Measuring Time and Frequency in Hawaii

Long range determination of standard frequency transmission characteristics continued despite propagation vagaries due to distance and ionospheric variation

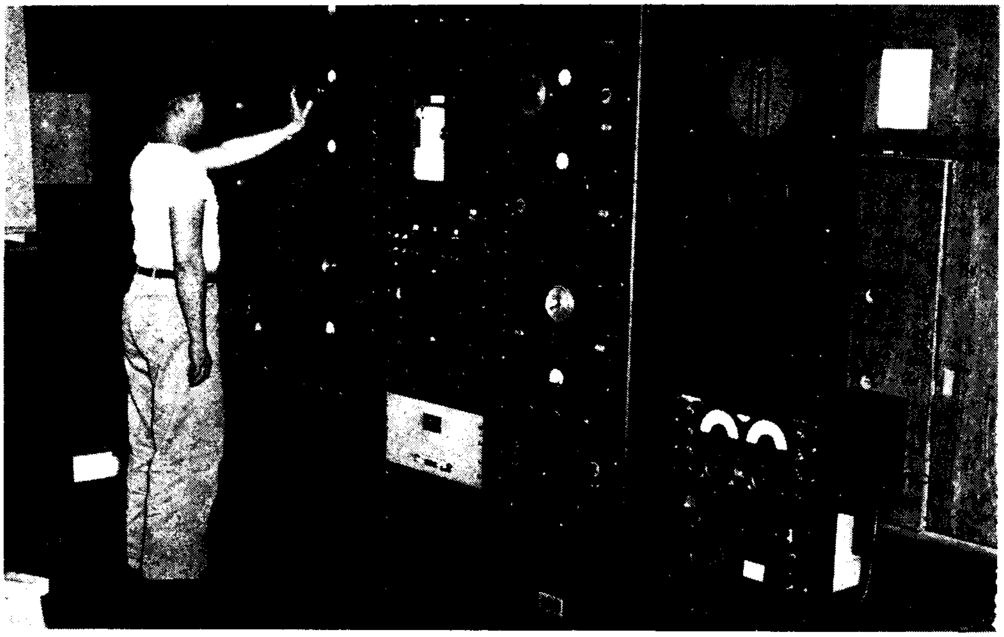

Fig. 1: View of measuring equipment at WWVH, Mauri, T.H. Shown are standard oscillators consisting of crystal-controlled bridge type oscillators, buffer amplifier, and two amplifier output stages. Temperature is controlled by mercury-glass thermostats and inner bridge type heaters. Batteries are used to power this equipment

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STANDARD frequency radio station WWVH (located at Maui, T. H.) has been in experimental operation since November 1948. The installation is very similar to that at WWV.[1] Its frequency and time determining equipment consist of three independent standard oscillators which are operated continuously from batteries. Each of these standards is essentially the same, consisting of a quartz crystal-controlled, bridge-type oscillator, a buffer amplifier and two output amplifier stages. The temperature control consists of an inner bridge-type heater, and an outer heater controlled by a mercury-glass thermostat working through an electron tube and a relay to control the heat. A photograph of this apparatus is shown in Fig. 1.

Two separate frequency dividers and clocks may be controlled by either of the three frequency standards. These dividers are of the regenerative-modulator type[2] and divide from 100 KC to decimal submultiples and 60 cycles. The 60-cycle output operates a synchronous motor clock from which cam-operated contacts and electronic circuits generate seconds pulses; these pulses are used for frequency and time determinations and are also used in generating or marking other accurate intervals of time: 1 minute, 4 minutes, 5 minutes, etc. Each of the standards is periodically adjusted to compensate for normal drift and to keep its frequency very close to that of WWV.

Synchronizing Radio Stations (3, 4)

If two or more stations are operated on the same nominal frequency, a primary requirement is extremely close agreement between the frequencies as broadcast. If the stations are within a reasonable distance of one another this agreement may be maintained by a transmission line over which a frequency may be sent to each station. This line frequency may be used to control the transmitted frequencies or to adjust local frequency standards to agreement. Any phase shifts which occur in the line or its associated apparatus would cause frequency variations at the transmitter. Poor signal to noise ratios on the line would cause noise on the transmitter output. If the stations are located some thousands of miles apart a wire line for synchronization may be impractical economically.

Quartz-crystal oscillators might be periodically calibrated and sent to the operating stations for frequency control. Such standards would vary in frequency between the time of calibration and the time of installation mostly because of vibration and changes in temperature during transportation. However, frequency deviations could be maintained less than 1 part in 10^7 with presently-available quartz-crystal units.

It is possible to link the stations by a system of radio relay stations. The overall installation cost of this type of control might be less than that of transmission lines but its reliability and maintenance requirements are not sufficiently well known.

