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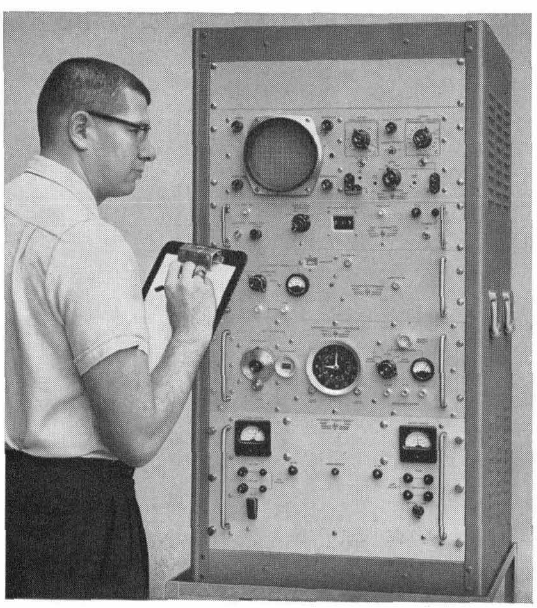
A New Frequency/Time Standard with 5 x 10^{-10}/Day Stability

IN the electronics field the need continues strong for more and more precision in generating and controlling frequency. The ready availability of higher precision in frequency is, for example, the keystone for higher precision in such work as navigation, missile and satellite guidance and observation, suppressed-carrier and narrow-band communications, and in innumerable timing situations.

In its capacity of designer of precision electronic instruments, the Hewlett-Packard Company has been actively concerned with the precision frequency problem, having recently made available substantial increases in the precision of the 10-megacycle frequency counter*, in secondary frequency standards, and in other developments to be announced.

Now, a new frequency/time standard has been placed in production to make available to those working with precision frequencies a standard with a stability rated at ±5 parts in 10^{10} per day. It is a standard in which performance in every area has been optimized. Its stability ratings apply over a temperature range from 0° to 50°C with better stability generally obtained under less severe envi-

*LaThare N. Bodily and Leonard S. Cutler, "5 x 10^{-8}/Week Time Base Accuracy in the 10 MC Frequency Counter," Hewlett-Packard Journal, Volume 10, No. 3-4, Nov.-Dec., 1958.



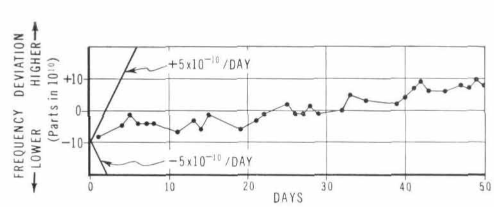


Fig. 2. *Typical long-term stability performance of -hp- 103AR Frequency Standard after several-week aging period and under laboratory conditions. Solid 5 x 10^{-10}/day lines indicate rated performance of standard over 0-50°C temperature range.*

Fig. 1. (At left) *New -hp- Model 103AR Frequency Standard (third unit from top) achieves very high stability of 5 parts in 10^{10} per day, can be combined with other -hp- instruments as shown here to form primary frequency standard or time standard having 10-microsecond resolution.*

