oscillator, first developed under the previous contract and later inactivated, was restored to its original condition and is presently under test. Frequency measurements are conducted by a beat process against a standard which demonstrates accuracies of better than 1 part in $10^8$.

Construction of temperature-insensitive cavities is presently restricted to coaxial resonators employing zero-temperature Stupalith as basic material. One cavity, assembled from separate components, has been rendered mechanically rigid by fusing the adjoining surfaces. Annealing, required to be executed at 2300°F, is to be completed and will be followed by measurements of the frequency characteristics of the cavity.

The problems associated with short-term (less than 1 second) frequency measurements have been investigated primarily from a theoretical standpoint, and four possible measurement procedures have been described. The most promising method employs a UHF discriminator combined with amplifiers and recording devices. The theoretical aspects of such discriminators are included, and, in particular, equations which define the optimum performance of these devices are given. One version of a discriminator, suitable for use at 600 mc, is presently under construction and will be subjected to experimental tests during the next period.
IV. SHORT-TERM FREQUENCY MEASUREMENTS

A. Introduction

One of the most important aspects of frequency control is the accurate determination of the absolute and the relative stability of the oscillating element, mechanical or electrical. The term "absolute" might be designated as "average" since frequencies are often compared with some accepted standard and the period of measurement is relatively long. In these measurements small frequency fluctuations about a mean are averaged out and may not appear as factors in the recorded frequency. It is evident that fluctuations, or deviations from the mean, may be significant in many applications and, in some cases, must be accounted for in the design of the network or system which incorporates the generator.

The present study is devoted to frequency measurements in the UHF region and considers short-term frequency variations of vacuum-tube oscillators operating in that region. The designation "short-term" signifies, in general, periods of measurement of less than 1 second. Measurements thus made are "relative" and are not necessarily applied to the average frequency although the results can be combined with simultaneous long-term frequency measurements.

The following paragraphs discuss in some detail the problems involved in making frequency measurements on a short-term basis and outline some possible methods of acquiring the desired information. Theory applicable to measurements made by employing UHF discriminators as frequency-sensitive elements is developed in the appendix, and excerpts therefrom appear in the body of this section when required for completeness or clarification.

B. Problems in Short-Term Measurements

The precision of measurement of frequency fluctuation about a mean is dependent upon many factors. One of the more important of these is the period of time during which information is being supplied to the measuring system and another factor of nearly equal significance is the rate of follow-up, that is, the "writing speed" or "sensing rate" of the system. Finally, the sensitivity of the system is of fundamental importance, and its ultimate value is determined by the noise figure of the network.
It is important to recognize that the frequency measurement of a periodic, or nearly periodic, voltage is primarily determined by a measurement of the phase of that voltage relative to some fixed or imaginary standard. This criterion is particularly useful when the measuring period is much less than a second. It will be seen in the next section that phase-sensitive detectors form the basic measuring devices in all the short-term frequency-measuring systems described.

The desired properties of a practical measuring system may be viewed in best perspective through comparison with the properties of an idealized system. The list of characteristics given below includes the more important properties of such a system. An ideal short-term frequency-measuring system should incorporate the following properties.

a. The noise figure of a practical measuring system may be viewed in best perspective through comparison with the properties of an idealized system. The list of characteristics given below includes the more important properties of such a system. An ideal short-term frequency-measuring system should incorporate the following properties.

The noise figure of an ideal signal generator, from a noise point of view, should generate no noise other than the thermal noise of its internal resistive component $R_o$. It is shown in the reference that the available noise power in the frequency interval $df$ from an ideal signal generator is

$$\text{Noise power} = kT df$$

where $k$ is Boltzman's constant and $T$ is the temperature in degrees Kelvin.

The noise figure of a network is defined in the following manner:

$$F = \frac{\text{available input signal power/ideal available input noise power}}{\text{available output signal power/available output noise power}}$$

The noise figure of a network is thus the ratio of the actual available output noise power to the available output noise power of an ideal network having the same gain characteristic. Therefore, the noise figure of an ideal network that generates no noise itself is $F = 1$; and, correspondingly, the part of the noise figure of any network due to internally generated noise is $F - 1$.

The use of a noise figure of a network originated with H. T. Friis (2). In this reference, the temperature of an ideal signal generator is given as

$$T = 290° \quad K = 17° \quad C = 63° \quad F$$

from which

$$kT = 4 \times 10^{-21} \text{ watt/cycle}$$
b. The sensing characteristics of the measuring and recording portions of the system should have a sufficiently rapid response that the relative phase variation of the input, during the period of measurement, is reflected in an output having a magnitude which is independent of time. That is, a phase deviation of $\Delta \phi$ will result in a voltage change in the output of $\Delta V$ irrespective of the time of measurement.

c. When the input is equal to or greater than the noise level due to an ideal signal generator, the sensitivity of the system should be of sufficient magnitude to produce a measurable output.

d. All components are completely insensitive to variation in local or ambient temperature.

e. The response of the system is linear or follows a prescribed law over a dynamic range which is equal to or greater than the limits of the maximum frequency deviation which shall occur during the period of measurement.

Evidently the characteristics of a practical system of measurement must fall short of the desired properties exhibited by the ideal system. In the succeeding discussion, it is assumed that idealized characteristics apply except when otherwise stated, whereas practical considerations will be considered in the design of individual components of any proposed system.

C. Possible Methods of Short-Term Measurements

Four possible methods of short-term frequency measurement are outlined or discussed below. The first three are not considered practicable at the present time for various reasons but are listed for purposes of completeness.

a. Comparison of a given frequency with a frequency standard can provide significant information under proper conditions. In such an arrangement, it would be necessary that the frequency standard be considerably more stable than the device under test, probably at least one order of magnitude. The method would desirably involve a beat-frequency technique in which the difference frequency would be very small and could be observed by Lissajou action on an oscilloscope.
b. Comparison of the wavelength of an original frequency, \( f_0 \), with the wavelength of a new frequency \( f_0 + \Delta f \) by means of the long-line effect is theoretically practicable for measurement of frequency changes when the period of measurement is very short, i.e., less than one microsecond, and the frequency under study is very high. The basic arrangement is illustrated in Figure 4.1 in which the output of the generator under test arrives at the phase-sensitive detector by each of two paths having a pathlength difference of \( L \) meters. If \( T \) is the period measurement, \( v \) is the velocity along the line and \( f_0 \) the basic frequency, the length of line is such that \( T = \frac{v}{L} \) then the first cycle generated will undergo a phase shift of \( 2\pi f_0 T \) radians in arriving back at the detector while the output of the generator will undergo a phase shift of \( 2\pi T (f_0 + \Delta f) \) radians, where \( \Delta f \) is the average incremental frequency change occurring during the time \( T \). The phase difference is compared and measured by the phase-sensitive detector.

\[
\text{Oscillator Under Test} \quad \frac{2n + 1}{2} \lambda \quad n = 0, 1, 2, \ldots
\]

\[\text{Output} \quad \text{Phase-Sensitive Detector} \]

\[\text{Matched Load} \]

Figure 4.1. Phase Difference by Long-Line Effect.

c. Comparison of frequencies through utilization of memory circuits is practicable at low frequencies. One version of a memory circuit which employs a variable frequency oscillator is described by Van Bladel (3). In the arrangement illustrated in the reference, the frequency of the oscillator is constrained to remain constant for a prescribed period. At the conclusion of this period, the original changing frequency which was to be measured is compared with the unchanged frequency of the oscillator, and a measure of the frequency change is obtained.
d. Measurement of the relative frequency changes of constant-amplitude voltages is possible by means of discriminators. Many versions of devices whose output voltage is related to the input frequency in a linear or prescribed manner are known and have been employed at low and at high frequencies. UHF and microwave discriminators are particularly applicable to the problem presently under study in this contract, and the succeeding discussions are devoted exclusively to that topic and to the resonant cavities which form a convenient frequency-sensitive device for use in the discriminator.

D. Utilization of Cavities in Frequency Measurements

Resonant cavities have found wide use in microwave discriminators because of their high-quality factors, screening of electric fields and relative insensitivity to temperature change. They may be used in a simple magnitude and/or phase-sensing arrangement, or may serve as transmitting or reflecting elements in hybrid transformers such as the "Magic Tee" or "Rat Race".

In the simplest form of measuring device, the cavity appears as an element in one arm of a two-way transmission system as shown in Figure 4.2. The system is arranged so that the losses of the attenuator balance the insertion loss of the cavity while the phase shifter is adjusted so that the voltage $V_2$ arrives at the phase-sensitive detector $\pi$ radians out of phase with $V_3$ when the input frequency is equal to $f_0$, the resonant frequency of the cavity.

It is shown in the appendix that the phase shift $\alpha$ through the cavity due to an incremental frequency change $\Delta f$ is given approximately by

$$\alpha = 2Q_L \frac{\Delta f}{f_0}$$

(4.1)

where $Q_L$ is the loaded $Q$ of the cavity, while the approximate amplitude change is given by

$$\Delta V = (Q \delta)^2$$

(4.2)

where $\delta$ is defined by the equation $f = f_0(1 + \delta)$.

It follows from equations 4.1 and 4.2 that small incremental changes in frequency produce negligible changes in amplitude while producing appreciable
changes in phase. It can be shown that if $V_2 = V_3 = V$ then this output voltage is given by

$$V_{\text{out}} = (2Q\Delta f/f_0)V.$$  \hspace{1cm} (4.3)

![Diagram](image)

**Figure 4.2.** Cavity Use in Phase-Sensitive Device.

The phase-sensing capabilities of the system can be augmented by the use of a hybrid transformer such as is illustrated in Figure 4.3. When energy arrives in arm 1, it divides out-of-phase by 180 degrees in arms 3 and 4. If one of these arms is longer than the other, that is, if one is of length $L$ and the other is of length $L + x$, the energies returned from equal mismatches (such as short circuits) will arrive out-of-phase by an appropriate angle. In particular, if $x = \lambda/8$ they will arrive in quadrature. But if one arm is terminated in a short circuit and the other in an impedance different from zero, the relative phasing will be different from 90 degrees.

![Diagram](image)

**Figure 4.3.** Magic Tee.
In either case, the vector sum of the voltages appears in arm 2 and the vector difference in arm 1. Finally, when the vectors are compared, the output voltage of this phase-sensing device can be shown to be given very closely by

\[ V_{\text{out}} = \left( \frac{4Q \Delta f}{f_0} \right) V \]  

(4.4)

from which it is seen that the effective voltage change is twice as great as was the case of the simplest sensing device shown in Figure 4.2.

A UHF version of the Magic Tee is the ring transformer or Rat Race illustrated in Figure 4.4. In this device, it is evident that energy from the generator will enter arm A and the cavity but will not enter arm B. In the same way, energy reflected from the cavity will enter arm B and the generator arm but will not enter arm A. Now if arm A is terminated in a short circuit, the reflected energy will enter the generator arm and arm B. It follows, from the number of wavelengths involved in each path that a detector in the generator arm may measure the difference of the vector voltages from A and the cavity while a detector in arm B may measure the sum of the same vector voltages. The final action is then equivalent to that of the Tee previously discussed.

The ring device, however, is a single frequency device because it is dependent upon path lengths for its properties of isolation. The Tee can be moderately broad-banded without departing greatly from a "null-measuring" bridge at any frequency within a specified band.

E. Experimental Procedures

The arrangements described above can be employed as elements in UHF or microwave discriminators. Present experimental procedures are devoted to the
assembly and/or construction of those elements considered to be basic to the measuring process. Plans have been drawn up and construction has been started on a ring device similar to that shown in Figure 4.4 with the path lengths adjusted for proper number of wavelengths at a frequency of 600 mc/sec. This frequency has been chosen because of the availability of locally constructed cavity-controlled oscillators which operate in that frequency range and also because of the availability of a 600-mc output of a secondary frequency standard (constructed and reported upon (4) during a previous contract).

It is tentatively planned to initiate experiments on short-term measurements by utilization of a system(s) which is analogous to the type(s) popularized by Pound (5), (6). A block diagram of a d-c system is shown in Figure 4.5. This figure illustrates a principle and is not necessarily representative of the actual equipment arrangement which is to be utilized. For instance, the difficulties occurring in d-c amplification may be avoided by employing a system of modulation of the r-f signal by an intermediate frequency in which case the output of the detectors contains a component at the intermediate frequency. In this case, amplifiers and phase-sensing devices at the intermediate frequency replace the d-c amplifier.

The sensitivity of an arrangement of this type is determined by the combination of several factors. Montgomery (7) has shown that if the detectors have a sensitivity of b volts per incident watt, the rate of change of output voltage with frequency (prior to amplification) is given by

\[
\frac{dV}{df} = \frac{4bQ_0 P_0}{(\alpha + 1)^2 f_0}
\]

(4.5)

where

- \(Q_0\) is the unloaded Q of the cavity,
- \(P_0\) is the incident power in watts,
- \(\alpha\) is the ratio of the power returned by the cavity to the input circuit to the power dissipated in the cavity walls and
- \(f_0\) is the resonant frequency of the cavity.

As an example, the same reference states that in the 9000-mc/sec region, with a \(Q_0\) of 25,000 and with \(\alpha\) equal to unity, \(b\) equal to 1 volt/mo (1N23 crystal),
Figure 4.5. Pound Frequency Stabilizing System.
\[ \frac{dV}{df} = 2.78 \text{ volts per mc/sec.} \quad (4.6) \]

Equation 4.6 represents the slope \( D \) of the discriminator curve in which case the output of the amplifier will be \( G_A D \) where \( G_A \) is the gain of the amplifier. If \( G_A \) were \( 10^6 \), then the final output would be \( 2.78 P_0 \) volts/cycle. It is seen that under idealized conditions that an appreciable voltage can be delivered by the system. The practical problems of ultimate amplifier gain, bandwidth and noise will add complexity to the design of the elements employed.

Initial experiments will attempt to determine the practical limitations of theory in UHF discriminators. Topics to be considered include selection of proper operating points on crystal detectors to assure a dynamic range sufficient in scope to relate input to output according to a prescribed law, minimization of noise in associated networks, minimization of temperature effects in all elements of the frequency-sensitive system and required isolation of the oscillator under test and means of procuring that isolation. Results of such experiments will be the subject of later reports.
V. TEMPERATURE-INSENSITIVE CAVITIES

During the course of the previous Contract No. DA-36-039-sc-42590, investigations were conducted with the purpose of rendering the resonant frequency of a cavity insensitive to temperature changes. The important conclusion established from these investigations was that temperature-compensated cavities can be constructed, the resonant frequencies of which will vary not more than 0.5 ppm/°C over a wide range of ambient temperatures. Construction of such cavities is, however, usually difficult and costly. Furthermore, optimum compensation is usually achieved at only one frequency. It may therefore be presumed that if cavities can be constructed of materials of low or possibly zero temperature coefficient, the resulting structure would be simpler to build and would occupy less space. Moreover, the possibility of tuning the cavity over a range of frequencies while maintaining zero expansivity would exist.

A material which appeared attractive as a basic substance in the construction of a temperature-insensitive cavity was a brand of magnesium-alumino-silicate, which is manufactured under the trade name of Stupalith. This material has a claimed-zero temperature expansivity over a very wide range of operating temperatures, but since it is a ceramic, methods had to be developed by which a highly conductive material could be applied to its surface. These methods were developed and sufficiently refined to produce a high Q resonator. A description of these methods can be found elsewhere (4). Various configurations, utilizing this material as a resonator base, were tested in the course of the present contract. Some of the methods of construction are described, and the results achieved are noted.

The first attempt at constructing a cavity utilizing a temperature-insensitive ceramic was a configuration which made use of an Invar outer conductor and end plates. The inner conductor, whose length was approximately a quarter wavelength at 785 mc, was formed from silver-plated Stupalith. The physical arrangement is shown in Figure 5.1.

Tests were made by placing the cavity in an oven and measuring its resonant frequency by methods described elsewhere (4). The temperature was varied in 15° C increments from 25° to 100° C, allowing a "heat soaking" period of about 2 hours at any given temperature, while the resonant frequency was continuously
Several such heating cycles were performed, all of which produced essentially the same data, i.e., a frequency change of about $-2\text{ppm}/\degree\text{C}$.

![Figure 5.1](image.png)

**Figure 5.1. Invar Cavity with Stupalith Center Conductor.**

It was tacitly assumed that the resulting temperature sensitivity, which was greater than the expansivity of either base material used, was influenced by factors that did not involve the expansivity of the cavity base materials. Silver-plated brass coupling loops were used in the cavity during the first few tests, however, these were replaced with silver-plated annealed Invar loops. No significant change in the temperature-sensitivity was observed after the change.

In a succeeding test, the Invar outer conductor was replaced with one of Stupalith. Invar end plates were used since Stupalith plates of sufficient size were unavailable at that time. The Invar end plates were soldered to the silver-plated Stupalith outer conductor. The inner conductor, having no screw threads, was slipped through a hole in the end plate and securely soldered with Cerrotru. The cavity was then heat-cycled in a manner similar to that described previously.
This configuration exhibited a greater temperature sensitivity during the heat-cycling tests than the previously mentioned cavity which utilized Invar as an outer conductor. Specific causes of this result are not evident, but possible sources of frequency sensitivity may be theorized.

If there are any stresses set up in the end plates due to improper annealing of the Invar, or due to the expansivity of the solder at the joints, there exists the possibility of these stresses translating movement to the unsupported end of the inner conductor. If the entire inner conductor was moved eccentrically as little as 0.002 inch, a rough calculation indicated that the resonant frequency of the cavity would be lowered by 160 ppm. While only the unsupported end would move in an actual cavity, this calculation gives the order of magnitude that should be expected due to movement of the inner conductor translated by stresses.

A strong indication that stresses were, in fact, the primary cause of the high temperature sensitivity of these cavities was given in subsequent tests which followed resoldering of the end plates. On the previous cavity, soldering of the end plates was accomplished by holding them lightly against the outer conductor and applying the solder. When they were resoldered, clamps were used to press them firmly into position. This new arrangement produced a temperature sensitivity which was significantly different although not significantly better.

In order to reduce the deleterious effects of stresses, a new inner conductor was designed for support at both ends of the cavity. Since a quarter-wavelength cavity was desired, the inner conductor was made long enough to be supported at both ends, but it was plated only about half the distance from one end. The unplated portion was to serve as an insulator support.

This particular cavity exhibited a very low Q under test and was not considered a practical resonator because of the high losses in the Stupalith "insulator" support. The same configuration could be used, however, if the inner conductor is plated over its entire length to produce a half-wavelength resonator. No attempt was made to build this type of structure since the primary interest is in quarter-wavelength resonators.
Since the solder joints and/or the Invar end plates set up stresses, it appears that the only successful structure would be one that is completely fabricated from Stupalith.

A cavity completely formed from Stupalith would have no solder joints, and, for this reason, deleterious stresses should be eliminated. Four such cavities have been ordered from The Stupalith Corporation and are scheduled for delivery sometime in September 1955.

Because of the long delivery time of the prefabricated cavity, tests have been performed on a cavity which is constructed entirely of Stupalith but in which the end plate and inner and outer conductors are fused together by use of a gas-oxygen flame. This resonator has been tested, and the results of the heat-cycling tests indicate that the temperature sensitivity is about \(-4\text{ppm/°C}\). This unsatisfactory result is apparently due to the fact that the fusing changes the properties of the material to some extent, whereby it loses its desirable characteristic of zero expansivity.

The manufacturer has confirmed this observation, but has suggested that improved characteristics may be achieved by annealing the completely fabricated structure at 2300°F. An oven of sufficient capacity that would attain this temperature is not available at this time, but if a satisfactory oven can be located, the results of annealing will be reported. Otherwise, further tests and reports on Stupalith cavities must await delivery of those units now on order.
VI. LONG-TERM STABILITY OF CAVITY-CONTROLLED OSCILLATOR

A. Introduction

Many investigators have shown that it is possible to construct cavity-controlled oscillators whose operating frequency is little affected by various types of disturbances. Controlled disturbances can be introduced in order to obtain a measure of the frequency instability of the operating system. The frequency shift in parts per million (ppm) due to rapid changes in anode potential, filament potential, ambient temperature variations, etc., can be used as an indication of the excellent performance of an oscillator in maintaining a given frequency. There is very little information available, however, concerning the long-term stability of cavity-controlled oscillators as measured over the period of months or years under almost ideal operating conditions.

The purpose of the present investigation is to make these long-term measurements on an oscillator which has exhibited good stability characteristics when subjected to the above-mentioned disturbances.

B. Description of Oscillator Tested

The oscillator under test has been described previously (4) and was constructed during the course of another project. This oscillator, whose maximum operating frequency is approximately 620 mc, is of the series-capacitor type and is mounted in an Invar cavity.

This particular unit, which had been out of service for some time, had apparently developed a leak which had allowed the dry nitrogen to escape, thus producing reduced output voltage and shifted operating frequency. Since these characteristics were of an unsatisfactory nature, the oscillator was disassembled for inspection. Subsequently, during the period when the cavity was disassembled, strong acid fumes entered the room from an adjacent area and produced a considerable amount of corrosion inside the resonator. Various cleaning methods were tried in an effort to remove the corrosion with little success, and it became necessary to again silver plate the inside of the cavity.

During reassembly of the oscillator, some difficulty was encountered in maintaining a good seal around the joint where series-capacitor projects through the end plate. Several capacitors were used before a proper seal was made.
After final satisfactory assembly was completed, the oscillator was placed in the frequency-measuring equipment. A block diagram of the measuring setup is shown in Figure 6.1. The Secondary Frequency Standard is a unit consisting of a 50-mc oven-controlled crystal oscillator whose output is fed through a harmonic generator to produce output frequencies consisting of harmonics of 50 mc up to X-band. The 600-mc harmonic is mixed with the cavity oscillator which is fed through an isolating section consisting of a 600-mc amplifier and attenuator. The difference frequency, which is adjusted to lie in the audio range, is passed through an amplifier to a count-rate type frequency meter whose accuracy is about ± 1 per cent. An output from the frequency meter is available to drive a recorder for continuous monitoring.

Figure 6.1. Block Diagram of Cavity Q-Meter.

The 50-mc secondary standard can be checked daily by another standard having a long-term accuracy of better than 1 part in $10^8$. By means of this comparison, the 50-mc standard has been found to be accurate to within 1 part in $10^7$ per day. The 12th harmonic at 600 mc can have an inaccuracy of ± 60 cycles. If the difference frequency is 2 kc, it can be measured within ± 20 cycles, so that the total inaccuracy of the measurement can be ± 80 cycles.
Tests were finally begun, but there is insufficient data at this writing to form any conclusions regarding tube aging effects, etc. This will be reported upon in the next progress report.
VII. CONCLUSIONS

In order to discern small frequency variations which occur in very short periods of time, it is necessary, particularly at high frequencies, to measure changes in phase which occur during the period of measurement. These phase variations may then be used to calculate the frequency shift, relative to some standard, which occurs during the specified interval.

Of the various frequency-measuring methods given preliminary investigation, the phase-sensitive discriminator appears to have the most desirable characteristics. When conditions are ideal, that is, when the noise level is a theoretical minimum and the sensitivity of the device is optimum, it appears that short-term frequency fluctuations of small magnitude can be measured with considerable accuracy. Specifically, it appears that when the period of measurement is considerably less than 1 second and the mean frequency lies within the UHF range that frequency fluctuations in the order of 1 part in $10^9$ can be measured. However, additional investigations will be required in order to determine the practical limitations. Problems concerned with noise, bandwidth and available amplification of the measuring equipment must be considered in greater detail.

In the field of temperature-insensitive cavities, poor results have been obtained with cavities constructed of Stupalith by assembly of individually fabricated components. It is presently concluded that it will be necessary to fabricate a cavity from a single piece of the ceramic in order to eliminate stresses which apparently develop in the solder joints of models thus far investigated.
VIII. PROGRAM FOR NEXT QUARTER

Theoretical investigations of possible methods of obtaining short-term stability measurements will continue. Initial investigations which were based on an ideal system must be expanded to give consideration to actual noise and amplifier-gain bandwidth that is found in a practical system. In order to make actual laboratory tests of these possible methods, construction of equipment, including the "Rat Race" hybrid, which is considered a basic unit in any UHF discriminator, will continue.

Work on temperature-insensitive cavities will, for the most part, be postponed until the fabricated Stupalith cavities are delivered. Efforts will be made to test a Stupalith cavity which has been fabricated by a fusing process and annealed at 2300° F.

Frequency-stability data will continue to be taken on the Series-Capacitor Cavity-Controlled Oscillator. Ideal conditions, such as regulated potentials and temperature will be maintained during these measurements.

Respectfully submitted:

Edward G. Holmes
Project Director

Donald W. Fraser
Research Associate

Approved:

J. E. Boyd
Head
Physics Division

Paul K. Calaway, Director
Engineering Experiment Station
IX. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

This project is under the direction of Mr. Edward G. Holmes, Research Engineer, who devotes full time to this work at present. Mr. Holmes holds the degree of Master of Science in Electrical Engineering. His experience in the electronics field includes 5 years of work with frequency-measuring apparatus and broadcasting equipment, 2 years as Electronics Officer in the U. S. Navy and 4 years of research and development work in UHF and microwave equipment.

Dr. Donald W. Fraser, who devotes one-third time to this work at present, is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Doctor of Philosophy in Electrical Engineering from this institution. Station project 229-198, "Precision Frequency Control Techniques," was under his direction. Dr. Fraser has been engaged in research and development at the Engineering Experiment Station for about 4 years. His other experience includes 5 years of electronic testing and research in the U. S. Navy.

Mr. James C. Sellers joined the project recently as Electronic Technician. He is currently devoting half time to the project. Mr. Sellers previously was engaged for 8 years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.
X. BIBLIOGRAPHY


A. Reflection and Transmission Properties of a Cavity

1. Transmission

A cavity with input and output, both matched to the characteristic impedance, \( Z_0 \), of the coupling lines, may be represented as follows:

\[
\frac{z_0}{\omega L} \quad \frac{1}{\omega R} \quad \frac{1}{\omega C} \quad \frac{z_0 n_2^2}{n_1^2}
\]

This arrangement may now be reduced to an equivalent shunt (Norton) generator circuit as follows:

\[
E = \frac{E}{Z_0}
\]

The output voltage is seen to be

\[
e_\text{out} = IY \left( \frac{n_1}{n_2} \right) \cdot \frac{1}{\frac{1}{Z_0} + \frac{1}{R} + \frac{1}{n_2^2 Z_0} + \frac{j \omega C n_1^2}{n_1^2} + \frac{j \omega L}{n_1^2}}
\]
Now employ the following definitions

\[ Q_0 = \omega_0 \text{ Maximum energy stored in cavity } = \omega_0 \text{CR} \]
\[ Q_1 = \omega_0 \text{ Power lost in cavity walls } = \omega_0 C Z_{0} n_1^2 = Z_0 n_1^2 / \omega_0 L \]
\[ Q_2 = \omega_0 \text{ Maximum energy stored in cavity } = \omega_0 C Z_{0} n_2^2 \]
\[ Q_L = \omega_0 \text{ Total power lost to cavity } = \omega_0 C \left( \frac{1}{R} + \frac{1}{Z_{0} n_1^2} + \frac{1}{Z_{0} n_2^2} \right) \]

The following successive steps permit simplification of the equation for \( e_{\text{out}} \)

\[ e_{\text{out}} = \frac{n_1}{n_2} E \cdot \frac{1}{Z_0 + \frac{n_1^2 Z_0}{R} + \frac{n_2^2}{n_1^2} + j n_1^2 Z_0 \left( \omega C - \frac{1}{\omega L} \right)} \]

but

\[ \frac{n_1^2}{n_2^2} = \frac{Q_1}{Q_2} \]

Now let

\[ \gamma = \frac{\omega}{\omega_0} \text{, whence} \]

\[ e_{\text{out}} = \frac{E \left( \frac{Q_1}{Q_2} \right)^{1/2}}{1 + \frac{Q_1}{Q_0} + \frac{Q_1}{Q_2} + j Q_1 \frac{n_1^2 Z_0 (\gamma^2 - 1)}{\omega_0 L (\gamma)}} \]

\[ \frac{\left( \frac{Q_1}{Q_2} \right)^{1/2}}{1 + \frac{Q_1}{Q_0} + \frac{Q_1}{Q_2} + j Q_1 \frac{(\omega + \omega_0)(\omega - \omega_0)}{\omega \omega_0}} \]

\[ \frac{\left( \frac{Q_1}{Q_2} \right)^{1/2}}{1 + \frac{Q_1}{Q_0} + \frac{Q_1}{Q_2} + j 2Q_1 \frac{\omega - \omega_0}{\omega_0}} \]
This can be written as

\[ e_{\text{out}} = \frac{\frac{Q_L}{\sqrt{Q_1Q_2}}}{1 + j2Q_L\frac{\omega - \omega_0}{\omega_0}}. \]

At resonance \( e_{\text{out}} = \frac{EQ_L}{Q_1Q_2} \), and if the transmission coefficient were unity, \( e_{\text{out}} \) would be \( E/2 \). Let \( T \) equal the transmission coefficient at resonance:

\[ T = \frac{E\frac{Q_L}{\sqrt{Q_1Q_2}}}{\frac{E}{2}} = \frac{2Q_L}{\sqrt{Q_1Q_2}}. \]

The transmission coefficient (for frequencies near resonance) is

\[ t = \frac{T}{1 + j\beta} \text{ where } \beta = 2Q_L\frac{\omega - \omega_0}{\omega_0}. \]

The amplitude variations due to changes in frequency are relatively small as may be seen by noting the impedance variations in the neighborhood of resonance. Since the impedance of the cavity is

\[ Z = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right) \]

and

\[ |Z| = \frac{1}{\sqrt{\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2}} = \frac{\omega_0 L}{\sqrt{\left(\frac{\omega_0}{R}\right)^2 + \left(\gamma - \frac{1}{\gamma}\right)^2}} \]

or

\[ |Z| = \frac{\omega_0 L}{\sqrt{\frac{1}{Q^2} + \left(\frac{f}{f_0} - \frac{f_0}{f}\right)^2}}. \]
The magnitude of voltage $|V|$ across the circuit due to a current $I$ is

$$|V| = I \frac{|Z|}{|Z|}$$

and the voltage at resonance ($|Z| = Z_r$) is

$$V_o = IZ_r = I\omega L Q$$

whence

$$\frac{V}{V_o} = \frac{1}{\sqrt{\frac{1}{Q^2 + \left(\frac{f}{f_o} - \frac{f_o}{f}\right)^2}} \sqrt{1 + Q^2 \left(\frac{f}{f_o} - \frac{f_o}{f}\right)^2}}.$$  

If $f \neq f_o$,

$$\frac{f}{f_o} - \frac{f_o}{f} = \frac{f^2}{f_o} - 1$$

and letting

$$f = f_o (1 + \delta),$$

$$\frac{V}{V_o} = \frac{1}{\sqrt{1 + 4Q^2 \delta^2}} \approx 1 - 2 (Q\delta)^2.$$  

For example, if $Q = 10^4$, $\delta = 10^{-2}$ then $(Q\delta)^2 = 10^{-10}$ which represents the magnitude of the relative amplitude.

2. Reflection

Consider the reflection properties of a cavity


\[ Y_C = \frac{1}{R_1} + j \omega C n_1^2 + \frac{1}{n_1^2} \]

\[ = n_1^2 \left[ \frac{1}{R} + j \left( \omega C - \frac{1}{\omega L} \right) \right] \]

\[ = \frac{n_1^2}{R} \left[ 1 + j \frac{R}{\omega L} \left( \gamma - \frac{1}{\gamma} \right) \right] \]

\[ = \frac{n_1^2 Z_0^2}{R} \left[ 1 + j 2Q_o \left( \frac{\omega - \omega_n}{\omega_o} \right) \right], \]

but

\[ \frac{n_1^2 Z_0^2}{R} = \frac{\alpha}{Q_o}. \]

Let \( \frac{1}{\alpha} = \frac{Q_1}{Q_o}. \) Then

\[ Y_C = \frac{Y_o}{\alpha} \left[ 1 + ja \right] \]

where

\[ a = 2Q_o \left( \frac{\omega - \omega_n}{\omega_o} \right). \]

The cavity reflection coefficient \( r \) is

\[ r = \frac{Y_o - Y_C}{Y_o + Y_C} = \frac{Y_o - \frac{Y_o}{\alpha} (1 + ja)}{Y_o + \frac{Y_o}{\alpha} (1 + ja)} \]

\[ = \frac{\alpha - (1 + ja)}{\alpha + (1 + ja)}. \]

\[ |r| \sin \theta = \frac{-2a\alpha}{(\alpha + 1)^2 + a^2}. \]

In microwave discriminators, the length of line between transformer and cavity can be adjusted so that the output of the discriminator is zero at the resonant frequency.
frequency of the cavity. For small changes of frequency, the real part of the admittance, $Y_C$, remains substantially constant. Therefore, the output voltage of the discriminator is proportional to the imaginary part of $Y_C$. Montgomery (9) gives the following development.

