HEWLETT-PACKARD
JOURNAL
TECHNICAL INFORMATION FROM THE -hp- LABORATORIES

Vol. 11 No. 3-4

PUBLISHED BY THE HEWLETT-PACKARD COMPANY, 275 PAGE MILL ROAD, PALO ALTO, CALIFORNIA

NOV.-DEC., 1959

A New Clock for Improving the Accuracy of Local Frequency and Time Standards

In line with the continually advancing maturity of the electronics field as a whole, the portion of the field concerned with frequency control has made significant forward strides in recent years. As a result, high-precision frequency standards employing quartz resonators presently achieve stabilities of a part in 10^9 per day or better, while atomic standards exhibit accuracies of one or two parts in 10^{10}.

In order to operate a frequency standard at or near presently attainable accuracies, it is necessary to minimize the error that may occur in comparing the standard with the primary signal against which the standard will be calibrated. In precision work such comparison error should be minimized, not only so that the uncertainty in the standard will be reduced, but also so that the drift characteristic that all quartz standards exhibit to a greater or lesser degree can be determined and monitored with maximum accuracy. As an indication of the degree to which it may be desirable to reduce comparison error, it should be noted that the accuracy of WWV carrier and time signals is currently 2 parts in 10^{10}.

COMPARISON CONSIDERATIONS

When calibrating a local standard against the transmissions from a standard radio station such as WWV or WWVH, the necessary comparison can be made by either of two basic methods. The more widely used but less precise method is the direct frequency comparison in which the local standard frequency (or its harmonic) is directly compared with the carrier frequency of the received standard transmission (or its harmonic). In this method the maximum accuracy achievable is determined by the uncertainty that variations in the transmission medium introduce into the transmission. For the usual case of sky-path transmission, the frequency, as received, can be different from that transmitted by up to several parts in 10^7 because of ionosphere movement and other effects. Although special techniques such

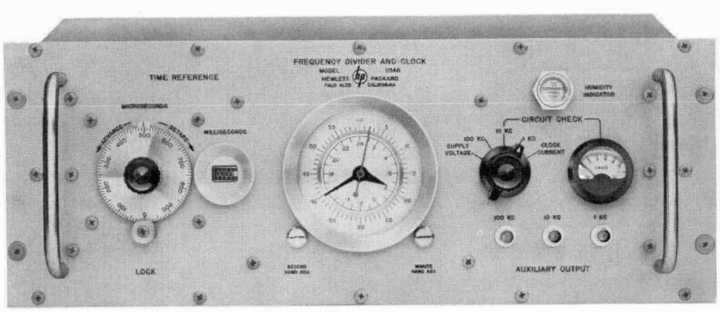

Fig. 1. New -hp- *Model 113AR Frequency Divider and Clock simplifies intercomparison of local frequency standards with national standards via broadcast time signals and increases resolution with which such comparisons can be made. Use of instrument with suitable local frequency standard also permits time to be kept on a local basis to within a millisecond. Instrument is fully transistorized and designed with fail-safe provisions.*

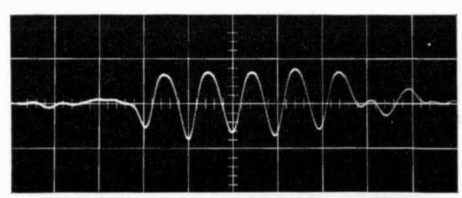

Fig. 2. *Oscillogram of WWV seconds pulse ("tick") as obtained using new Clock in typical set-up. Sweep time is 1 millisecond/-cm, indicative of high resolution of time comparison that Clock permits.*