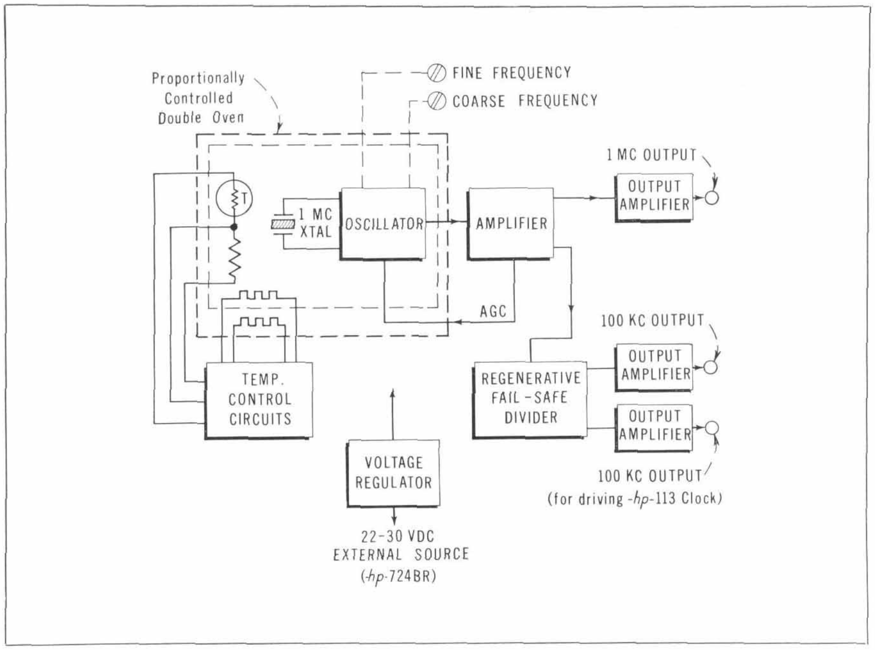


Fig. 3. *Basic circuit arrangement of -hp- 103AR Frequency Standard. Instrument is fully transistorized. Oscillator section is located inside double oven.*

ronment. It is virtually unaffected by supply voltage changes, has good short-time stability, and is insensitive to load. It is fully transistorized to achieve advantages regarding long life, small power consumption, and light weight. Finally, the new standard has available for it companion -*hp*- instruments to enable it to form a primary frequency standard, or a time standard with a resolution of 10 microseconds. These companion instruments also enable a laboratory to readily trace its precision in frequency to the United States Frequency Standard (USFS) by means of National Bureau of Standards' stations WWV, WWVL, etc.

DESIGN CONSIDERATIONS

The basic circuit arrangement of the new standard is indicated in Fig. 3. The oscillator section is crystal-controlled and operates at 1 megacycle, the selection of this frequency being based on the optimization of the factors that control long-term stability in a crystal oscillator. The circuit is one, for example, in which amplifier phase-shift variations have a minimum effect on the operating frequency. Further enhancement of long-term stability is achieved by maintaining power dissipation in the crystal at a very low level of about 2/10 microwatt. The crystal itself is one with a Q typically above 2.5 million and is aged in the circuit until its long-term drift is about 2 parts in 10^{10} per day.

Both the crystal and the oscillator circuit are housed in a double oven which is shock-mounted in the equipment. At normal room temperatures oven temperature is maintained constant within a few thousandths of a degree Centigrade. Even over a 0°—50°C range, oven temperature is maintained within about 0.01°C. The oven is controlled by a proportional-control type system so that heat-cycling effects are avoided.

The oscillator circuit is followed by a multi-stage amplifier that isolates the oscillator to the degree that changes in the load at the amplifier output produce no detectable effect on the oscillator. The amplifier is provided with an AGC circuit which reacts on the oscillator to maintain the crystal amplitude essentially constant. To assist in achieving this constancy, the amplifier from which the AGC voltage is taken is itself highly stabilized with feedback.

FAIL-SAFE DIVIDERS

As indicated in the circuit block diagram, the equipment provides an output at 100 kc as well as at 1 megacycle. Both outputs are well isolated from one another so that one terminal can be shorted without affecting the other.

The 100 kc output is obtained by dividing the 1 megacycle output in a regenerative-type divider which has the property that loss of an input causes the divider to cease operation. In other words, the presence of a 100 kc output assures the user that the instrument has been operating without hiatus. Where the standard is used with a clock system, this fail-safe divider will assure that the clock will either be correct or stopped. Such behavior is essential in systems where small undetected time errors would be intolerable. In the event