Another method, presently in use and described in this paper, is to make relative measurements of the frequency and time of the different stations. Data so obtained are processed in an approved manner and a value of frequency is immediately determined for each station. The oscillators at all stations are then adjusted for more precise agreement of the frequencies broadcast.

The frequency and time standards at WWVH are checked once every twelve hours with reference to the

Reprinted from TELE-TECH • March, 1951

received signals from WWV, at 0900 to 0940 and 2100 to 2140 HST (1400 to 1440 and 0200 to 0240 EST) when the path for the received signal is expected to be most stable.

At present the monitoring is done in the WWVH transmitter building. This requires that the transmitters be off for the 40-minute measuring period. A radio receiver connected to a rhombic or Yagi antenna, oriented on WWV, is used. The 100-kc frequency from a local standard oscillator is fed to a frequency multiplier or harmonic generator. Output from this generator, along with the WWV energy from the receiving antenna, is fed to the radio receiver. This gives the desired difference frequency in the receiver's output.

Direct Frequency Measurement

As is well known, energy radiated by a transmitter is propagated to a distant receiver by reflection from one or more of the principal ionospheric layers, or by multiple reflections between these layers and the ground. As long as radio conditions are constant, a fixed receiver will receive the same frequency as radiated from the transmitter. However, when the layers are moving up or down the frequency of the signal at the receiver will decrease or increase, respectively, and will, therefore, depart from the transmitted frequency. The degree of this departure increases with the speed of the motion, in accordance with the familiar doppler effect. The variations in height of the reflecting layers are a function of time of day, time of year, geographical location and sunspot activity. Although on the average the conditions are such that the constancy of the path-length may be predicted, however, at a particular time the actual conditions may be far from the average. The height of the ionosphere layers is relatively stable over the Washington-Maui path when noon or midnight occurs at a point half way between the transmitter and receiver.[5, 6]

As an illustration of the possible magnitude of such an effect let us assume that a principal reflecting layer (F_2 layer) is the one from which the reflections take place between Washington and Maui (4800 miles great circle distance), and that the height of this layer changes from 200 to 230 miles in one hour. For a three-hop transmission, i.e., three reflections from the ionosphere and two from the earth, the received signal would be approximately three parts in 10^8 lower in frequency, perhaps, per hop, than the transmitted one. For the total distance the effect might be expected to be less than three times this amount as the changes in layer height might be less on two of the three hops.

For direct frequency measurements the radio receiver should be fed approximately equal energy from the local standard harmonic generator and the WWV antenna. When reception is good the difference frequency is indicated as a variation in the S-meter reading on the receiver. During interference and fad-