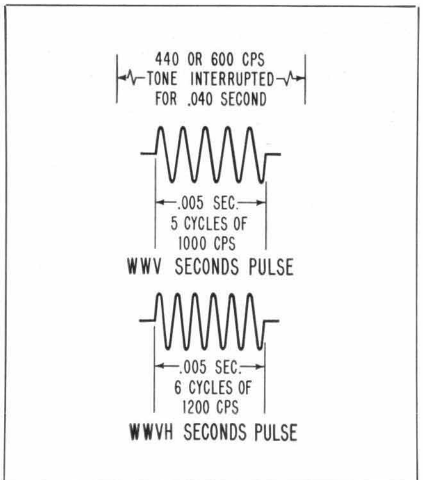

Fig. 3. *Detail of seconds pulses transmitted by WWV and WWVH.*

as determining the median of many readings can reduce this uncertainty to parts in 10^8, a different approach is necessary if the comparison is to achieve the higher accuracy required for operating a precision frequency standard of modern performance levels or if precision time checks are to be made.

TIME SIGNAL COMPARISONS

A second method for making comparisons is based on the time signals ("ticks") transmitted at precise one-second intervals by most standard stations including WWV and WWVH[1] (Fig. 3). In this method a measurement is made of the time variations that occur over an interval of one or more days between a time signal derived from the local standard oscillator and the time signal as received from the standard station. Although propagation effects of the type mentioned above also influence the transmission of these time signals, the comparison error is small because of the length of the interval over which transmission time variation is integrated or averaged. It is known, for example, that the signals arrive at a receiving point consistently within a fraction of a millisecond, even over transmission lengths of several thousand miles of surface distance.[2] Considering that there are some 10^8 milliseconds in a 24-hour day, two time-signal comparisons made a day apart thus normally result in a frequency comparison having an accuracy of $1/10^8$ or better, while time comparisons made over several days can yield comparison accuracies of a few parts in 10^{10} or better.

Besides the potential for better accuracy in comparisons, the time comparison method has a second advantage which is of considerable importance for certain fields. This is that the method provides true time accurately within a tolerance of a millisecond or better, thus permitting a local time standard to be maintained.

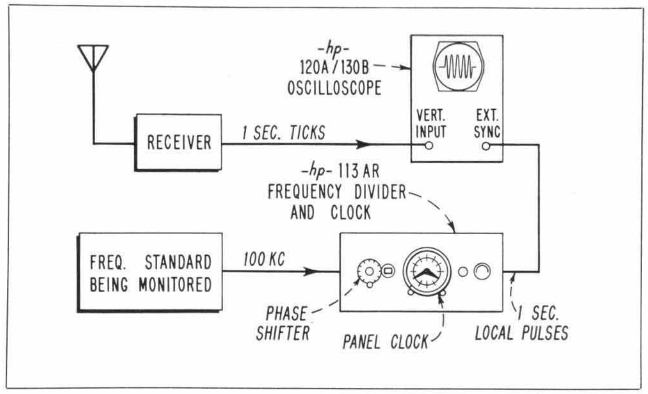

Fig. 4 (right). *Typical equipment arrangement for using new Clock for intercomparing local standard with standard transmissions.*

SIMPLIFIED TIME COMPARISONS

To simplify measuring and monitoring the performance of a precision standard oscillator on a time-comparison basis and to enable keeping time locally to high precision, the new Clock shown in Fig. 1 has been developed.[3] This Clock is arranged to operate from the local standard so as to produce a sharp pulse at precise one-second intervals as based on the local standard frequency. Since they are derived from the local standard, these one-second intervals will contain as a time discrepancy whatever error and drift there are in the local standard frequency. By connecting the Clock in an arrangement like that in Fig. 4, the pulse from the Clock will trigger the oscilloscope sweep so as to display the received time signals from the standard station in their time relation to the local pulse. Over a period of time error and drift in the local standard frequency will then change the time relationship of the local pulse with respect to the received time signal. This change can be measured with the Clock by means of a calibrated phase shifter operated from the panel. The phase-shifter restores the local pulse to its original time relationship, thereby measuring the error and drift in the local standard in terms of time.