If the detectors on both arms (of a microwave discriminator such as a Magic Tee or a Rat Race Ring) give an output voltage proportional to the incident power, then the difference between the output voltages is proportional to

$$\frac{P_4 - P_3}{P_0} = \frac{2\alpha}{(\alpha + 1)^2 + \alpha^2}$$

where $P_0$ is the power delivered to the discriminator and $P_4$ and $P_3$ are the powers delivered to the crystals.

The slope at the crossover point is

$$\left[ \frac{d}{da} \frac{P_4 - P_3}{P_0} \right]_{a=0} = \frac{2\alpha}{(\alpha + 1)^2}$$

which is a maximum for $\alpha$ equal to unity.

If the detectors have a sensitivity of $b$ volts per incident watt, the rate of change of output voltage with frequency is

$$\frac{dV}{df} = \frac{4\beta Q_0 P_0}{(\alpha + 1)^2 f_0}$$
ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

QUARTERLY REPORT NO. 2
PROJECT NO. A-216

INVESTIGATIONS OF PRECISION FREQUENCY CONTROL TECHNIQUES

By
ROBERT E. MEEK and SAMUEL N. WITT, JR.

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CONTRACT NO. DA-36-039-sc-64597

DEPARTMENT OF THE ARMY PROJECT: 3-99-11022
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I. PURPOSE

The purpose of this project is (a) to investigate methods by which temperature-insensitive coaxial cavities may be constructed, (b) to obtain data, over a period of several months, on the long-term frequency stability of a cavity-controlled oscillator which has exhibited good short-term stability, (c) to investigate methods by which very short-term frequency-stability measurements, for periods of the order of 0.1 to 1.0 second, may be made with an accuracy not exceeding 1 part in $10^9$ and (d) to investigate other related topics as may be mutually agreed upon by the Contracting Officer and Georgia Institute of Technology during the course of this project.
II. ABSTRACT

The discriminator method for initial measurements of short-term frequency stability has been adopted. Two prospective systems are described. The Pound d-c discriminator circuit is found to be somewhat inadequate for the degree of accuracy required, primarily because of the noisiness of the crystal diodes at very low frequencies. The equal-arm modification of the Pound i-f system overcomes this basic limitation by using higher frequencies and by employing a somewhat different phase-comparison scheme. A description of this system and its associated circuitry is given.

Preliminary results of initial tests on the completed coaxial-ring transformer are reported, and a mechanical sketch showing the basic elements of its construction is included. Terminal isolation of 40 db has been obtained.

Results from an accumulated 550-hour operation of an Invar cavity-controlled oscillator are tabulated and discussed. Several factors which contributed to the resulting frequency-stability characteristics are traced to a few basic equipment weaknesses in the measuring system. A block diagram of the system is presented along with a discussion of the function of the principal components. Material improvement in the over-all performance of the cavity oscillator is obtained by a few refinements in its physical construction. Influence of oscillator-tube temperature variation and cavity losses is given as basis for these modifications.
III. SHORT-TERM FREQUENCY MEASUREMENTS

A. Introduction

Quarterly Report No. 1 discussed some of the problems involved in short-term frequency-stability measurements. The methods suggested for making such measurements were (1) comparison of an unknown frequency with a sufficiently accurate standard, (2) use of the long-line effect, (3) comparison by means of memory circuits and (4) use of discriminators. The first three of these methods do not appear to be suitable for the measurements required by this contract since (1) no standard of sufficient stability is available for use in the frequency-comparison scheme, (2) the long-line method lacks sufficient sensitivity and (3) the memory-circuit method does not appear to be practical at UHF. The use of discriminators appears to be the most promising of the suggested methods. Many systems using UHF discriminators have been proposed. Some of these are discussed in the following section.

B. Frequency Measurements Using Discriminators

Discriminators have been used widely for stabilizing klystron and other UHF and microwave oscillators. The use proposed by this project is for frequency measurement rather than frequency control. Only the frequency changes occurring in the period of 0.1 to 1.0 second are of present concern. The frequency change of cavity oscillators may be of the order of 1 part in $10^6$ per hour, while the short-term change to be measured may be as small as 1 part in $10^9$. This requires the measuring equipment to have extreme sensitivity to frequency variations over a relatively wide frequency range. In order to reduce the required frequency range, it is desirable to control the average oscillator frequency without restricting or affecting the short-time frequency changes which are to be observed. This may be accomplished by introducing time delay between the frequency-measurement point and the oscillator frequency-control system. Such a system is illustrated in Figure 3.1. This measurement system is very similar to the various servo-frequency-stabilizing systems discussed in the literature. The problem then is to choose a system with sufficient sensitivity and to provide suitable visual indicators and time-delay networks.
C. Comparison of UHF Discriminator Systems

The frequency-stabilizing systems using discriminators may be classified as either d-c systems or i-f systems. The d-c systems usually consist of (1) the oscillator or signal source to be controlled, (2) a reference device such as a reflection or transmission cavity, (3) a discriminator with one or more outputs whose amplitudes are in some way proportional to the difference between the oscillator frequency and the reference frequency, (4) one or more detectors which convert the discriminator output to direct current and (5) d-c amplifiers and control systems.

Of the several types of d-c systems which have been used for frequency control, the Pound discriminator\textsuperscript{1} has been found to be the most sensitive. This system was briefly discussed in Quarterly Report No. 1. The major disadvantage of this system is its susceptibility to noise. Initial calculations have indicated that d-c amplifiers can be built with sufficiently low noise to permit measurements with an accuracy of better than 1 part in
However, the over-all usable sensitivity of the amplifier is greatly reduced by the noise produced in crystal diodes at low frequencies. Because of this, none of the d-c systems are considered practical for high-accuracy measurements.

Several types of a-c or i-f frequency-control systems are also in common use. Notable among these systems is the Pound i-f system, which uses many of the same components as the Pound d-c system. A block diagram of the i-f system for microwave generators is shown in Figure 3.2. A magic T is illustrated in the diagram; however, this would be replaced by a ring transformer for UHF measurements.

Figure 3.2. Block Diagram of Pound I-F Discriminator System.
The Pound i-f stabilizer is described as follows. Energy at the frequency to be measured enters the T and divides equally between the cavity arm and the mixer arm. The mixer crystal is matched to the line so that no energy is reflected. All of the energy that is reflected from the cavity divides between the input arm and the modulator arm. An i-f signal is injected into the modulator crystal producing sidebands equally spaced about the incoming frequency. However, the crystal in the modulator arm is matched at the incoming frequency so that none of this energy is reflected. The sidebands which are not matched are returned to the T and divide equally between the mixer and cavity arms. In the mixer arm, the sidebands are combined with the incoming energy. If the phase relationships are correct, the i-f energy may be recovered by amplitude demodulation. However, if a net phase shift of 90 degrees occurs, no i-f energy will be recovered. The normal adjustment of the system is such that no i-f energy is recovered when the incoming frequency is exactly equal to the resonant frequency of the cavity. Under this condition, a change in incoming frequency will result in a phase shift in the cavity which will produce an i-f output at the mixer crystal. The phase of the i-f output will depend on whether the incoming frequency increases or decreases. Thus, by the use of a suitable i-f amplifier and a lock-in mixer, a d-c output voltage can be obtained which is proportional to the deviation of the input frequency from the resonant frequency of the cavity. This voltage may be re-applied to the UHF oscillator for frequency-correcting purposes through a time-delay network. Short-time deviations in this voltage will then indicate the short-time instability of the oscillator. The literature has indicated that the noise in this system may be made sufficiently small to permit measurements of instabilities as small as 1 part in 10^9.

The Pound i-f system may be modified, as shown in Figure 3.3 by interchanging the positions of the modulator and mixer crystals. This results in equal signal-path lengths between the mixer crystal and the cavity and modulator elements. This modification is known as the equal-arm discriminator^3 and, in microwave application, possesses several fundamental advantages over the preceding system. The most important among these are:
1. Spurious signals are greatly reduced as a result of smaller reflections.

2. With the same input power, the over-all discriminator sensitivity is increased because the sideband energy is transmitted to the detector with greater efficiency.

3. For the same detector-crystal noise, the power input may be several decibels greater.

4. The carrier energy, rather than the sideband energy, is a function of frequency; thus, the output of the detector varies as a function of the carrier to sideband ratio.

5. Wider bandwidths of operation are obtained because of path equalization.
In view of these advantages, the equal-arm discriminator system has been chosen for initial studies of short-time stability of cavity oscillators.

D. The Coaxial-Ring Transformer

As mentioned above, a coaxial-ring transformer (rat race) will be used in the discriminator in place of the magic T shown in Figures 3.2 and 3.3. This is desirable at UHF since the entire system is designed around coaxial transmission lines rather than around large and cumbersome waveguides. The principle of operation of the transformer was described in Quarterly Report No. 1 of this project.

Figure 3.4 is a sketch of the coaxial ring that has been constructed, showing principal parts and dimensions. The entire ring and the center conductor are constructed of brass, annealed after machining, then polished and silver plated. General Radio, type 874A, 50-ohm connectors are to be used to connect the various crystal and cavity elements to the ring. The characteristic impedance of the circular coaxial section was designed for 70 ohms, and, through the transformation properties of the quarter-wave sectors, the arm impedances become 50 ohms.

Preliminary tests on the ring indicate that its properties of impedance and isolation are satisfactory enough to justify its application in a discriminator system. The VSWR of the input arm was measured to be 1.06 at 600 mc when the arms corresponding to the cavity and modulator crystal were properly terminated. A maximum signal isolation of 40 db has been measured between the input arm and the mixer crystal arm (output arm).

E. Associated Circuitry

A commercial i-f amplifier for use in this system has been ordered. It provides a 120 db gain at 30 mc with a 2-mc bandwidth. The noise figure is claimed to be only 1.3 db. This amplifier will provide all of the amplification necessary from the mixer crystal to the lock-in mixer. It will also provide a nonphase-locked, d-c output which will be useful for tuning the system.

A typical lock-in mixer is shown in Figure 3.5. Two i-f inputs are provided, the first from the i-f amplifier and the second from the i-f oscillator.
Figure 3.4. Mechanical Details of Coaxial-Ring Transformer.
The oscillator input voltage is large enough to drive the tube well beyond its linear region. Thus, the plate current is essentially zero during half of the input cycle. During the other half of the input cycle, the plate current depends upon the potential applied to the control grid. The input to the control grid will be either exactly in phase with the i-f oscillator or 180 degrees out of phase. When the in-phase condition exists, an increase in control grid signal will cause the average d-c plate voltage to decrease since the average plate conduction is greater. When the control grid signal is 180 degrees out of phase with the oscillator, an increase in control-grid-signal amplitude will decrease the average plate current causing an increase in the d-c output voltage.

The meter, M, which may be a high-speed recording voltmeter, will indicate the instantaneous frequency deviation of the cavity oscillator from the reference cavity.

The servo loop will be closed through a time-delay network, and a cavity-oscillator control system such that the frequency of the cavity oscillator will be maintained near the resonant frequency of the reference cavity.
cavity. The time-delay network will be provided so that no appreciable frequency correction will occur during periods of time less than about one second. This delay network will be a low-pass filter such as an integrating network.

The i-f oscillator will be a conventional 30-mc crystal-controlled oscillator with buffer amplifiers between it and the two required outputs.

The modulator and mixer crystals will be conventional, high-frequency, crystal diodes. It is anticipated that considerable experimentation will be necessary in order to match the crystals to the coaxial-ring transformer.

F. Cavity-Oscillator Control System

In order for this system to perform properly, it is necessary that the cavity-oscillator frequency be electrically controlled. This can be accomplished by several methods. One possible method is to use an electro-mechanical system where a motor is used to drive a tuning slug. Another method is to use some type of reactance-tube control. Still another is to use thermal control where a bimetallic strip, heated electrically, is used to control the frequency.

The control method to be used by the project has not yet been selected.
IV. LONG-TERM FREQUENCY STABILITY MEASUREMENTS

A. Introduction

Recorded measurements on the long-term frequency stability of an Invar cavity-controlled oscillator constructed on a previous project were begun in the early part of August, and, as of September 30th, data from about 550 hours of operation have been collected. Actual operation of the oscillator under test was begun near the end of the preceding quarter, but no recordings were kept. This "dry run" period provided an opportunity to observe the performance of the measuring system and to spot any weaknesses in it. Also, since ideal conditions of temperature and supply voltages are desired, observation of these factors were made to determine their reliability.

B. Description of Measuring System

Figure 4.1 shows the block diagram of the principal components of the measuring system for long-term frequency stability of the cavity-controlled oscillator. The data being collected are primarily in the form of a strip chart which continuously records the audio-frequency difference between the frequency of the cavity oscillator and the frequency of a secondary standard.

The cavity oscillator is located in an oven whose temperature is maintained at 48°C ±0.5 with a Fenwal-type 17310 thermoswitch and visual monitoring of the temperature is provided by a Sim-Ply-Trol model 2613 indicating pyrometer. The ambient change in the room where the oven is located is about ±5°C. The internal air of the oven is circulated by a blower having a capacity of 25 cubic feet per minute. The d-c plate power for the oscillator is supplied from a two-stage regulated supply which has a long-term stability of about 400 parts in 10^6 per day. The heater is supplied by a constant voltage transformer that maintains its output within ±1 per cent of rated voltage.

Isolation of the oscillator from the rest of the measuring system is provided by two 10-db pads and a UHF amplifier. This amplifier not only
Figure 4.1. Block Diagram of Frequency-Measuring System for Long-Term Stability Measurements.
Quarterly Report No. 2, Project No. A-216

provides isolation but also restores the level of the oscillator energy to that level existing at the input to the attenuator pads. The combined frequencies of the oscillator and the secondary standard are applied to the input of the receiver where they are mixed, amplified and fed as an audio beat frequency to the frequency counter. This counter converts the a-c energy to d-c energy, which is applied to an Esterline-Angus model AW, 1.0-ma, pen recorder.

The system is, of course, designed to operate continuously 24 hours a day and, thus, demands reliable performance of all its components. This continuous operation has revealed defective operation in some components and, hence, has resulted in several interruptions. The major change in the system, since the start of the test, has been the substitution of another frequency counter in place of the one on the chassis of the Philco Crystal Duplicator. Severe nonlinearity in the output current as a function of input frequency and undesirable response to fluctuations in the amplitude of the input wave were discovered. The present frequency counter is a Georgia Tech built unit with four ranges (500, 1000, 5000 and 10,000 cycles), providing both narrow and wide frequency-deviation measurements. Its linearity on all ranges has remained reliably fixed within 1.0 per cent, and the output current is absolutely independent of amplitude variations of the input when this level is maintained above 5.0 x 10^-3 volts.

The secondary frequency standard is checked daily with WWV through the medium of a Berkeley model 5570 frequency meter.

C. Analysis of Data

The tabulations of data in Table 4.1 show values obtained from several periods of continuous operation. The periods are listed in the chronological order of their operation and are nonuniform in duration because of failures occurring in the measuring system or oscillator beyond the control of operating personnel. Data based on weekly periods are significant for study in future reports, however, this does not mean the operation of the oscillator will be interrupted if it is performing satisfactorily.
TABLE I

TABULATION OF RESULTS OF LONG-TERM FREQUENCY-STABILITY
MEASUREMENTS FOR INVAR CAVITY-CONTROLLED OSCILLATOR
(Oscillator Frequency: 600 mc)

<table>
<thead>
<tr>
<th>Periods of Continuous Operation (hours)</th>
<th>Beat Frequency Start (cycles)</th>
<th>Beat Frequency Finish (cycles)</th>
<th>Total Frequency Change (cycles)</th>
<th>Maximum Frequency Change Within Period (cycles)</th>
<th>Stability Factor Min. (parts/10⁶)</th>
<th>Stability Factor Max. (parts/10⁶)</th>
</tr>
</thead>
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<tr>
<td>5</td>
<td>----</td>
<td>----</td>
<td>250</td>
<td>500</td>
<td>0.41</td>
<td>0.83</td>
</tr>
<tr>
<td>17</td>
<td>1600</td>
<td>4700</td>
<td>3100</td>
<td>4500</td>
<td>5.0</td>
<td>7.5</td>
</tr>
<tr>
<td>109</td>
<td>2800</td>
<td>-3400</td>
<td>6200</td>
<td>9000</td>
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<tr>
<td>14.5</td>
<td>900</td>
<td>3600</td>
<td>2700</td>
<td>3200</td>
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<td>2400</td>
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<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>14</td>
<td>700</td>
<td>650</td>
<td>50</td>
<td>1000</td>
<td>0.083</td>
<td>1.7</td>
</tr>
<tr>
<td>70</td>
<td>1900</td>
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<td>1500</td>
<td>1900</td>
<td>1900</td>
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<tr>
<td>14</td>
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<td>70</td>
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<td>5000</td>
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<td>75</td>
<td>2900</td>
<td>5000</td>
<td>2100</td>
<td>3800</td>
<td>3.5</td>
<td>6.2</td>
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<tr>
<td>Over-all Average of Tabulated Values</td>
<td></td>
<td></td>
<td>2040</td>
<td>3160</td>
<td>3.4</td>
<td>5.3</td>
</tr>
</tbody>
</table>

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The column giving the total frequency change is derived from the algebraic difference between the beat frequency at the start and that at the end of the period and is related to the average-frequency change. The relative stability of the average frequency of the oscillator for each period is given in the column designated as the "Minimum Stability Factor". This value is derived from the ratio of the total beat-frequency change to the frequency of the secondary standard and is given in parts per million. The negative sign associated with two of the entries in the third column represents the fact that the frequency of the cavity oscillator was observed to pass from one side to the other of zero beat with the secondary standard. Since the system has no sensing provision, these cases must be observed and the sense determined manually by operating personnel at the time they are occurring. It is planned to investigate methods of automatic sensing that might be employed in order to reduce the monitoring periods by personnel and also increase the flexibility and range of the system.

The column designated "Maximum Frequency Change" represents values of the difference between points of maximum-frequency excursion within the period tabulated. Its evaluation in terms of stability is presented in the last column, designated as the maximum-stability factor of the oscillator for that period. This value is the ratio of maximum-frequency change to the center frequency of the oscillator and is expressed in parts per million. These deviations from the average frequency in any one direction were, in most cases, of short-term duration as compared with the total period of observation.

D. Influence of Various Factors

During the course of the long-term frequency-stability measurements, several factors that affect the performance of the oscillator have been under observation. These studies have resulted in some changes that have reduced losses in the cavity and lowered frequency sensitivity to fast rates of temperature change. In line with the spirit of the contract, however, the purpose of these refinements has not changed the basic circuit configuration of the cavity oscillator originally specified for test but
rather have treated symptoms that curtail optimum performance. Actually, two companion oscillators, constructed on a previous project, have been used to test each refinement before applying it to the principal unit.

Reduced losses in the cavity were obtained by removing as much lossy material as possible associated with the oscillator tube from the cavity space. The tubular ceramic by-pass capacitor for the grid was replaced with one constructed by using a mica sheet between two conducting surfaces; one surface being the end of the cavity center conductor, the other a thin metal washer straddling the tube base. Feed-through bushings mounted around the tube base by which a-c power and d-c power were supplied to the tube were removed, and leads for this purpose, consisting of thin copper strips, were inserted beside the pin jacks in the tube socket and brought out on the tube side.

Rounding the corners at the base of the inner and outer conductors inside the cavity should reduce the current density at these points and, hence, lower losses.

Periodic cycling of the frequency from day to day was noted and found to result from heater voltage variations. Since the tube is mounted inside the center conductor element of the cavity, the majority of the heat generated by the tube is dissipated by this element. As a result, steep temperature gradients are set-up along the inner conductor. Even when the cavity is immersed in an oven set to 50°C and temperature equilibrium is reached, there is still a fairly large temperature difference between the end of the center conductor and its base. The low thermal coefficient of Invar permits very slow adjustment of this equilibrium condition when a heat disturbance is introduced. Hence, heater voltage variations were found to introduce temperature changes which influenced the frequency. Since the frequency of the cavity is highly sensitive to any disturbances to the center conductor, any elongation or tilting caused by temperature effects is undesirable. To minimize this condition, the tube was removed from the center conductor and placed on the cap of the overhang portion of the cavity. Basically, this is the same circuit configuration as before,
since the series capacitor is still connected between the oscillator tube anode and one terminal (center conductor) of the resonant cavity. The fundamental improvement in this new configuration is that the material of the frequency-controlling portion of the cavity is essentially at the same uniform temperature, and, hence, internal stresses are reduced by minimizing the temperature gradients. Short-term evaluation of this change had been completed at the end of this quarter on a prototype unit, and the results were good enough to make the change in the Invar cavity under long-term test. No data from this modified unit were available for this report since the change was initiated at the end of the quarter.
V. TEMPERATURE-INSSENSITIVE CAVITIES

The molded one-piece Stupalith cavities have been received. Therefore, these cavities will be evaluated during the next quarter. One sectionalized cavity constructed of Stupalith, on hand as of the first quarterly report, has been heat treated and coated with silver. No conclusive data have been obtained on its performance, but it will be retained for comparison tests with the other units when they are processed and tested.

The technique of measurement of the frequency-temperature characteristics that will be utilized is the cavity Q-meter technique.¹
VI. CONCLUSIONS

A. Short-Term Stability Measurements

The capability of the Pound d-c discriminator system in measuring short-term frequency changes in the order of 1 part in $10^9$ is limited by reduction in sensitivity of the d-c amplifier because of the large noise factors of crystal diodes at very low frequencies. The i-f systems overcome this limitation by utilizing a frequency where crystals possess much lower noise factors. Thus the inherent sensitivity of a high-gain amplifier is more nearly realized.

Modification of the Pound i-f system by the equal-arm configuration should provide improved characteristics in both adjustment and operation.

In order to utilize the full dynamic range of the measuring system, some means is necessary to maintain the average frequency of the cavity oscillator at the resonant frequency of the reference cavity. To avoid interference with short-term observations, the frequency-correcting system should have a control delay greater than 1.0 second.

B. Long-Term Stability Measurements

Information on the reliability of the controlled parameters (voltage, current and temperature) of the measuring system for long-term stability observations is necessary in order to reveal properly the effects of tube and cavity aging on frequency stability of the cavity oscillator. Permanent recordings of the characteristics of these various controlled parameters should be made to establish their long-term stability and also to study the correlation between any variations in them and variations in oscillator frequency.

Recent experience with frequency recording indicates a desirability for expanding the bandwidth of the beat-frequency measuring system. One proposed method is to introduce a sensing function that will automatically determine the position (above or below) of oscillator frequency with respect to that of the secondary standard during unattended monitoring periods. This will actually double the useful measuring range of the present system.
VII. PROGRAM FOR NEXT QUARTER

Further investigation will be made on the ring transformer to decrease the isolation ratio between the output and input arms which is important for a highly sensitive discriminator system. It is expected that the principal components of the associated circuitry, which have been on order, will be received and preliminary tests carried out on the system before the end of the third quarter. The reference cavity to be used in the discriminator is under construction and will be tested for Q and stability when it is complete.

Mediums of frequency control of the cavity oscillator under test will be investigated to determine which of the three methods cited in this report is most practical. In connection with this test, the inherent frequency-stability characteristics of this cavity oscillator will be observed under varying ambient temperature conditions.

Frequency-stability measurements will continue on the Invar cavity oscillator under controlled conditions of temperature and supply voltages. The stability of each of these controlled parameters over a period of a week will be observed and studied for possible improvement.

The problem of automatically sensing the relative position of the oscillator frequency, with respect to the frequency of the secondary standard, will be investigated for application to the system.

The four Stupalith cavities, which have been received from the manufacturer, will be processed for silver plating. A cavity Q-meter system will be assembled for measurement of frequency of the silver-plated units. It is expected that a few preliminary runs will be made before the end of this quarter to determine frequency-temperature characteristics.
VIII. IDENTIFICATION OF KEY PERSONNEL

Dr. Donald W. Fraser devoted one-third time to the project from April to August 1955. He was Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Doctor of Philosophy in Electrical Engineering from this institution. Dr. Fraser has been engaged in research and development at the Engineering Experiment Station for about 4 years. His other experience included 5 years of electronic testing and research in the U. S. Navy.

Mr. Edward G. Holmes, who holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology, was director of this project from April to September 1955. His experience in the electronics field included 5 years of work with frequency-measuring apparatus and broadcasting equipment, 2 years as Electronics Officer in the U. S. Navy and 4 years of research and development work in UHF and microwave equipment.

This project is now under the direction of Mr. Robert E. Meek, Research Engineer, who assumed these duties September 1, 1955. He joined the project August 1, 1955, and is at present devoting full time to this work. Mr. Meek holds the degree of Bachelor of Science in Electrical Engineering from the University of Kentucky. He has previously been associated with the University of Kentucky and with this station on several projects since 1951.

Mr. James C. Sellers joined the project as Electronic Technician. He is currently devoting half-time to the project. Mr. Sellers previously was engaged for 8 years in nuclear instrumentation with the ACE at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.

Mr. Samuel N. Witt, Jr., Research Engineer, joined this project August 1, 1955 and is presently devoting one-half time to the work. Mr. Witt, who holds the degree of Master of Science in Electrical Engineering from Georgia Tech, is currently pursuing studies toward a Doctor of Philosophy degree in that field. He served 1 year as Electronics Instructor
in the U. S. Navy and has been associated with the Tennessee Polytechnic Institute and with this station on several projects since 1951.

Respectfully submitted:

Robert E. Meek
Project Director

Samuel N. Witt, Jr.
Research Engineer

Approved:

J. E. Boyd, Chief
Physical Sciences Division

Paul K. Calaway, Director
Engineering Experiment Station
IX. BIBLIOGRAPHY.


ENGINEERING EXPERIMENT STATION  
of the Georgia Institute of Technology  
Atlanta, Georgia  

QUARTERLY REPORT NO. 3  
PROJECT NO. A-216  

INVESTIGATIONS OF PRECISION FREQUENCY CONTROL TECHNIQUES  
By  
ROBERT E. MEEK and SAMUEL N. WITT, JR.  

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CONTRACT NO. DA-36-039-sc-6597  
DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022  
SIGNAL CORPS PROJECT: 142E  

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OCTOBER 1 to DECEMBER 31, 1955  

PLACED BY THE U. S. ARMY  
SIGNAL CORPS ENGINEERING LABORATORIES  
FORT MONMOUTH, NEW JERSEY
INVESTIGATIONS OF PRECISION FREQUENCY CONTROL TECHNIQUES

By

ROBERT E. MEEK and SAMUEL N. WITT, JR.

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CONTRACT NO. DA-36-039-sc-64597

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022

SIGNAL CORPS PROJECT: 142B

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I. PURPOSE

The purpose of this project is (a) to investigate methods by which temperature-insensitive coaxial cavities may be constructed, (b) to obtain data over a period of several months on the long-term frequency stability of a cavity-controlled oscillator which has exhibited good short-term stability, (c) to investigate methods by which very short-term frequency-stability measurements for periods of the order of 0.1 to 1.0 second may be made with an accuracy not exceeding 1 part in $10^9$ and (d) to investigate other related topics as may be agreed upon by the Contracting Officer and Georgia Institute of Technology during the course of this project.
II. ABSTRACT

The individual elements of the short-term frequency measuring system are described and the complete system is evaluated theoretically. Under certain assumptions, a sensitivity of 0.0637 mv/cycle of frequency change is indicated. This represents the available i-f voltage input to the i-f amplifier where a maximum additional gain of 140 db is available. An overall sensitivity which will permit the detection of one cycle per second frequency change is anticipated.

Data are presented on the long-term performance of an invar cavity-controlled oscillator immersed in a temperature regulated oven. Constructional details of this oscillator are illustrated. Integration of frequency stability factors from 28 long-term runs shows a weekly stability value of +11 ppm and -13 ppm. Several factors such as capacitor instability, oven temperature drift, and tube aging which influence this stability are discussed but are not totally evaluated. Performance of an invar cavity oscillator operating at room temperature is evaluated and the frequency is found to be stable within +48 ppm and -50 ppm for a five day period.

Results of measuring the temperature-frequency characteristics of silver-plated Stupalith cavities are given. Frequency stability values for these units range from 0.24 ppm/°C to 1.16 ppm/°C. The problem of initial coating of these cavities is found to be the poor adherence of the coating material to the ceramic surface in the bottom and in the corners of the cavity. The quality of the coating in these regions has definite effect on the Q of the cavity and values between 10 and 30 per cent of the optimum of 5500 were experienced in the first two units coated.
III. CONFERENCES

Mr. O. P. Layden, Project Engineer for the Signal Corps on this contract, visited the laboratories of Georgia Tech October 18 and 19, 1955. The purpose of this visit was to discuss certain material in Quarterly Report No. 1. An explanation was made by project personnel of the theory and functioning of the Pound discriminator system which had been adopted for use in the short-term frequency stability measurements. The integral-piece Stupalith cavities, which had recently been received, were inspected. Methods of processing these units for silver plating and subsequent measurement of their temperature-frequency characteristic were described.

Dr. G. K. Gutwein visited the project facilities on November 16, 1955 and inspected various phases of laboratory work. A discussion followed concerning problems of evaluating factors that influence long-term frequency drift of the invar cavity oscillator in the temperature regulated oven. It was agreed that if time and facilities were available, recordings should be made of oven temperature and oscillator tube heater current. Also, operation of cavity-controlled oscillators, constructed of brass, invar and Stupalith should be observed at room temperature. Recordings of the temperature and frequency variations would be made for a period of a week for each type.

A copy of a report of recent telephone inquiries to various laboratories and manufacturing concerns made by Mr. M. F. Timm was left with the project for reference purposes. The essence of this report is a rough estimate of the over-all status of cavity development and performance in this country with particular regard to the UHF region.
IV. SHORT-TERM FREQUENCY STABILITY MEASUREMENTS

A. Introduction

Work has continued on the short-term frequency-stability measurements problem. Most of the components to be used have been investigated both experimentally and mathematically. An i-f oscillator with buffers has been constructed for use in the Pound equal-arm system described in Quarterly Report No. 2. The problem of reference cavity impedance matching has been investigated as has the problem of properly matching the mixer and modulator crystals. The complete discriminator system has been evaluated mathematically using experimental data obtained in the laboratory.

B. Modulator and Mixer Crystal Matching

The problem of matching the modulator and mixer crystals to the 50 ohm coaxial line has been investigated experimentally in the laboratory. Microwave cartridge crystals as well as the lower frequency types have been studied. It has been found possible to match the G. E. Type 1N72 crystal, for use as a mixer, to the 50 ohm coaxial line without lumped resistive loading. The method is shown in Figure 4.1. The G. E. diode was chosen because its tapered

![Diagram](https://example.com/diagram.jpg)

Figure 4.1. Matching of Mixer Crystal.
construction permitted easier mounting within coaxial elements. With the set-up shown, both the adjustable line and shorted stub are adjusted until the impedance at the Tee is 50 ohms resistive. With this arrangement, the conversion efficiency of various diodes may be readily measured.

It is not necessary that the modulator crystal be matched to the coaxial line. However, it is very important that the line be properly terminated at the discriminator center frequency. To accomplish this, a G. R. Type 874 mixer rectifier has been used. It was found necessary to modify the mixer rectifier by replacing the 250 ohm series resistor in the center conductor with a 50 ohm unit. A short circuit is attached to the 50 ohm end. With this arrangement, the termination at 600 mc is very good.