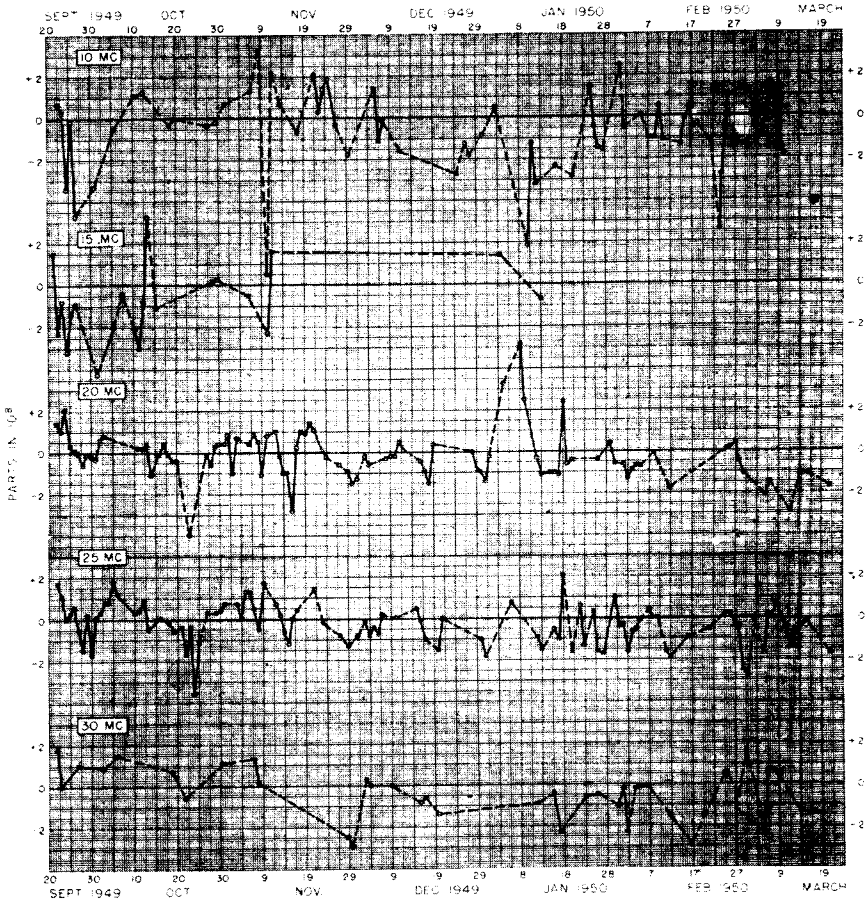
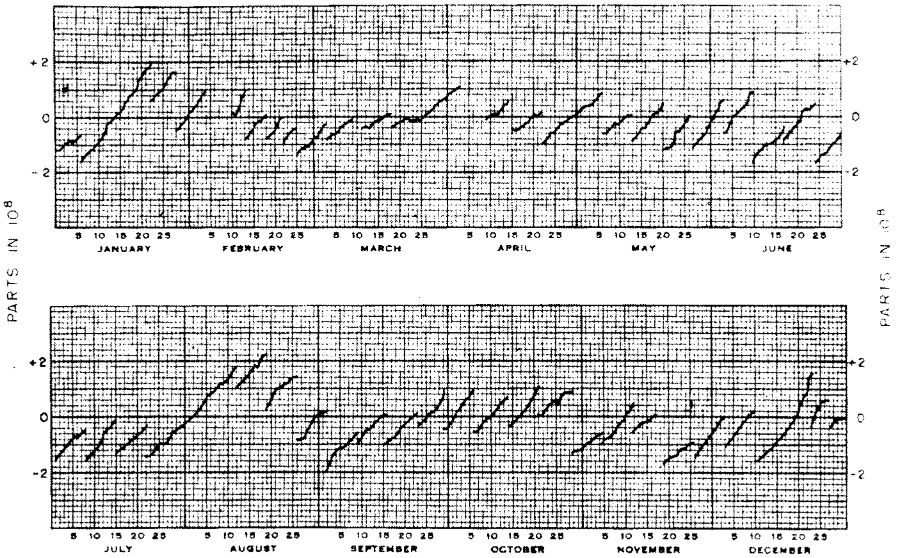


Fig. 2: Daily frequency deviation recordings of WWV, made at WWVH, Maui, T.H., note superiority of higher frequency transmissions which produced more consistent results

Fig. 3: Graphs of daily frequency errors compared with WWV broadcast by WWVH; discontinuities in trace indicate frequency deviation correction to local generator



ing, listening to the beats helps in choosing the desired beat from any undesired ones. The number of beats and corresponding time in seconds is determined, using a stop watch, for a period long enough to give the desired accuracy. This measurement should be made two or three times to check the timing. When fading is severe, more measurements over shorter intervals should be made. Individual cycles may be added or suppressed by fading. These should be ignored and the count continued at the same rate during a measurement. Recording of beats is preferable as it permits more precise analysis of results when the receiving conditions are good.[7]

Experience at Maui has shown a considerable difficulty in determining the frequency difference when it was small. This was caused by variations in received signal strength (fading). Therefore, during a measurement, the frequency of the spare standard was purposely adjusted low in frequency by about one part in 10^7. It then could be most readily determined in terms of WWV. The difference in frequency between the local main, spare and standby standards was then obtained using the beat method. Thus the difference between WWV and WWVH frequencies was determined.

A typical example of a measurement at Maui is as follows: assume that the beat difference, at 20 MC, between WWV and the spare standard "S" (which is known to have a frequency less than 100 KC) is 34 beats in 100 seconds. The frequency difference would be the number of beats per second, 0.34. Therefore standard "S" has a frequency difference in terms of WWV of —17 parts in 10^9. Let us assume that the counted beat for the standard "M" (controlling WWVH) in terms of standard "S", at 10 MC, is 16 beats in 100 seconds. This frequency difference is +0.16 cycles per second or +16 parts in 10^9. Adding these two values algebraically we find the error of WWVH in terms of WWV is —1 x 10^9.

In Fig. 2 are shown frequency measurements made in this way on consecutive days. A number of measurements were omitted because of interfering stations, rapid fading, or very weak signals from WWV. It may be noted that higher frequencies gave much more consistent values than 10 MC and 15 MC; 2.5 MC and 5 MC were not received. The agreement between consistent data is of the order of ±2 parts in 10^8 with a few values in error by as much as 1 part in 10^7.

Another method of frequency determination, based entirely on the rate of the clock at WWVH, gives high precision data for measuring periods of one day or greater in spite of the various difficulties. The value of frequency so obtained is an average. But as the oscillator drift and change in drift are quite small and predictable, average frequency during a period will be the same as the instantaneous value for the middle of that period.

