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A New Performance of the "Flying Clock" Experiment

A new experiment has been made to compare clocks in the U.S. and Europe to higher precision. The results will be used by the various official agencies of the two continents in improving their time synchronization.

Fig. 1. *Data being logged in Switzerland at the Observatoire de Neuchatel by Alan S. Bagley of the –hp– Frequency and Time Laboratories. Atomic clock in left foreground carried time to Switzerland aboard transatlantic passenger flight.*

SEE ALSO:
Measuring the ratio of Cs_{133} and Hydrogen, p. 6
Plant distribution of a dc standard voltage, p. 9

THE PROBLEM of correlating the time of day at widely separated locations with great accuracy is one that has absorbed chronologists, navigators, astronomers and cartographers for hundreds of years. As vehicles grow faster and the range of exploration reaches far into outer space, more accurate time determinations become increasingly necessary. Precise timing and coordination of events far apart may determine the success of precise mapping operations, satellite orbital placement, astronomical observations, or missile landings.

In recent years, intercontinental time of day comparisons gradually reached an accuracy of about one millisecond through use of h-f radio signals, the limit being imposed by propagation-time uncertainties of high frequency waves. Considerably higher accuracy is, however, possible. For example, two recent means have emerged to achieve intercontinental time of day correlations with accuracy of the order of a few microseconds.

One method has been to fly an accurate clock, set precisely to a given time standard, from point to point, effectively bringing the time standard to each. U. S. government experiments have used quartz oscillator-driven clocks as well as "atomic" clocks in this manner. In 1960, for example, Reder, Brown, Winkler, and Bickart, of the U. S. Army Signal Research and Development Labora-

Fig. 2. *The two atomic clocks being fastened in passenger seats aboard airliner. Operating power in flight was supplied by plane.*

tory employed the flying clock method[1] to achieve synchronization of within about 5 microseconds among Pacific Ocean Area stations. In this instance, a KC-135 jet tanker, carrying an atomic clock, flew the time from station to station.

In a second method, Telstar I was used as a relay to synchronize clocks[2] between the U. S. and Great Britain. An accuracy of about one microsecond was achieved between these points.

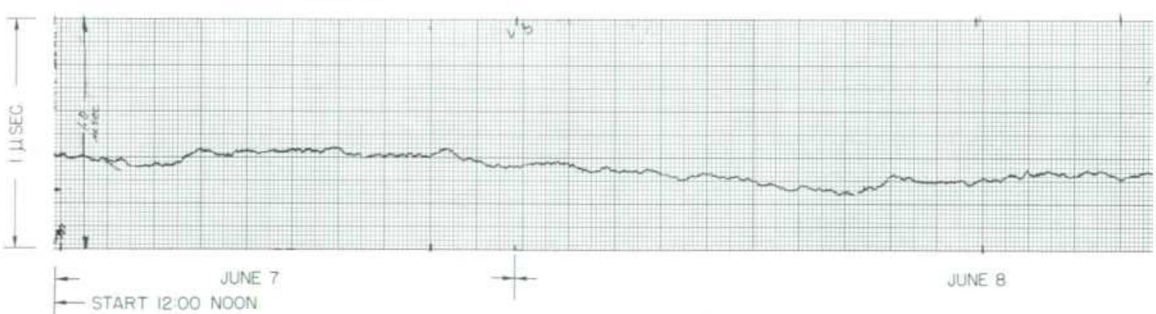
Recently, engineers from the Frequency and Time Laboratories of the Hewlett-Packard Company performed the flying clock experiment anew, this time between the U. S. and continental Europe (Switzerland) using a newly-developed atomic frequency standard and clock. The equipment successfully compared time of day standards of the U.S. with those of Switzerland to an accuracy of about one microsecond. The equipment was sufficiently light and small that it was flown as a "passenger" on regularly scheduled passenger airlines.