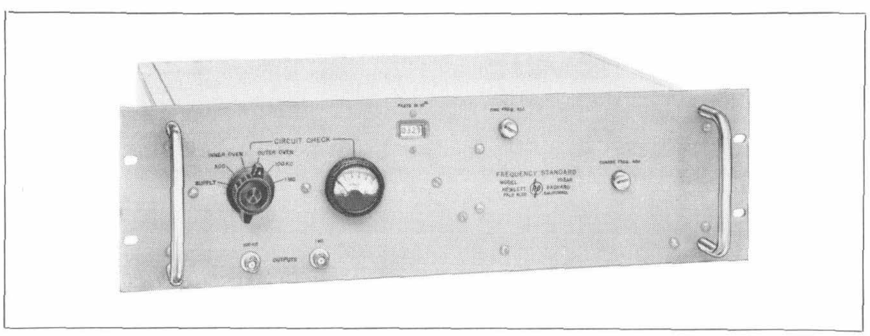


Fig. 4. *Panel view of new Frequency Standard. Panel height is 5¼". Output terminals are also provided on rear panel.*

that the divider loses its input signal, it can be re-started by means of a manually-operated switch provided at the back of the unit.

The divider and isolating amplifier are further followed by selective output amplifiers to provide the necessary output level together with low extraneous components. Harmonic components, for example, are each at least 40 db below the main signal, while any non-harmonic components are each at least 80 db down.

STABILITY

The electrical measure of quality of a frequency standard is, of course, its stability. The principal stability implied by this statement is long-term stability, since it is the long-term stability that determines the ultimate accuracy of which the standard is capable. Also included in the statement is short-term stability, however, since it is short-term stability that determines the accuracy with which any one comparison or measurement with the standard can be made.

The stability achieved through the careful refinement of the factors mentioned earlier has given the new standard the long- and short-term stabilities typified by the data in the accompanying illustrations. The long-term stability representative of the standard after having been in use for several weeks is shown in Fig. 2. This curve covers a 50-day interval and shows the standard to exceed its ratings by a substantial amount. This curve represents the frequency of the oscillator versus the USFS.

It is also interesting to consider the long-term stability data presented in Fig. 5. Fig. 5 shows sections of a continuous phase comparison made daily between one of the new standards and Bureau of Standards' Station WWVL. Since NBS in turn compares the average daily frequency of WWVL with the United States Frequency Standard, these data can be used to compare the 103AR to the USFS. WWVL transmits in the vlf region at 20 kc so that during daylight its signals as received at a point distant from the transmitter are essentially free from propagation variations and have virtually the full precision of the signals as broadcast. In