C. I-F Oscillator and Buffers

The i-f oscillator and buffer unit has been constructed. A block diagram is shown in Figure 4.2. The oscillator uses a cathode-coupled, dual-triode circuit and operates at 10 mc with crystal control. The output is taken from a 30 mc tuned circuit in series with the plate of one of the triode sections. The buffers are conventional pentode amplifiers using variable cathode bias to control the output amplitude. The unit is completely

![Diagram of Oscillator-Buffer Unit](image-url)
enclosed with all chassis junctions soldered to prevent i-f leakage. Both
the filament and B+ connections are multisection filtered to prevent coupling
to the mixer i-f amplifier.

D. I-F Amplifier

A 30 megacycle amplifier, Model IF-30, was purchased from Linear Equip-
ment Laboratories to be used with the discriminator system. This unit will
raise the signal energy level at the output of the mixer crystal to a value
sufficient to operate the lock-in mixer. Commercial specifications for the
amplifier were 120 db gain, a 2 mc bandwidth, and a noise figure of 1.3 db.
Provision is included to use automatic gain control if needed. Modifications
were made to obtain an increase in gain and a slight improvement in noise
figure so that its present characteristics show a maximum gain of approximately
140 db, a bandwidth of 1.0 mc, and a noise figure of about 1.15 db. Threshold
sensitivity to input signals is about 0.3 µv. With an input signal modu-
lated 30 per cent, the amplifier is capable of handling a 40 db dynamic range
of input levels with less than 5 per cent distortion in the demodulated output
waveform. Observations of the transient shifts in the frequency of cavity-
controlled oscillators reveal that the bandwidth required in the discriminator
and amplifier will be much less than a megacycle. Drift in the resonant
frequency of the reference cavity due to temperature effects, however, may cause
greater concern for the bandwidth of the discriminator. Since the 30 mega-
cycle oscillator is crystal controlled, there will be no concern about the band-
width of the amplifier to allow for drift of the oscillator frequency.

E. Reference Cavity Construction

The reference cavity is constructed of brass and measures 4 inches in
diameter by 5 3/4 inches in length. All junctions in the frequency controlling
position of the cavity are soldered before final silver plating. The fre-
quency of the cavity is variable from 580 to 630 mc by means of a trimmer slug.
The Q of the cavity has not yet been accurately determined but is expected to
be greater than 10,000.

The cavity will be mounted in a heat insulated chamber, but without
thermostatic control since it is necessary to maintain a constant frequency
reference over only relatively short periods of time.
The cavity will be connected to the discriminator by a rigid coaxial line which will include an adjustable line section. The cavity coupling loop will be such that it presents a 50 ohm impedance to the line.

F. Physical System Block Diagram

Figure 4.3 shows a block diagram of the short-term frequency stability measuring system. All of the components which merit detailed description have been discussed in this report or in Quarterly Report No. 2. The lock-in mixer and d-c test oscillator control system have not yet been constructed, however, these components are not necessary for initial evaluation and tests of the assembled system. These tests are scheduled for the next report period.

It has not been decided whether the system will be rack or table-top mounted. The physical nature of the equipment is such that some difficulty has been experienced in supporting the various components. It is anticipated that these problems will be initially solved by using a "bread-board" set-up.

G. Theoretical Evaluation of System

The "Magic Tee" equivalent of the coaxial ring transformer will be used in the following mathematical development. The voltage components arriving at the mixer crystal are shown in Figure 4.4. Voltages are assumed to be RMS values. \( E \) is the magnitude of the input to the system and \( M \) is the modulation factor. The angle between the voltages arriving at the mixer crystal is designated \( \Theta \).

From Figure 4.4 (1)

\[
E_t = \left[ \left( \frac{E |r|}{2} \sin \Theta + \frac{EM}{2} \cos \omega t \right)^2 + \left( \frac{E |r|}{2} \cos \Theta \right)^2 \right]^{1/2}
\]

The term \((E |r|/2) \cos \Theta\) represents a carrier component 90° out of phase with the original carrier which was eliminated at the modulator. Therefore, it does not contribute to the i-f output amplitude and may be dropped from the expression for \(E_t\) leaving

\[
E_t = \frac{E |r|}{2} \sin \Theta + \frac{EM}{2} \cos \omega t.
\]
Figure 4.3. Physical System Block Diagram of Short-Term Frequency Stability Measuring System.
Application of Fourier's Theorem to $E_t$ yields a component of voltage at the i-f frequency

$$E_S = \frac{1}{\pi} \left\{ E |r| \sin \theta \left[ 1 - \left( \frac{|r| \sin \theta}{M} \right) ^2 \right] + EM \sin^{-1} \left( \frac{|r| \sin \theta}{M} \right) \right\}.$$

Figure 4.4. Equal-Arm Discriminator.

Near resonance and with 100 per cent modulation

$$\frac{|r| \sin \theta}{M} \ll 1$$

and

$$\sin^{-1} \left( \frac{|r| \sin \theta}{M} \right) \approx \frac{|r| \sin \theta}{M}.$$
Therefore,

\[ E_s \approx \frac{1}{\pi} (E|r| \sin \Theta + E|r| \sin \Theta) \]

\[ = \frac{2E|r|}{\pi} \sin \Theta. \]

The i-f output voltage from the mixer crystal is

\[ v = E_s \left( \frac{Z_{i-f}}{L_c Z_0} \right)^{\frac{1}{2}} \]

where \( Z_{i-f} \) is the i-f impedance of the mixer crystal, \( L_c \) is the crystal conversion loss, and \( Z_0 \) is the coaxial line impedance.

The quantity \( |r| \sin \Theta \) was evaluated for the reflection cavity in Quarterly Report No. 1 as

\[ |r| \sin \Theta = \frac{-2a\alpha}{(\alpha + 1)^2 + a^2} \]

where

\[ a = 2Q_0 \left( \frac{\omega - \omega_0}{\omega_0} \right), \]

\[ Q_0 = \omega_0 CR, \]

\[ \alpha = \frac{R}{n_1^2 Z_0}. \]

\( R \) and \( n_1 \) are defined by the equivalent circuit shown in Figure 4.5.
Figure 4.5. Equivalent Circuit of a Reflectron Cavity.

The peak i-f voltage in terms of the above parameters becomes

\[ v = \frac{2E}{\pi} \left( \frac{Z_{i-f}}{L_c Z_0} \right)^{1/2} \frac{-2a\alpha}{(\alpha + 1)^2 + a^2} \]

The rate of change of the i-f voltage with respect to frequency becomes

\[ \frac{dv}{df} = \frac{2E}{\pi} \left( \frac{Z_{i-f}}{L_c Z_0} \right)^{1/2} \frac{1}{2} \frac{a\alpha}{(\alpha + 1)^2 + a^2} \times \frac{1}{L_c Z_0} \]

\[ = \frac{SEQ}{\omega_0} \left( \frac{Z_{i-f}}{L_c Z_0} \right)^{1/2} \frac{(\alpha + 1)^2 - a^2}{[(\alpha + 1)^2 + a^2]^2} \cdot \]

At resonance \( a = 0 \) and

\[ \frac{dv}{df} = \frac{SEQ}{\pi \omega_0} \left( \frac{Z_{i-f}}{L_c Z_0} \right)^{1/2} \frac{\alpha}{(\alpha + 1)^2} \]
which has a maximum value when \( \alpha = 1 \). Therefore, when \( \alpha = 1 \),

\[
\frac{dv}{df} \bigg|_{\text{max}} = \frac{2E\Omega}{\pi f_0} \left( \frac{Z_{i-f}}{L Z_0} \right)^{\frac{1}{2}}.
\]

A typical value of \( Z_{i-f} \) for a 600 mc carrier and a 30 mc modulation appears to be 450\( \Omega \). \( L_c \) is assumed to be 4 and \( Z_0 = 50\Omega \) giving

\[
\frac{Z_{i-f}}{L Z_0} = 2.25.
\]

It is assumed that \( E = 5 \) volts RMS can be put into the discriminator and that a \( Q_o \) of 10,000 is reasonable for the reference cavity at 600 mc.

Substitution of these values gives

\[
\frac{dv}{df} \bigg|_{\text{max}} = \frac{2 \times 5 \times 10^4 \times 1.5}{3.14 \times 6 \times 10^8} = 0.637 \times 10^{-4}
\]

\[
= 0.0637 \text{ mv/cycle}.
\]

From Quarterly Report No. 1, page 29,

\[
Y_c = \frac{Y_0}{\alpha} (1 + ja).
\]

For \( \alpha = 1 \) and \( a = 0 \), \( Y_c \) must equal \( Y_0 \) which requires that the cavity be matched to the coaxial line.

This development assumes that the carrier can be completely eliminated at the modulator crystal and that infinite rejection is obtained in the direct path between the discriminator input and the mixer crystal.
V. LONG-TERM FREQUENCY STABILITY MEASUREMENTS

A. Introduction

Long-term frequency stability measurements are being made on cavity-controlled oscillators of the type that have exhibited excellent medium-term stability characteristics. Prior to this project, very little information had been compiled from operation of oscillators of this type over a period of several months. In this case, the type refers to a category of construction where the coaxial-cavity resonator constitutes the base or chassis on which the tube and its associated circuitry is mounted, making an integral compact unit which maintains a reasonably stable frequency.

Quarterly Report No. 2 contained frequency stability measurements derived from test runs during the period 12 August to 30 September 1955. The following section of this report presents data for the three month period 1 October to 30 December 1955 supplementing information gathered during the preceding period.

The purpose of this observation, in addition to determining stability characteristics, is to identify and attempt to evaluate factors such as tube aging, power supply variations, and temperature effects that influence this stability.

B. Modification Details of the Invar-Cavity Oscillator

The previous report mentioned a change in the physical arrangement of the tube and circuit components that became necessary because of the observance of temperature effects. The original oscillator was constructed with the tube mounted inside the center conductor of the cavity and instantaneous changes, by a small percentage, in the heater voltage caused rapid changes of the frequency of the oscillator. Therefore, the tube and its associated circuitry were relocated on the cap enclosing the overhang region of the cavity. There was a noticeable reduction in the magnitude of short-term frequency excursion with heater voltage changes when this modification was made. The construction details of this modified-cavity oscillator are shown in Figure 5.1.
Figure 5.1. Cavity-Controlled Oscillator.
Short term evaluation of this modification was carried out on a prototype brass-cavity oscillator at the beginning of this quarter and the results were found satisfactory enough to apply this modification to the invar-cavity oscillator in the temperature controlled oven. The series-tuning capacitor which was originally mounted on the end cap of the cavity was moved to the end of the center conductor and tuning adjustment was accomplished through the outside opening of the center conductor. Additional reduction in short-term sensitivity to temperature changes was noted when the open end of the center conductor was closed, isolating this space from immediate influence of the temperature of the external air circulating around the cavity. This result would be expected because small temperature changes of the center conductor have greater influence on the frequency than equivalent changes in temperature of the outer conductor.

When the tube was relocated on the end cap, it was considered necessary to enclose it, and the associated circuitry, in an air-tight compartment. This compartment is constructed of brass which provides fairly rapid dissipation of the heat generated within the compartment. Also, it acts as a better heat sink for the heat conducted through the end cap than do the outside walls of the invar cavity. Perhaps it is recognized that all of these modifications have been aimed toward maintaining the active portions of the cavity at a uniform temperature throughout. The result has been a minimization of short-term temperature effects. However, there was very little influence in reducing the effects of long-term temperature changes. One desirable effect from the location of the series-tuning capacitor on the end of the center conductor was a material increase in the tuning range of the oscillator over the previous case. Screwing the slug inward resulted in increasing the capacity and the electrical length of the center conductor at the same time. Conversely, the opposite effect is produced by screwing the slug outward. This provided almost a 50 per cent increase in the tuning range compared to that of the previous model.

C. Discussion of Recorded Data

Twenty-eight test runs, totaling about 1380 hours, were recorded during the third-quarter period and the results of evaluation are presented in Table 5.1.
### TABLE 5.1
RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR CAVITY-CONTROLLED OSCILLATOR

<table>
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<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
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TABLE 5.1 (Continued)
RESULTS OF TEST RUNS FOR MEASUREMENT OF
FREQUENCY STABILITY OF INVAR CAVITY CONTROLLED OSCILLATOR

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<td></td>
<td>+5.3 kc</td>
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<td>-14.6 kc</td>
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<tr>
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<td>599.999130</td>
<td>70</td>
<td>+14.2</td>
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<tr>
<td></td>
<td>-2.9 kc</td>
<td></td>
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</tr>
</tbody>
</table>

Notes:
1. Operating conditions
   a. oven temperature 45° ± 1/2° C
   b. regulated plate and heater supplies
2. Average of the run durations - 50 hours.

Due to the volume of material contained in the original recordings, only a sample portion is included in this report. A representative sample is shown in Figure 5.2. It was hoped that several week-long runs would be obtained for this report but the drift of frequency during the test runs was greater than expected and necessitated frequent retuning of the oscillator. However, the average length of runs recorded was approximately 50 hours as compared to 36 hours on the average during the previous quarter.
The values in the column labeled "Average Frequency of Run" in Table 5.1 were determined by dividing the algebraic sum of the hourly ordinates of frequency by the length in hours of the run. This value was considered significant as a basis for predicting the performance of the oscillator frequency for runs of the same length under similar conditions. The tolerances associated with this value of average frequency represent the magnitude of the maximum positive and negative excursions of frequency relative to the line representing the average frequency drawn on the original recording. The stability of the average frequency is given in the fourth column and is determined by dividing the values of maximum frequency excursion by the absolute average frequency of the oscillator.

Using the method of least squares, a line was located on the original recording from which the mean rate of frequency change for the run was determined. This value is presented in column three. The sign associated with this figure designates the trend of frequency variation of the oscillator as an increase or a decrease in the absolute frequency. The fifth column presents a normalization of this value.

Figure 5.2. A Sample Recording of the Frequency Characteristic of an Invar Cavity Controlled Oscillator.
Data of further interest resulted from an integration of the stability factors of average frequency from all the runs plotted against run duration in hours. A line representing the mean value of all the stability factors, with respect to time, can be drawn on this plot. Information on the typical stability of this type of oscillator for any particular period of past experience can then be determined. This graph is shown in Figure 5.3. As an example, the stability of the average frequency of the oscillator for a period of a week is shown by the mean line to be +11 parts per million and -13 parts per million. How close this is to an accurate typical value will be determined from more experience with long term runs.

D. Factors Influencing Frequency Stability

The cause of long-term frequency drift of the oscillator is still not well understood. Several influencing factors have been identified but the character of contribution of each has not been evaluated.

During this quarter, one 6AF4 tube weakened to the point where it would not operate in a cavity oscillator. The emission was found to be very low. This tube had been operating for approximately 510 hours. Several hours before the oscillator stopped, the frequency wandered erratically but with a trend toward a higher frequency. Operation of these tubes in an ambient of 50°C may have rapid deteriorating effects on its aging characteristics. In addition, the operating-plate current is in the neighborhood of 70 per cent of the maximum specified emission for this tube type. Therefore, fluctuations in the total emission may be an appreciable factor in determining the admittance value seen by the terminals of the cavity.

Occasional trouble was experienced with instability of the series-tuning capacitor. This capacitor was a JFD type VC-5 tubular trimmer constructed of quartz and invar. This instability was more noticeable immediately following a tuning adjustment of the oscillator and would last several hours. The trouble seemed to be associated with the loading spring on the base of the capacitor which created a braking action against the threads of the rotor shaft. The threaded rider against which the spring was compressed was not rigidly clamped in the guides that prevented its rotating with the shaft.
Figure 5.3. Integration of the Stability Factors of All Test Runs.
Any torsional stress in the spring may have caused a slow shift in the position of the capacitor slug. A lock nut screwed on the rotor shaft against the base of the capacitor has eliminated most of this effect. However, the presence of this lock nut makes the tuning adjustment of the oscillator very difficult when the unit is located in the oven.

Spot checks of the oven temperature revealed random shifts in the value of the control point. The shifts were found to be as much as 3° C. The short-term control still seems to be within one-half degree as reported previously but the long term characteristics are apparently much different. The oven-control thermostat being used is a series 17,000 Fenwall. Experience of other users of these thermostats has since confirmed that these shifts of the control point is not uncommon. It is highly probable that this condition has caused a great deal of the frequency drift observed. Work is in progress now to correct this by using a different type of control element.

E. Performance of Measuring System

Since the original frequency measuring system described in Quarterly Report No. 2 could not determine the location (above or below) of the absolute frequency of the oscillator relative to that of the standard, it was found necessary to find some method to provide this information during measurements. The method found most practical was periodical check of the recording (to see if the oscillator had passed through the region of zero beat) with the reference frequency and then measuring the absolute frequency of the oscillator with a frequency meter. The appropriate notation from this measurement was then made on the recording. There was very little difficulty in determining what happened during the unattended periods since the characteristics of oscillator drift rate was low enough in the majority of cases that not more than one or two crossings would be made.

The APN-4 receiver employed at the time of writing of Quarterly Report No. 2 has been replaced with a simple crystal mixer utilizing a G. E. LN72 diode. An additional stage of gain was placed between the mixer output and the frequency counter input to compensate for the gain lost in removing the receiver. This change was made to broaden the frequency response of the
element driving the frequency counter when it was anticipated that greater ranges of frequency measurement would be needed. The reliability of the system has also been improved somewhat since an active element of many tubes has been replaced with a passive element of few parts and simplifying operation.

A record of the measurement of the frequency standard against WWV showed that it did not drift more than 24 cycles at 600 megacycles during the entire third quarter.

F. Room Temperature Run

A test run was made with an invar-cavity-controlled oscillator placed in the open to operate at the ambient temperature. Plate and heater power were supplied to the oscillator from a regulated source. No attempt was made to control the temperature of the room other than the regular heat control system of the building. This maintained the temperature to about an 8 per cent variation about the mean. A continuous recording of the temperature variations was made during the entire run so that correlation could be observed between frequency and temperature. The data from the original recordings of temperature and frequency have been reproduced in graphical form and are presented in Figure 5.4. The duration of the run was about 120 hours but only about 100 hours were considered satisfactory for evaluation for this report. A sample of the original recordings of frequency and temperature are shown in Figure 5.5. Further evaluation of the performance of the oscillator is presented on the graph in the form of lines representing the average frequency of the run and the mean value of frequency change. The data corresponding to these plots are tabulated in Table 5.2. The stability of the oscillator frequency about the average is obtained by dividing the maximum excursions from this mean value by the absolute average frequency. For this particular run, the stability of the average frequency was +50 parts per million and -48 parts per million. The stability of the mean rate of frequency change is ±0.67 parts per million per hour.

G. Temperature Recording

Several attempts have been made to record temperature on Varian or Esterline-Angus pen recorders. Most of these attempts have used the iron-
Figure 5.4. Frequency Characteristic of Invar Cavity Controlled Oscillator Operating at Room Temperature.
Figure 5.5. Sample Recordings of Original Frequency and Temperature Variation for Room Temperature Operation of Cavity Oscillator.
TABLE 5.2
RESULTS OF TEST RUN OF INVAR CAVITY-
CONTROLLED OSCILLATOR AT ROOM TEMPERATURE

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>500.023960</td>
<td>334</td>
<td>+50</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>+25.0 kc</td>
<td></td>
<td>-48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-24.0 kc</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conditions: Regulated Electrode Supply
Average Humidity: 40 per cent

constantan thermocouples. Since it was desirable to measure variations in room and oven temperatures, an ice water bath was used for the reference junction. However, even with five thermocouples in series, sufficient voltage was not available to drive any of the recorders directly (approximately 7 mv of d-c output was obtained at room temperature). Suitable d-c amplifiers are not presently available to provide the necessary gain.

Other temperature measuring methods, including the use of Thermistors and bimetallic strips, have been investigated but are not considered suitable because of the complexity of associated equipment.

At present, a Bendix-Friez Hygrothermograph Model 160 pen recorder is being used. A disadvantage of this instrument is that the recording is made on a card rather than on a roll chart. However, the instrument is small and is driven by a spring-wound motor which makes it highly portable. Oven use of this recorder is restricted by the range of temperature (0 - 110° F) it will handle.
VI. TEMPERATURE INSENSITIVE CAVITY MEASUREMENTS

A. Introduction

During this quarter, measurements were initiated on two of the Stupalith cavities fabricated by the Stupakoff Division of the Carborundum Company of Latrobe, Pennsylvania. Development of these cavities is a pursuit of the proposal (concluded from previous work concerning temperature-compensated cavities)(2) that cavities of stable frequency characteristics over a wide temperature range might be built from materials of low or possibly zero temperature-expansivity coefficients. One material found to have the required temperature characteristics is a magnesium-alumino-silicate compound manufactured under the trade name "Stupalith".

Previous experience with the assembly of cavities made partly or entirely of Stupalith revealed deliterious effects on the temperature-frequency characteristics traced principally to the materials used to bond various sections of the resonator together. Because of these difficulties, the fabricating facilities of Stupakoff, who manufacture this material, were investigated and found to be capable of producing a cavity to our specifications. Two separate sections of Stupalith were moulded and bonded together by fusing the intersections. The entire assembly was then thoroughly annealed to relieve all internal stresses. These integral-piece, unplated cavities were received at the end of last quarter and the process of coating, firing, and silver-plating was performed by project personnel. Figure 6.1 shows the mechanical details and dimensions of these cavities.

B. Evaluation of Cavity Coating

A procedure, developed on a previous project (2), for coating ceramic materials of this type was followed in processing these cavities. Instead of spraying the basic coating material onto the surface, as specified in the above procedure, however, the entire cavity was dipped into the solution and rotated while submerged. The unit was then removed and positioned so that the excess solution would drain off easily. After air drying the first cavity about four hours, the surface appeared to be uniformly covered and firing of the coat proceeded. Inspection of the surface following the firing procedure
Figure 6.1. Construction Details of Stupalith Cavity.
revealed a very poor covering, particularly in the bottom and in the corners of the cavity. It was decided, however, to proceed with electroplating of silver onto this base to learn what effects would result. It was found that the thin-coat areas did not electroplate well.

After electroplating, two coupling loopholes were drilled into the cavity on opposite sides of the center conductor about 1/2 inch from the bottom. The Q of the cavity was measured and found to be around 500, which was considerably lower than expected. The theoretical Q of these cavities with silver plating should be in the neighborhood of 5500, which is somewhat less than optimum for a coaxial cavity.

The second cavity was dipped about four times in the coating solution with about two hours drying between coats. After firing at the proper temperature, inspection of the surface revealed a good uniform coverage except in the bottom and in the corners. Poor adherence to the ceramic material may have been the cause of this condition in the corners, where the coating material had large surface cracks as though shrinkage had set in during the cooling period. Another troublesome factor could have been gas pockets, either in the ceramic itself or between the coating and the ceramic surface, which may have been blown out during firing. It is not known why the covering was thin on the bottom since the sides of the center and outer conductor coated very well. Investigation of methods to eliminate these conditions will be carried on during the next quarter. Measurement of the Q of this cavity gave a figure of 1500 which is still quite low.

C. Measurement Procedure

Figure 6.2 shows the block diagram arrangement of the various components used in measuring the temperature-frequency characteristics of the Stupalith cavities as passive elements. Initial tests employed the cavity as a transmission element whereas later tests utilized it as a reflection element. Since there was noticeable influence from the presence of one coupling loop in the cavity space, it was considered that an additional loop would increase the effect. The block diagram shows the system set up with the cavity as a reflection element which has worked quite satisfactorily. An adjustable line is
placed between crystal detector and the cavity and adjusted to an integral number of half-wave lengths (less some compensation for the loop inductance) at the frequency of resonance. Thus, the detector would see a replica of the impedance characteristic of the coupling loop as the incident energy passed through the region of cavity resonance. The resistor between the sweep generator and the detector provides a voltage variation proportional to the impedance.
variation. A d-c scope is used to observe the response characteristic of the cavity and to determine proper adjustment of the marker signal on the point of resonance.

The marker signal is generated by a cavity-controlled oscillator and its frequency is observed with a heterodyne-frequency system consisting of another cavity oscillator and a crystal mixer element. The beat frequency generated between this oscillator and the marker oscillator is fed to a decade frequency counter where it is continuously monitored. The frequency of the reference oscillator is also monitored with a frequency meter to maintain its frequency at a constant value. With this arrangement, the delay between adjustment of the marker and reading of the frequency is minimized. In measuring the temperature-frequency characteristics, only the changes in frequency were of interest. Therefore, the procedure did not require knowledge of the absolute frequency of cavity resonance except at the beginning or at the end of a test run.

D. Evaluation of Tests

Three temperature runs have been made on the two silver plated Stupalith cavities described. The range of temperature variation was from room temperature (approximately $27^\circ C$) to $100^\circ C$, a variation of $70^\circ$. In the first run, the temperature checks were made at $10^\circ$ intervals and in other runs the checks were made at $20^\circ$ intervals. Graph A of Figure 6.3 presents the temperature-frequency characteristics of this unit when utilized as a transmission element in the measuring system, whereas graph B depicts the operation of the same unit as a reflection element. A line representing the mean value of the trend of frequency change has been drawn on the graphs to convey typical information regarding the stability of this type of cavity with temperature variation. The stability value of the first run indicates quite good results for this cavity as compared to the second run although it is believed that the measurements made in the second run are more reliable. This conclusion is justified by comparing the dispersal of points about the mean value line for the two cases. The difference in stability values is not clearly understood but it is believed that the measurements have been influenced by temperature effects on the coupling loops and upon that portion of the coaxial line which lies inside the oven. Furthermore, the input and output lines used in the transmission mode
Quarterly Report No. 3, Project No. A-216

Figure 6.3A  Run No. 1  11-28-55

Temperature-Frequency Characteristics of Stupalith Cavity, Model No. 1
(Cavity as transmission element; one base coat before silver plating.)

0.24 ppm/°C
Mean value of frequency change

Figure 6.3A

Temperature-°C

FREQUENCY - MC

664.11
664.10
664.09
664.08
664.07
664.06
664.05

20 30 40 50 60 70 80 90 100 110 120 130 140 150

Figure 6.3B  Run No. 2  12-19-55

Temperature-Frequency Characteristics of Stupalith Cavity, Model No. 1
(Cavity as reflection element in heterodyne frequency system.)

1.1 ppm/°C
Mean value of frequency change

Figure 6.3B

Temperature-°C

FREQUENCY CHANGE - KC

630
620
610
600
590
580
570

20 30 40 50 60 70 80 90 100 110 120 130 140 150

Figure 6.3. Temperature-Frequency Characteristics of Plated Stupalith Cavity No. 1.
system may have had compensating effects upon each other such that the results produced may be more typical of the cavity characteristics. During the next quarter, investigation will be carried on to evaluate and reduce these effects which may be masking true cavity characteristics. Figure 6.4 presents the temperature-frequency characteristics of the second of the two plated cavities and the results are comparable with those of the second run on the first cavity. The deviation of points from the mean value line is somewhat less in this case and is probably due to refinement of the measurement procedure.

![Temperature-Frequency Characteristics of Plated Stupalith Cavity No. 2.](image)

**E. Stupalith Cavity-Controlled Oscillator**

During recent conferences, interest has been expressed by Signal Corps representatives in the characteristics of a Stupalith cavity-controlled oscillator. Construction of mounting elements for an oscillator tube and associated circuitry has begun and operation of the unit will be observed next quarter. It is planned to operate the oscillator at room temperature for a period of one week, which should give data that are typical of this application for short and medium term duration.
VII. CONCLUSIONS

Calculations indicate that the proposed system for measuring short-term oscillator stability will be adequate for measuring the stability of presently available cavity oscillators. Several factors which have not been fully evaluated but which affect the ultimate characteristics of the system are (a) lack of infinite isolation in the ring transformer, (b) discriminator bandwidth, (c) i-f amplifier stability, (d) reference cavity Q and temperature stability and (e) reference cavity impedance matching characteristics. It should be possible to measure frequency changes as small as one cycle per second before the system is limited by noise. Thus, the reference cavity stability primarily determines the minimum measurable frequency change. Temperature stabilization of the reference cavity may not be necessary because of the short-term nature of the measurements.

Long-term frequency stability values from 28 runs lie in the neighborhood of +11 ppm/week to -13 ppm/week. Primary cause of long-term frequency drift has not been completely isolated. The factors found to influence this condition were oven-temperature drift, series tuning capacitor instability, oscillator tube aging, and heater current variation.

Operation of an invar cavity oscillator at room temperature produced a frequency stability value for five days of +50 ppm to -48 ppm. Room temperature variation was the significant influence in producing frequency variation.

Problems still exist in obtaining satisfactory coating in the bottom and corners of the Stupalith cavities. Evaluation of this condition has been made only in terms of the Q of the cavity.

The best frequency stability of the runs made was obtained from the first of the plated cavities utilizing the transmission mode of the cavity. Values of stability from runs using the reflection mode coupled with the heterodyne frequency system were significantly different. The measurements obtained, however, were found to be statistically more reliable. Transmission line and coupling loop temperature effects appear to be the factors that mask the true cavity frequency-stability characteristics.
Design and construction of suitable modulator and mixer-crystal assemblies for use with the short-term frequency stability measuring set up will be completed. Suitable regulated power supplies will be constructed to supply power to the i-f oscillator and amplifier. The various termination arms of the ring transformer will be aligned and assembled. The complete system will be tested first without the lock-in mixer and d-c oscillator control system. The discriminator characteristic will be evaluated with regard to sensitivity and stability. The possibility of measuring cavity oscillator stability without the use of a lock-in mixer of d-c control system will be considered. The remaining time will be devoted to actual short-term oscillator stability measurements.

Long-term frequency stability measurements will be continued. Attempts to make recordings of oven-temperature drift will be continued. Room temperature performance of cavity oscillators constructed of brass and of Stupalith is programmed for completion.

The remaining cavities of Stupalith will be silver plated and their temperature-frequency characteristic measured. Methods of evaluating and minimizing temperature effect of the coupling loop and transmission line will be investigated.
IX. IDENTIFICATION OF KEY PERSONNEL

Dr. Donald W. Fraser devoted one-third time to the project from April to August 1955. He was Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Doctor of Philosophy in Electrical Engineering from this institution. Dr. Fraser has been engaged in research and development at the Engineering Experiment Station for about four years. His other experience included five years of electronic testing and research in the U. S. Navy.

Mr. Edward G. Holmes, who holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology, was director of this project from April to September 1955. His experience in the electronics field included five years of work with frequency-measuring apparatus and broadcasting equipment, two years as an electronics officer in the U. S. Navy and four years of research and development work in UHF and microwave equipment.

Mr. James E. Lane joined the project December 12, 1955 as a technical assistant. He is currently devoting one-half time to project work. Mr. Lane has previously been connected with the station as a technician on various other projects. He has had four years experience in military electronic maintenance and is at present a third year student in Industrial Management at Georgia Tech.

This project is now under the direction of Mr. Robert E. Meek, research engineer, who assumed these duties September 1, 1955. He joined the project August 1, 1955, and is at present devoting full time to this work. Mr. Meek holds the degree of Bachelor of Science in Electrical Engineering from the University of Kentucky. He has previously been associated with the University of Kentucky and on several projects at this station since 1951.

Mr. James C. Sellers was employed half-time as an electronic technician on the project from April to December 1955. He was previously engaged for eight years in nuclear instrumentation with the A. E. C. at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.
Mr. Samuel N. Witt, Jr., research engineer, joined this project August 1, 1955 and is presently devoting one-half time to the work. Mr. Witt, who holds the degree of Master of Science in Electrical Engineering from Georgia Tech, is currently pursuing studies toward a Doctor of Philosophy degree in that field. He served one year as an electronics instructor in the U. S. Navy and has been associated with the Tennessee Polytechnic Institute and with this station on several projects since 1951.

Respectfully submitted:

Robert E. Meek
Project Director

Samuel N. Witt, Jr.
Research Engineer

Approved:

J. E. Boyd, Chief
Physical Sciences Division

Paul K. Calaway, Director
Engineering Experiment Station
I. BIBLIOGRAPHY


INVESTIGATIONS OF PRECISION FREQUENCY-CONTROL TECHNIQUES

By

ROBERT E. MEEK and SAMUEL N. WITT, JR.

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CONTRACT NO. DA-36-039-sc-61597
DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 142B
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JANUARY 1 TO MARCH 31, 1956

PLACED BY THE U. S. ARMY
SIGNAL CORPS ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY
INVESTIGATIONS OF PRECISION FREQUENCY-CONTROL TECHNIQUES

By

ROBERT E. MEEK and SAMUEL N. WITT, JR.