TYPICAL COMPARISONS

When the measuring arrangement indicated in Fig. 4 is initially set up to compare a local standard with the time ticks from WWV or other standard station, it will be known only that the Clock's reference pulse is within ½ second of the nearest tick. This initial time relationship can then be adjusted with the continuously-variable calibrated phase shifter on the instrument to achieve a convenient reference condition in which the local pulse is coincident with or just precedes the received tick by a millisecond or two. The calibrated dial and revolutions counter on the phase shifter enable a reference reading to be made of the time position of the local pulse when the desired initial time relations are obtained. Fig. 2 (front page) shows a typical oscilloscope display obtained when the local pulse has been positioned for convenience of measuring the relative arrival-time of the tick.

Once the local pulse has been initially positioned with respect to the tick, the quantity of interest thereafter is the change required in the phase shifter setting to maintain the local pulse in its same time relation to the tick, i. e., to keep the tick at the same place on the oscilloscope sweep. This change is normally determined by maintaining a suitable log. If measurements were being made on a local standard with an error of 1 part in 10^9, for example, the time reference control would require advancing or retarding, depending on whether the frequency is low or high, at the average rate of about 1/10 millisecond per day to maintain the initially-established pulse-to-tick relationship. A typical performance curve obtained on a precision frequency stand-

[1]The time signals from WWV are broadcast to a stated accuracy of 2 parts in 10^{10} $\pm$ 1 microsecond. They are referred to astronomical time, since they are maintained in close agreement with mean solar time corrected for polar variation and annual fluctuation in the rate of the earth's rotation, as determined by the U. S. Naval Observatory. Where the most precise time signal data are required, final correction data on the broadcast time signals are available from the Observatory.

[2]Alvin H. Morgan, "Precise Time Synchronization of Widely Separated Clocks," National Bureau of Standards Technical Note No. 22, July, 1959.

[3]Where VLF transmissions are being utilized, the new Clock is equally valuable, since its local pulse permits phase comparisons to be made with carrier cycles or time comparisons to be made where time signals are being broadcast at VLF, such as at Naval Radio station NBA at 18 kilocycles.

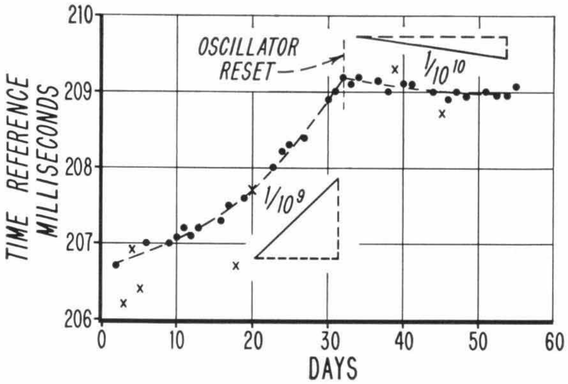

Fig. 5 (left). *Plot of time-comparison record of a precision oscillator using new Model 113AR Clock. In such a plot constant oscillator frequency error appears as a linear time change, while oscillator drift appears as a non-linear time change. Triangles in figure display $1/10^9$ and $1/10^{10}$ error slopes for reference purposes. Early in the plot the oscillator is shown operating with an error of about 4 parts in 10^{10} which, through drift, becomes about four times as large at the end of 30 days. Average drift is thus about 4 parts in 10^{10} per week. Oscillator frequency is shown reset on the 32nd day; oscillator error is then a negative error of 1 to 2 parts in 10^{10}. X's indicate readings made under poor reception conditions.*

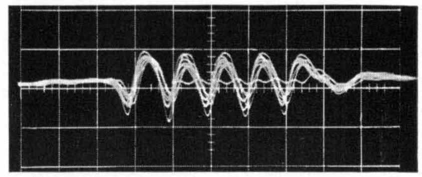

Fig. 6. *Multi-exposure oscillogram of received ticks from WWV on 1 millisecond/cm time base. Since ionospheric effects introduce a variable transmission delay into the received signal (in this case of about ⅓ millisecond), such oscillograms are valuable in establishing arrival-time of earliest-received tick to high resolution.*

ard from time-comparison data measured in this manner is shown in Fig. 5.