The *-hp-* atomic clock became available as the result of the development in the *-hp-* Frequency and Time Laboratories of a new cesium beam frequency standard of very high performance. The new standard was to be described in a paper at the International Conference on Chronometry, a conference held every five years at Lausanne, Switzerland. In this way a convenient opportunity arose on the same jour-

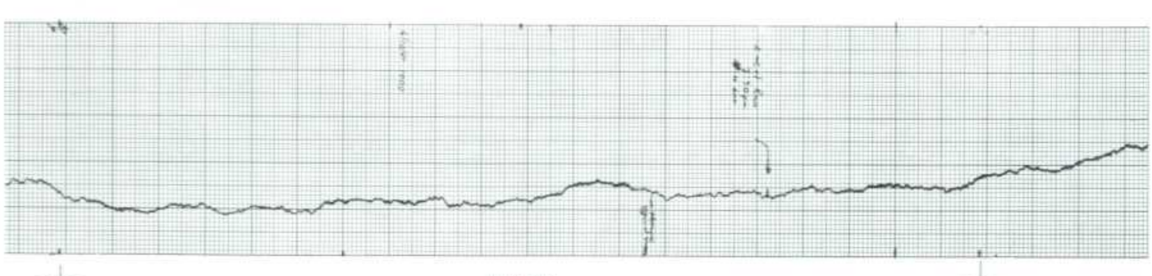
[1] F. Reder, P. Brown, G. Winkler, and C. Bickart, "Final Results of a World-Wide Clock Synchronization Experiment," Proc. of the 15th Annual Symposium on Frequency Control, 1961.

[2] J. McA. Steele, Wm. Markowitz, and C. A. Lidback, "Telstar Time Synchronization" **Conference on Precision Electromagnetic Measurements,** June 23-25, 1964. To be published in **IEEE Transactions on Instrumentation and Measurement.**

See also: Wm. Markowitz, "International Frequency and Clock Synchronization," **Frequency,** Vol. 2, No. 4, July-August, 1964.



(a)



(c)

Fig. 3. *Strip recording made at exhibit associated with International Conference on Chronometry in Lausanne, Switzerland. Record is of the time difference between the two atomic clocks used in the experiment and is thus a*

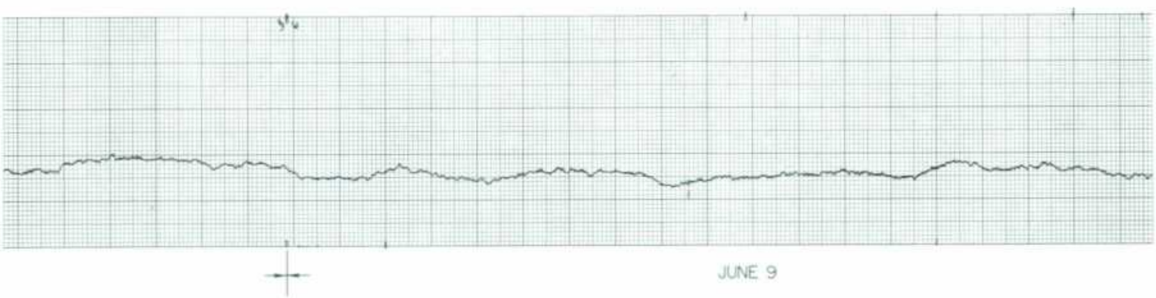
ney to use the new standard to compare time of day standards in the U.S. and Switzerland and also to compare the performance of the new standard with the instruments used by both countries for their primary frequency standard determinations.

Two of the new -*hp*- cesium-beam frequency standards were used. Each was combined with an -*hp*- Model 115BR electronic clock which, among other functions, provides accurate electrical "ticks" from the standard frequency for comparison purposes. A special standby battery power supply was included, resulting in a complete atomic clock. Since the equipment would have to be powered from whatever source might be at hand, the supply was designed to accept power from a variety of frequencies and voltages, including dc voltages. Even an auto cigar-lighter plug was provided.