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JANUARY 1 TO MARCH 31, 1956
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I. PURPOSE

The purpose of this project is (a) to investigate methods by which temperature-insensitive coaxial cavities may be constructed, (b) to obtain data over a period of several months on the long-term frequency stability of a cavity-controlled oscillator which has exhibited good short-term stability, (c) to investigate methods by which very short-term frequency-stability measurements for periods of the order of 0.1 to 1.0 sec may be made with an accuracy not exceeding 1 part in $10^9$ and (d) to investigate other related topics as may be agreed upon by the Contracting Officer and the Georgia Institute of Technology.
II. ABSTRACT

Only slight improvement appeared in the results of runs on Invar cavity-oscillators during long-term measurements as compared to similar runs of the previous quarter. A compiled study of 4th quarter data showed a stability factor for a typical run was about ± 9 ppm/week. Various factors in the case of Invar cavity-oscillators were found to have different degrees of influence on frequency variations observed. Temperature and humidity effects appeared to be the principal factors as they contributed a combined value of 4.75 ppm/°C, per cent R.H. Stability of power sources for plate and heater voltage produced a total disturbance of only 0.028 ppm/v. Other factors of relatively minor influence such as tube aging, capacitor variations and mechanical distortion were studied and were found to have random effects that could not be forecast. Two cases of oscillator stoppage were found to result from gassy tube conditions at the end of approximately 600 hours of service.

Room temperature runs on Invar and Stupalith cavity-oscillators produced greatly improved results compared to the results for an Invar cavity-oscillator operated under similar conditions during the previous quarter. Five runs of the Invar oscillator gave a stability value of about ± 10 ppm/day and 2 runs of the Stupalith oscillator indicated ± 3 ppm/day.

Results of runs to determine temperature-frequency characteristics of Stupalith ceramic-cavities revealed the influence of temperature effects on connecting cables to be negligible. Three runs gave essentially similar data to those obtained previously (1.0 ppm/°C).

Some causes of low sensitivity and thus low resolution in the short-term frequency-stability measuring system are discussed. These include low input amplitude, low modulation efficiency, low reference cavity Q and low mixer efficiency. The diode modulator assembly is described in detail. Evaluation of the modulator shows that, in the production of sidebands, it has a voltage efficiency of only 10 per cent. Data on the i-f amplifier and mixer components of the system reveal noise interference in the form of microphonics and thermal noise to be appreciable. Hum modulation in the i-f amplifier was found to be
as great as 50 per cent when an a-c heater source was used. A procedure is outlined for setting up the complete system prior to making measurements. A comparison of the actual performance of the system with that predicted in Quarterly Report No. 3 shows that a loss in sensitivity by a factor of 200 is unaccounted for. Since the noise level of the present system is near the theoretical minimum, any increase in resolution must come from increased signal sensitivity. The present resolution of the system is limited by low sensitivity and noise to approximately 1 ppm of frequency change.
III. CONFERENCES

Mr. R. E. Meek and Mr. W. B. Wrigley of Georgia Tech met with representatives of the Signal Corps at the Signal Corps Engineering Laboratories on 13 March 1956 to discuss results of work on cavity-oscillator design and stability, and to agree on subjects to be treated in the final report. A conference was held with Mr. O. P. Layden and Dr. G. K. Guttwein to discuss various phases of project work. Particular interest was shown in the development of a workable system for short-term frequency-stability measurements. The conclusions reached in this conference were that a three month's extension of the contract would be advisable in order to obtain more conclusive results on short-term measurements. It was felt that much improvement could be made in the present system and that a workable assembly could be delivered to the Signal Corps for application to their own purposes. This extension would cover the period 1 April 1956 to 30 June 1956 (with the final report due 31 July 1956) and would be budgeted at approximately the same quarterly rate as is now in effect. It was agreed that studies of long-term stability would be concluded at the end of the 4th quarter. A quarterly-type report would be submitted at the end of the present contract period in lieu of the final report originally specified.

A highly interesting and informative tour was made of the new facilities of the Signal Corps laboratories following this conference.

Advance information on the date and place of the Tenth Annual Frequency Control Symposium was released during the visit and a request for a paper on a subject related to the results of work on this contract was made.
IV. LONG-TERM FREQUENCY STABILITY MEASUREMENTS

A. Introduction

The statistical data on the long-term frequency stability of cavity-controlled oscillators gathered during the 4th quarter of the contract conclude the tests on this phase of the project. Little significant change appeared in the frequency-stability performance of these oscillators during this quarter as compared with their previous performance. From this observation, it seems that sufficient data have been recorded to establish a good understanding of the typical characteristics of these units under conditions of regulated power and controlled environment.

The problem of temperature control of the oven stated in Quarterly Report No. 3 was only slightly reduced during this quarter so that there is still a need for further research to improve this condition. However, the degree of influence from this source was sufficiently understood so that other factors affecting frequency could be isolated for study.

Some minor changes in the oscillator circuit resulted in a reduction of the short-term frequency transients which were noticeable previously and, also, an improvement in the plate voltage-frequency characteristic.

Room temperature runs were continued during this quarter on the Invar cavity-oscillator as well as on the cavity-oscillator constructed of brass. Results from the performance of the Invar oscillator showed nearly a fivefold improvement over the performance of a similar oscillator operated during the previous quarter.

B. Evaluation of Recorded Data

A total of 812 hours of data from 12 test runs of an Invar cavity-oscillator in a temperature-controlled oven were obtained during the 4th quarterly period. Figure 4.1 shows a sample recording of a test run during this quarter and reveals considerable reduction in the short-term frequency excursions that were evident in earlier runs.

The results of the evaluation of these data are given in Table 4.1. The construction of this table is the same as that appearing in Quarterly Report
Combining the stability values of average frequency from the several runs in Table 4.1 on a plot of frequency stability vs duration of run in hours, gives a picture of the time performance characteristic of a typical oscillator of this kind. Figure 4.2 shows a plot of this type and has a line drawn through the points representing the mean value of frequency stability against run duration. From this mean-value line it is seen that a run duration of one week may typically result in a stability of 9 ppm. Comparing this result with that from a similar plot in Quarterly Report No. 3 reveals some improvement in stability for the same period.

C. Oscillator Characteristics

Several factors associated with the characteristics of cavity-controlled oscillators have been studied and evaluated, at least qualitatively, in...
TABLE 4.1
RESULTS OF FOURTH QUARTER TEST RUNS ON TEMPERATURE-CONTROLLED INVAR CAVITY OSCILLATOR

<table>
<thead>
<tr>
<th>Duration of Run (Hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency of Run (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>-11.1 kc</td>
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<td>33</td>
<td>600.005465</td>
<td>169</td>
<td>+7.5</td>
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</tr>
<tr>
<td></td>
<td>+4.5 kc</td>
<td></td>
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<td>-4.5 kc</td>
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<td></td>
<td></td>
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<td>+6.5</td>
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</tr>
<tr>
<td></td>
<td>+3.9 kc</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>-2.4 kc</td>
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<tr>
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</tr>
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<tr>
<td></td>
<td>-4.5 kc</td>
<td></td>
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</tbody>
</table>
Figure 4.2. Stability-Time Characteristics from 4th Quarter Temperature-Controlled Runs.
previous reports. Since tests on this phase of the project are being concluded, a brief summary of these various factors and their influence on frequency stability is presented in this section. Specific effects that have received attention in analysis of oscillator characteristics are temperature, humidity, plate and heater voltage fluctuation, mechanical distortion, tube aging and tuning capacitor instability.

It is easily recognized that sensitivity to temperature changes is perhaps the major characteristic of a cavity-controlled oscillator that must be considered in evaluating performance. The sources of heat that establish the temperature of the oscillator are the ambient and the power dissipation of the oscillator tube. Control of the oscillator ambient temperature to close tolerances during eight months of operation has been a major problem and has caused considerable difficulty in evaluating the other factors which have appeared to have influence on the long-term frequency-stability performance of these oscillators. Since each of the materials of which the oscillator is constructed have a certain temperature-coefficient of expansion, various effects occur that influence the oscillator frequency when temperature changes. Primarily, the effect is to change the dimensions and/or position of the material so as to disturb one or more parameters of the electrical circuit. Some examples are the elongation of the center conductor of the cavity which amounts to a change in circuit inductance, expansion of the outer conductor wall causing a change in the $Z_0$ value of the cavity, disturbance of the element spacing in the oscillator tube resulting in an effective change of the susceptance values across the terminal of the resonant circuit. Study of the combined effects of temperature reveal that stabilities of about 2.0 ppm/°C was typical for a cavity oscillator constructed of Invar and about 22.0 ppm/°C for one constructed of brass.

In several cases cavity-oscillators under test operated without being hermetically sealed and it was found necessary to place a desicant such as activated alumina in the oven enclosure to keep its atmosphere as dry as possible. If the cavity is not hermetically sealed, then breathing will occur, causing external atmosphere and any water vapor it contains to be drawn into the cavity

-9-
space during the intake portion of the breathing cycle. Water vapor affects the value of the dielectric constant of the cavity space, and hence, any changes in the amount of this vapor will cause changes in the resonant frequency of the circuit. It was apparent that this was occurring since tests of the oven atmosphere revealed its relative humidity to average about 10 ± 2 per cent at 45°C. The changes observed in oscillator frequency, as well as changes in oven humidity, were found to correlate very closely with changes in the humidity of the room. Employing a nomograph on humidity effects in cavities\(^1\), the magnitude of influence of humidity variation on frequency change was determined to be about 2.75 ppm/per cent R.H. and was considered to be approximately correct in view of the frequency changes observed. Although this factor appears to have an appreciable influence on the frequency of the oscillator, it can be virtually eliminated by filling the cavity space with an absolutely dry atmosphere and sealing it off.

The influence of changes in plate and heater potentials was found to be relatively minor compared to the effects of the two previous factors discussed. From long-term measurements on the plate-voltage supply, its stability was found to be about 500 ppm/day and short-term variations lasting a few seconds or more amounted to about 20 per cent of this value. Plotting the oscillator frequency changes against plate voltage for various values of grid resistance produced the characteristic shown in Figure 4.3a for an Invar cavity-oscillator. From this graph it is seen that better stability was obtained at a plate voltage of about 100 V with a grid resistance of 2200 ohms than at lower voltages and larger grid resistances. Taking a frequency stability value of 2 ppm/V (which corresponds closely to that value for 70 V on the plate), the change in frequency due to the short-term variations of the supply is about 0.014 ppm. At 600 mc this would be 8.4 cycles. The variation due to the long-term voltage drift would be about five times this value.

Heater-voltage changes were not recorded over long periods as were plate-voltage variations but short-term tests were carried out from which signifi-

Figure 4.3A
A-C HEATER POTENTIAL: 6.5 V. RMS

Figure 4.3B
PLATE POTENTIAL: 70 V.
$R_g = 11.0K$ ohms

Figure 4.3. Frequency-Voltage Characteristic of an Invar Cavity-Oscillator.
Significant information on the long-term characteristics might be derived. The heater-voltage frequency characteristic shown in Figure 4.3b was obtained from an Invar cavity-oscillator using a d-c heater-voltage supply. The heater supply for oscillators undergoing long-term measurements, however, was an a-c source in most of the runs recorded. From the above graph it is seen that the frequency-stability factor for changes in heater voltage is about 25 ppm/v. The a-c supply mentioned above was a Sola type 30492 constant-voltage transformer which specifies a 1 per cent regulation of the output for wide variations of the input. An electromechanical voltage-regulator was in series with the input line and provided regulation of the line voltage of ±1 v at 115 v. Assuming a change of 1 v on the line the heater voltage at the output of the transformer would experience a change of \(0.55 \times 10^{-3}\) v.

From this it is seen that the resulting frequency change of the oscillator would be negligible compared to other much greater influences.

Some effects on frequency change were noted when pressure was applied to the sides and the bottom of the cavity oscillator. Pressure at certain points caused greater frequency excursions than the same pressure at other points. Not only would there be a temporary change in frequency during the application of pressure but there would also be a hysteresis effect in the recovery characteristic which would cause the frequency to be at some value different from that before pressure was applied. This condition could account for hysteresis effects that appear under the influence of temperature changes. The root of this phenomenon would seem to be in the yield or aging characteristics of the metal from which the oscillator is constructed. The magnitude of this influence has not been evaluated conclusively because of unknown variables involved. Experience has shown that in gripping the cavity with one hand so that pressure is applied to opposite sides, a frequency change of about 3000 cycles is typical. The pressure applied is probably in the neighborhood of 7 or 8 lbs. A permanent "set" in frequency would be about 600 cycles for the above case after pressure was released. The only recommendation that seems practical in obtaining a reduction of this condition would be to design the cavity wall to have greater thickness, or to employ some sort of rigid bracing.
The instability of the series tuning capacitor was noted as another cause of frequency variations in earlier runs. As noted in Quarterly Report No. 3, this produced a random change in frequency, particularly following a tuning operation on the oscillator. This effect was virtually eliminated by the use of a lock nut on the rotor shaft of the capacitor. Vernier adjustment of the frequency after the main tuning capacitor has been set and locked is accomplished by turning a short 6-32 screw tapped through the outside of the cavity wall near the free end of the center conductor. This affords a fairly broad range of frequency adjustment without being unduly critical. One turn causes a frequency change of about 10,000 cycles and the setting is quite stable.

The influence attributed to tube aging has not been well-defined because of lack of control of the other factors over long periods of time so that the effects from changes in tube parameters could be isolated. One observation that was traced to tube aging was a random characteristic in the frequency variations as the end of tube life approached. Two cases of tube failure were found to be due to a gasy condition that may have been caused by high tube-envelope temperatures of long duration. They had each been operating at a plate current of about 15 ma for around 600 hours. Extending the life of the oscillator tube would probably result from reducing the plate dissipation or by using ruggedized tubes. In one case, where the oscillator was operating satisfactorily, the tube was removed and its transconductance was checked to be about 1000 micromhos as compared to a new tube value of 6600. It was not known how long this tube had been in operation.

D. Problems With Temperature Control

In the previous report, it was pointed out that a random shift in the median value of the temperature was noted over long periods of time. Investigation of the cause of this change revealed its source to be the oven thermoswitch which apparently had inherent characteristics of this nature. It was recognized also that room-temperature variations contributed somewhat to the results noted above because of inadequate insulation properties of the oven. Also, since the thermoswitch was sensing the temperature of the oven...
atmosphere at the point where it entered the intake part of the blower system, the coefficient of coupling between the heat source for the oven and the switch was considered quite low. This produced a delayed feedback action that permitted overshoots in temperature during the on and off periods of heat supply. One move to correct the condition of variation in temperature was to install a Princo mercury-thermometer-type thermoswitch in place of the bimetallic type. This produced an apparent improvement in temperature stability in the atmosphere around the oscillator. There were, however, slight changes in the temperature from time to time even with this type thermoswitch. This is attributed to inadequate isolation between the temperature of the oven and that of the room. A complete solution to this problem can be fairly well specified from the previous discussion. These are: improvements in the oven insulation, closer coupling between the oven heat supply and the control element, and inherently-stable temperature characteristics for the thermoswitch. Use of the mercury-thermometer-type thermoswitch reduced the temperature differential during the on and off periods tenfold, as indicated by a mercury thermometer in the immediate vicinity of the cavity oscillator and, hence, greatly reduced frequency changes of the oscillator. On the basis of this observation the next step appeared to be improvement of the oven characteristics as influenced by room temperature variations. However, the magnitude of improvement was considered small compared to that obtained in changing the thermoswitch. Therefore, in view of the short time remaining for modification and test of an improved oven structure, it was considered impractical to make any changes in the present system. Sufficient data have been gathered on the magnitude of temperature effects on these oscillators to predict what results could be obtained from an improved oven and control-element design.

E. Room Temperature Operation

Five runs containing data covering 274 hours were obtained with an Invar cavity-oscillator operating at room temperature. An evaluation of these data is presented in Table 4.2. The oscillator under test was placed in an insulated box to reduce the influence of room-temperature variations on the ambient
of the oscillator. Long-term temperature variations in the box were limited to about ± 3.5°C as compared to ± 5°C in the room and short-term temperature transients were effectively eliminated.

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<td>-7.6 kc</td>
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</tbody>
</table>

A plot of average frequency-stability values of all runs similar in construction to that of Figure 4.2 is shown in Figure 4.4. This indicates that a typical performance under these conditions will give an average frequency-stability of ± 10 ppm/day. Compared with the performance of the oscillator discussed in Quarterly Report No. 3, this later performance is much improved. The improvement resulted primarily from a modification of the connection between the oscillator tube and the series-tuning capacitor. Also, the cavity had been operating approximately 4 to 5 days continuously before the test run was started, so that short-term aging, which seems to accompany the warm-up period of this type of oscillator, was complete.
A brass cavity-oscillator was also operated at room temperature, but because of extreme sensitivity to temperature, the variations of frequency were greater than the measuring system could record over an extended period of time. The longest period from which data were obtained was about 18 hours, during which the frequency changed a maximum of 50 kc about an average. This gave a stability factor of about ± 4.6 ppm/hr. This indicates that brass cavity-oscillators are much less desirable than the Invar cavity-type for this condition of operation. Where temperature control of the cavity is possible, the stability is much improved.
V. SHORT-TERM FREQUENCY-STABILITY MEASUREMENTS

A. Introduction

The short-term frequency-stability measuring system has been completed and partially evaluated. The system has been found to perform basically as expected with the exception that its present usefulness is severely limited by noise, low sensitivity and instability. The chief factors contributing to those limitations are (1) the modulation efficiency is much lower than expected, (2) the lack of sufficient rigidity in the coaxial elements causes considerable instability due to mechanical vibrations, (3) the diode mixer and i-f amplifier contribute more noise than was anticipated, (4) additional instability is caused by variations in i-f amplifier heater, bias and plate supply voltages and (5) because of difficulties encountered in adjustment, optimum performance is not always obtained. Each of these factors will be discussed in more detail in the following sections of this report.

B. The Modulating System

A diagram of the modulator system is shown in Figure 5.1.

![Figure 5.1. Diode Modulator System.](image-url)
The basic modulator element is a General Radio type 874 MR mixer-rectifier which has been modified by replacing the series 250-ohm resistor with a 50-ohm unit to facilitate adjustment for proper termination. Shorted stub No. 3 is used to reflect the termination to the proper point. Perfect termination at the carrier frequency cannot be obtained with this simplified system because of the parallel resistance of the crystal. Since the purpose of the system is to produce a double-sideband-zero-carrier reflection, stub No. 2 is added to phase out any remaining carrier due to lack of a perfect termination. Adjustable line No. 2 is used to produce the proper phase of the modulation components so that a null is obtained when the source-carrier frequency is at the center frequency of the reference cavity.

Initial adjustment of the modulator system is performed by connecting the mixer-rectifier (with stub No. 3 attached) to an admittance bridge and adjusting the stub to produce a resistive impedance of 50 ohms. Stub No. 2 and adjustable line No. 2 are then attached to the mixer-rectifier and the complete assembly is connected to the ring.

Laboratory measurements on the modulator system have shown that, for 1-volt input at the carrier frequency, the total combined output voltage at the two sideband-frequencies is approximately 0.063 v. This may be compared with a maximum output of a perfect modulator of 0.707 v. Thus, the voltage efficiency of the modulator of Figure 5.2 is less than 10 per cent. The efficiency in terms of power is only about 1 per cent. In the theoretical evaluation in Quarterly Report No. 3 an efficiency of 100 per cent was assumed.

The low modulator-efficiency is attributed to two principal causes. First, the efficiency of the crystal as a modulator is low because of the low impedance into which it must work. Second, sideband energy is lost in the carrier termination because of the wide bandwidth of the shorted stub.

C. Microphonic Instability

The frequency-stability measuring system has been found to be particularly sensitive to mechanical vibrations. This has been observed as a low-frequency noise modulating the output. The methods of mechanically mounting the
Figure 5.2a. Noise and Gain -vs- Bias Voltage.

Figure 5.2b. Gain -vs- Plate Voltage Supply.
elements around the ring have been improved; however, the effects are still appreciable. The elements which appear to be most microphonic are the reference cavity and the modulator-matching-section. The reference cavity has been stabilized to some extent by decreasing its tuning range so that a total range of 5 mc is covered by the piston-tuning capacitor.

It has also been observed that the i-f amplifier is microphonic. Possibly the substitution of ruggedized tube types for the first two amplifier tubes would improve this situation.

D. Mixer Diode and I-F Amplifier Noise

The noise contributions of both the mixer diode and the i-f amplifier have been found to be greater than originally anticipated. When the mixer system, which was shown in Figure 4.1 of Quarterly Report No. 3, was connected to the i-f amplifier, instability was observed in the form of a tendency to oscillate. This was due primarily to the high input-impedance of the i-f amplifier and high output-impedance of the mixer crystal. The only successful method of eliminating this trouble was to terminate the mixer crystal with a 50-ohm resistance. This, of course, greatly reduced the output voltage which in turn greatly decreased the signal-to-noise ratio. Other mixer systems are presently being considered in an effort to increase the output signal and reduce the output noise. In particular, use of a General Radio 874 MR mixer-rectifier is being considered.

The i-f amplifier noise is due principally to the first two stages of amplification. As noted in Quarterly Report No. 3, the bandwidth of the i-f amplifier has been decreased in an attempt to improve the signal-to-noise ratio and to increase the amplifier's dynamic signal-handling range. The present performance of the amplifier is shown by the curves of Figure 5.2. These data were obtained using an a-c heater supply and regulated bias and plate supplies.

In addition to the noise indicated by the curves, a 60-cycle a-c modulation component is also present when an input i-f signal is applied. The modulation is in some cases greater than 50 per cent, depending upon the
amplitude of the input signal. The source of the modulation was traced to the heater supply but was apparently not due to heater-cathode leakage as would normally be expected. It is presently planned to use a storage battery for the amplifier-heater supply (and possibly to supply the heaters of other units).

Figure 5.2 also shows that the gain of the i-f amplifier is greatly dependent upon the plate and bias voltages. As indicated in previous reports, suitable regulated power-supplies have been constructed for use as plate supplies. A special bias supply is presently under construction.

E. System Set-Up Procedure

The present short-term frequency-stability measuring system is shown in Figures 5.3 and 5.4. The system is basically the same as was shown in Figure 4.3 of Quarterly Report No. 3 except that the oscillator frequency-control system has not yet been added and the adjustable line in the reference cavity arm of the ring has been moved to the modulator arm (it should be noted that the box labeled "Oscillator" in Figure 4.3 of Quarterly Report No. 3 should have been labeled "Oscillator Control").

The following procedure has been tentatively adopted for setting up the system prior to making stability measurements. References refer to Figure 5.3.

1. The reference cavity, mixer and modulator are initially adjusted so that their impedances at the operating frequency are 50-ohms resistive, as indicated by a General Radio admittance meter. This is accomplished for the reference cavity by adjusting the size and orientation of the coupling loop. The mixer and modulator are adjusted by means of the shorted stubs and adjustable lines. The i-f oscillator and i-f amplifier must be connected and operating while making these adjustments.

2. The oscillator to be tested is connected to the ring and its r-f voltage-output amplitude and frequency are measured and recorded.

3. The oscillator to be tested is replaced by a sweep oscillator having a 30 or 40 mc sweep width. The voltage amplitude at the test frequency
Figure 5.3. Short-Term Frequency-Stability Measuring System.
Figure 5.4. Laboratory Set-up of Short-term Stability Measuring System.
is adjusted to the value read in step 2. This amplitude must be maintained as the sweep width is varied and other adjustments are made.

4. With the oscilloscope synchronized to the sweep oscillator, a dip in output will be observed at the reference-cavity frequency. The i-f amplifier gain should be set between $10^5$ and $10^6$. The sweep width may be adjusted for convenience in observing the dip. The reference cavity frequency is adjusted until it is exactly equal to the test frequency.

5. Shorted stub No. 2 is adjusted for one quarter-wavelength at the test frequency. Adjustable line No. 2 is varied until a maximum dip is obtained. If a dip to zero voltage is not obtained, shorted stub No. 2 and adjustable line No. 2 are simultaneously readjusted (only slightly). The maximum dip obtainable should be limited only by the noise level of the i-f amplifier and mixer crystal.

6. The i-f amplifier gain is increased for the desired sensitivity and step 5 is repeated. If the sweep oscillator is calibrated as to sweep width, the system sensitivity may now be calibrated.

7. The sweep oscillator is replaced by the test oscillator and the reference cavity is adjusted for a minimum reading on the indicating voltmeter. The oscillator amplitude should be adjusted to be exactly the same as recorded in step 2. If this is not possible, adjustable line No. 2, shorted stub No. 2 and the reference cavity may be readjusted slightly for minimum-indicating voltmeter reading.

8. Short-term frequency variations of the test oscillator may now be observed directly on the indicating voltmeter or oscilloscope.

This set-up procedure generally provides satisfactory results; however, certain difficulties often arise. One such difficulty is attributed to test-oscillator voltage amplitude variations. The basic difficulty is apparently the sensitivity of the modulator phase-characteristic to signal amplitude. This, in effect, causes a mismatch to occur at the modulator when the input amplitude is changed. Also, the input amplitude cannot be adjusted on the basis of the average output of the sweep generator, since the output of the
sweep generator is usually dependent upon instantaneous frequency within the sweep band.

Another difficulty arose from the necessity of operating the i-f amplifier at high gain, which causes saturation of the amplifier when the sweep generator is employed. The high gain is required to obtain sufficient sensitivity at the null frequency. However, the saturation apparently affects the gain of the amplifier during the unsaturated periods. Thus, the calibration of the system may no longer be correct when the test oscillator is re-connected.

Another item of concern is the adjustment of shorted stub No. 2. This stub is necessary, first, to help attenuate the 30 mc signal which may be radiated directly to the ring and then to the mixer and, second, to help control the phase characteristic of the 600 mc carrier which is reflected from the modulator because of lack of perfect termination. The 30 mc direct signal is also attenuated by shorted stub No. 1 as well as other low impedances at 30 mc. It may appear that the effect of shorted stub No. 2 is identical to that of the adjustable line No. 2. However, experimental evidence indicates that the effects are not identical. Because of the similarity, the proper adjustment of shorted stub No. 2 is often uncertain. The latter part of step No. 5 of the set-up procedure can even lead to complete misadjustment of the system in which case the entire step must be repeated.

Successive set-ups using the above procedure have often resulted in overall sensitivities varying as much as 2 to 1.

F. Control of Average Frequency

The short-term measuring system has a bandwidth of calibration which requires that the average frequency of the source being tested be prevented from drifting beyond the boundaries of this band for best results. Since long-term measurements have revealed that average oscillator frequency will drift even during medium intervals of time, some means must be employed to maintain its frequency inside the calibration band.

One phase of the problem in controlling the frequency of the oscillator is to find some electronic or electromechanical method to influence a change
in some parameter of the oscillator circuit which will produce changes in frequencies. An electromechanical scheme that has been tried is one of mounting a single headphone element of the HS-30 type in the outside wall of the coaxial cavity so that its diaphragm faces the center conductor. This provided a means to produce a controlled incremental change in resonant circuit capacity. Preliminary tests indicate that a maximum of 5 kc change may be obtained for a 100 ma change of current through the headphone. An increase in effect for the same current change can be easily obtained by adding a metallic extension to the diaphragm so that the change in circuit-capacity is greater.

One method of electronic control is that of changing the oscillator tube plate-voltage. Investigation of this method reveals that its characteristics are somewhat difficult to evaluate. Step function changes of voltage produce only temporary step function changes of frequency, after which the frequency gradually drifts back toward its original value. The final frequency difference several minutes later is only a small per cent of the original frequency difference. A typical characteristic of this scheme is a 300-cycle change per volt of plate-voltage change.

G. Laboratory Data

No specific data on the short-term stability of cavity oscillators have yet been obtained because of the difficulties already mentioned. The overall sensitivity of the system has been measured on several occasions. Typical sensitivity at the output of the i-f amplifier (adjusted to a gain of $2 \times 10^5$) is 1 mv/cycle of frequency change. This implies a sensitivity at the mixer crystal of only 0.005 $\mu$V/cycle as compared to $6\mu$V/cycle predicted in Quarterly Report No. 3. It has not yet been possible to account for so great a loss in sensitivity; however, the following factors account for some of the loss.

1. Typical input amplitudes have been 1 v rather than 5 v as assumed in the previous calculations.

2. A typical effective modulation-efficiency of 10 per cent has been obtained rather than 100 per cent as assumed.

3. The Q of the reference cavity is approximately 5000 rather than the 10,000 assumed.
4. Losses in the coaxial system were not considered in the original calculations.

5. The efficiency of the mixer assembly is much lower than originally anticipated.

The efficiency of the mixer has not yet been accurately determined; however, it appears to be only about 10 per cent of the value assumed previously. As mentioned above, this is caused principally by the 50-ohm load resistor at the mixer output. It is estimated that for 1 v of i-f input to the mixer only 0.2 v of output is obtained.

From Quarterly Report No. 3, the mixer output voltage is given as

\[ \frac{dv}{df} = \frac{2Eq_o (i-f \text{ voltage conversion factor})}{f_o} \]

For

\[ E = 1 \text{ volt}, \]
\[ Q_o = 5000, \]
\[ (i-f \text{ voltage conversion factor}) = 0.2, \]

\[ \frac{dv}{df} = \frac{2 \times 1 \times 5 \times 10^3 \times 0.2}{3.14 \times 600 \times 10^6} \]

i.e., 1 \( \mu \)v/cycle of frequency change.

This may be compared with the value 0.005 \( \mu \)v/cycle actually obtained. Thus, a loss in sensitivity by a factor 200 is unaccounted for. No estimate can be given for the coaxial system loss, however, it is not believed to be appreciable. It should be observed that the modulation efficiency, although it is listed as a possible source of loss, does not greatly affect the output voltage since envelope detection was assumed in the original derivation and
since the sideband-to-carrier ratio is very large at the mixer. This, of course, assumes that the system is operating near resonance.

The over-all sensitivity obtained would be adequate if the i-f amplifier and mixer noise could be reduced sufficiently. Appreciable noise reduction at this point is impractical since the noise level of the present mixer is only about 2 μv. Two microvolts of mixer noise limits the resolution of the system to about 400 cycles or slightly better than 1 ppm. The equivalent noise input of the i-f amplifier may be anywhere between 1.5 and 4 μv, depending on the gain. If a typical value of 2 μv is assumed, the resolution of the system is limited to 600 cycles or 1 ppm. This accounts for the earlier statement that no specific data has yet been obtained on the short-term stability of cavity oscillators since the short-term stability of most cavity oscillators is considerably better than 1 ppm.
VI. TEMPERATURE-INSENSITIVE CAVITY MEASUREMENTS

A. Temperature-Frequency Characteristics

During the 4th quarterly period, methods of testing cavities previously plated were investigated to determine ways to reduce the temperature effects on the connecting cable between the measuring equipment and the cavity. Because of greater attention required by other phases of the project, only about 10 per cent of this quarter could be devoted to studies of the temperature-frequency characteristics of silver-plated Stupalith ceramic-cavities. Only one new cavity was coated but due to a faulty coating process the unit was unusable and it will be necessary to recoat it.

A different oven was employed in order that a procedure could be used to make connection to the cavity coupling-loop only during the minute or so that measurements were being made. Thus, it was felt that temperature effects on the coupling cable would be negligible and would permit more characteristic data on cavity performance to be obtained. Figure 6.1 shows a plot of three different runs on cavity model No. 2 which was used for data presented in Quarterly Report No. 3. The results indicate that the actual temperature effect on coupling lines suspected before were apparently negligible because essentially the same order of magnitude of frequency change with temperature was obtained from these later runs as was obtained previously. Coupling-loop effects from temperature have not been completely evaluated at this time so that this factor remains to be studied in the remaining contract period. Since neither the oven nor the cavity are hermetically sealed, humidity effects cannot be neglected, and therefore, measures must be taken to reduce or eliminate this factor by filling the oven with a dry atmosphere under pressure during the temperature run. Dry nitrogen is available and will be used for this purpose in the future program.