OSCILLOSCOPE READINGS

The accuracy with which measurements can be made with the Clock is essentially the accuracy with which the time position of the tick can be resolved on the oscilloscope face by the viewer.[4] Under normal conditions this reading can be made visually to considerably better than a millisecond, i.e., to less than one major graticule division in Fig. 2. The actual visual reading accuracy involves to some extent the skill of the viewer, since visual persistence, variable transmission delay and noise may all play a part in a reading.

While visual readings are entirely practical and can be made to the accuracy stated, a significant increase in resolution can be achieved by making the observation photographically. One recommended technique is to record from 10 to 20 sweeps in one oscillogram so that the earliest-received tick, which is the proper tick to observe, becomes much easier to establish. Fig. 6 shows such a multiple-exposure oscillogram. The reading from such an oscillogram can often be made to a resolution of within about 100 microseconds. This enables a comparison accuracy of about 2 parts in 10^9 to be achieved for a 24-hour comparison. Besides improving comparison accuracy, the photographic method has the advantage of providing a permanent record of the measurement and of minimizing reading mistakes.

MAINTAINING PRECISE TIME

On the 59th second of the minute WWV and WWVH omit the time tick and at other specified times these stations have silent periods, thus providing a means whereby the hands on the panel clock can be synchronized with the broadcast standard time. Screwdriver controls available at the panel can be used to position the hands with no effect on the reference pulse so that an established relation for the pulse will not be disrupted.

When the panel clock has been synchronized in the above manner and the reference pulse previously adjusted to be coincident with the broadcast time ticks, a precision frequency standard becomes a precision local clock with an electronic pulse accurately marking the seconds. This pulse can then be used for such purposes as marking the seconds on strip-chart, magnetic tape, or film records of phenomena where true time is of significance. If desired, the one-second intervals between pulses can easily be subdivided by means of a coherent train of 1 kc pulses provided at a terminal on the instrument.

SYNCHRONIZATION ACCURACY

Locally-maintained time kept in the above manner can be synchronized with the time signals *at the point of transmission* to an accuracy of within a fraction of a millisecond by suitably correcting for the transmission delay from the station. Where highest accuracy is not required, the correction can be made by estimating the transmission delay, using as a rule of thumb that 1 millisecond of delay occurs for each 186 miles between transmitter and receiving location. Where highest accuracy is required, the transmission delay can be calculated to within a fraction of a millisecond. The National Bureau of Standards has published data which simplify such calculations.[5]

FAIL-SAFE DESIGN CONSIDERATIONS

Mention should be made of the design of the Clock itself, since a number of valuable features of both an electrical and a mechanical nature have been incorporated. As indicated by the general circuit arrangement shown in Fig. 7, the instrument accepts a standard frequency of 100 kc and divides this to 1 kc. As a precautionary measure, the input circuit has been designed to offer high discrimination against spurious voltages present with the signal. Voltage steps of ±300 volts applied with the 100 kc signal, for example, do not cause the instrument to miss or skip a cycle. Similarly, the 100 kc-1 kc divider circuitry has been designed to be manual-starting with a push-to-start switch, rather than self-starting, so that any failure or interruption of the standard frequency will stop the operation of the instrument. A regenerative rather than a pulse-type divider has been used because its superior ability to discriminate against noise gives it the advantage of neither gaining nor losing time with respect to the output of the driving oscillator.

The divider makes available 10 kc and 1 kc submultiples of the standard frequency for general purpose use and also applies an output at 1 kc to the continuously-variable phase shifter. The phase shifter is a high-quality resolver calibrated in 10-microsecond increments and accurate within ±10 microseconds in terms of local time.