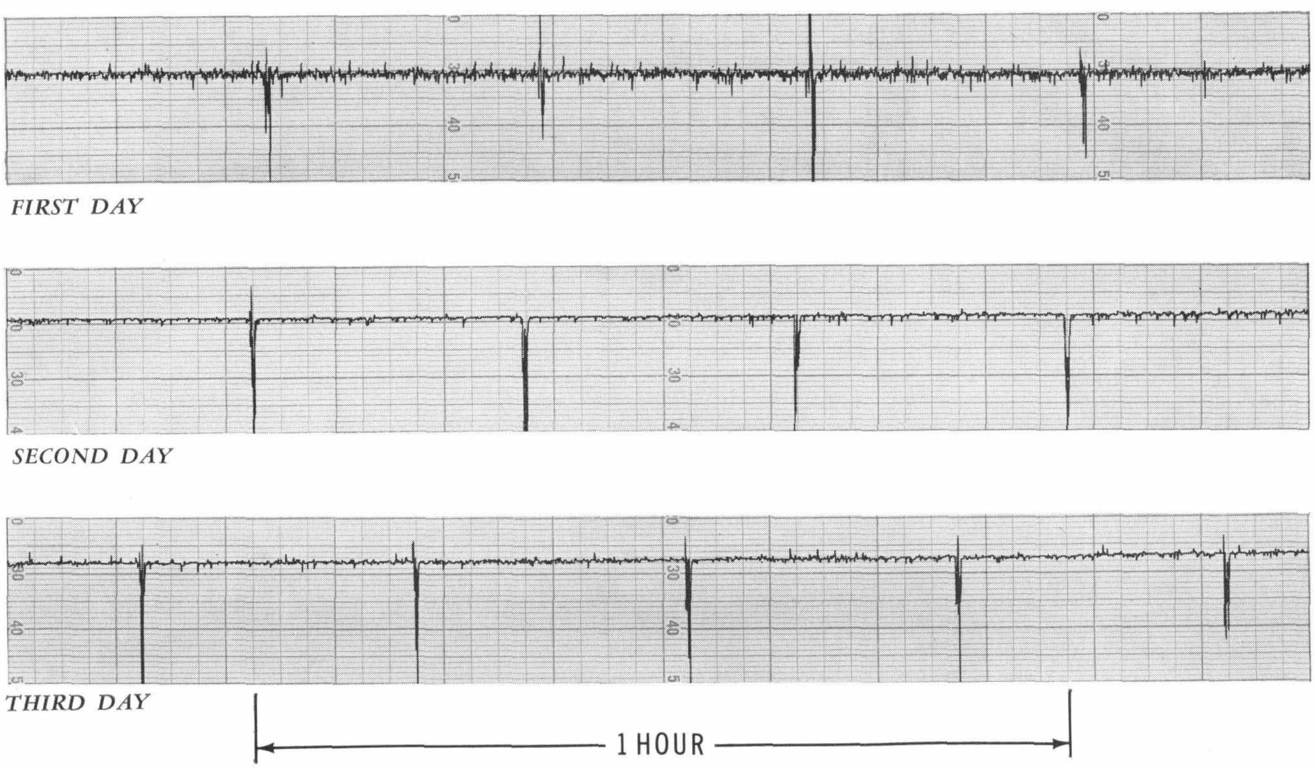


Fig. 5. *Sections taken over ten-day period from stability record comparing aged -hp- 103AR Frequency Standard with NBS station WWVL. This comparison is a phase comparison, so constant slope in these records indicates constant frequency and changes in slope indicate changes in frequency. In the (smoothed) curves a slope of 1 small division per 3 hours, that is, 1 microsecond in 10,800 seconds (the minimum interval over which a measure-*

(Curves continued on next page)