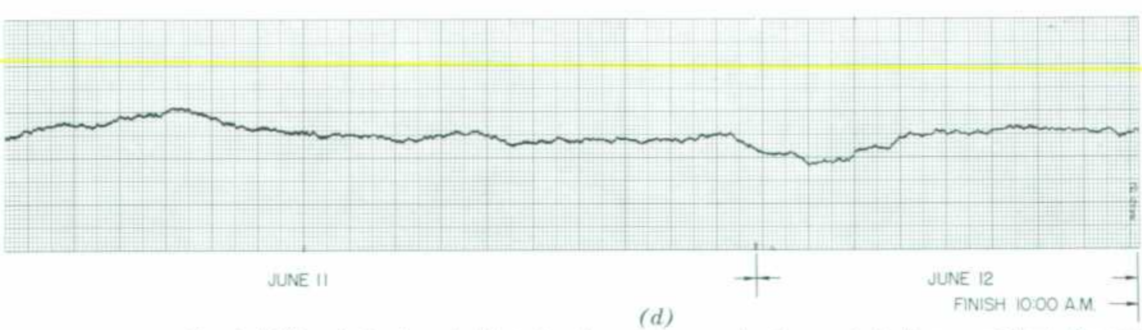
Fig. 4. *Panel view of one of "atomic" clocks used in experiment. Cesium standard in middle drives electronic clock (top) which integrates standard frequency and also produces very accurate electrical "ticks" based on driving frequency. Power supply unit at bottom provides for operation from a range of ac and dc voltages.*

As preparation for the experiment, two newly-manufactured standards were carefully checked and their C-fields adjusted to the prescribed value. The standards were then turned on, the first time they had ever operated. Measurements were begun to compare their frequencies by means of VLF phase comparisons with the frequencies of National Bureau of Standards stations WWVL and WWVB at Boulder, Colorado. No adjustments of any sort were made on the standards. A 12-day comparison with these stations showed the frequency of the standards to be within 5 parts in 10^{12} of the United States Frequency Standard.

The plan for the experiment was first to transport the standards to Washington to compare their time reading against the official U. S. time standards at the U. S. Naval



(*b*)



(*d*)

measure the stability of the two driving standards. No effort was made to synchronize the standards. While short-term fluctuations of a larger magnitude are evident, the record shows the standards were within 2 parts in 10^{12} of one another as averaged over the full 5-day period.

Fig. 5. *Frequency comparison being made between one standard and the "long" cesium beam standard (foreground) at the Laboratoire Suisse de Recherches Horlogeres, Neuchatel, Switzerland. This long standard is considered one of the world's best cesium standards.*

Observatory. The next part was to transport the standards to Switzerland for a comparison against the Swiss time standards and to make measurements of the time of arrival there of WWV time ticks. The clocks would then be returned to NBS station WWV for time comparisons that would permit calculating propagation time. These would include the time of occurrence of the WWV ticks and a comparison against WWV clocks. The standards would next be taken to the Naval Observatory for a second check there against the U. S. master clock to determine the tolerance on the time measurements.

Lastly, a stop would be made at NBS, Boulder, Colo., to compare the standards against the long cesium-beam standard maintained there and to make further time checks.

On Friday, June 5, 1964, the experiment was begun by taking the standards to San Francisco International Airport by station wagon. At the airport they were placed in passenger seats on a regularly-scheduled DC-8 flight bound for Washington, D.C. Power was provided during the flight by the DC-8's electrical system.

In Washington on June 5, the units were transported to the U.S. Naval Observatory for a comparison against the official U. S. time standards. Records were kept of the comparison for future use.

SWITZERLAND

That evening, the clocks were taken by rental station wagon to New York. During this and other ground-transport times throughout the trip, the standards operated from external storage batteries or from internal batteries while being hand-carried. At New York they were placed aboard a regular transatlantic flight, again operating from the plane's power. The next morning, Saturday, June 6, the standards arrived in Switzerland, and were transferred to the Observatoire de Neuchatel. Time of day comparisons were then made at this Swiss observatory, which maintains the Swiss national standard. In addition, one standard was driven to the Laboratoire Suisse de Recherches Horlogeres Neuchatel for a frequency comparison with the long cesium-beam standard maintained there.