The 1 kc output from the resolver is applied through a power amplifier and used to drive a precision synchronous motor which in turn drives the panel clock hands through a suitable gear train. Like the dividers, the motor is manual-starting to avoid the possibility of making a measurement

[4]This assumes an oscilloscope with a triggered-type sweep such as the -*hp*- oscilloscopes, since fundamentally the reading is being made with respect to the Clock's reference pulse which triggers the sweep.

[5]Morgan, *op. cit.*

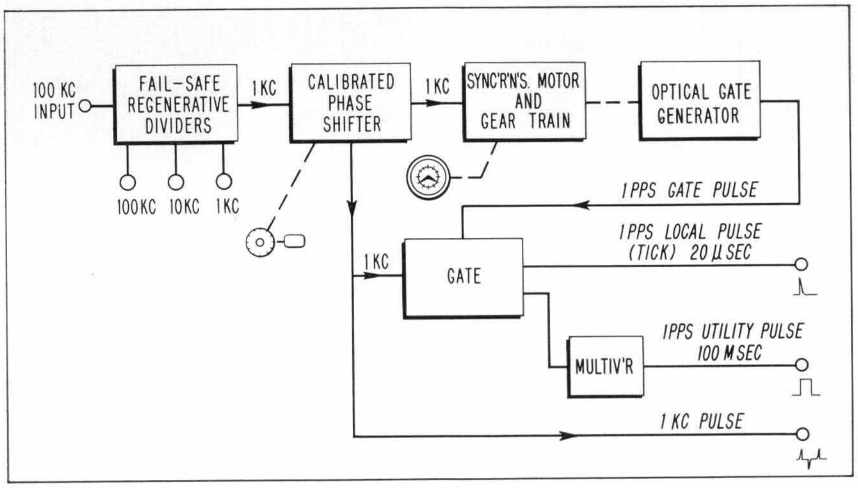

Fig. 7. *Basic circuit arrangement of new Frequency Divider and Clock.*

involving an unknown hiatus. The motor is also a salient-pole type which has an additional fail-safe feature in that the loss of synchronous speed for even one cycle of the input frequency will stop the motor to preclude erroneous readings.

OPTICAL GATE GENERATOR

Design-wise, one of the features that contributes to the instrument's accuracy and reliability is that the reference pulse is obtained by electronic means so as to avoid the use of mechanical contacts. The reference pulse is selected out of the 1 kc frequency coming from the phase shifter by a gate which is locked to a particular cycle in the 1 kc frequency. Locking to a discrete cycle is obtained by operating the gate from an optical gate generator which is coupled to the gear train in the phase shifter output. Since the gear train is synchronously driven by the phase shifter output, it is possible to use it to gate out a particular cycle for reference. After passing through the gate, the reference cycle is made available externally as a short positive pulse with a rise time of less than 10 microseconds. Owing to the stability achievable in electronic circuits which originate this pulse, the pulse has less than a microsecond of jitter, a negligible amount for this application.

Two other outputs are provided in phase with the reference pulse. One is a pulse of 100 milliseconds duration whose leading edge is coincident with the reference pulse. This pulse is available as an auxiliary pulse and for synchronizing other equipment with the reference pulse. Secondly, the 1 kc output of the phase shifter is available in the form of alternate positive and negative pulses corresponding to the alternate half-waves of the 1 kc signal. This output is useful in special situations for check purposes.

TRANSISTORIZATION

Many measures have been included to assure for the instrument the high order of reliability that the purpose of the instrument demands. The instrument is fully transistorized with only two transistor types being employed. The instrument has further been designed to meet the shock, temperature and other environmental conditions of class 4 equipment under specification MIL-E-16400 including sealing against humidity and dust. A meter is provided at the panel with a switching circuit that enables the meter to read the current in various circuits. The arrangement is intended to serve as a check on possible long-term as well short-term operational malfunctions or aging effects. The meter is also arranged to permit the supply voltage to the instrument to be monitored.