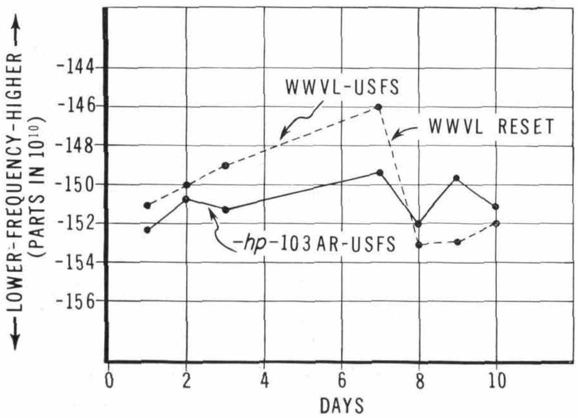
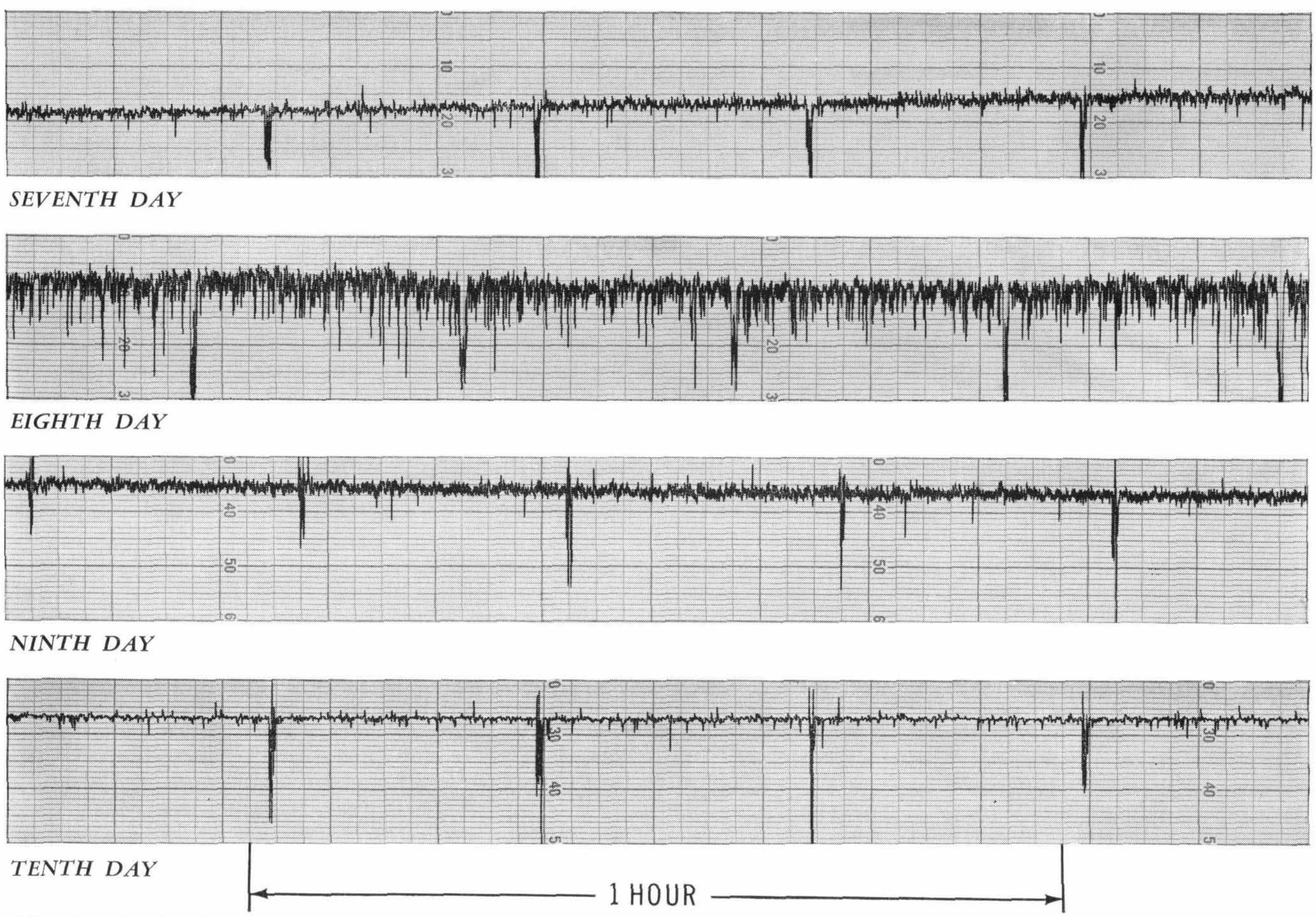


Fig. 6. *Average daily frequency of -hp- 103AR Frequency Standard obtained from record shown in Fig. 5 plotted with respect to United States Frequency Standard by comparison with received WWVL signal. 103AR curve corrected for published WWVL drift (dashed curve).*

examining Fig. 5 it should be noted that, since the measurement is a phase measurement, the *slope* of the smooth curve indicates the frequency difference between the *-hp-* standard and the reference frequency (WWVL). It should also be noted that a constant slope indicates a constant frequency; only changes in slope indicate a change in frequency.

While the curves as presented in Fig. 5 indicate a high order of performance that is well within ratings, the curves also contain the frequency drift of the reference signal (WWVL) itself. By subtracting the published data for the frequency of WWVL over this same period, shown as the dotted curve in Fig. 6, the actual frequency difference between the -*hp*- 103AR and the USFS is obtained. This is the solid curve of Fig. 6. The nominal frequency of WWVL is offset —150 parts in 10^{10} with respect to the USFS. Note that over the period shown the 103AR varied only about $\pm$ 1 parts in 10^{10} with respect to the USFS around an offset of —151 parts in 10^{10}.