A cathode-ray oscilloscope is used in comparing the local seconds pulses with those received from WWV. The linear sweep circuit is controlled at 60 cycles per second from the frequency dividers which provide the seconds pulses and other frequencies to the local transmitters. The local seconds pulses are connected to the vertical deflection and the oscilloscope is adjusted so that they start at a reference line marked on the screen. Then the local seconds pulses are replaced by those from WWV fed from the radio receiver through a filter to eliminate the unwanted modulation. These pulses, as received, may be multiple during the first 0.2 second of each second. This may be caused by paths of different lengths including round-the-world signals. The 1000-cycle phase-shifter of the local standard is adjusted until the earliest seconds pulse from WWV also starts at the reference mark. (This adjustment of the phase-shifter does not change the phase relationship between the local 60-cycle frequency and the local seconds pulses, both of which are obtained by dividing the 1000-cycle frequency *after* passing through the phase shifter.)

The time of arrival of the seconds pulses from WWV will occasionally vary up to 5 milliseconds, indicating a variation of path-length between Washington and Maui up to 1000 miles. The earliest pulse to arrive is considered the one which followed the shortest path. Computation for 3-hop transmission shows that the shortest path between WWV and WWVH, 4800 miles on the surface, would cause a delay of 0.027 second. At the setting of the phase-shifter for agreement with the received signal the local clock is set 0.027 second slow with respect to WWV. For broadcast purposes the phase-shifter is then advanced 0.027 second from the setting at which it agreed with the received signal from WWV to synchronize the seconds pulses as transmitted from the two stations. (The phase-shifter dial is graduated in 0.01 millisecond divisions.)

The average frequency error in terms of WWV is determined by dividing the change in the phase-shifter setting for synchronizing with WWV by the number of seconds in the period during which the change took place. The basic period for the computation of the frequency at station WWVH is six days for the daytime and five days for the nighttime determinations, the value so computed being the frequency error for the middle day of the period. Such a computation is based on the time at WWV being correct. For example: suppose that on the morning of November 4 the phase-shifter setting was 0.346 second and on November 10 it was 0.343 second. The change in setting is +0.003 second in 6 days. The average frequency error then is equivalent to an error of +0.00058 CPS and the frequency is 100,000.00058 CPS which is the frequency for November 7. An extrapolation of the plot of these frequencies will indicate when the local standard should be adjusted to maintain the agreement with WWV.

At times it becomes necessary to adjust the frequency of the standard oscillator controlling the frequency at station WWV to compensate for normal drift. Extrapolation of the frequency curve for this standard indicates when such adjustment should be made and a radiogram is sent to the Maui station two days before the adjustment to state the date and magnitude of such adjustment to be made simultaneously at both stations. Such adjustments, ordinarily made once a week, are of the order of —1 part in 10^8.

The main and standby frequency standards at WWVH have been in continuous operation since October 1948 and the spare only since August 1949. Occasionally short interruptions have occurred since then. At present the drift of the main and standby standards is less than +2 parts in 10^9 per day. As the length of operation increases, the drift will become less.

Since November 23, 1948, the operation of station WWVH has been continuous except for scheduled interruptions and occasional power failures. Figure 3 shows a graph of the daily error of the frequencies broadcast by WWVH in terms of

WWV. Adjustments of frequencies are indicated by the discontinuities of the curve. The agreement of WWVH is better than ±2 parts in 10^8 at all times. Most of the time the agreement is better than ±1 part in 10^8. The time as broadcast by WWVH has agreed with that from WWV within ±2 milliseconds.

The agreement between the 6-day periods for daytime measurements and the corresponding 5-day periods for night values is ±1 part in 10^9 or better. This difference in many instances is caused by the rounding off in the computation. As a check the data are also computed for the 2-day daytime and 3-day night values. Any error in determining the time-agreement values caused by personal error or change in the height of the ionospheric layer would be expected to cause more variation in the value for the shorter periods. However, the disagreement between the value of frequency for a particular day based on a 2 or 3-day period and that for the 6-day period has been 0 to ±3 parts in 10^9, the majority of disagreements being 0 or ±1 part in 10^9.

Since the service was started from Maui the frequency and time as broadcast were maintained in agreement with those broadcast from radio station WWV. As may be seen in figure 3, the agreement in 1949 was better than ±2 parts in 10^8; it was better than 1 part in 10^8 86% of the time. The agreement in time has been within ±2 milliseconds at all times. With best performance of the present-day quartz-crystal oscillators, there should be little difficulty in maintaining widely separated radio stations in frequency agreement to a few parts in 10^9.

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