At this time in Neuchatel, data were recorded in raw form because of tight schedules. Some time later, however, calculations revealed the time difference between Swiss and U. S. time of day standards. This had already been known, from HF radio comparisons, within about a millisecond. The comparison made with the Hewlett-Packard flying clocks established the value within about one microsecond.

Late Saturday afternoon the standards were taken from Neuchatel and, after an overnight stop, arrived at the exhibit of the International Conference on Chronometry in Lausanne, Switzerland, on the morning of Sunday, June 7.

At noon on Sunday a chart recording was begun of the difference between the time "ticks" produced by the two standards. This record was made continuously during the exhibit in public view until the morning of Friday, June 12. The record, reproduced here, showed that the two *–hp–* standards were within 2 parts in 10^{13} of each other as averaged over the full five days. Again, no effort was made to standardize or synchronize the standards before making the record or at any time before or during the whole experiment.

An opportunity also arose during the exhibit to make a high-precision comparison of the frequency of the cesium-beam standards with that of a hydrogen maser; this is described in an accompanying article.

On Saturday, June 13, the standards were returned to the Observatory in Neuchatel for further measurements against the "long" cesium-beam standard.

The trip, in fact, permitted the *–hp–* standards to be compared against two of the best of the world's long cesium-beam standards: the one in Neuchatel and, later, that of the U. S. Bureau of Standards in Boulder, Colorado, which is used with other standards to maintain the U. S. Frequency Standard.

Since the long-beam standard is actually located at the Laboratoire Suisse de Recherches Horlogeres Neuchatel, a telephone line was used in the comparison. The *-hp-* standards were measured as being $(+2 \pm 6) \times 10^{-12}$ and $(+6 \pm 5) \times 10^{-12}$, respectively, with respect to the long-beam standard.

Fig. 6. *Leonard S. Cutler (left), -hp- Frequency and Time Laboratories, and Dr. Jacques Bonanomi, director of Observatoire de Neuchatel, Switzerland.*

UNITED STATES

On Monday morning, June 15, the standards were flown to New York, again as "passengers" on a regular flight. From New York they were taken to station WWV at Beltsville, Maryland, arriving early on Tuesday, June 16. Upon arrival, measurements of the time of occurrence of WWV time ticks were made to establish the propagation time between Neuchatel and WWV to enable the other time comparisons to be made. This measurement yielded a propagation time of 23,709 $\pm$200 microseconds, the tolerance being mainly the uncertainty in establishing the time of arrival of ticks in Neuchatel. Prior to the experiment the propagation time had been estimated at 22,800 microseconds.

Later Tuesday, the standards were taken to the Naval Observatory for further time checks. On the basis of these measurements the tolerance of approximately 1 microsecond in the correlation between the time of day in the United States and Switzerland was established.

In addition, however, measurements showed that the time kept by the *-hp-* standard was still within 1.5 microseconds of the time kept by the Naval Observatory. In terms of frequency, this measurement meant that the *-hp-* standard was within 2×10^{-12} of the weighted mean of the standards utilized by the Naval Observatory for the complete period from June 5 to June 16.

The time difference on June 16 between station WWV ticks and the Naval Observatory master clock was also measured, the value being 2397 microseconds.

The next morning, Wednesday, June 17, the standards while operating on airplane power were flown from Washington D. C., to Denver, Colorado, and then driven by car to the Bureau of Standards in Boulder. Checks were there made against the long cesium-beam standard referred to earlier and known as U. S. Frequency Standard No. 3. These checks showed that the frequency of the two *-hp-* standards were $(-3.9 \pm 3) \times 10^{-12}$ and $(-2.7 \pm 3.3) \times 10^{-12}$ with respect to the NBS standard. The measurements were based on 44 and 45 200-second samples, respectively. Measurements were also made of propagation time between Washington and Boulder.