(Fig. 5. *Continued*)

ment is normally made) represents a frequency difference of 1 part in 10^{10}. This difference will also include change in frequency of WWVL, which is subtracted from these data in Fig. 6. Large excursions at 20-minute intervals in records are station identification signals. Width of curves is essentially a measure of noise in received signal. During fourth through seventh day, WWVL did not broadcast.

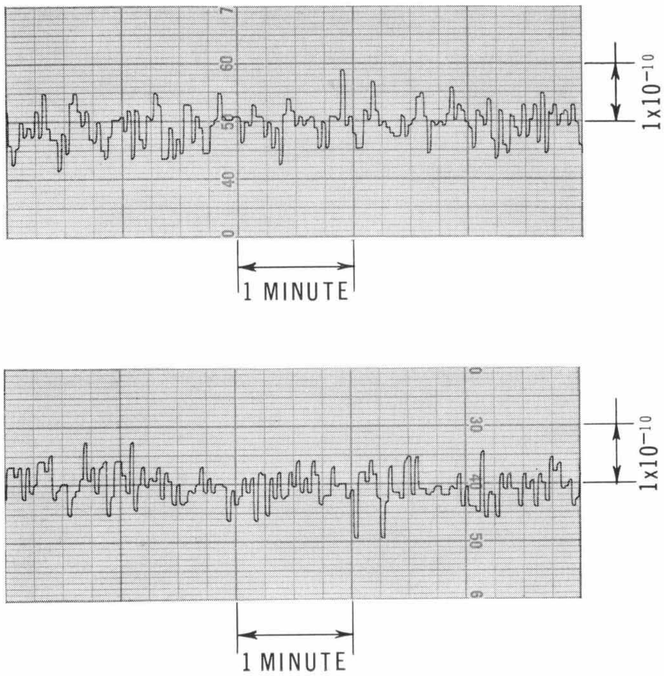


Fig. 7. *Record of short-term stability of three typical -hp- 103AR Frequency Standards made by comparing unit A against unit B (upper curve), then unit B against unit C (lower curve). Each curve composed of 1-second averages.*

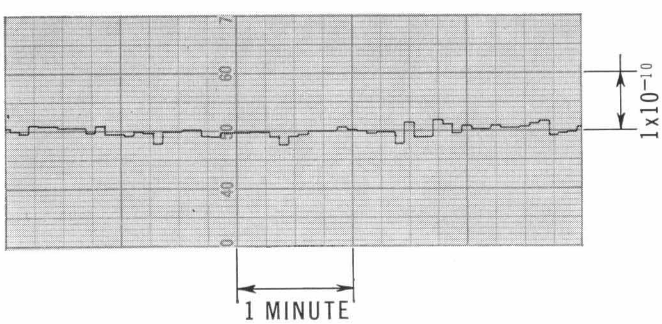


Fig. 8. *Short-term stability record of two Frequency Standards, as in Fig. 7, except using 10-second averaging to indicate more fully the random nature of short-term instabilities.*

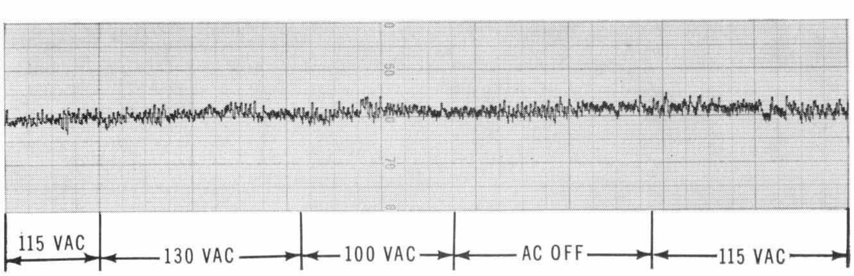
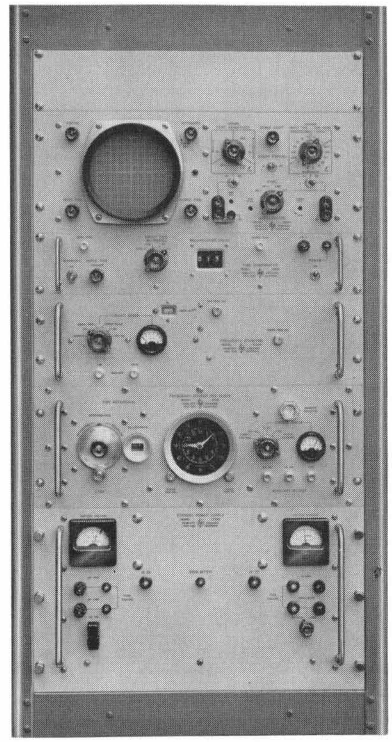