EXTERNAL POWER SUPPLY

The instrument has been arranged to operate from an external dc supply so that provision can be made for automatic standby battery operation to prevent equipment stoppage in the event of power interruption. Such an external supply will be in production in the near future as the Model 724AR Standby Power Supply.

The instrument itself operates from 26 ± 2 volts dc and draws from 10 to 25 watts, depending on operating conditions.

WWV-WWVH SERVICES

Information herein concerning WWV and WWVH services is based on National Bureau of Standards Boulder Laboratories' Letter Circular LC1023 and on private communications.

ACKNOWLEDGMENT

Acknowledgment is made to consulting engineer Harold F. Elliott for original mechanical design work. Appreciation is also expressed to Mr. Harris F. Hastings of the U. S. Naval Research Laboratory for valuable comment and suggestion.

The *-hp-* design team for the instrument included Ted Pichel, Raymond Smelek, and Malcolm De Young.

—Dexter Hartke

SPECIFICATIONS

***-hp-* MODEL 113AR**

FREQUENCY DIVIDER AND CLOCK

Frequency Input: 100 kc for solar time; input bandwidth is ±300 cps. 100.3 kc for sidereal time on special order.

Accuracy: 1) Accuracy of output pulse and sine-wave signals determined by accuracy of input frequency.
2) Time reference dial accuracy: ±10 μsec.

Effect of Transients: The Model 113AR will operate through:
1) ±300 volt step function on 100 kc input.
2) 0 to ±50 volt pulses, 0 to 500 pps, 1 to 10 μsec duration on 100 kc input
3) ±4 volt step in 26 vdc input.

Voltage Input: 0.5 to 5 volts rms.

Input Impedance: 300 ohms nominal.

Tick Output:
Pulse Rate: 1 pps
Jitter: Less than 1 μsec
Amplitude: +10 volts minimum
Rise Time: Less than 10 μsec
Duration: 20 ±10 μsec
Source Impedance: 5k ohms nominal

100 MS Pulse:
Pulse Rate: 1 pps
Amplitude: +4 volts minimum
Rise Time: Less than 10 μsec maximum
Duration: 100 ms ±3 ms
Source Impedance: 50 ohms nominal

1 KC Pulses:
Pulse Rate: 1000 pps
Amplitude: + and — pulses, at least 4 volts peak
Duration: 8 μsec nominal
Source Impedance: 5k ohms nominal

Time Reference: Continuously adjustable. Directly calibrated in millisecond and 10 microsecond increments.

Auxiliary Output: 100, 10, and 1 kc sinusoidal: 0.25 volts rms; source impedance 1.2k ohms.

Frequency Divider: Regenerative type, fail-safe (manual starting).

Clock: Manual start; 24 hour dial; minute hand adjustable, in 1 minute steps; second hand continuously adjustable. Front panel adjustment of clock hands does not affect tick output. 12 hour dial on special order.

Monitor Meter: Ruggedized meter and selector switch on front panel for checking supply voltage, divider current (100 kc, 10 kc, 1 kc) and clock current.

Power Required: 26 ±2 volts dc, 10 to 25 watts depending on operating conditions. Designed to connect to *-hp-* Model 724AR Standby Power Supply.

Dimensions: 19 in. wide, 7 in. high, 19½ in. deep behind panel, including 3 in. allowance for mating connectors.

Weight: Net 35 lbs. shipping approximately 51 lbs.

Accessories Furnished: 113A-16E Cable, 6 ft. long; connects 113AR to 724AR.

Complementary Equipment: *-hp-* Model 724AR Standby Power Supply. *-hp-* Model 120AR Oscilloscope.

Price: Model 113AR, rack mount, $2,500.00 f.o.b. Palo Alto, California.

Data subject to change without notice