B. Stupalith Cavity Oscillator

A Stupalith cavity-oscillator was constructed and put into operation during this quarter and frequency measurements were recorded on it under room temperature conditions. Analysis of data from two runs is shown in
Figure 6.1. Frequency-Temperature Characteristic for Stupalith Ceramic-Cavity.
Quarterly Report No. 4, Project No. A-216

Table 6.1. The oscillator was placed in a well insulated box and temperature variations were recorded during the runs. Because of good isolation between the atmosphere in the box and that of the room, temperature variations in the box were reduced. Short-term transient temperature excursions of the room were completely absent in the box. The circuit configuration of this oscillator is the same as that of the Invar cavity-oscillators. Invar metal parts were used for oscillator tube and series capacitor mountings.

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (me)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
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<tr>
<td>20</td>
<td>600.000838 +7.1 kc -7.6 kc</td>
<td>229 +1.2 -1.3</td>
<td></td>
<td>0.382 -0.175</td>
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<tr>
<td>235</td>
<td>599.996338 +20.1 kc -17.0 kc</td>
<td>-105 +33.5 -28.4</td>
<td></td>
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TABLE 6.1
RESULTS OF ROOM TEMPERATURE OPERATION OF STUPALITH CAVITY OSCILLATOR
VII. CONCLUSIONS

Further improvement of the long-term frequency stability of an Invar cavity-controlled oscillator calls for better control of the ambient temperature and the need for sealing a dry atmosphere in the cavity space. Operated under laboratory conditions, a typical stability value of $\pm 9$ ppm/week may be expected for these units. Isolation of tube-aging effects will require further study to derive conclusive data.

Room temperature runs indicated greatly improved performance compared to that for the previous quarter. This improvement was aided primarily by enclosing the oscillator under test in a heat-insulated box so that the effects of room temperature variations were reduced. Improvement in this case also points to a need for hermetically sealing a dry atmosphere in the cavity space.

The influence from temperature effects on the cable connecting the measuring system to the Stupalith cavity undergoing temperature-frequency tests was found to be negligible. Essentially the same characteristics were obtained in this quarter's temperature-frequency studies as those of the previous quarter. The magnitude of contribution to this characteristic by temperature effects on the coupling loop is not considered negligible and remains to be evaluated by further study.

Tests have indicated that the short-term frequency-stability measuring system performs, in principle, as expected. The resolution is limited by the combined effects of low sensitivity and high noise levels. The sensitivity (and consequently the resolution) is, however, much lower than predicted by original calculations. Reasons have been found for some of this loss in sensitivity while much of it is yet unexplained. The principal sources of loss appear to be the lower reference cavity Q, lower discriminator input signal amplitude, and low mixer efficiency. Higher reference cavity Q is not readily obtainable. The discriminator input amplitude can be increased if necessary to obtain adequate sensitivity. The mixer efficiency can possibly be improved by redesigning the mixer to include the first stage of i-f amplification. Sources of noise are the microphonics and thermal noises in the
Quarterly Report No. 4, Project No. A-216

i-f amplifier and other components. It is believed that the i-f amplifier microphonics can be reduced by the substitution of ruggedized tubes. Other sources of microphonics may be more difficult to eliminate. Reduction of mixer and i-f amplifier thermal-noises would also improve the resolution. However, these noises are now near the theoretical minimum. Typical resolution of the present system without the above changes is 1 ppm of frequency change.
VII. PROGRAM FOR NEXT QUARTER

In accordance with the request of SCEL, studies of the long-term stability measurements will not be continued during the period provided by the extension. Full attention will be given to the study of problems in the short-term stability-measurement system.

Investigation of possible sources of signal loss in the short-term frequency-stability measuring system will be emphasized. Attempts will be made to redesign the various components to reduce losses. In particular, the mixer will be studied with respect to noise and efficiency. Plans for the construction of a lock-in mixer and d-c oscillator control system will be formulated.
IX. IDENTIFICATION OF KEY PERSONNEL

Mr. James E. Lane joined the project December 12, 1955 as a technical assistant. He is currently devoting one-half time to project work. Mr. Lane has previously been connected with the station as a technician on various other projects. He has had four years experience in military electronic maintenance and is at present a third year student in Industrial Management at Georgia Tech.

The project is under the direction of Mr. Robert E. Meek, research engineer, who assumed these duties September 1, 1955. He joined the project August 1, 1955, and is at present devoting full time to this work. Mr. Meek holds the degree of Bachelor of Science in Electrical Engineering from the University of Kentucky. He has previously been associated with the University of Kentucky and has worked on several projects at this station since 1951.

Mr. Samuel N. Witt, Jr., research engineer, joined this project August 1, 1955 and is presently devoting one-half time to the work. Mr. Witt, who holds the degree of Master of Science in Electrical Engineering from Georgia Tech, is currently pursuing studies toward a Doctor of Philosophy degree in that field. He served one year as an electronics instructor in the U. S. Navy and has been associated with the Tennessee Polytechnic Institute and with this station on several projects since 1951.

Respectfully submitted:

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QUARTERLY REPORT NO. 5
PROJECT NO. A-216

INVESTIGATIONS OF PRECISION FREQUENCY-CONTROL TECHNIQUES

By

ROBERT E. MEEK AND SAMUEL N. WITT, JR.

CONTRACT NO. DA-36-039-sc-61597
DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 142B

APRIL 1 TO MAY 31, 1956

PLACED BY THE U. S. ARMY
SIGNAL CORPS ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY
INVESTIGATIONS OF PRECISION FREQUENCY-CONTROL TECHNIQUES

By

ROBERT E. MEEK AND SAMUEL N. WITT, JR.

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CONTRACT NO. DA-36-039-sc-64597

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022

SIGNAL CORPS PROJECT: 142B

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APRIL 1 TO MAY 31, 1956
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I. PURPOSE

The purpose of this project is (a) to investigate methods by which temperature-insensitive coaxial cavities may be constructed, (b) to obtain data over a period of several months on the long-term frequency stability of a cavity-controlled oscillator which has exhibited good short-term stability, (c) to investigate methods by which very short-term frequency stability measurements for periods of the order of 0.1 to 1.0 sec may be made with an accuracy not exceeding 1 part in $10^9$ and (d) to investigate other related topics as may be agreed upon by the Contracting Officer and the Georgia Institute of Technology.
II. ABSTRACT

Work has continued on the short-term frequency stability system to improve its sensitivity and resolution. Thus far the system has been capable of measuring short-term stabilities of a UHF source to a few parts in $10^7$.

A 12-db, 600-mc cavity amplifier was constructed to assure an input voltage of 5 v to the discriminator. Regulation of the amplitude of this input signal is required to prevent erroneous indications of frequency variation. An improvement in system performance of about one order of magnitude is anticipated from satisfaction of this requirement. Further improvement in sensitivity is expected by the employment of a 3-tube preamplifier which presents a high input impedance to the mixer crystal and mounts directly on the mixer assembly. Preliminary tests reveal that the mixer is now capable of detecting a 100-microvolt signal applied to the discriminator system.

More recent measurements on the UHF coaxial ring transformer reveal 48-db terminal isolation between the input and output arms at the center frequency, and a 3-db bandwidth of 60 mc.
III. CONFERENCES

Mr. R. E. Meek and Mr. S. N. Witt attended the 10th Annual Frequency Control Symposium at Asbury Park, New Jersey, on May 15, 16 and 17, 1956. A paper entitled "Long and Short Term Frequency Stability of UHF Cavity-Controlled Oscillators" was presented by R. E. Meek.

During the course of the Symposium, discussions concerning problems encountered in project investigations were held with Signal Corps representatives and other parties engaged in related work. Material contained in Quarterly Report No. 4 was elaborated on during a conference held with Dr. G. K. Guttwein of SCEL. Plans for investigation of methods of improving the resolution and sensitivity of the present short term frequency measuring system were outlined and discussed. A need was seen for a conference in August to agree on details for the final report.

A request was placed with the Signal Corps for technical memorandum No. 1665 entitled "Precision Measurements of Short Time Intervals," which has since been received and reviewed.
IV. INTRODUCTION

This report is actually an interim report covering activity during the two-month period of April and May 1956. Administrative delays in negotiating a three-month extension of project work requested by SCETI dictated curtailment of technical effort because of reduced funds. Full effort will again be applied on June 1, 1956 and will be devoted to work on the short term frequency stability measurement of UHF sources.
V. SHORT-TERM FREQUENCY STABILITY SYSTEM

A. Introduction

Work has continued on the UHF equal arm discriminator system, described in earlier reports of this project, to improve its sensitivity and resolution. The goal of this effort is to observe and record frequency variations of a UHF source as small as 1 part in $10^9$ for a period of .1 sec. Thus far, noise and instability of the system have limited measurements of variations to a few parts in $10^7$. The source that has been tested is a UHF invar cavity oscillator operating at 600 mc which possesses a long-term frequency stability characteristic of $\pm 20$ ppm per week under room temperature conditions.

More recent measurements on the coaxial ring transformer revealed somewhat better terminal isolation than that recorded earlier. Data was obtained concerning the frequency characteristics of this element and comparison made with reports on a similar element constructed by another group.

Sensitivity of the mixer circuit was measured under light loading conditions. The circuit was found capable of detecting a minimum signal, as a mixer element, of 100 microvolts. A preamplifier designed to provide high input impedance for the mixer crystal was constructed and tested.

An electromechanical capacitor element for frequency control was constructed; its characteristic is to be evaluated. Its use as a frequency modulator is expected to facilitate calibration of the discriminator system.

B. Input Signals

In Quarterly Report No. 4 it was recorded that the input level was in the neighborhood of 1 v rather than the 5 v anticipated; therefore a means was investigated to increase the level of the test signal. A 600-mc cavity amplifier employing a 6AN4 in a grounded grid circuit was constructed and preliminary tests show a gain of about 12 db. Increasing the coupling value at the source of the test signal will provide sufficient drive for the cavity amplifier to give the required discriminator input voltage. The selectivity characteristic of this amplifier is shown in figure 5.1.
Figure 5.1. Selectivity Characteristic of 600 mc Cavity Amplifier.
Influence of amplitude variations of the input signal voltage and the i-f oscillator voltage on the discriminator output has been found to produce erroneous indications of frequency variations of the signal being observed. The amount of influence is not exactly known but it is believed that reduction of these variations could possibly account for an improvement of about one order of magnitude in the resolution and sensitivity of the discriminator system. A scheme to regulate the voltage amplitude of both of these signals is being planned in order to minimize this influence.

C. Discriminator Circuit

More recent measurements on the coaxial ring transformer than those reported earlier have resulted in better values (up to 48 db) of terminal isolation of the input and output arms. Figure 5.2 shows a frequency characteristic of the attenuation values for the ring between these arms.

![Figure 5.2. Frequency-Attenuation Characteristic Between Input and Output Arms of Coaxial Ring Transformer.](image)
A similar unit was constructed by Sayer and De Bell to operate at 611.5 mc and showed a rejection of 27 db between the isolated arms. Another ring built to operate at 79 mc gave a 38-db isolation value.

The mathematical development of the production of i-f voltage at the mixer from discriminator action of the equal arm system was shown in Quarterly Report No. 3. The energy components that are involved in this development are shown in the vector diagram of figure 5.3. $E | r |$ is that component from the reference cavity that results from the frequency of $E$ being different from the resonant frequency of the cavity. $EM \cos \omega t$ is that component involving the sidebands equally spaced at the i-f frequency about the carrier frequency, $E$, that are produced by the modulator. Since the i-f frequency is 30 mc the total spectrum for which the mixer arm must provide equal transmission characteristics is 60 mc. The mixer has been matched to the line by a matching section consisting of an adjustable line and an adjustable shorted stub, but this has provided a relatively narrowband matching scheme in view of what is required. Broadband matching has been accomplished by terminating the mixer arm with a 50-ohm resistor. Laboratory evaluation of this modification has not been completed but preliminary tests have revealed that the phasing adjustment of the discriminator is now somewhat less critical than was previously experienced.

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It was found in previous observations that heavy loading at the output terminal of the mixer crystal was necessary to stabilize the i-f amplifier. However, this caused appreciable reduction in the conversion gain of the mixer so that much of the system's sensitivity was lost at this point. To remedy the instability and increase the sensitivity, a small 3-tube i-f preamplifier with cascode input and cathode follower output was constructed to be mounted directly on the mixer crystal assembly. This provides a high input impedance for the mixer and a low output impedance to drive a high level i-f amplifier. The gain of the preamplifier is about 33 db with a noise figure around 1.2 db.

E. Frequency Stabilization

As mentioned in Quarterly Report No. 4 an electromechanical capacitor element was constructed and tested. The data indicated that this element should work satisfactorily in connection with the frequency control circuit to control the frequency of cavity oscillators under test. However, it was noted that the initial device was unstable and possessed hysteresis characteristics that were undesirable. Modifications have been made to eliminate these defects but these modifications were not completed in time to obtain results for this report.

This capacitor element may be used as a frequency modulator for a UHF cavity oscillator to facilitate calibrating the discriminator, i.e., determine its frequency sensitivity characteristic.

A lock-in-mixer and a current amplifier are under construction to operate the frequency control element. Requirements for this control element indicate the dynamic range of the current amplifier must be about 40 db and it must deliver a maximum current of about 100 ma. Preliminary operation of the short term system will be made using manual frequency correction. Information for manual correction will be obtained from observation of the frequency change monitor.
VI. CONCLUSIONS

Employment of a UHF cavity amplifier at the input, and a preamplifier for the mixer should improve the sensitivity and resolution of the UHF discriminator for short term frequency stability measurements. Amplitude regulation of the input signal and the i-f oscillator voltage will produce improvement in the system stability.

Broadband matching is necessary in the mixer input to provide equal transmission characteristics for the energy components fed to it which consist of the sidebands and the carrier.

The bandwidth of the isolation characteristic between the input and output arms of the coaxial ring transformer has been found to be wide enough to provide uniform balance in the adjustment of the discriminator.
VII. PROGRAM FOR FINAL QUARTER

Technical activity for the final quarter of the contract will be devoted to the completion of the UHF discriminator system and the measurement of the short term frequency stability of several UHF sources.

The schedule by which work will proceed is outlined as follows:

1. Measure the mixer circuit sensitivity.

2. Utilize an amplitude regulator circuit for control of the input signal and the i-f oscillator voltage.

3. Calibrate the discriminator system for frequency sensitivity characteristic.

4. Test the feedback circuit for control of the average frequency of the UHF cavity oscillator.

5. Obtain recordings of short term frequency stability of several UHF sources.

6. Compile a set of system operating instructions to be submitted with the completed assembly.
VIII. IDENTIFICATION OF KEY PERSONNEL

Mr. James E. Lane joined the project December 12, 1955 as a technical assistant. He is currently devoting one-half time to project work. Mr. Lane has previously been connected with the station as a technician on various other projects. He has had four years experience in military electronic maintenance and is at present a third year student in Industrial Management at Georgia Tech.

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Respectfully submitted:

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FINAL REPORT
PROJECT NO. A-216

INVESTIGATIONS OF PRECISION FREQUENCY-CONTROL TECHNIQUES

By

ROBERT E. MEEK AND SAMUEL N. WITT, JR.

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CONTRACT NO. DA-36-039-sc-64597
DEPARTMENT OF THE ARMY PROJECT NO. 3-99-11-022
SIGNAL CORPS PROJECT NO. 142B
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1 APRIL 1955 TO 31 OCTOBER 1956

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SIGNAL CORPS ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY
ENGINEERING EXPERIMENT STATION
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I. PURPOSE

The purpose of this project was (1) to investigate methods by which temperature-insensitive coaxial cavities may be constructed, (2) to obtain data over a period of several months on the long-term frequency-stability of a cavity-controlled oscillator which has exhibited good short-term stability, (3) to investigate methods by which very short-term frequency-stability measurements for periods of the order of 0.1 to 1.0 second may be made with an accuracy not exceeding 1 part in $10^9$, and (4) to investigate other related topics as may be agreed upon by the contracting officer and the Georgia Institute of Technology.
II. ABSTRACT

Data derived over an eight-month period from long-term frequency-stability measurements on invar-cavity oscillators under temperature and voltage regulated conditions are discussed. Temperature, humidity, and tube deterioration, even under quasi-regulated conditions, are the principal factors responsible for an average stability value of ± 10 ppm/week for these oscillators. Results of operation of various models of cavity oscillators under room temperature and humidity conditions show that a frequency-stability of ± 10 ppm/day is possible.

Duration of measurement, writing speed, and system sensitivity were factors guiding the choice of techniques to measure the short-term (less than one second) frequency-stability of various frequency sources. One promising technique tested was a UHF Equal-Arm I-F Discriminator System employing a coaxial-ring transformer and reference cavity. Measurements of frequency-stability with an accuracy of about 5 parts in $10^8$ were possible. A frequency-comparison technique was investigated and data indicated a resolution of about 1 part in $10^9$ is possible. Accuracy of measurement with this technique depends upon the frequency-stability of the reference frequency being inherently much better than the frequency under test.

Methods of constructing temperature insensitive cavities which are to be subjected to wide temperature variations are discussed. Stupalith, a zero expansivity material, was the basic material utilized in the assembly of several cavities which gave a frequency-temperature value of -2 ppm/°C to -4 ppm/°C. It was found that the Stupakoff Company of Latrobe, Pennsylvania could mold one-piece cavities of Type A2417 Stupalith. Tests revealed that a frequency-temperature characteristic of + 1.0 ppm/°C is typical of these units.
III. CONFERENCES AND PUBLICATIONS

A. Conferences

A total of five conferences were held between members of the project and representatives of the Signal Corps during the course of the contract. In addition, informal discussions on various project items occurred between the same groups during their attendance at the 9th and 10th Annual Frequency Control Symposia.

B. Publications

1. A paper on "Frequency Control Above 500 MC" was presented by D. W. Fraser and E. G. Holmes at the 9th Annual Frequency Control Symposium, 1955.

2. "Long and Short-Term Frequency-Stability of UHF Cavity-Controlled Oscillators," a paper by R. E. Meek presented at the 10th Annual Frequency Control Symposium, 1956, was included in the official proceedings of the symposium.
IV. INTRODUCTION

A. History of the Contract

This project, entitled "Investigations of Precision Frequency-Control Techniques," was sponsored by the Signal Corps, U. S. Army, through the Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey. The initial contract was numbered DA-36-039-sc-64597 and work was started on this project 1 April 1955. The number A-216 was assigned to this project by the Engineering Experiment Station of the Georgia Institute of Technology. An extension of the original contract for a period of five months was received on 30 March 1956. At the request of the contractor, the termination date was delayed until 30 September 1956 and the delivery date of the final report was delayed until 31 October 1956.

B. Objectives and Methods of Approach

As outlined in Chapter I, the work was divided into three major tasks:

1. to evaluate the long-term frequency-stability characteristics of a particular type of coaxial cavity-controlled oscillator over a period of several months under regulated conditions,

2. to investigate methods of making very short-term frequency-stability measurements of the order of 0.1 to 1.0 second with an accuracy not exceeding 1 part in $10^9$, and

3. to investigate methods by which temperature-insensitive coaxial cavities may be constructed.

In addition to the above three categories an agreement was in force to investigate other related topics pertinent to the subject of "Precision Frequency-Control Techniques." No additional tasks were evolved out of the course of investigations in the original tasks.
Most of the investigations in each task were carried out in the UHF region of the frequency spectrum. This area of work was primarily established by the groundwork and facilities inherited from the previous contract which performed much of its investigation between 500 and 1000 mc. Also, it was mutually felt by the contractor and sponsor that increased usage of this region of the spectrum posed problems of frequency control that required additional knowledge of the stability characteristics of various frequency generating devices.

The program to obtain data concerning the long-term frequency characteristic of a type of cavity oscillator was organized to observe and evaluate all factors influencing this characteristic. Considerable importance was placed upon the need for a reliable measuring system and adequate regulation of various independently controllable factors.

It was proposed at the outset of the measurements that data should be taken:

a. under certain regulated conditions of operation such as temperature, atmosphere, and supply voltages,
b. to observe the long-term frequency drift and evaluate extraneous factors that cause this drift,
c. to observe medium-term frequency variations and isolate factors which contribute to this effect,
d. to determine the effects of oscillator tube aging, and
e. to observe the effects of various electrical and physical modifications made on the cavity oscillator to provide improved characteristics.

The majority of the original data was made in the form of a permanent strip-chart pen recording with written notations included at appropriate points.
Initial tests were made on a cavity oscillator model which had been developed and tested by the previous project and which had shown good medium-term frequency stability. This unit was replaced by subsequent models of the same basic oscillator circuit with various refinements and modifications.

As stated in Chapter I, one of the general objectives of this project was to devise methods of measuring small frequency variations occurring in very short periods of time (less than one second). Investigation of the literature related to the problem revealed several possible methods of accomplishing the desired results. After further investigation and study of complexity, reliability, and accuracy factors, the discriminator class of frequency-measuring devices was chosen for laboratory development. The choice was eventually narrowed to an adaptation of the Equal-Arm Pound I-F Frequency Stabilizer system.

The necessary equipment for the Equal-Arm system was constructed and evaluated. The evaluation showed that this system had a maximum resolution of 5 parts in $10^8$ in its final form. It was, however, capable of making such measurements in small fractions of one second. The resolution of the system was limited by such factors as noise, available input signal amplitude, and stability of components.

A final effort was made to develop an alternate system based on phase-sensing beat-frequency techniques. The necessary equipment for such a system was assembled and tested. The resolution of this system was limited to approximately one part in $10^9$ for short periods of time by the stability of the available UHF standard signal source, however, definite verification of this resolution was not obtained. In addition, this system required an appreciable fraction of one second to obtain a reliable stability measurement.
The program on the task involving the construction of temperature-insensitive cavities was guided by recommendations growing out of work on previous contract investigations of methods to construct cavities having a very low or a complete absence of sensitivity to temperature changes over a large temperature range. This objective received impetus from the fact that certain ceramic materials of the magnesium-alumino-silicate class were being manufactured having a claimed zero-temperature expansivity over a wide range of operating temperatures. The particular brand of this material that appeared most promising was made under the trade name "Stupalith." Since this material is a ceramic, methods had to be developed to apply a highly-conductive metal film to its surface. These methods were developed and sufficiently refined to produce a resonator of satisfactory Q.

The investigation was carried on in two phases. The first phase was to test a resonator assembled by the project from Stupalith parts. The second step was to investigate the facilities of the manufacturer of this material and have him fabricate one-piece Stupalith cavities. These cavities were assembled for the project and, after plating, were tested for their temperature-frequency characteristics. The results of tests and problems encountered in each phase are reported.
V. LONG-TERM FREQUENCY-STABILITY OF CAVITY OSCILLATORS

A. Introduction

Coaxial-cavity-controlled oscillators have received much attention within the past few years as possible stable frequency sources in the UHF region. Widespread employment of the cavity resonator for frequency stabilization in microwave systems has revealed the highly stable frequency characteristics of this element. Construction of cavity units at lower resonant frequencies has shown that this stability is essentially still retained. Interest in the UHF cavity oscillator has been attracted because of its compact and rigid construction which, in comparison with the size and shape of conventional multiplier systems that produce UHF frequencies from low frequency sources, appears much more applicable in portable designs. In addition, the lower power consumption involved in the direct generation of UHF energy in such a device is a further advantage.

There are several possible electrical and mechanical configurations for the cavity oscillator but in all cases the resonator can be considered to be the mounting base or chassis on which the oscillator tube and its associated circuitry are built. The particular type of oscillator evaluated in this report is one in which the oscillator tube is attached more or less to the external part of the cavity rather than being built into the cavity.

Medium-term evaluation of the frequency-stability of various types of cavity oscillators developed on a previous project were also carried out on that project. As a result of these tests one type emerged having greater promise than the others of exhibiting good long-term frequency-stability.
The oscillators being tested were subjected to continuous day and night operation, under regulated conditions of temperature, voltage and ambient atmosphere while their frequency characteristics were observed. Data from a large number of runs covering eight-months' time were compiled and have been evaluated in this section. In light of these results various factors which appeared to have significant influence on oscillator frequency are discussed.

Evaluation of oscillator characteristics was also made for operation under the ambient temperature conditions of the room. Thus information of more practical usage was derived.

B. Oscillators Tested

Oscillators that underwent measurements to determine their long-term frequency-stability characteristics were of the coaxial cavity type designed to operate in the region of 600 mc. A few of the oscillators utilized were products of a program of development of cavity-controlled oscillators from a previous project. Other cavity oscillators tested were constructed during the period of the present project employing the same electrical configurations as the earlier types but having a somewhat different mechanical arrangement. This change in the mechanical configuration provided improved features in oscillator characteristics relative to the earlier types that will be revealed in the discussion below.

The two different mechanical configurations involved in the construction of the cavity oscillators are shown in Figure 5.1. It is seen that these two configurations are distinguished from each other principally by the location of the oscillator tube. There were other distinguishing factors associated with tube location but these were of minor importance.
Figure 5.1. Mechanical Arrangement of Cavity Oscillators.
To demonstrate that the mechanical arrangements did not alter the fundamental electrical configuration of the oscillator circuit in either case, attention is directed to Figure 5.2. This figure shows the circuit schematic and the equivalent circuit for the oscillator. The circuit arrangement is essentially that of a Clapp oscillator in which a small capacitor is placed in series with the grid-to-plate inductance. This grid-plate inductance is represented by the cavity and forms a series resonant circuit in combination with the capacitor, which effectively places the terminals of the oscillator tube at a point of low impedance. Therefore, physically locating the tube at either position, on the center conductor or on the outer conductor, does not alter the basic circuit as long as the series capacitor and cavity are...
connected across the grid-plate terminals of the oscillator tube. There is, however, marked differences between the two arrangements in their performance characteristics.

Figure 5.1a shows the oscillator tube located inside the cavity center conductor with the series tuning capacitor located on the cap covering the overhang region. This is the configuration of the oscillators produced by the previously mentioned project, which has been demonstrated to possess good medium-term-frequency-stability characteristics. Figure 5.1b gives the configuration of a later construction where the location of the tube and capacitor are interchanged. This modification was made to obtain reduced effects from large temperature gradients established along the cavity center conductor by the heat dissipation of the enclosed oscillator tube. In addition, lack of normal cooling inside the center conductor necessitated operating the tube at power levels much lower than the rated values to avoid deleterious effects on the tube itself. Also the removal of lossy materials such as those composing resistors, capacitors and tube sockets (components associated with the oscillator tube) from the r-f field near the end of the center conductor reduced undesirable cavity losses.

The tuning range of the cavity oscillator was increased by a large factor due to the location of the series-tuning capacitor on the end of the center conductor. Since the principal type of capacitors used were the JFD VC-5 tubular trimmers, the in-and-out movement of the rotating slug produced a dual effect of changing circuit capacity and cavity line length (inductance) at the same time. An increase in capacity in this case is accompanied by an increase in inductance which results in a decrease of the resonant frequency. The tuning range thus
obtained was over 50 per cent greater than that found in the early types corresponding to Figure 5.1a. A typical example was an oscillator of the early type which tuned from 590-620 mc whereas the later type had a range of 70 mc (560-630 mc).

An increase in oscillator efficiency was realized by using a different capacitor configuration for the grid bypass than was used in earlier models. This is shown in Figure 5.1b. The grid side of the capacitor is a silver-plated flat washer straddling the tube socket and is insulated, by a mica dielectric, from the mounting base which acts as the opposite plate at ground potential.

To avoid using feedthrough bushings to supply power from the top side of the chassis to the terminals of the oscillator tube, thin copper strips were inserted alongside the tube socket pin jacks and brought out for power connections on the top side of the socket.

The construction of Figure 5.1a was more compact but no more rugged structurally than the construction of Figure 5.1b. Removal of tube, and performance of any maintenance operations were very difficult in the former type. Not only were these conditions greatly improved by the later configurations but the assembly operation during construction was more easily accomplished.

Materials employed in the construction of the cavity resonators on which the oscillators circuits were built were brass and invar. Silver plating was applied to all units to assure low losses and resist corrosion. Oscillators built on brass cavities were subject to extensive frequency changes as a result of the cavity material possessing a large temperature-coefficient of expansion. Invar which has a very small temperature coefficient of expansion proved more practical for use in the long term tests and hence oscillators constructed
entirely of this material are the principal types that will be discussed in this section. However, the brass cavity units were utilized to check out many of the proposed mechanical and electrical modifications before applying these modifications to the invar oscillators undergoing long-term tests.

C. Measurement Techniques

Measurement of the long-term frequency-stability of cavity-controlled oscillators was obtained by the heterodyne beat-frequency method between the frequency of the oscillator and the frequency of a secondary standard. The difference frequency between the two sources was adjusted to be in the audio frequency region. The audio frequency produced was then converted into D-C in a manner such that its magnitude was linearly related to the input frequency. This D-C energy was used to drive a pen recorder to provide a permanent time-frequency record of the oscillator's stability characteristic. Direct aural monitoring of the mixer output was also provided since the frequency produced was in the audio range and thus an additional evaluation (qualitative) of the oscillator's performance was possible. Complexity of the heterodyne system was maintained as simple as possible in order to realize as nearly trouble free operation as possible over a long period of time. Two minor problems were encountered with the particular setup used. One of these problems was the pulling effect on the oscillator by the standard when the difference between their two frequencies was in the neighborhood of 100 cps or less. The other problem was that sense information on the frequency position of the oscillator relative to the frequency of the standard was not directly obtainable from the recordings since they indicated only the magnitude of the frequency difference.
In most of the tests reported, the input frequencies to the mixer unit from the oscillator and from the standard were 600 mc. Since the secondary standard was designed to generate outputs at every 50 mc point in the UHF spectrum a few tests were made with the oscillators at 550 mc and at 650 mc. The results of these runs were not significantly different from those made at 600 mc. The long-term frequency-stability of the secondary standard was determined by comparing its frequency periodically with the frequency from a primary standard located at Georgia Tech. A stability value of five parts in 10^7 per month was determined from this measurement. The primary standard is known to be stable to about 4.8 parts in 10^8 per month.

Figure 5.3 shows a block diagram of the long-term frequency measuring system. The cavity oscillator under test was enclosed in a temperature-regulated oven set to operate at 50°C. The box shape oven had a volume of about 1.5 cu ft, was constructed of 5/8-in. plywood material and was lined with aluminum foil insulation. A shelf was built in the central portion of the box to support the oscillator and its cradle device. Oven air was circulated by a blower system having a capacity of 25 cu ft/min. Humidity of the oven atmosphere was controlled primarily by activated alumina placed so that the oven air was circulated through this material continuously. Outside atmosphere bearing some moisture could leak into the oven and, therefore, it was necessary that the activated alumina be changed periodically to maintain a low percentage of relative humidity. The heater for the oven was a two section system placed near the exhaust port of the blower so that the circulating air would pass directly across it. One heater section was on continuously while the other was operated in an on-off manner by the oven thermoswitch. Leaving
Figure 5.3. Block Diagram of Frequency Measuring System for Long-Term Stability Measurements.
one heater unit on continuously increased the period between the on and off times of the supplemental heater section and also reduced the overshoot magnitude of temperature before and after operation of this section. The principal oven temperature control device utilized during the tests was a Fenwal differential expansion type thermoswitch, series 17300. Temperature stability with this unit was approximately ± 1.5°C about a mean value setting during a 24-hour period and short-term variations were around ± 0.5°C. Typical room temperature variation during a 24-hour period was about ± 3°C. In search of a thermoswitch with better stability and closer regulation, a unit manufactured by Precision Thermometer and Instrument Company was found to be better than any others tested. This unit is a mercury-in-glass type thermostat that provided temperature regulation in the oven of ± .1°C per day. Unfortunately the particular unit tested was fixed at 65°C and hence could not be employed in the long term tests. Delivery delay and installation time for a unit fixed at 50°C was prohibitive due to the small amount of contract time remaining.

The outputs of the oscillator and secondary frequency standard were fed to a mixer element where the audio beat frequency was generated. To reduce pulling of the oscillator frequency, isolation elements were inserted between the oscillator and mixer and also between the standard and mixer. UHF TV boosters were utilized in initial runs as isolation elements but were later replaced by loss pads which were just as satisfactory and more reliable for long term operation.
One element used as the mixer consisted of a UHF crystal diode (1N72) built into a coaxial-T assembly. A commercial unit found satisfactory for this application was the General Radio type 874-MR mixer rectifier.