Fig. 9. *Record showing 103AR output frequency as a function of large line voltage excursions when typical 103AR is operated from -hp- 724 Standby Power Supply. Vertical scale is 10^{-11} per small division, time scale is 20 minutes per large division.*



New *-hp-* high-stability 103AR Frequency Standard can be obtained with companion *-hp-* instruments as shown here to form a primary Frequency Standard as well as a time standard with a resolution of approximately 10 microseconds. System can be calibrated against standard high- or low-frequency stations by use of suitable receiving system.

SHORT-TERM STABILITY

To illustrate the short-term stability of the new standard, the output signal from a group of three of the standards were compared in two groups of two each. Each resulting measurement thus includes the sum of the instabilities of two of the new standards. The curves that resulted from these comparisons are shown in Figs. 7 and 8. It is readily seen in these curves that, although short-term stability for the standard is rated at ± 5 parts in 10^{-10}, this rating applies over a severe environment and that considerably higher short-term stabilities are usually obtained under less severe environment.

In making the short-term stability comparisons shown in Fig. 7, a frequency counter was used to average the

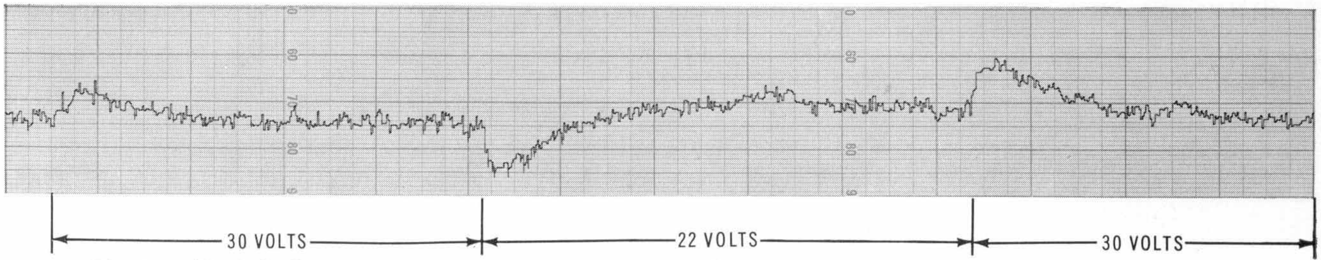


Fig. 10. *Typical effect on 103AR output frequency of very large changes in power supply voltage. Such large changes are considerably in excess of ratings but are useful in establishing coefficients of performance. Vertical scale is 10^{-11} per small division, time scale is 20 minutes per large division.*

stability measurement over an interval of 1 second. While this counting period provides an indication of the stability to a high degree of accuracy, it is also interesting to see the stability averaged over a 10-second interval, as in Fig. 8. The random nature of the short-term excursions result in a large amount of self-cancellation in this type of measurement.

LINE VOLTAGE COEFFICIENT

Since many installations that employ frequency/time standards follow the desirable practice of using standby power equipment for a standard to guard against power-line failure, the new standard has not been provided with an internal power supply. Instead, as indicated in Fig. 3, the new standard is provided with a voltage regulator circuit but is otherwise arranged to operate from an external 26-volt ±4-volt dc source. A companion power supply that provides this voltage and contains an internal standby battery as well is available for the standard as the Model 724 Standby Power Supply.