The audio frequency signal of the mixer was fed directly into the unit designated on the block diagram as the Frequency Counter, which converted the frequency into D-C to drive a recorder. This unit consisted of a high-gain broadband audio amplifier with frequency-integrating circuits. Reliable frequency counting could be obtained when the input signal level exceeded 2 mv. Linearity of D-C output versus input frequency was within one per cent of full scale readings on all ranges, and was reasonably independent of power supply voltage variations. The frequency ranges provided were 500, 1000, 5000 and 10,000 cps.

A model AW,0-1.0 ma Esterline Angus pen recorder was employed. Adequate resolution for analysis of the time-frequency characteristic of the oscillator was provided with a chart speed of 3/4-in./hr.

Filament and plate supply for the oscillator under test was provided from well-regulated sources. The plate supply section consisted of two regulator units in cascade to provide a stable voltage value. The regulator circuit directly supplying the oscillator utilized a battery-voltage reference rather than a glow discharge-tube reference because experience had shown that the former (under shelf storage conditions) had better long-term voltage stability than the latter. A typical voltage stability value over a 24-hour period was approximately 500 ppm. The heater voltage supply for the oscillator tube was obtained from a constant-voltage, filament transformer (Sola type 30492) which had a one per cent regulation of output voltage corresponding to an input-line
voltage variation of 10 per cent. Line variations, however, were limited to approximately two per cent by an electromechanical regulator supplying the entire bench on which the long-term measuring system was located.

D. Resulting Data

As mentioned in the preceding section the data collected on the long term frequency-stability characteristics were in the form of strip-chart pen recordings. These recordings were obtained from continuous day and night operation under controlled environment and energy supply conditions. Frequent notations were made on the chart regarding various observations of conditions that had significant influence on the performance of the oscillator at a particular time. This might be evaluation of aural monitoring of the audio beat note, oven temperature reading, oscillator-plate current reading, or anything pertinent to a particular observation.

Figures 5.4 and 5.5 are samples of typical frequency-time characteristics recorded during various periods of the project operation. Figure 5.4 represents

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**Figure 5.4.** Typical Frequency Characteristic Recording of Initial Cavity Oscillator Model.
Final Report, Project No. A-216

SAMPLE RECORDING OF FREQUENCY CHARACTERISTIC FOR LONG-TERM STABILITY MEASUREMENTS.
FROM RUN NO. 20
NOV. 15, 1955  PROJECT A-216

a. Typical Frequency Characteristic of Oscillator After Changing Tube Location.

SAMPLE RECORDING OF FREQUENCY CHARACTERISTICS FOR LONG-TERM STABILITY MEASUREMENTS
FROM RUN NO. 32  JANUARY 9, 1956
PROJECT A-216

b. Typical Frequency Characteristic of Final Model of Cavity Oscillator.

Figure 5.5. Sample Recordings of Frequency Characteristics.
the characteristics of an oscillator unit constructed by the previous project in which the oscillator tube was mounted in the center conductor of the cavity resonator. Figure 5.5a is a sample of the early runs produced by an invar oscillator with the oscillator tube mounted outside on the cover of the overhang region. Figure 5.5b is a characteristic sample of the final performance of an invar oscillator after further minor improvements were made in its physical and electrical configuration.

Approximately 2700 hours of experience were obtained from long-term observations during a period of eight months. The average length of a run was 50 hours with the actual runs being from 3 hours to about 400 hours in length. There were much data, amounting to 100 hours or so of short runs, that were unusable because of erratic and totally unreliable recordings resulting from malfunction of the heterodyne system. The majority of these times would occur during unattended periods usually after working hours. The satisfactory runs were terminated in most cases by drift of the oscillator frequency beyond the frequency range of the recording system. This extreme excursion of frequency would result from such factors as power failure, defective temperature control, oscillator-tube deterioration, etc.

It is apparent from the sample recordings that the position of oscillator frequency relative to the frequency of the standard was not directly designated. During unattended periods there would often be several "zero beat" crossings. In order to obtain complete frequency-characteristic information an indirect means was employed to determine frequency "sense." If the initial position of the oscillator was determined at the beginning of a run by means of a frequency meter then this information, correlated with the "zero" crossings of
the characteristic, could be utilized to determine the frequency position thereafter during the run. This method was somewhat cumbersome but sufficiently satisfactory for the majority of the recordings analyzed.

E. Evaluation of Data

The problem in the long-term measurements was to determine the frequency-stability of cavity oscillators of a given type. This may be done by determining the average frequency of a run and indicating the variations of frequency about this average. Because of the bulk of the recorded material it was considered awkward to present the complete characteristic of each run for evaluation. Therefore, the choice of giving the maximum frequency excursions relative to the average frequency during the run was considered the best type of information in concise form that could be presented. In addition the trend, or net frequency drift, was also considered important in revealing certain characteristics of these oscillators.

To analyze the data, recorded from the temperature regulated runs, the frequencies at hourly points were chosen from the charts and tabulated. The average frequency of the run was determined by dividing the sum of hourly frequency values by the total number of hours + 1. To find the net frequency drift the method of least squares was employed to determine the straight line which would best represent the curve of the frequency characteristic. If a set of \( f \) (frequency) values corresponding to a set of \( h \) (hours) are known then a line

\[ f = a + bh \]

can be located where \( a \) is the \( f \) intercept of the line and \( b \) is the slope. Applying the principle of least squares to the set of observed values of frequency
and time the values of \( a \) and \( b \) may be determined. These are obtained by evaluating the relations

\[
na + (\sum h)b = \Sigma f, \\
(\sum h)a + (\sum h^2)b = \sum hf.
\]

where \( n \) = numbers of hours + 1.

The preceding computations were made and the results are tabulated in Table 11.1 in the Appendix. A sample of the table is shown in Figure 5.6. The runs are tabulated in chronological order of their occurrence. Stability of the average frequency during each run is based on the maximum excursions of the frequency characteristic relative to the computed average. The mean rate of frequency change shows the trend in cycles per hour of the oscillator and the associated sign designates an increase or decrease in the absolute frequency.

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.0</td>
<td>600.00683</td>
<td>41.5</td>
<td>+2.5</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>+1.5 kc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3.5 kc</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.6. Sample Portion of Table 11.1, Appendix 11-D.

Combining the stability values of average frequency from all the runs, made during the project, on a plot of frequency-stability in ppm versus duration-of-run in hours, gives a picture of the typical time-performance of an oscillator of this type under various conditions. Figure 5.7 shows a plot
Figure 5.7. Average Frequency-Stability for Temperature-Regulated Operation of Invar-Cavity Oscillator.
of this kind. The line labeled "mean-stability value" was located primarily by optical judgement with weight given to the fact that a certain minimum value appears to be established by the shorter runs and the trend in these values by the longer runs. Based on this assumption, the typical frequency-stability value for a week appears to be about ± 10 ppm.

F. Room-Temperature Operation

Several test runs were made with invar-cavity oscillators operating at room temperature. In most cases the oscillator under test was heat insulated sufficiently to reduce effects of short-term room-temperature transients on oscillator frequency but still show the effect of slow changes, proportional to the period and magnitude, of long-term temperature excursion. These tests were made because it was determined that practical application of these units could occur under such conditions; therefore, knowledge of this characteristic data would be helpful. Room-temperature variation, as was mentioned previously, averaged about ± 3° C relative to a mean value over a 24-hour period. Continuous temperature recordings were made on some runs so that correlation could be observed between frequency and temperature changes.

Figure 5.8 shows a sample of a room-temperature run with both the temperature and frequency characteristics given for corresponding periods of time. The data from the original recordings of temperature and frequency for the complete run indicated in the previous figure is reproduced in condensed form in Figure 5.9. Lines are included representing the average frequency value and the mean frequency change. No heat insulation was employed in this particular case to isolate the oscillator from the influence of room-temperature transients and, therefore, the frequency excursions are seen to be larger than the case
Figure 5.8. Sample Recordings of Frequency and Temperature Variation for Room-Temperature Operation of Invar-Cavity Oscillator.
Figure 5.9. Frequency Characteristics of Complete Run of Invar-Cavity Oscillator Operating at Room Temperature.
where heat insulation was used. An example of the latter condition is shown in Figure 5.10.

![Sample Recording of Frequency Characteristic for Invar Cavity Oscillator at Room Temperature (Heat Insulation) 15 February 1956 Project A-216 Room 229 Engineering Experiment Station](image)

**Figure 5.10.** Frequency Characteristic of Invar-Cavity Oscillator at Room Temperature—Heat Insulated Condition.

Six runs containing data covering 394 hours were obtained under room temperature conditions. One of the runs (120 hours) was made under conditions corresponding to those indicated in Figure 5.9 (no heat insulation); whereas, the remaining runs represent heat insulated conditions. All the data were tabulated and analyzed by the same methods as those used for the temperature-regulated runs. The tabulations for the room-temperature runs appear in Table 7.1. A plot of the stability of average frequency against run duration is shown in Figure 5.11 for the five runs of the heat-insulated conditions. This plot demonstrates that typical performance under these conditions will
TABLE 5.1
RESULTS OF TEST RUNS OF INVAR CAVITY-CONTROLLED OSCILLATOR AT ROOM TEMPERATURE

give an average frequency-stability of about ± 10 ppm/day. The one run for the uninsulated case produced a total variation, from average frequency during the period, of ± 50 ppm. A run for the insulated case, of similar length, had a variation of ± 15 ppm or about 3-fold better.

A brass-cavity oscillator was also operated at room temperature, but, because of extreme sensitivity to temperature, the variations of frequency were greater
than the measuring system could record over an extended period of time. The longest period from which data were obtained was about 18 hours, during which the frequency changed a maximum of 50 kc about an average. This performance showed a stability of average frequency of about ± 4.6 ppm/hr. This indicates that brass-cavity oscillators are much less desirable for frequency control than the invar type for this condition of operation. Where temperature regulation of the cavity is possible, the stability of both types is much improved.

![Graph showing frequency stability over run duration hours](image-url)

*Figure 5.11. Frequency-Stability for Room-Temperature Operation.*
G. Discussion of Oscillator Characteristics

Several factors that contributed to the frequency characteristics of cavity-controlled oscillators were observed and evaluated, at least qualitatively from data gathered during eight-months' operation. The difficulties encountered in quantitative evaluation of some factors was the inability to sufficiently control, during a measurement, the influence of various extraneous factors so that reliable data could be taken. However, it is felt that most of the conclusive data in these cases are within ± 50 per cent of the correct values.

The specific factors to be discussed in this section that were observed and evaluated are temperature, humidity, supply voltage variation, mechanical distortion, tube aging and series capacitor instability.

It was recognized that sensitivity to temperature changes was perhaps the major characteristic of a cavity-controlled oscillator that must be considered in evaluating performance. The sources of heat that establish the temperature of the oscillator are the ambient and the power dissipation of the oscillator tube. Control of the oscillator-ambient temperature to close tolerances during eight months of operation was a major problem and caused considerable difficulty in evaluating the influence of other factors on the long-term frequency-stability performance of these oscillators. Since the materials of which the oscillators were constructed have a certain temperature-coefficient of expansion, various effects occur that influence the oscillator frequency when temperature changes. The primary effect is a change in the dimensions and/or position of the material so as to disturb one or more parameters of the electrical circuit. Some examples are the elongation of the center conductor of
the cavity which amounts to a change in circuit inductance, expansion of the outer conductor wall causing a change in the $Z_0$ value of the cavity, and disturbance of the element spacing in the oscillator tube resulting in an effective change of the susceptance values across the terminals of the resonant circuit. Study of the combined effects of temperature reveal that stabilities of about -2.0 ppm/°C was typical for a cavity oscillator constructed of invar and about -22.0 ppm/°C for one constructed of brass.

In several cases cavity oscillators under test were operated without being hermetically sealed, therefore, it was necessary to place a desiccant such as activated alumina in the oven enclosure to keep its atmosphere as dry as possible. When the cavity is not hermetically sealed, breathing will occur, causing the external atmosphere and any water vapor it contains to be drawn into the cavity space during the intake portion of the breathing cycle. Water vapor effects on the value of the dielectric constant of the cavity space are well known and, hence, any changes in the amount of this vapor will cause changes in the resonant frequency of the circuit. It was apparent that this was occurring since tests of the oven atmosphere revealed its relative humidity to average about 10 ± 2 per cent at 45° C. The changes observed in oscillator frequency, as well as changes in oven humidity, were found to correlate very closely with changes in the humidity of the room. Employing a nomograph on humidity effects in cavities, the magnitude of the influence of humidity variation on frequency change was determined to be about 2.75 ppm/% RH and was considered to be approximately correct in view of the frequency changes observed. Although this factor appears to have an appreciable influence on the frequency of the oscillator, it can be virtually eliminated by filling the cavity space with an absolutely dry atmosphere and sealing it off.
The influence of changes in plate and heater potentials was found to be relatively minor compared to the effects of the two previous factors discussed. From long-term measurements on the plate-voltage supply, its stability was found to be about 500 ppm/day and short-term variations lasting a few seconds or more amounted to about 20 per cent of this value. Plotting the oscillator frequency changes against plate voltage for various values of grid resistance produced the characteristic shown in Figure 5.12a for an invar-cavity oscillator. From this graph it is seen that somewhat better stability was obtained at a plate voltage of about 100 v with a grid resistance of 2200 ohms than at lower voltages or with larger grid resistances. Taking a frequency stability value of 2 ppm/v (which corresponds closely to that value for 70 v on the plate), the change in frequency due to the short-term variations of the supply is about 0.014 ppm. At 600 mc this would be 8.4 cycles. The variation due to the long-term voltage drift would be about five times this value.

Heater-voltage changes were not recorded over long periods as were plate-voltage variations but short-term tests were carried out from which significant information on the long-term characteristics might be derived. The heater-voltage frequency characteristic shown in Figure 5.12b was obtained from an invar-cavity oscillator using a D-C heater-voltage supply. The heater supply for oscillators undergoing long-term measurements, however, was an A-C source in most of the runs recorded. From the above graph it is seen that the frequency-stability factor for changes in heater voltage is about 25 ppm/v. The A-C supply mentioned above was a Sola type 30492 constant-voltage transformer which specifies a one per cent regulation of the output for wide variations of the input. An electromechanical voltage-regulator was in series with
Figure 5.12. Frequency Voltage Characteristic of a Cavity-Controlled Oscillator.
the input line and provided regulation of the line voltage of ± 1 v at 115 v. Assuming a change of 1 v on the line the heater voltage at the output of the transformer would experience a change of \(0.55 \times 10^{-3}\) v. From this it is seen that the resulting frequency change of the oscillator would be negligible compared to other much greater influences.

Some effects on frequency change were noted when pressure was applied to the sides and the bottom of the cavity oscillator. Pressure at certain points caused greater frequency excursions than the same pressure at other points. Not only would there be a temporary change in frequency during the application of pressure but there would also be a hysteresis effect in the recovery characteristic which would cause the frequency to be at some value different from that before pressure was applied. This condition could account for hysteresis effects that appear under the influence of temperature changes. The root of this phenomenon would seem to be in the yield or aging characteristics of the metal from which the oscillator is constructed. The magnitude of this influence has not been evaluated conclusively because of unknown variables involved. Experience has shown that in gripping the cavity with one hand so that pressure is applied to opposite sides, a frequency change of about 3000 cycles is typical. The pressure applied is probably in the neighborhood of 7 or 8 lbs. A permanent "set" in frequency would be about 600 cycles for the above case after pressure was released. The only recommendation that seems practical in obtaining a reduction of this condition would be to design the cavity wall to have greater thickness, or to employ some sort of rigid bracing. In comparing these units with the so called lumped-constant type of circuit utilized in this frequency region, the resistance to shock and vibration was much greater in the
case of the cavity element than for the lumped circuit. This is an important consideration in portable or mobile equipment designs. A few crude tests were carried out by jarring the oscillator with hand slaps. The resulting frequency shift from several such slaps was in the neighborhood of 8 to 10 kc.

The instability of the series tuning capacitor was noted as another cause of frequency variations in earlier runs. This effect produced a random change in frequency, particularly following a tuning operation on the oscillator. Use of a lock nut on the rotor shaft of the capacitor virtually eliminated this effect. Vernier adjustment of the frequency after the main tuning capacitor has been set and locked was accomplished by turning a short 6-32 screw tapped through the outside of the cavity wall near the free end of the center conductor. This affords a fairly broad range of frequency adjustment without being unduly critical. One turn produced a frequency change of about 10,000 cycles and the setting was quite stable.

The influence attributed to tube aging was not well-defined because of lack of control of the other factors over long periods of time making effects from changes in tube parameters difficult to isolate. One observation that was traced to tube aging was a random characteristic in the frequency variations as the end of tube life approached. Accompanying this variation was a slight drift in frequency toward a higher absolute value. Two cases of tube failures were found to be due to a gassy condition that may have been caused by high tube-envelope temperatures of long duration. They had each been operating at a plate current of about 15 ma for around 600 hours. A single case was noted where failure occurred from a depletion of emission but no record was kept on this tube to indicate the length of time it had been operating. Extending the
life of the oscillator tube would probably result from reducing the plate
dissipation or by using ruggedized tubes. In one case, where the oscillator
was operating satisfactorily, the tube was removed and its transconductance
was checked to be about 1000 micronhos as compared to a new tube value of 6600.
It was not known how long this tube had been in operation. Records had shown
that the plate current of the latter tube had changed only about 1 ma out of
10 ma during a period of six weeks.

H. Conclusions

For temperature-regulated conditions a typical frequency-stability value
for one weeks' period of operation is about ± 10 ppm. Frequency drift of the
oscillator during this period of time tended to be in the direction of increas­ing
frequency.

The major factors affecting the medium-term frequency variations appear to
be temperature effects.

Tube aging was noted in a few cases to cause very erratic variation of
frequency as the end of tube life approached.

Plate and heater supply variations showed little influence on frequency.

The need for hermetic sealing of the cavity space is seen to be an impor­tant consideration to reduce humidity effects.

Effects of mechanical distortion show need for more rigid construction.

Room-temperature operation of an invar-cavity oscillator shows a typical
frequency-stability value of about ± 10 ppm/day for the heat-insulated case
and ± 50 ppm/day for the uninsulated case.
VI. SHORT-TERM FREQUENCY-STABILITY MEASUREMENTS

A. Introduction

One of the purposes of this project was to devise methods for measuring frequency variations occurring in very short periods of time, particularly in periods of time less than 1 second. Most equipment for precision measurement of frequency depends upon a finite period of time for the measurement to be made. For example, the Berkeley Model 5570 Frequency Meter requires a period of 2 seconds for frequency determinations within ± 1 cps of frequency error. This accuracy is obtained at higher frequencies only if a highly stable reference standard is available. Even with a highly stable standard, the frequency measurements represent only the average frequency over the period of 2 seconds. If a count time of 0.2 second is used, the frequency reading will have an uncertainty of ± 10 cps. Thus the cycle counting method is not a solution to the problem.

To restate the purpose of the investigation, it was desirable that methods be developed to permit the determination of changes in frequency during periods of time of from 0.1 to 1 second with an accuracy not exceeding one part in 10^9 and at a base frequency in the UHF range. A base frequency of 600 mc was chosen since other project work was being conducted at this frequency. In terms of cps of frequency change, this required that frequency differences of 0.6 cps be readable during an elapsed time of less than 1 second. Thus, systems based on whole numbers of cycles could not be used. It might be stated that the problem was to measure changes in absolute phase at a frequency of 600 mc.
It is important to recognize that the frequency measurement of a periodic, or nearly periodic, voltage is primarily determined by a measurement of the phase of that voltage relative to some fixed or imaginary standard. This criterion is particularly useful when the measuring period is much less than a second. It will be seen in the next section that phase-sensitive detectors form the basic measuring devices in all the short-term frequency-measuring systems described.

The desired properties of a practical measuring system may be viewed in best perspective through comparison with the properties of an idealized system. The list of characteristics given below includes the more important properties of such a system. An ideal short-term frequency-measuring system should incorporate the following properties.

1. The noise figure should be equal to unity, i.e., the noise output from the measuring system should be no greater in terms of frequency changes than the noise input from the signal source being measured.

2. The sensing characteristics of the measuring and recording portions of the system should have a sufficiently rapid response that the relative phase variation of the input, during the period of measurement, is reflected in an output having a magnitude which is independent of time. That is, a phase deviation of $\Delta \phi$ will result in a voltage change in the output of $\Delta V$ irrespective of the time of measurement.

3. When the input is equal to, or greater than, the noise level due to an ideal signal generator, the sensitivity of the system should be of sufficient magnitude to produce a reliable output.

4. All components should be completely insensitive to variation in local or ambient temperature, changes in power sources and other external parameters.
5. The response of the system should be linear or follow a prescribed law over a dynamic range which is equal to or greater than the limits of the maximum frequency deviation which may occur during the period of measurement.

The characteristics of any practical system must, of course, fall short of the desired properties exhibited by the ideal system. In the systems to be discussed attempts will be made to point out the principle deficiencies of each system with respect to the ideal system.

Four possible methods of short-term frequency measurement have been discussed with various conclusions in previous reports. These discussions will be repeated here although application of two of these methods has not been made.

1. Comparison of a given frequency with a frequency standard can provide significant information under proper conditions. In such an arrangement, it is necessary that the frequency standard be considerably more stable than the device under test, preferably at least one order of magnitude. Also, the frequency at which the comparison is to be made should be high enough so that a 1 cps frequency difference is no greater than the minimum required resolution, thus making possible measurements on the frequency basis rather than on the phase basis. The method would desirably involve a beat-frequency technique in which the difference frequency would be very small and could be observed on an oscilloscope or plotted by a recorder.

2. Comparison of the wavelength of an original frequency, \( f_0 \), with the wavelength of a new frequency \( f_0 \pm \Delta f \) by means of the long-line effects is theoretically practical for measurement of frequency changes when the period of measurement is very short, i.e., less than one microsecond, and the
frequency under study is very high. The basic arrangement is illustrated in Figure 6.1 in which the output of the generator under test arrives at the phase-sensitive detector by each of two paths having a path-length difference of L meters. If $T$ is the period of measurement, $v$ is the velocity along the line, $f_0$ is the basic frequency, and the length of line is such that $T = v/L$, then the first cycle generated will undergo a phase shift of $2\pi T f_0$ radians in arriving back at the detector while the output of the generator will undergo a phase shift of $2\pi T (f_0 + \Delta f)$ radians, where $\Delta f$ is the average incremental frequency change occurring during the time $T$. The phase difference is compared and measured by the phase-sensitive detector.

![Diagram of Oscillator Under Test and Phase-Sensitive Detector](image)

**Figure 6.1. Phase Difference by Long-Line Effect.**

3. Comparison of frequencies through utilization of memory circuits is practical at low frequencies. One version of a memory circuit which employs a variable-frequency oscillator is described by Van Bladel. In the arrangement illustrated in the reference, the frequency of the oscillator is constrained to remain constant for a prescribed period. At the conclusions of this period, the original changing frequency which was to be measured is compared with the unchanged frequency of the oscillator, and a measure of the frequency change is obtained.
4. Measurement of the relative frequency changes of constant-amplitude voltages is possible by means of discriminators. Many versions of devices whose output voltage is related to the input frequency in a linear or prescribed manner are known and have been employed at low and high frequencies. UHF and microwave discriminators are particularly applicable to the purpose described here.

No attempt was originally made to design a practical system based on method 1 since a standard having sufficiently known short-term stability was not available. However, later experimentation has demonstrated that this system may be both simple and highly accurate if a sufficiently stable standard is available. Large amounts of laboratory data have recently been collected on various signal sources and standards. From this data it has been concluded that stability measurements to within two or three parts in $10^9$ per second can generally be made with this type of system using equipment available to the project and recently determined to be suitably stable for this demonstration.

It is obvious that in order to use the system described in method 2, physical distance measurements must be made with extreme accuracy, exceeding that presently practical. Thus no application has been made of this system.

No use has been made of system 3 because of the unavailability of sufficiently stable memory circuits for use in the UHF region.

The principle efforts of the project on short-term stability measurements have been directed toward the application of the discriminator system 4. A UHF ring-discriminator and associated equipment have been constructed and tested. The best resolution that has been reliably obtainable with this system is 5
parts in $10^8$. The maximum response time is less than 0.1 second. Thus changes in frequency greater than 5 parts in $10^8$ per 0.1 second may be measured.

The two systems which have received extensive investigation by the project are discussed in detail in the following sections.

**B. Ring-Discriminator Frequency-Stability Measurement System**

Several discriminator systems were given consideration in the initial planning of the short-term frequency-stability measurement system. All of the systems considered were based on the use of UHF cavities as the reference elements. The choice of cavity references was made because of their relative inherent frequency-stability and insensitivity to temperature changes during short-term periods. The screening of electric fields afforded by the cavities was also of importance.

The eventual choice of the type of discriminator to be constructed was determined from literature and mathematical studies. The criteria was to determine the type of discriminator which would yield the greatest stability, sensitivity and freedom from noise. Information contained in one technical report helped to narrow the choice to a configuration originally described by Pound.

The original Pound discriminator system which was designed for frequency stabilization is shown in Figure 6.2. This system made use of a D-C control voltage to correct the frequency of the oscillator to be stabilized. The system, as described, operated at microwave frequencies. The sensitivity of an arrangement of this type is determined by the combination of several factors. Montgomery has shown that if the detectors have a sensitivity of $b$
Figure 6.2. Pound Frequency-Stabilizing System.
volts per incident watt, the rate of change of output voltage with frequency (prior to amplification) is given by

\[ \frac{dv}{df} = \frac{4\beta Q_o P_o}{(\alpha + 1)^2 f_o} \]  \hspace{1cm} (6.1)

where

- \( Q_o \) = the unloaded Q of the cavity,
- \( P_o \) = the incident power in watts,
- \( \alpha \) = the ratio of the power returned by the cavity to the input circuit to the power dissipated in the cavity walls and
- \( f_o \) = the resonant frequency of the cavity.

As an example, the same reference states that in the 9000-mc/sec region, with \( Q_o = 25,000 \), \( \alpha = \text{unity} \), \( b = 1 \text{ volt/mw (1N23 crystal)} \) and \( P_o = 1 \text{ watt} \),

\[ \frac{dV}{df} = 2.78 \text{ volts/mc} \]  \hspace{1cm} (6.2)

Equation 6.2 represents the slope, \( D \), of the discriminator curve, in which case the output of the D-C amplifier will be \( G_A D \) where \( G_A \) is the gain of the amplifier. If \( G_A \) were \( 10^6 \), then the final output would be 2.78 volts/cycle.

It is seen that under idealized conditions an appreciable voltage can be delivered by the system. The practical problems of ultimate amplifier gain, bandwidth and noise will add complexity to the design of the elements employed.

The operation of the system shown schematically in Figure 6.2 may be better understood by considering the operation of the Magic Tee shown in Figure 6.3. When energy arrives in arm 1, it divides out-of-phase by 180° in
arms 3 and 4. If one of these arms is longer than the other, i.e., if one is of length L and the other is of length L + x, the energies returned from equal mismatches (such as short circuits) will arrive out-of-phase by an appropriate angle. In particular, if \( x = \lambda/8 \) they will arrive in quadrature. But if one arm is terminated in a short circuit and the other in an impedance different than zero, the relative phasing will be different than 90°.

To provide satisfactory operation of the discriminator system in the UHF range required several modifications, one of which is the replacement of the Magic Tee of Figure 6.2 by equivalent UHF coaxial circuitry. One device equivalent to the Magic Tee is the coaxial-ring transformer illustrated in Figure 6.4. In this device it is evident that energy from the generator arm will enter arm A and the cavity arm but will not enter arm B. In the same way, energy reflected from the cavity will enter arm B and the generator arm but will not enter arm A. Now, if arm A is terminated in a short circuit, the reflected energy will enter the generator arm and arm B. It follows, from the number of wavelengths involved in each path, that a detector in the generator arm will measure the difference of the vector voltages from arm A and the cavity while a detector in arm B will measure the sum of the same vector voltages. The final action is thus equivalent to that of the Magic Tee. The ring transformer, however, is a single frequency device because it is dependent upon path lengths for its properties of isolation. The Tee, on the other hand, can be moderately broad-banded without departing greatly from a "null-measuring" bridge at any frequency within a specified band. A detailed description of the ring which has actually been constructed follows later.
Figure 6.3. The Magic Tee.

Figure 6.4. A Ring Transformer.
The discriminator system just described is, of course, not without disadvantages, a few of which are:

1. high D-C gain with adequate stability is difficult to obtain,
2. the bandwidth of the system is severely limited by the ring transformer,
3. the relative D-C noise level of crystal diodes is high, and
4. the output calibration would be greatly affected by input signal amplitude.

The noise problem alone is sufficient to make the D-C Pound system unusable for frequency measurements to 1 part in $10^9$.

Several types of frequency-control systems have in the past used A-C or i-f discriminators. Notable among these systems is the Pound i-f system, which uses many of the same components as the Pound D-C system. A block diagram of the i-f system for microwave generators is shown in Figure 6.5. A Magic Tee is illustrated in the diagram; however, this is replaced by a ring transformer for UHF application.

The Pound i-f stabilizer is described as follows. Energy at the frequency to be measured enters the Tee and divides equally between the cavity arm and the mixer arm. The mixer crystal is matched to the line so that no energy is reflected. All of the energy that is reflected from the cavity divides between the input arm and the modulator arm. An i-f signal is injected into the modulator crystal producing sidebands equally spaced about the incoming frequency. However, the crystal in the modulator arm is matched at the incoming frequency so that none of the energy at this frequency is reflected. The sidebands which are not matched are returned to the Tee and divide equally.
between the mixer and cavity arms. In the mixer arm the sidebands are combined with the incoming energy. If the phase relationships are correct, the i-f energy may be recovered by amplitude demodulation. However, if a net phase shift of 90° occurs, no i-f energy will be recovered. The normal adjustment of the system is such that no i-f energy is recovered when the incoming frequency is exactly equal to the resonant frequency of the cavity. Under this condition, a change in incoming frequency will result in a phase shift in the cavity which will produce an i-f output at the mixer crystal. The
phase of the i-f output will depend on whether the incoming frequency increased or decreased. Thus, by the use of a suitable i-f amplifier and a lock-in mixer, a D-C output voltage can be obtained which is proportional to the deviation of the input frequency from the resonant frequency of the cavity. This voltage may be reapplied to the UHF oscillator for frequency-correcting purposes through a time-delay network. Short-time deviations in this voltage will then indicate the short-time instability of the oscillator. The literature has indicated that the noise in this system may be made sufficiently small to permit measurements of instabilities as small as 1 part in $10^9$.

The Pound i-f system may be modified, as shown in Figure 6.6, by interchanging the positions of the modulator and mixer crystals. This results in

![Diagram of Equal-Arm Modification of the Pound I-F Discriminator](image)

Figure 6.6. Equal-Arm Modification of the Pound I-F Discriminator
equal signal-path lengths between the mixer crystal and the cavity and modulator elements. This modification is known as the equal-arm discriminator and, in microwave application, possesses several fundamental advantages over the preceding system. The most important among these are:

1. spurious signals are greatly reduced as a result of smaller reflections,
2. with the same input power, the over-all discriminator sensitivity is increased because the sideband energy is transmitted to the detector with greater efficiency,
3. for the same detector-crystal noise, the power input may be several decibels greater,
4. the carrier energy, rather than the sideband energy, is a function of frequency; thus, the output of the detector varies as a function of the carrier-to-sideband ratio, and
5. wider bandwidths of operation are obtained because of path equalization.

For these reasons the Pound equal-arm discriminator using the coaxial-ring transformer was chosen for the construction of a short-term frequency measuring system. Several factors had to be considered in adapting this discriminator system to use at UHF. Among these factors were:

1. reference cavity impedance matching,
2. modulator and mixer crystal matching,
3. long-term frequency correction, and
4. substitution of coaxial components for the waveguides.

Various of these factors will be discussed on the following pages.

A physical block diagram of the system as initially proposed is shown in Figure 6.7. All interconnections were made using 50-ohm coaxial cables.
General Radio Type 874 connectors were chosen for most UHF cables while BNC connectors were used for other circuits.