When the standard is operated from the Model 724, the oscillator frequency is virtually isolated from normal power line voltage variations, including complete power line failure if the internal standby batteries are used. This is clearly illustrated in the record of Fig. 9, which shows typical oscillator stability as a function both of wide excursions of power line voltage as well as failure and re-start of the power line.

In cases where it is desirable to operate the standard from existing power equipment, the curve in Fig. 10 can be used to determine the desired degree of regulation of the power source. This curve shows typical oscillator stability as a function of full-tolerance excursions of supply voltage. In this regard it is interesting to note that the voltage coefficient of frequency of the instrument is only about 1 part in 10^{10} per 4-volt dc supply change.

OTHER CONVENIENCES

Several physical features of the new standard contribute to its operational convenience. It is supplied in rack mount form with an overall panel height of only 5¼″. The oscillator circuit is provided with a *Coarse* and a *Fine* frequency adjustment control, the *Fine* control being further provided with an indicator calibrated in parts per 10^{10}. The range of the indicator is approximately ±300 parts in 10^{10}, while the range of the *Coarse* control is approximately 1.5 parts in 10^6.

The instrument is also provided with a panel meter and switching arrangement that enables monitoring of six circuits in the instrument, including the 1-megacycle and 100 kc outputs. If desired, a log of these circuit readings can be maintained as a guide to long-time performance trends in the instrument. Additionally, the meter can be used to obtain a quick check on performance at key circuit points.

DESIGN GROUP

The electrical design group for the new standard included LaThare N. Bodily, while the mechanical design was carried out by Glenn Elsea and Rex Brush.

—Leonard S. Cutler

SPECIFICATIONS

-hp- MODEL 103AR FREQUENCY STANDARD

Stability: Short term: Better than 5 parts in 10^{10} averaged over 1 sec. intervals. Long term: 5 parts in 10^{10} per day.

Output Frequencies: 1) 1 mc sine waves, 1 volt rms into 50 ohms 2) 100 kc sine waves, 1 volt rms into 50 ohms 3) 100 kc output for driving *-hp-* 113AR Frequency Divider and Clock, 0.5 volt rms.

Harmonic Distortion: At least 40 db below rated output.

Non-Harmonically Related Output: At least 80 db below rated output.

Output Terminals: Outputs 1 and 2: BNC connectors on front panel and at rear. Output 3: BNC connector at rear.

Frequency Adjustments: Coarse: Screwdriver adjustment with range of approximately 1 part in 10^6. Accessible through front panel by removing threaded plug. Fine: Front panel control with range of approximately 600 parts in 10^{10}. Accessible through front panel by removing threaded plug. Digital indicator calibrated directly in parts in 10^{10}.

Monitor Meter: Ruggedized front-panel meter and associated selector switch monitors:
1) SUPPLY voltage
2) OSC current
3) INNER OVEN current
4) OUTER OVEN current
5) 100 KC output
6) 1 MC output

Temperature Range: 0-50°C.

Size: Rack Mount: 5¼ in. high, 19 in. wide, 12 in. deep behind panel.

Weight: Net approximately 17 lbs.

Power Requirement: 22 to 30 volts dc, approximately 5 watts after warmup at room temperature. Approximately 9.5 watts during warmup. *-hp-* 724AR Standby Power Supply with standby battery recommended.

Accessories Furnished: Cable for connecting *-hp-* 103AR Frequency Standard to *-hp-* 724AR Standby Power Supply.

Price: $2500.00 f.o.b. Palo Alto, Calif.

Complementary Equipment: *-hp-* Model 724AR Standby Power Supply.
-hp- 1420-0007 20 ah Standby Battery for Model 724AR.
-hp- Model 113AR Frequency Divider and Clock.
-hp- Model 120AR Oscilloscope.
Receiver for Standard Time signals (not available from Hewlett-Packard Company).
Data subject to change without notice.