The system was constructed and operated as shown in Figure 6.7 except that the blocks labeled "Time-Delay Element," "D-C Amplifier," "Oscillator Control" and "Lock-in Mixer" were omitted. Manual long-term frequency correction of the test oscillator was substituted. This simplified setup is shown in Figure 6.8. During this operation it was found that the manual long-term frequency corrections were adequate for the proposed application of the system. Thus the blocks mentioned above were never constructed. The omission of the "Lock-in Mixer" had one additional consequence, i.e., the sense or direction of the frequency variation could not be determined from the recording meter or the visual indicator. An advantage was, however, that no additional system instability would be introduced by an added circuit. (A simple diode detector has much better stability than the circuitry required for a lock-in mixer.)

Figure 6.9 shows an operational setup corresponding to Figure 6.8 except that the positions of the reference cavity and modulator system have been interchanged (which has negligible effect according to theory). The data obtained using this setup show a sensitivity of only about one part in $10^6$.

Several factors contributing to this low sensitivity are i-f leakage in the modulator-crystal matching system, leakage in the mixer-crystal matching system, leakage in the cable between the mixer crystal and i-f amplifier, amplitude instability in the test oscillator and i-f oscillator. The system was accordingly modified to obtain improved sensitivity.

The final block diagram of the system is shown in Figure 6.10. The important changes resulting in this diagram are elimination of the mixer-crystal
Figure 6.7. Physical System Block Diagram of the Initially Proposed Short-Term Frequency-Stability Measuring System.
Figure 6.8. Short-Term Frequency-Stability Measuring System.
Figure 6.9. Equipment Setup for Measuring Short-Term Frequency-Stability.
Figure 6.10. Final Block Diagram of the Short-Term Frequency-Stability Measuring System.
matching system, physically locating the i-f amplifier close to the mixer crystal, addition of shields to all coaxial connectors, stabilizing the test oscillator with pads and amplifiers, and the addition of traps and terminations where necessary.

The test oscillators used with this system have been discussed elsewhere in this report. The 600-mc amplifier is a grounded grid amplifier using a cavity as the plate tuned circuit. It has a gain of approximately 12 db. The attenuator is a conventional UHF coaxial attenuator providing an attenuation of 10 db. The net increase in test signal amplitude to the ring is 2 db. The selectivity characteristic of the amplifier is shown in Figure 6.11.

The coaxial-ring transformer indicated in Figure 6.10 is a narrow-band device that is designed for a specific frequency as well as for a specific impedance. The choice of 50-ohm coaxial cable for interconnecting the system required that the impedance of the coaxial portion of the ring transformer be 70.7 ohms. The center frequency of 600 mc was determined by the availability of other equipment.

The final coaxial-ring transformer with appropriate dimensions is shown in Figures 6.12 and 6.13. As may be seen, the outer coaxial conductor has a circular cross section while the inner conductor is of square cross section. From the standpoint of ease in design a circular cross section would have been chosen for both conductors; however, from the standpoint of the mechanical mounting of the terminal arms, it was desirable that the inner conductor be square. No handbook data has been found on the design of transmission lines with this configuration. Thus, to obtain the required dimensions, it was necessary to plot the potential fields and, through a conformal transformation,
Figure 6.11. Selectivity Characteristic of the 600-mc Cavity Amplifier.
Figure 6.12. Mechanical Details of the Coaxial-Ring Transformer.

Figure 6.13. Coaxial-Ring Transformer Assembly.
obtain a relation between the unit-capacitance-and-inductance and the physical dimensions. The originally constructed ring was within 12 per cent of the correct impedance. The final dimensions shown in Figure 6.12 were obtained by a process of machining new center conductors and then making measurements to determine if the correct impedance had been obtained. It was also necessary to take into account a predetermined thickness of silver plating. The final impedance of the ring transformer was within one per cent of the desired value of 70.7 ohms.

With the reference cavity arm and the modulator arm of the transformer properly terminated, the VSWR of the input arm was measured to be 1.07. The isolation between the input and mixer arms was 48 db. Both the VSWR and the isolation are functions of frequency, the values mentioned being obtained at 600 mc. Figure 6.14 shows the variations in isolation as a function of frequency.

The performance of this ring transformer compared favorably with other units constructed elsewhere.  

The reference cavity in Figure 6.10 is of conventional design, proportioned to give maximum Q. It is constructed of silver-plated brass with particular emphasis on mechanical rigidity. The coupling loop is designed to produce an impedance of 50-ohms at resonance.

The modulator system is shown in detail in Figure 6.15. The crystal diode is terminated in a 50-ohm resistance and matched to the ring by means of an adjustable line and shorted stub so that the complete system presents a 50-ohm impedance to the ring at 600 mc. The i-f oscillator voltage is injected into the crystal diode to generate the required sidebands. The proper impedance
match at the ring is somewhat dependent upon the magnitude of the injected i-f voltage. Thus, when adjusting the shorted stub and adjustable line the proper i-f voltage should be applied.

Figure 6.15. The Modulator System
The i-f oscillator consists of a 10-mc oscillator-tripler with two output buffer-amplifiers. A 12AT7 vacuum tube is used as a cathode-coupled oscillator with the output plate tuned to 30 mc. Two output channels each use a 68H6 vacuum tube as a buffer-amplifier. The output voltage is in excess of one volt into a 50-ohm load. The output amplitude is controlled by potentiometers in the cathodes of the buffers. The heater and plate voltage supplies are well isolated to prevent 30-mc leakage from the oscillator. A schematic diagram of the oscillator is shown in Figure 6.16.

The mixer system consists of a 50-ohm termination, an i-f trap, and a series crystal-diode mixer whose output is connected directly into the i-f amplifier. The termination and diode assembly is a modified General Radio 874-MR mixer containing an internal 50-ohm resistor and short-circuit. The i-f trap consists of a 50-ohm coaxial line section (which is one-quarter wavelength long at 600 mc) and a terminating capacitor. At 30 mc the line is equivalent to a series inductance. The terminating capacitor tunes this inductance to resonance at 30 mc while essentially providing a short-circuit at 600 mc so that the line section will present a high impedance at the higher frequency. The only mixer loading is that provided by the i-f amplifier input impedance which is approximately 10,000 ohms.

The i-f amplifier is a modified Linear Equipment Laboratories, Inc. Model IF 30 amplifier. The noise level of the amplifier as originally received was excessive due principally to a wider frequency bandpass than required for this application. The input circuit was redesigned, several of the tuned circuits were replaced, and other circuit modifications were made. This resulted in a gain increase of from 120 db to greater than 130 db and a noise reduction
Figure 6.16. Schematic Diagram of the 30-mc Oscillator.
to less than 1.3 db. The dynamic range was also improved considerably. The schematic diagram of the modified amplifier is shown in Figure 6.17. Figures 6.18 and 6.19 show respectively the noise-gain-vs-bias voltage and the gain-vs-plate voltage characteristics of the modified amplifier.

A high-input impedance i-f preamplifier was constructed to couple the mixer to the linear i-f amplifier. However, it was later found that the preamplifier did not contribute to the performance of the discriminator system, thus it was not incorporated into the final system.

The setup and operational procedure for the ring-discriminator system is as follows:

1. Connect the equipment as shown in Figure 6.10 using a sweep oscillator such as the Philco Model G-8002.

2. Adjust the sweep oscillator for minimum sweep width and maximum rf output at 600 mc.

3. Adjust the modulator adjustable line and shorted stub for minimum reading on the recorder or indicator. If an oscilloscope is used as the indicator, a conventional discriminator loop may or may not be observed, depending upon the adjustment of the other components. The i-f amplifier gain must be kept sufficiently low so that saturation of the amplifier does not occur.

4. Adjust the reference cavity adjustable line and frequency vernier (it is assumed that the cavity has been set up approximately 600 mc) for minimum indication at 600 mc. Increase the i-f amplifier gain as necessary.

5. Adjust the 30-mc trap for further null.
Figure 6.17. Modified LEL Model IF 30 Amplifiers.
Figure 6.18. Noise and Gain-vs-Bias Voltage.

Figure 6.19. Gain-vs-Plate Voltage Supply.
6. Repeat steps 3 and 4 while increasing the i-f amplifier gain as necessary until the best null is obtained. A discriminator characteristic should now be seen on the oscilloscope.

7. Replace the sweep oscillator by the cavity oscillator to be tested. Repeat steps 3 and 4 while at the same time adjusting the test oscillator frequency for a minimum indication. Since the test oscillator is not being swept, a discriminator characteristic will not be seen on the oscilloscope.

8. Adjust the i-f amplifier gain to calibrate the system for known frequency changes. This may be done by producing a known frequency change in the test oscillator.

By following the above procedure a maximum sensitivity of about 5 parts in $10^8$ for a signal-to-noise ratio of unity can be obtained.

**C. Short-Term Frequency-Stability Measurements Using Beat-Frequency Technique**

One of the methods of measuring the short-term stability of cavity oscillators is beating the oscillator to be tested against a frequency standard having sufficiently good short-term stability. This method was considered early in the project but was discarded in favor of the coaxial-ring discriminator described above for the following reasons:

1. A highly stable standard was not available at 600 mc.

2. The best standard available at lower frequencies as a W.E. Type 0-76/U oscillator operating at a frequency of 100 kc. The short-term stability characteristics of this oscillator were not sufficiently known.

3. It was also doubtful that suitable multipliers with sufficiently small short-term phase modulation could be constructed even if the basic 0-76/U oscillator stability were satisfactory.
4. Such a comparison system could not conveniently provide sense (or
direction) information.

5. Medium-term (average) frequency correction could not easily be pro-
vided.

6. Analysis of data would be a lengthy and indirect process.

Sufficient personnel time was not available to further pursue the develop-
ment of such a system while at the same time developing the coaxial-ring dis-
criminator system. However, late developments with the coaxial-ring discrimi-
nator indicated that sensitivity of one part in $10^9$ would not be obtained.
Therefore, parallel work has recently been conducted on the beat frequency
method.

Two principle problems were encountered in applying the beat frequency
 technique to short-term frequency stability measurements. The first of these
problems was concerned with obtaining a suitable stable reference signal source.
The second was concerned with recording and analyzing the required data.

The Western Electric Type 0-76/U, 100-kc oscillator with suitable multi-
pliers has been accepted as the best available standard. Thus, most of the
data presented here is based on the stability of this oscillator. Two other
oscillators, the 1-mc oscillator in the Berkeley Model 5570 Frequency Meter
and a 50-mc crystal oscillator, have also been used to some extent. No con-
cclusive results have been obtained concerning the short-time stability of the
W.E. oscillator; however, from a study of the circuits and construction to-
gether with data on the long-term stability over a period of 4 years, it is
believed that the short-term stability may approach one part in $10^9$ for periods
of a few seconds.
Some 60-cps frequency modulation has been observed; however, this modulation is removed by integration in the recording process where the measurement times are 0.1 seconds or greater. Most of this frequency modulation has been found to occur in one of the frequency multipliers. This particular multiplier chain, with an input at 100 kc and an output at 1 mc, introduces 60-cps frequency modulation with a deviation in excess of one part in $10^6$. Other multiplier chains from 100 kc or 1 mc to 600 mc were found to be almost entirely free of 60-cps frequency modulation.

That the frequency multipliers themselves had adequate stability was verified by operating two 1 mc to 600 mc multipliers from the same input and then comparing the outputs at 600 mc. The method of connection is shown in Figure 6.20. The outputs were compared by mixing the two 600-mc signals in approximately equal amplitudes at the input of a UHF receiver and then recording the signal-level-meter deflection with a sensitive D-C recorder such as the Sanborn

![Figure 6.20. Setup for Determining the Performance of the Frequency Multipliers](image-url)
Model 127 recorder with a Model 126 amplifier. The recorder thus indicated the relative phase relationship between the two 600-mc signals. If the two signals were in phase, a maximum reading was obtained, and if they were out-of-phase by 180°, a minimum reading was obtained.

Figure 6.21 shows a typical recording made in this manner. During the first 2 seconds of the recording, phase shifts were artificially introduced into one of the multipliers for calibration purposes. During the latter part of the recording, the multipliers were undisturbed. The corresponding frequency stability was calculated from the relation

\[
\frac{df}{dt} = \frac{2 \Delta \phi}{360 \Delta t} \cdot \frac{1}{600 \cdot 10^6} \text{ cps per second} \quad (6.3)
\]

where \( \Delta \phi \) is the number of degrees of phase shift occurring during the time \( \Delta t \).

(The phase shift is assumed to occur in such a manner that the equivalent rate of change in frequency is a constant.)

Figure 6.21. Typical Stability of Frequency Multipliers.
For example, if a phase shift of $180^\circ$ occurs during a time of one second, a $\Delta f$ of 1 cps is indicated giving an instability of approximately two parts in $10^9$ per second. This would, of course, be the combined instability of the two multipliers. To help assure that cancelation of phase changes did not occur, the two multipliers were operated from separate heater and plate voltage supplied. One of the multipliers was operated from a D-C heater source. Under these conditions, typical combined instability of the multipliers was less than one part in $10^{10}$ per second.

Figure 6.22 shows the general setup used to determine the stability of various oscillators. The isolation was in the form of attenuators and amplifiers. In some cases a frequency offset was used to produce a beat frequency of 1 mc which was then compared with a harmonic of the output of the W.E. standard oscillator. To obtain sufficient sensitivity a UHF receiver was usually used as the mixer. When this was done the output was obtained from the signal-level-meter circuit. When frequency offset was used with the receiver the output was taken at the video terminal.

![Diagram of setup for measuring oscillator instability]

Figure 6.22. Setup for Measuring Oscillator Instability
Recordings were made using many combinations of cavity oscillators and standards as indicated in Table 6.1. In the table, the numbers given are the numbers assigned to the various runs.

**TABLE 6.1**

**RUN NUMBERS ASSIGNED TO VARIOUS BEAT-OSCILLATOR COMBINATIONS**

<table>
<thead>
<tr>
<th>Runs</th>
<th>0-76/U (100 kc)</th>
<th>0-76/U (1 mc)</th>
<th>Berkeley (1 mc)</th>
<th>Presto (50 mc)</th>
<th>Cavity 1</th>
<th>Cavity 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-76/U (1 mc)</td>
<td>17</td>
<td>15,18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Berkeley (1 mc)</td>
<td>2,13,19</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presto (50 mc)</td>
<td>3</td>
<td>12,16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity No. 1</td>
<td>5</td>
<td>8</td>
<td>10,11</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity No. 2</td>
<td>6,7</td>
<td>9</td>
<td></td>
<td>23,24,27</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Cavity No. 3</td>
<td>14</td>
<td></td>
<td></td>
<td>25,26</td>
<td>21,22</td>
<td></td>
</tr>
</tbody>
</table>

Figures 6.23, 6.24, and 6.25 show samples of some of the runs. In all cases it was necessary to adjust the frequency of the oscillator under test to be nearly equal to that of the reference oscillator and then depend on random drift to produce the results shown. Thus, in some cases many minutes were required to obtain a sufficient number of natural drift crossings of the frequencies. It should be noted that with this type of recording no information is obtained concerning the direction of frequency changes; however, from the recordings it can be determined whether or not a zero-crossing has occurred.
Figure 6.23. Beat Frequency Between Invar-Cavity Oscillator No. 1 and the W. E. 0-76/U Standard.

Figure 6.24. Beat Frequency Between Invar-Cavity Oscillator No. 2 and the W. E. 0-76/U Standard.
The relative stabilities of various oscillator combinations can be estimated by observing a large number of recordings of the type shown. However, to obtain numerical values for the instabilities a mathematical process is required. For this purpose, it is assumed that the frequency of the reference oscillator is absolutely constant and that all frequency variations of the oscillator under test occur in such a fashion that the frequency-vs-time curve may be approximated by a number of straight line segments.

In the illustrated recordings, considerable distortion occurred depending upon the type of mixer action involved. In order that consideration of this would not be necessary, only complete half-cycles of the recorded frequency were considered. Thus, if the test oscillator voltage is assumed to be

\[ e_t(t) = E \cos(2\pi(f_0 t + gt + \phi)), \]  

(6.4)
the recorded voltage will be

\[ e(t) = E \cos 2\pi(gt + \alpha) \]  

(6.5)

where \( f_0 \) is the frequency of the reference oscillator and \( g \) determines the frequency actually plotted by the recording meter.

Since change in frequency is the only information required from the recordings, it may be seen that changes in \( e(t) \) represent cycle-for-cycle the respective changes in \( e(t) \). Thus it is only necessary to determine the frequency change from the recorded charts. This can readily be accomplished by measuring the periods of complete cycles when the frequency is constant. However, when \( g \) is changing with respect to time (it is necessary to use the term frequency rather loosely for this purpose) the period of a cycle does not accurately indicate the frequency during that time. This is particularly true if \( g \) is changing rapidly.

From equation 11.50 in the Appendix the rate of frequency change, \( \frac{df}{dt} \), is given by

\[ \frac{df}{dt} = \frac{a(b - c)}{(b \cdot c)(b + c)} \quad \text{cps/second} \]  

(6.6)

where \( b \) is the time for some integral number, \( a \), of half-cycles and \( c \) is the time for the next equal number, \( a \), of half-cycles.

Sample data were calculated using equation 6.6 for all of the combinations listed in Table 6.1. The quantity \( \frac{df}{dt} \) was then plotted as a function of time for the various oscillators. It should be stressed that \( \frac{df}{dt} \) is not the frequency but rather the rate of change of frequency in cycles per second per
second (cps/second). The actual instantaneous frequency cannot be readily obtained from the procedure illustrated in the Appendix. However, the frequency as calculated from the reciprocals of the cyclic periods on the charts was also plotted. This frequency is, of course, only an approximation since the frequency is the reciprocal of the period only when the frequency is constant. Figure 6.26 shows a sample of the curves obtained. It may be observed that the rate of change of frequency curve is very irregular. This violates the assumption under which equation 6.6 was derived. On the other hand, the changes in the frequency-vs-time curve of Figure 6.26 agree substantially with the df/dt-vs-time curve. A more complicated mathematical procedure is needed, however, to obtain adequate precise information from the recorded charts. Time was not available on the project to perform this additional analysis.

Even though the errors may be large, a summary of the data obtained from 17 curves of the type shown in Figure 6.26 is tabulated in Table 6.2. These tabulations should give a relative indication of the short-term stabilities of the various oscillators.

It is interesting to observe that in Table 6.2, the "Min. Δf" values are always less than the "Min. cps/sec." values. This means that, although the rate of change of frequency may at times be very high, the total change in frequency over any period of time will be considerably less because of the random nature of the frequency variations. The changes in frequency tend to compensate, thus improving the medium and long-term stability.

A study of the data in Table 6.2 will show that the 0-76/U oscillator apparently has considerably better short-time stability than the cavity oscillators. Thus, most of the instability observed when beating the 0-76/U with
Figure 6.26. Results of a Typical Beat-Frequency Run.
### TABLE 6.2

**SUMMARY OF DATA ON SHORT-TERM STABILITY OF VARIOUS OSCILLATORS**

<table>
<thead>
<tr>
<th>Oscillator Pair</th>
<th>Max cps/sec</th>
<th>Typ cps/sec</th>
<th>Min cps/sec</th>
<th>Max Δf</th>
<th>Min Δf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berkeley-vs-0-76/U</td>
<td>3</td>
<td>± 1</td>
<td>0.4</td>
<td>1.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Presto-vs-0-76/U</td>
<td>20</td>
<td>± 3</td>
<td>6.0</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Cavity 1-vs-0-76/U</td>
<td>10</td>
<td>± 4</td>
<td>3.0</td>
<td>3.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Cavity 2-vs-0-76/U</td>
<td>10</td>
<td>± 1.5</td>
<td>2.0</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Cavity 3-vs-0-76/U</td>
<td>18</td>
<td>± 4</td>
<td>1.5</td>
<td>4.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Cavity 1-vs-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 2</td>
<td>90</td>
<td>± 20</td>
<td>12.0</td>
<td>17.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Cavity 1-vs-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 3</td>
<td>33</td>
<td>± 8</td>
<td>9.0</td>
<td>10.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Cavity 2-vs-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity 3</td>
<td>39</td>
<td>± 9</td>
<td>3.0</td>
<td>11.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

† These values are calculated from equation 6.6. Maximum values are the peak instantaneous values. Typical values represent the optical average or mean. Minimum values are the minimum peak values for any one second period of time.

†† Maximum total change in frequency in cps occurring in any one second period of time.

††† Minimum total change in frequency in cps occurring in any one second period of time.

The various cavity oscillators may be attributed to the cavity oscillators. Therefore, useful information on the stability of the cavity oscillators is obtained. It should be pointed out that cavity oscillator number 1 was not working properly when it was heterodyned with cavity oscillator number 2, thereby accounting for the high values in this row.
It is believed that this system would be very effective for determining the short-time instability of oscillators

1. if the short-time stability of the 0-76/U oscillator can be verified (for example, by comparing it with another similar oscillator) and

2. if a more accurate and less time-consuming mathematical data analysis procedure can be developed.
VII. TEMPERATURE-INSENSITIVE CAVITIES

A. Introduction

During the course of the previous Contract No. DA-36-039-sc-42590, investigations were conducted to make the resonant frequency of a cavity insensitive to temperature changes. The important conclusion established from these investigations was that temperature-compensated cavities can be constructed with resonant frequencies which will vary not more than ±0.5 ppm/°C over a wide range of ambient temperatures. Construction of such cavities is, however, usually difficult and costly. Furthermore, optimum compensation is usually achieved at only one frequency. Therefore, it may be presumed that if cavities can be constructed of materials of low or possibly zero-temperature coefficient, the resulting structure would be simpler to build and would occupy less space. Moreover, the possibility of tuning the cavity over a range of frequencies while maintaining zero expansivity would exist.

A material which appeared attractive as a basic substance in the construction of a temperature-insensitive cavity was a brand of magnesium-alumino-silicate, which is manufactured under the trade name of "Stupalith." This material has a claimed-zero temperature expansivity over a very wide range of operating temperatures, but since it is a ceramic, methods had to be developed to apply a highly conductive material to its surface. These methods were developed and sufficiently refined to produce a high Q resonator. Various configurations, utilizing this material as a resonator base, were tested in the course of the present contract. Some of the methods of construction are described, and the results achieved are noted.
B. Cavities Assembled from Stupalith Parts

The first attempt at constructing a cavity utilizing a temperature-insensitive ceramic was a configuration using an invar outer conductor and end plates. The inner conductor, whose length was approximately $1/4\lambda$ at $785\,\text{mc}$, was formed from silver-plated Stupalith. The physical arrangement is shown in Figure 7.1.

![Figure 7.1. Invar Cavity with Stupalith Center Conductor.](image)

Tests were made by placing the cavity in an oven and measuring its resonant frequency. The temperature was varied in $15^\circ\text{C}$ increments from $25^\circ\text{C}$ to $100^\circ\text{C}$, allowing a "heat soaking" period of about 2 hours at any given temperature, while the resonant frequency was continuously monitored. Several such heating cycles were performed, all of which produced essentially the same data, i.e., a frequency change of about $-2\,\text{ppm/}^\circ\text{C}$. 
It was tacitly assumed that the resulting temperature sensitivity, which was greater than the expansivity of either base material used, was influenced by factors that did not involve the expansivity of the cavity base materials.

In a succeeding test, the invar outer conductor was replaced with one of Stupalith. Invar end plates were used since Stupalith plates of sufficient size were unavailable at that time. The invar end plates were soldered to the silver-plated Stupalith outer conductor. The inner conductor, having no screw threads, was slipped through a hole in the end plate and securely soldered with Cerrotru. The cavity was then heat-cycled in a manner similar to that described previously.

This configuration exhibited a greater temperature sensitivity during the heat-cycling tests than the previously mentioned cavity which utilized invar as an outer conductor. Specific causes of this result are not evident, but possible sources of frequency sensitivity may be theorized.

If there are any stresses set up in the end plates due to improper annealing of the invar, or due to the expansivity of the solder at the joints, there is a possibility these stresses may translate movement to the unsupported end of the inner conductor. If the entire inner conductor was moved eccentrically as little as 0.002 inch, a rough calculation indicated that the resonant frequency of the cavity would be lowered by 160 ppm. While only the unsupported end would move in an actual cavity, this calculation gives the order of magnitude that should be expected due to movement of the inner conductor translated by stresses.

A strong indication that stresses were, in fact, the primary cause of the high-temperature sensitivity of these cavities was given in subsequent tests.
which followed resoldering of the end plates. On the previous cavity, soldering of the end plates was accomplished by holding them lightly against the outer conductor and applying the solder. When they were resoldered, clamps were used to press them firmly into position. This new arrangement produced a temperature sensitivity which was significantly different although not significantly better.

In order to reduce the deleterious effects of stresses, a new inner conductor was designed for support at both ends of the cavity. Since a quarter-wavelength cavity was desired, the inner conductor was made long enough to be supported at both ends, but it was plated only about half the distance from one end. The unplated portion was to serve as an insulator support.

This particular cavity exhibited a very low Q under test and was not considered a practical resonator because of the high losses in the Stupalith "insulator" support. The same configuration could be used, however, if the inner conductor is plated over its entire length to produce a half-wavelength resonator. No attempt was made to build this type of structure since the primary interest was in quarter-wavelength resonance.

C. One-Piece Stupalith Cavities

Since the solder joints and/or the invar end plates set up stresses, it appears that the only successful structure would be one that is completely fabricated from Stupalith. A cavity completely formed from Stupalith would have no solder joints, and for this reason, deleterious stresses should be eliminated.

Tests were performed on an all-Stupalith cavity assembled at Georgia Tech in which the end plate and inner and outer conductors were fused together by means of a gas-oxygen flame. This resonator was tested, and the results of the heat-cycling tests indicated the temperature sensitivity to be about - 4 ppm/°C.
This unsatisfactory result was apparently due to the fact that the fusing changes the properties of the material to some extent, whereby it loses its desirable characteristic of zero expansivity. The manufacturer confirmed this observation, but suggested that improved characteristics could be achieved by annealing the completely fabricated structure at 2300°F. Following this recommendation, annealing was performed and test of the cavity was repeated. A reduction of only 1 ppm compared to the first test was observed. Speculation on this result was that improper annealing operations could be the cause since facilities for close process control may not have been as good as the control which the manufacturer assumed in his suggestion. During the course of the preceding experiments on Stupalith cavities assembled locally, the fabricating facilities of Stupakoff Division of the Carborundum Company, Latrobe, Pennsylvania, were investigated and found to be capable of producing one-piece cavities of Stupalith (Type A-2417) to prescribed specifications. The manufacturer built the cavities moulding two separate sections of the cavity from Stupalith and then fusing these two sections together. The entire assembly was then thoroughly annealed to relieve all internal stresses. Figure 7.2 shows the mechanical details and dimensions of these cavities.

D. Stupalith Cavity Coating

Metal coating of the cavities received from the Stupakoff Company was carried out by project personnel at Georgia Tech. A procedure, developed on a previous project, for coating ceramic materials of this type was followed in processing these cavities. Instead of spraying the basic coating material onto the surface as specified in the above procedure, the entire cavity was dipped into the solution and agitated while submerged. The unit was then
Figure 7.2. One-Piece Cavity Constructed of Zero-Temperature Expansivity Stupalith.
removed and positioned so that the excess solution drained off easily. After air-drying several hours, the coating could be inspected to determine if additional coatings were necessary. When the final coating was thoroughly air-dried, oven firing was carried out.

The material used in all cases for the initial coating of the surface was DuPont Conductive Silver Coating No. 4756. It is specified for use with low-expansion ceramic bodies and is fired at a temperature of 1250-1350°F. The fired film is then suitable for silver plating or direct soldering.

Three cavities were coated with slightly different procedures used on each one. The first cavity was fired after only one dipping in the coating solution. Inspection of the surface following the firing procedure revealed very poor covering, particularly in the bottom and in the corners of the cavity. It was decided, however, to proceed with electroplating of silver onto this base to learn what effects would result. It was found that the thin-coat areas did not electroplate well.

After electroplating, two coupling loopholes were drilled into the cavity on opposite sides of the center conductor about 1/2 inch from the bottom. The Q of the cavity was measured and found to be around 500, which was considerably lower than expected.

The second cavity was dipped about four times in the coating solution with about 2 hours drying between coats. After firing at the proper temperature, inspection of the surface revealed a good uniform coverage of the walls but the bottom and the corners had noticeable cracks and thin spots in the surface of the coating. Poor adherence to the ceramic material may have been the cause of this condition in the corners--here the coating material had large surface
cracks as though shrinkage had set in during the cooling period. Another troublesome factor could have been gas pockets, either in the ceramic itself or between the coating and the ceramic surface, which may have been blown out during firing. It is not known why the covering was thin on the bottom since the sides of the center and outer conductor coated very well. Measurement of the Q of this cavity gave a figure of 1500 which is still quite low.

The third cavity was covered with five coats with the first coating being "scrubbed" into the surface during the dipping process. The succeeding coats were applied without scrubbing and the cavity was then baked at 100° C for several hours before the actual firing was performed. This pre-baking was done to eliminate, as nearly as possible, the volatile products of the coating vehicle before the firing cycle. The result of this process was very disappointing. A large continuous crack occurred in the surface of the coating at the intersections of the inner and outer conductor walls with the bottom. Thus, electrical continuity was completely broken. Attempts were made to repair this crack but with no success.

E. Measurement Procedure

Figure 7.3 shows the block diagram arrangement of the various components used in measuring the temperature-frequency characteristics of the Stupalith cavities as passive elements. Initial tests employed the cavity as a transmission element but later tests utilized it as a reflection element. Since there was noticeable influence from the presence of one coupling loop in the cavity space, it was considered that an additional loop would increase the effect. The block diagram shows the system set up, with the cavity as a reflection element, that worked quite satisfactorily. An adjustable line was placed between
crystal detector and the cavity and adjusted to an integral number of half wavelengths (less some compensation for the loop inductance) at the frequency of resonance. Thus, with the applied signal being swept in frequency, the detector would see a replica of the impedance characteristic of the coupling loop.
as the frequency of the incident energy passed through the region of cavity resonance. A D-C scope was used to observe the response characteristic of the cavity and to determine proper adjustment of the marker signal on the point of resonance.

Because of its high output and satisfactory stability, a cavity-controlled oscillator was used as the generator for the marker signal. Monitoring of the frequency of this marker signal was performed with a Berkeley Model 5570 frequency counter by means of a heterodyne system. The local or reference oscillator of this heterodyne system was fixed so that its frequency differed from the frequency of the marker signal to produce a frequency within the range of the Berkeley frequency counter. A crystal check point on a Gertsch FM-3 frequency meter was employed to monitor the frequency of this reference oscillator. By means of the preceding system it was possible to minimize the delay between adjustment of the marker on the response curve and reading the frequency. In measuring the temperature-frequency characteristics, only the frequency changes were of interest. This procedure did not require knowledge of the absolute frequency of cavity resonance except at the beginning or at the end of a test run.

The oven utilized for these tests could be sealed sufficiently to effectively reduce admission of room atmosphere once the test was started. After placing the cavity in the oven, the entire system was flushed with dry nitrogen and a desicant (activated alumina) was used in the oven to reduce the effect of any possible entrance of outside atmosphere. Thus, the humidity effects pointed out in Chapter V were kept to a minimum.

The temperature of the cavity during the test run was monitored with a mercury thermometer attached to the inside of the cavity center conductor by means
of a copper sheath. About 45 minutes to 1-1/2 hours were allowed for heat soaking between successive temperature readings.

F. Frequency-Temperature Characteristics of One-Piece Stupalith Cavities

A total of 12 temperature runs were made on two of the three cavities plated. As was indicated earlier, the third cavity could not be utilized because of coating difficulties. However, it is felt that the data obtained from the two cavities presented conclusive information regarding the typical frequency-temperature characteristics of this particular material and method of construction.

The range of temperature variation in all cases was from room temperature (approximately 25° C) to 100° C. Temperature readings were taken in 10° or 20° steps.

Figure 7.4 presents a graph of the frequency-temperature characteristic of the first of the one-piece Stupalith cavities (Model 1) to be plated. Graph a shows the characteristic of the cavity used as a transmission element in the measuring setup whereas graph b shows the characteristics for the same cavity used as a reflection element. A line representing the mean value of the points has been drawn on each graph to convey typical information regarding the stability of this type of cavity with temperature variation. The results appear to indicate that the value established in the transmission case is quite good when compared with the reflection case but a repeat test of each case showed that the points for the reflection case could be matched much closer than the points for the transmission case. The reason for inconsistency of the data in the transmission case was never clearly revealed but there was a possibility that random temperature characteristics of the input and output coupling loops may have been a major factor.
Temperature-Frequency Characteristics of Stupalith Cavity, Model No. 1
(Cavity as transmission element; one base coat before silver plating.)

.24 ppm/°C
Mean value of frequency change

Temperature-Frequency Characteristics of Stupalith Cavity, Model No. 1
(Cavity as reflection element in heterodyne frequency system.)

1.1 ppm/°C
Mean value of frequency change

Figure 7.4. Frequency-Temperature Characteristics for Stupalith Cavity Model 1.
A question was raised in earlier runs about the effects of the connecting cables with temperature variation but modification of the measuring technique showed that influence of factors associated with cabling were negligible.

The remaining 8 runs were made on the second cavity (Model 2) to be plated. The results of runs numbered 4, 6, and 7 on this model are shown in Figure 7.5. The data on run number 4 was obtained from the first test of this model. The run was made with the temperature increasing from that of the room. It was assumed that the oven atmosphere was dry so that humidity effects could be neglected. The length of time between readings was about 1 hour. In the second graph, run number 6 was made with the temperature decreasing to room value and the total time of observation and recording was about 12 hours. Comparison between this run and number 4 shows essentially the same characteristic value of frequency versus temperature. Run number 7 was made several days later with temperature increasing from room value and a very different shape of the characteristic was noted. Investigation revealed that the cause of this was humidity from the atmosphere which had leaked into the oven since the previous run. Reflushing the oven system with dry air and renewing the desicant produced data on the remaining five runs that corresponded closely with data from runs 4 and 6.

It is noted from the data in each of the figures that the temperature coefficient of expansion was negative for the particular batch of Stupalith from which these cavities were made. Whether or not the changes in frequency resulted from changes in the center conductor length was not entirely certain. Temperature effects could also produce changes in dimensions and position of sections of the cavity other than the center conductor.
Figure 7.5. Frequency-Temperature Characteristics for Stupalith Cavity Model 2.
On the assumption that the frequency changes came primarily from a change in the center conductor length, the temperature coefficient of expansion may be calculated for the Stupalith material used in the manufacture of these cavities. This value was computed to be \(-1.5 \times 10^{-6}/^\circ C\) corresponding to the data obtained from run number 6.

G. Stupalith-Cavity Oscillator

A cavity oscillator was constructed using a one-piece Stupalith cavity resonator and was operated for several hours at room temperature conditions. These conditions were similar to those used in the room temperature runs of the invar-cavity oscillator described in Chapter V. The construction was similar to that shown in Figure 5.2 except that the cap enclosing the cavity overhang was made of invar instead of Stupalith. Also the mounting for the series tuning capacitor was an invar plate clamped to the end of the center conductor.

Two individual runs were recorded totaling 255 hours. The evaluation of these two runs is presented in Table 7.1 and a sample of the recorded frequency

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>600.000838</td>
<td>229</td>
<td>+1.2</td>
<td>0.382</td>
</tr>
<tr>
<td></td>
<td>+7.1 kc</td>
<td></td>
<td>-1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-7.6 kc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>235</td>
<td>599.996338</td>
<td>-105</td>
<td>+33.5</td>
<td>-0.175</td>
</tr>
<tr>
<td></td>
<td>+20.1 kc</td>
<td></td>
<td>-28.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-17.0 kc</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
characteristic is shown in Figure 7.6. From the table it is seen that a stability of approximately ± 30 ppm/10 day is possible. If the room temperature is stable to ± 5° C over the same period, the frequency of the oscillator should be affected by about ± 5 ppm, assuming a temperature-frequency characteristic for Stupalith of 1.0 ppm/°C. The remainder of the frequency change is probably the result of humidity and tube-aging effects.

In comparison with the invar-cavity oscillators operating under the same conditions, the performance of the Stupalith oscillator is not significantly better. The ability to withstand shock is a factor in favor of the invar oscillator since Stupalith is a highly fragile ceramic.

H. Conclusions

Temperature-insensitive cavities built with an invar outer conductor and Stupalith center conductor did not exhibit any improvement over a cavity built
entirely of invar which possesses a temperature-frequency characteristic of -2 ppm/°C.

A cavity assembled by a welding process entirely of Stupalith parts resulted in a temperature-frequency characteristic poorer than the invar-Stupalith combination.

The best frequency-temperature values were obtained from one-piece moulded cavities of Stupalith (Type A-2417), constructed by the Stupakoff Company of Latrobe, Pennsylvania. The typical temperature-frequency characteristics of these cavities average about -1.0 ppm/°C over a 70° range.

The problem of metal coating of the ceramic surface is not completely solved but a better control of coating and firing may improve the results.

The performance of the Stupalith-cavity oscillator is not significantly better than the invar oscillator under the same conditions.

Stupalith is a fragile ceramic and cannot stand severe shock.
VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The results of eight-months observation of invar-cavity-controlled oscillators show a typical frequency-stability characteristic under temperature and voltage regulated conditions of about ± 10 ppm/week.

Principal factors contributing to frequency variation were found to be temperature, humidity, and tube aging. Other factors such as plate and heater voltage variation and series capacitor instability were influences of minor importance. Temperature drift caused a frequency change of about -2.0 ppm/°C. Humidity effects caused a frequency change of approximately -2.75 ppm/% RH. Oscillator tube deterioration was considered to cause the remainder of the frequency drift but the amount was not exactly determined. This deterioration factor did appear to cause drift in the direction of increasing frequency.

The invar-cavity oscillator demonstrated ability to withstand a reasonable amount of shock. A test on one oscillator unit indicated a deviation of no more than 8 to 10 kc from the initial frequency of 600 mc for each shock applied.

Operation at room temperature demonstrated a typical frequency-stability of invar-cavity oscillators of ± 10 ppm/day. A brass-cavity oscillator operating under similar conditions showed a stability of ± 4.6 ppm/hr.

The project was not completely successful in developing a method for measuring the short-term stability of UHF signal sources to the desired accuracy. The Equal-Arm discriminator system was capable of a maximum resolution of 5 parts in $10^8$. However, it satisfied the requirement as to response time. The complexity of the system and the set-up time required are

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disadvantages which may or may not be objectionable, depending upon the eventual application of the system. Improved resolution is believed to be possible but would require extensive modifications. It would be necessary that such modifications provide:

1. improved mechanical stability,
2. increased signal amplitude,
3. improved signal and i-f amplitude stability,
4. vernier control of adjustable components,
5. improved signal shielding, and
6. improved calibration techniques.

The beat-frequency method of short-term frequency-stability measurements is capable of the desired resolution and response time with minor modifications. A resolution of approximately one part in $10^9$ was obtained with the described equipment. The response time was less than one second but greater than the desirable value of 0.1 second. Thus, if the standard used with the system is assumed to have adequate short-term stability, the target requirements can be met. The accuracy, resolution, and response time are capable of improvement by:

1. using a standard of improved short-time stability, and
2. using a recorder capable of more rapid response.

This system could also be appreciably improved by frequency-multiplying the signals to be compared into the microwave region where comparison could be made on the basis of frequency rather than phase. In such an application it is conceivable that a frequency-counting technique might be employed in the place of chart type recording. For example, with the Berkeley Model 5570
Frequency Meter and a suitable microwave converter, a frequency measurement to an accuracy of one part in $10^9$ could be made in 0.2 second via multiplication of the frequency to be measured to 10,000 mc.

Temperature-insensitive cavities built with an invar outer conductor and Stupalith center conductor did not exhibit any improvement over a cavity constructed entirely of invar.

A cavity assembled by welding process, entirely of Stupalith parts, resulted in a temperature-frequency characteristic poorer than the invar-Stupalith combination, which possesses a characteristic of -2 ppm/°C.

A one-piece molded cavity of Stupalith (Type A-2417) can be constructed by the Stupakoff Company of Latrobe, Pennsylvania. Typical temperature-frequency characteristics of these cavities averages about 1.0 ppm/°C over a 70° range.

Performance of a Stupalith-cavity-controlled oscillator under room temperature conditions was not significantly better than the invar-cavity oscillator under the same conditions.

The problem of metal coating of the ceramic surface is not completely solved; however, a closer control of coating and firing may improve the results.

B. Recommendations

The results of observations of the long-term-frequency performance of cavity oscillators indicate that development in the following areas should provide improvement in performance:

1. development of an oven for cavity oscillators that possess better temperature stability characteristics, and

2. development of a reliable type 6AF4 vacuum tube for service in this type of oscillator.
Investigations of methods to measure very short-term frequency excursions of signal sources indicates work should continue along the following lines:

1. investigation of the microwave versions of the Equal-Arm discriminator system to measure short-term frequency variation of frequencies multiplied to the microwave region,

2. investigation of beat frequency techniques involving multiplication of reference and test frequencies to magnify frequency variations, and

3. development of phase-stable frequency multipliers for application in the preceding techniques.

The results of work in the development of temperature-insensitive cavities indicate further investigations in the following items would be productive:

1. fabrication of Stupalith cavities containing large filleted inside-corners to improve coating conditions in these areas,

2. refinement of coating and firing processes for metal coating of onepiece Stupalith cavities, and

3. fabrication of cavities from Stupalith samples varied slightly in mixture composition and/or processing to develop an assembled cavity possessing a true zero frequency-temperature characteristic.
IX. IDENTIFICATION OF KEY PERSONNEL

Dr. Donald W. Fraser devoted one-third time to the project from April to August, 1955. He was Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Doctor of Philosophy in Electrical Engineering from this institution. Dr. Fraser has been engaged in research and development at the Engineering Experiment Station for about four years. His other experience includes five years of electronic testing and research in the U. S. Navy.

Mr. Edward G. Holmes, who holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology, was director of this project from April to September, 1955. His experience in the electronic field includes five years of work with frequency-measuring apparatus and broadcasting equipment, two years as an electronics officer in the U. S. Navy and four years of research and development work with UHF and microwave equipment.

Mr. James E. Lane joined the project December 12, 1955 as a technical assistant on a half-time basis. Mr. Lane has previously been connected with the station as a technician on various other projects. He has had four years experience in military electronics maintenance and is a student in Industrial Management at Georgia Tech.

This project was under the direction of Mr. Robert E. Meek, research engineer, who assumed these duties September 1, 1955. He joined the project August 1, 1955, devoting full time to this work. Mr. Meek holds the degree of Bachelor of Science in Electrical Engineering from the University of Kentucky. He has previously been associated with the University of Kentucky and on several projects at this station since 1951.
Mr. James C. Sellers was employed half-time as an electronic technician on the project from April to December, 1955. His previous experience included eight years with the AEC at Oak Ridge, Tennessee, where he worked as a technician in the design, assembly and testing of electronic circuits for nuclear instrumentation.

Mr. Samuel N. Witt, Jr., research engineer, joined this project August 1, 1955 devoting half-time to the work. Mr. Witt, who holds the degree of Master of Science in Electrical Engineering from Georgia Tech, is pursuing studies toward a Doctor of Philosophy degree in that field. He served one year as an electronics instructor in the U. S. Navy and has been associated with the Tennessee Polytechnic Institute and with this station on several projects since 1951.

Respectfully submitted:

Robert E. Meek
Project Director

Samuel N. Witt, Jr.
Research Engineer

Approved:

J. E. Boyd, Chief
Physical Sciences Division

Paul K. Calaway, Director
Engineering Experiment Station
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XI. APPENDIX

A. Tabulation of Evaluated Data for Long-Term Frequency-Stability Measurements

**TABLE 11.1**

RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED OSCILLATOR

(Temperature and Voltage Regulated Conditions)

<table>
<thead>
<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
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(continued)
TABLE 11.1 (continued)

RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED OSCILLATOR

(Temperature and Voltage Regulated Conditions)

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<tr>
<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
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TABLE 11.1 (continued)
RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED OSCILLATOR
(Temperature and Voltage Regulated Conditions)

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<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
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TABLE 11.1 (continued)
RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED CONTROLLED (Temperature and Voltage Regulated Conditions)

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<th>Average Frequency of Run</th>
<th>Mean Rate of Frequency Change</th>
<th>Stability of Average Frequency</th>
<th>Normalized Mean Rate of Frequency Change</th>
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TABLE 11.1 (continued)
RESULTS OF TEST RUNS FOR MEASUREMENT OF
FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED OSCILLATOR
(Temperature and Voltage Regulated Conditions)

<table>
<thead>
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<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
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RESULTS OF TEST RUNS FOR MEASUREMENT OF FREQUENCY STABILITY OF INVAR-CAVITY-CONTROLLED OSCILLATOR
(Temperature and Voltage Regulated Conditions)

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<th>Duration of Run (hours)</th>
<th>Average Frequency of Run (mc)</th>
<th>Mean Rate of Frequency Change (c/hr)</th>
<th>Stability of Average Frequency (ppm/run)</th>
<th>Normalized Mean Rate of Frequency Change (ppm/hr)</th>
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<td>112 ± 8.8, - 7.7</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>94.0</td>
<td>599.999130 ±8.8 kc, -2.9 kc</td>
<td>70 ±14.2, - 4.8</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>600.001272 ±8.7 kc, -4.5 kc</td>
<td>44 ±14.5, - 7.5</td>
<td>0.073</td>
<td></td>
</tr>
</tbody>
</table>
B. The Reflection Properties of UHF Cavities

When operating as reflection elements, UHF cavities may be represented by the equivalent circuit shown in Figure 11.1. The driving-point admittance for this circuit is

\[ Y_c = n^2 \left( \frac{1}{R} + j\omega C + \frac{1}{j\omega L} \right) \]  \hspace{1cm} (11.1)

\[ = n^2 \left[ \frac{1}{R} + j(\omega C - \frac{1}{\omega L}) \right]. \]

If the resonant frequency is

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]  \hspace{1cm} (11.2)

giving

\[ \omega_0 C = \frac{1}{\omega_0 L} \]  \hspace{1cm} (11.3)

then, the frequency variable portion of equation 11.1 becomes

\[ \omega C - \frac{1}{\omega L} = \frac{\omega_0 \omega C}{\omega_0} - \frac{\omega_0}{\omega_0 \omega L} \]  \hspace{1cm} (11.4)
Therefore, equation 11.1 becomes

\[
Y_c = \frac{n^2}{R} \left[ 1 + j \frac{2R}{\omega_0 L} \left( \frac{\omega - \omega_0}{\omega_0} \right) \right]
\]

(11.5)

where \( Q_0 \) is the conventional quality factor for a parallel resonant circuit.

To simplify the notation in equation 11.5, let

\[
a = 2Q_0 \left( \frac{\omega - \omega_0}{\omega_0} \right).
\]

Also, let \( \alpha \) be the ratio between the admittance of the transmission line to which the cavity is connected and the admittance of the cavity at resonance; that is, let
\[ \alpha = \frac{Y_o}{n^2/R} \]

Then, equation 11.5 becomes

\[ Y_c = \frac{Y_o}{\alpha} (1 + ja). \]  \hspace{1cm} (11.6)

The reflection coefficient of the cavity connected to a transmission line with a characteristic admittance, \( Y_o \), is

\[ r = \frac{Y_o - Y_c}{Y_o + Y_c} \frac{[1 - (1 + ja)/\alpha]}{[1 + 0.5 (1 + ja)]} \]  \hspace{1cm} (11.7)

\[ = \frac{\alpha - 1 - ja}{\alpha + 1 + ja} = |r| \frac{\theta}{\theta}. \]

The real part of the reflection coefficient is

\[ |r| \cos \theta = \frac{\alpha^2 - 1 - \frac{a^2}{\alpha + 1}}{\alpha + 1}^2 + a^2 \]  \hspace{1cm} (11.8)

The imaginary part is

\[ |r| \sin \theta = \frac{-2a\alpha}{\alpha + 1} \]  \hspace{1cm} (11.9)

At resonance, \( a \) is zero and thus the real part of the reflection coefficient is determined by \( \alpha \). If \( \alpha \) is unity, no reflection occurs. The imaginary part of the reflection coefficient is zero at resonance regardless of the value of \( \alpha \).
The variation of the reflection coefficient with frequency near resonance is of interest. Solving for the derivative of the real part of the reflection coefficient of $a$ equal to zero yields

$$\left[\frac{d}{dw} |r| \cos \theta \right]_{a=0} = \left[\frac{d}{dw} \frac{\alpha^2 - 1 - a^2}{(\alpha + 1)^2 + a^2} \right]_{a=0}$$

$$= \left\{ (\alpha^2 - 1 - a^2) (-1) \left[ (\alpha + 1)^2 a^2 \right]^{-2} \right\}$$

$$+ \left[ (\alpha + 1)^2 + a^2 \right]^{-1} (2a) \left( \frac{2Q_o}{w_o} \right)$$

$$= 0.$$

Thus, the real part of the reflection coefficient is not changing at resonance. Similarly, for the imaginary part of the reflection coefficient

$$\left[\frac{d}{dw} |r| \sin \theta \right]_{a=0} = \left[\frac{d}{dw} \frac{-2a\alpha}{(\alpha + 1)^2 + a^2} \right]_{a=0}$$

$$= \left\{ -2a\alpha (-1) \left[ (\alpha + 1)^2 + a^2 \right]^{-2} \right\}$$

$$- 2\alpha \left[ (\alpha + 1)^2 + a^2 \right]^{-1} \left( \frac{2Q_o}{w_o} \right)$$

$$= \frac{-4Q_o}{w_o (\alpha + 1)^2}.$$

Thus, the rate of change of the imaginary part of the reflection coefficient with frequency at resonance is a function of $\alpha$. This rate of change may be
maximized by differentiating equation 11.11 with respect to $\alpha$ and equating the result to zero. Thus,

$$\frac{d}{d\alpha} \frac{\alpha}{(\alpha + 1)^2} = -\frac{2\alpha}{(\alpha + 1)^3} + \frac{1}{(\alpha + 1)^2} = 0. \quad (11.12)$$

The solution to equation 11.12 is $\alpha$ equal to unity. This shows that the rate of change of the reflection coefficient at resonance is a maximum when the cavity is matched to its transmission line.

C. Theoretical Evaluation of the Equal-Arm Pound I-F Discriminator System

It is desirable to evaluate the voltage arriving at the mixer crystal of the Pound Equal-Arm I-F Discriminator System. With an input voltage, $E \cos \omega_0 t$, from a source under test, voltage components arrive at the mixer through two paths, the first containing the modulator and the second containing the reference cavity, as shown in Figure 11.2.

![Figure 11.2. Voltage Distribution in the Coaxial-Ring Transformer.](image)
The voltage arriving at the modulator crystal from the source is

\[ \frac{E}{\sqrt{2}} \cos (\omega_0 t + \alpha_1). \]

At the modulator crystal this voltage is modulated by an i-f voltage at a frequency \( \omega_b \). The output of the modulator is

\[ E_M = \frac{E}{\sqrt{2}} (1 + M \cos \omega_b t) \cos (\omega_0 t + \alpha_1). \]  \hspace{1cm} (11.13)

By proper termination at the modulator, the carrier component in equation 11.13 is eliminated. Also, only one-half of the energy represented by the side-band components in equation 11.13 arrives at the mixer crystal. Thus, the voltage arriving at the mixer crystal is

\[ \frac{E}{2} M \cos \omega_b t \cos (\omega_0 t + \alpha_2). \]

The angle \( \alpha_2 \) results from the path length between the source terminal and the mixer crystal.

The voltage arriving at the reference cavity from the source is

\[ \frac{E}{\sqrt{2}} \cos (\omega_0 t + \beta_1). \]

This voltage is reflected from the reference cavity as determined by the reflection coefficient as was previously derived. The portion of the reflected energy arriving at the mixer crystal is only one-half of that reflected. Thus the voltage arriving at the mixer crystal from the reference cavity is
\[ E = \frac{|r|}{\theta} \cos \left( \omega_0 t + \beta_2 \right). \]

The angle \( \beta_2 \) results from the path length between the source and the mixer crystal.

No voltage arrives at the mixer crystal directly from the source because of the path lengths. It may be observed that the direct path length is \( \lambda/2 \) through the short side of the ring and \( \lambda \) through the long side. Thus, cancellation at the mixer occurs.

The total voltage arriving at the mixer is, therefore,

\[ E_t / \phi = \frac{E M}{2} \cos \omega_s t \cos \left( \omega_0 t + \alpha_2 \right) + \frac{E |r| / \theta}{2} \cos \left( \omega_0 t + \beta_2 \right). \] (11.14)

If the reference cavity and modulator transmission lines are so chosen that \( \alpha_2 \) and \( \beta_2 \) differ by 90\(^\circ\), the resultant mixer voltage will be as shown in Figure 11.3. To recover the i-f voltage, \( E_t / \phi \) may be demodulated by a variety of techniques.

![Figure 11.3. Voltages Arriving at the Mixer Crystal.](image)
of devices which have square-law, envelope or other detection characteristics. If a simple crystal diode is used, envelope detection will result. The envelope of the resultant sum is merely the magnitude, \( E_t \), which is

\[
E_t = \left[ \left( \frac{EM \cos \omega_s t}{2} + \frac{E|r| \sin \theta}{2} \right)^2 + \left( \frac{E|r|}{2} \cos \theta \right)^2 \right]^{\frac{1}{2}} \quad (11-15)
\]

It is now necessary to determine the component of equation 11.15 at the frequency, \( \omega_s \). This can be more readily accomplished by first considering the relative magnitudes of the terms in equation 11.15 at resonance. At resonance, \( |r| \) is zero if the cavity is matched to its transmission line. Thus, near resonance

\[
\left( \frac{E|r| \cos \theta}{2} \right)^2 \ll \left( \frac{EM \cos \omega_s t}{2} + \frac{E|r| \sin \theta}{2} \right)^2 \quad (11.16)
\]

and \( E_t \) may be approximated as

\[
E_t \approx \frac{EM}{2} \cos \omega_s t + \frac{E|r|}{2} \sin \theta . \quad (11.17)
\]

Reinserting the carrier frequency, \( \omega_0 \), gives

\[
E_t \approx \left\{ \frac{EM}{4} \left[ \cos(\omega_0 + \omega_s) + \cos(\omega_0 - \omega_s) \right] + \frac{E|r|}{2} \sin \theta \cos \omega_0 t \right\} . \quad (11.18)
\]

A Fourier analysis of equation 11.18 yields a component of voltage at the i-f frequency given by
Near resonance and for a large modulation index

\[
\frac{|r| \sin \theta}{M} \ll 1 \quad (11.20)
\]

and thus,

\[
\sin^{-1} \frac{|r| \sin \theta}{M} \approx \frac{|r| \sin \theta}{M} \quad (11.21)
\]

Therefore, equation 11.19 becomes

\[
E_s \approx \frac{1}{\pi} \left( E |r| \sin \theta + E |r| \sin \theta \right) = \frac{2E |r|}{\pi} \sin \theta. \quad (11.22)
\]

where the frequency term, \( \cos \omega_s t \), has been omitted. If envelope detection of this i-f voltage with 100 per cent efficiency is assumed, equation 11.22 will also represent the D-C output voltage.

With either the mixer or the i-f detector, increased output voltage can be obtained by matching the impedance of the source to that of the mixer or detector. In general, however, the improvement is small in the UHF and i-f frequency ranges. Therefore, it will be assumed that impedance matching is not used.

The term \( |r| \sin \theta \) in equation 11.22 will be recognized as the imaginary part of the reflection coefficient of the reference cavity. This was evaluated in equation 11.9 as

\[
|r| \sin \theta = \frac{-2 \alpha \alpha}{(\alpha + 1)^2 + \alpha^2}. \quad (11.23)
\]
It was shown in equation 11.12 that at resonance \( (\alpha = 0) \) this quantity is maximum when \( \alpha \) is unity. For \( \alpha = 1 \), the i-f voltage from equation 11.22 becomes

\[
E_s = \frac{2E}{\pi} \frac{2a}{a^2 + 4}
\]

(11.24)

where the negative sign has been omitted since the interest is only in the magnitude.

Since

\[
a = 2Q_0 \left( \frac{\omega - \omega_0}{\omega_0} \right),
\]

(11.25)

the variations in the i-f voltage of equation 11.24 may be evaluated as a function of frequency from

\[
\frac{dE_s}{df} = \frac{d}{df} \left( \frac{2E}{\pi} \frac{a}{a^2 + 4} \right)
\]

(11.26)

\[
= \frac{4E}{\pi} \left[ a \left( a^2 + 4 \right)^{-2} \frac{d}{df} \frac{da}{df} \right]
\]

\[
+ \left( a^2 + 4 \right)^{-1} \frac{d}{df} \frac{d}{df} \left( a^2 + 4 \right)
\]

\[
= \frac{4E}{\pi} \left[ \frac{2a^2}{(a^2 + 4)^2} + \frac{1}{a^2 + 4} \right] \frac{da}{df}
\]

\[
= \frac{4E}{\pi} \left[ \frac{2a^2}{(a^2 + 4)^2} + \frac{1}{a^2 + 4} \right] \frac{2Q_0}{f_0}
\]

At resonance \( (\alpha = 0) \),

\[
\frac{dE_s}{df} = \frac{2EQ_0}{\pi f_0}
\]

(11.27)
Equation 11.27 gives the maximum slope of the discriminator characteristic (which occurs at resonance, i.e., for $a = 0$) with the assumption that the reference cavity is perfectly matched to its transmission line ($\alpha = 1$). For mismatched conditions, equation 11.23 must be substituted into equation 11.22 and the derivative re-evaluated.

D. Determination of the Rate of Short-Term Frequency Variation from Strip-Chart Recordings

It is desired to determine the rate of frequency change from a recording of a voltage expressed mathematically as

$$e(t) = E \cos 2\pi (gt + \alpha). \quad (11.28)$$

In equation $11.28$ $g$ is an arbitrary function of time and is not the frequency. The frequency may be determined by using the definition that frequency is the time-rate-of-change of phase. When $g(t)$ is a linear function of time, that is, when

$$g(t) = kt, \quad (11.29)$$

the phase may be expressed as

$$\theta = 2\pi (kt^2 + \alpha). \quad (11.30)$$

The frequency may then be found from

$$2\pi f = \frac{d\theta}{dt} = \frac{d}{dt} [2\pi (kt^2 + \alpha)] \quad (11.31)$$

giving

$$f = 2kt. \quad (11.32)$$
The rate of change of frequency with respect to time is

\[ \frac{df}{dt} = \frac{d}{dt} 2kt = 2k. \]  \hspace{1cm} (11.33)

It will be assumed that the frequency-vs-time curve may be approximated by straight line segments. Thus a particular value of \( k \) must exist for each of the segments. Let

\[ 2k_r \]  \hspace{1cm} \text{the rate of frequency change during the } r^{th} \text{ straight line segment}

and

\[ n_1 \]  \hspace{1cm} \text{an integer representing the number of half-cycles from the first point of zero voltage after a point of zero frequency to another point where the voltage is zero. It is assumed that this second zero voltage point will lie in the first straight line segment.}

Thus, \( n_1 \) is related to the zeros of equation 11.28. The zeros of this equation may be found by setting

\[ E \cos 2\pi(gt + \alpha) = 0 \]  \hspace{1cm} (11.34)

or

\[ 2\pi(gt_1 + \alpha) = 2\pi(0.25 + 0.5n_1) \]  \hspace{1cm} (11.35)

where \( t_1 \) is the time to the \((n + 1)\)th zero voltage crossing.

Solving for \( g(t) \) gives

\[ g(t) = \frac{0.25 + 0.5n_1 - \alpha}{t_1} = k_1 t_1. \]  \hspace{1cm} (11.36)

The term \( k_1 \) is appropriate since, from the definition of \( n_1 \), the initial frequency is assumed to be zero. Thus,
From the recordings it is difficult to determine the exact point of zero frequency. The angle, $\alpha$, is also difficult to evaluate. In addition, it is often desirable to obtain information from sections of the recording outside of the first reasonable straight line frequency-vs-time segment. Since the rate of frequency change, $2k_1$, must be constant within the straight line frequency-vs-time segment, any number of half-cycles, $n$, may be substituted into equation 11.37 provided the corresponding time, $t_n$, is also substituted. Thus,

$$k_1 = \frac{0.25 + 0.5n_1 - \alpha}{t_1^2} = \frac{0.25 + 0.5n_2 + \alpha}{t_2^2} = \ldots$$  \hspace{1cm} (11.38)$$

where $n_1$, $n_2$, $t_1$ and $t_2$ all belong to the first straight line segment for which $k_1$ is to be evaluated. Since the zero frequency crossings cannot be accurately located, it is desirable that $k_1$ be evaluated from differential time measurements. For example, the time $(t_2 - t_1)$ for $(n_2 - n_1)$ half-cycles may be readily measured as may the time $(t_3 - t_2)$ for $(n_3 - n_2)$ half-cycles.

Equation 11.38 may be rewritten as

$$k_1 t_1^2 = 0.25 + 0.5n_1 + \alpha$$  \hspace{1cm} (11.39)$$

and

$$k_1 t_2^2 = 0.25 + 0.5n_2 + \alpha$$  \hspace{1cm} (11.40)$$

and so forth for other values of $n$ and $t$. 

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Subtracting 11.39 from 11.40 yields
\[ k_1(t_2^2 - t_1^2) = 0.5 (n_2 - n_1). \] (11.41)

Similarly,
\[ k_1(t_3^2 - t_2^2) = 0.5 (n_3 - n_2). \] (11.42)

If the number of half-cycles considered are equal for equations 11.41 and 11.42, these equations may be combined to give
\[ t_2^2 - t_1^2 = t_3^2 - t_2^2 \] (11.43)
or
\[ (t_2 - t_1)(t_2 + t_1) = (t_3 - t_2)(t_3 + t_2). \] (11.44)

The right side of 11.44 may be rewritten as
\[ (t_3 - t_2)(t_3 + t_2) = (t_3 - t_2)[(t_2 + t_1) + (t_3 - t_2) + (t_2 - t_1)]. \] (11.45)

Substituting 11.45 into 11.44 and rearranging gives
\[ (t_2 + t_1)[(t_2 - t_1) - (t_3 - t_2)] = (t_3 - t_2)[(t_3 - t_2) + (t_2 - t_1)]. \] (11.46)

Solving for \((t_2 + t_1)\) gives
\[ (t_2 + t_1) = \frac{(t_3 - t_2)[(t_3 - t_2) + (t_2 - t_1)]}{(t_2 - t_1) - (t_3 - t_2)}. \] (11.47)

The right side of equation 11.47 involves only differences in time which may be readily measured from the recording without reference to the zero frequency point. Substituting 11.47 in 11.41 gives
where \( a \) is the number of half-cycles over which the time difference was measured.

Equation 11.48 may be simplified by letting \( b = (t_2 - t_1) \) = the time for any group of half-cycles and \( c = (t_3 - t_2) \) = the time for the next equal group of half-cycles. Then equation 11.48 becomes

\[
\frac{k_1}{0.5a} = \frac{0.5a}{(t_2 - t_1)} = \frac{(t_3 - t_2)}{(t_2 - t_1)} \frac{[(t_3 - t_2) + (t_2 - t_1)]}{(t_3 - t_2)} \frac{(t_2 - t_1)}{(t_3 - t_2)}
\]

Equation 11.49 does not involve the zero frequency crossover point in any way. Thus, this same equation may be applied to any other straight line segment under the assumption that if the frequency had continued to vary at the same rate it would have passed through zero frequency as some positive or negative value of time.

Thus, to determine the rate of change in frequency at any point on the recording it is only necessary to measure the time, \( b \), for some integral number, \( a \), of half-cycles and then measure the time, \( c \), for the next equal number, \( a \), of half-cycles. These numbers are substituted into equation 11.49 and \( k \) is obtained in cps per second. It must be remembered that the rate of change in frequency is two times the value of \( k \) or

\[
\frac{df}{dt} = \frac{a(b - c)}{(b \cdot c) (b + c)}
\]
The direction of change in frequency of the test oscillator is arbitrary, depending upon the sign of $g$ in the original equation for the test oscillator voltage. To obtain the instability figure for the test oscillator, $2k$ may be normalized by dividing by $f_0$ (mathematically, $f_0 \pm 2g$ must be used but $2g$ is insignificant compared to $f_0$). It should again be stated that this result is accurate only if the frequency variation is linear with time over the range for which $k$ is to be evaluated. The actual frequency variation may be calculated more accurately by a more complicated mathematical procedure but it is believed that this is not warranted because of the limited resolution of the recorded charts.