On Thursday the standards were returned to Denver, placed aboard a regular airline and operated on airplane power en route to San Francisco, and finally taken to the *-hp-* F and T laboratories in Palo Alto.

GENERAL

The experiment is considered to have been highly successful with the following information established with an accuracy not previously attained:

(a) The time of day was correlated in Switzerland with that of the United States to an accuracy of about one microsecond.

(b) The propagation time between station WWV and Neuchatel was measured to a tolerance of about 200 microseconds.

(c) The two *-hp-* standards were compared with two well-known long

(continued on p. 8)

TABLE OF MAJOR CHARACTERISTICS
-hp-
Cesium Beam Frequency Standard

OUTPUT FREQUENCIES:	5 MHz, 1 MHz, and 100 kHz, in A-1 or UT_2 time scale as specified.
ACCURACY:	± 2 parts in 10^{11}.
LONG-TERM STABILITY:	Within ± 1 part in 10^{11}.
SHORT-TERM STABILITY:	RMS Fractional Frequency Deviation $\frac{(\Delta f_{rms})}{f}$ for 1-second averaging is less than 1 part in 10^{10}.
NOISE-TO-SIGNAL RATIO:	At least 87 db below rated 5 Mc output; filter bandwidth is approximately 125 cps.
CESIUM BEAM TUBE LIFE:	10,000 hours operating guaranteed.

A MEASUREMENT OF THE RATIO OF THE ZERO-FIELD HYPERFINE SPLITTINGS OF CESIUM 133 AND HYDROGEN

During the recent International Conference on Chronometry in Lausanne, Switzerland, an opportunity arose to make a high-precision measurement of the ratio of the frequencies of a hydrogen maser and a cesium-beam frequency standard. This ratio is of special interest, since it permits calculating the ratio between two fundamental constants of nature: the hyperfine transition frequencies of hydrogen and cesium atoms. These transitions are quantum-mechanical effects in which the hydrogen and cesium atoms change their energy levels and presumably produce invariant frequencies of 1420.405+ MHz (Mc) for hydrogen and 9192.631+ MHz for cesium. While this ratio has been measured before, it was realized by Dr. Jacques Bonanomi of the Observatoire de Neuchatel that the equipment was at hand during the exhibit associated with the Conference to make this measurement to a higher precision than had previously been done. The following account by Leonard S. Cutler of the -hp- Laboratories is thus believed to present this ratio to a new precision. A few days after this measurement, a similar measurement by others was made with much the same results against the long cesium-beam standard at Laboratoire Suisse de Recherches Horlogeres Neuchatel as noted below in footnote 2.

—Editor

THE ratio of the hyperfine splittings of cesium 133 and hydrogen, $\frac{\nu_{Cs}}{\nu_H}$, has been measured by comparison of the frequency of a Hewlett-Packard 5060A Cesium Beam Frequency Standard with that of a Varian H-10 Hydrogen Maser. Fig. 1 shows a block diagram of the system used in the comparison.

The zero-field hyperfine splitting for cesium 133 is taken to be exactly 9,192,631,770.0 hertz (cps) in accord with the A-1 time scale. The 5060A Cesium Standard used in the measurement includes a synthesizer which provides output frequencies of 5.0, 1.0, and 0.1 megahertz in a uniform time scale which approximates UT-2. By present international agreement frequencies in this time scale are offset -150×10^{-10} from those in the A-1 time scale. Consequently the 5060A frequencies as measured in the A-1 time scale are $5.0\,(1-150 \times 10^{-10})$ megahertz, etc. In all the calculations we will use the 5060A time scale and convert to A-1 time scale.

The -hp- 5100A/5110A Synthesizer, the Gertsch FM-4 Multiplier and all the associated equipment are used to produce a difference frequency which is translated to about 200 kHz and which is uniquely related to the frequencies ν_1 and ν_5 of the 5060A Cesium Standard and the H-10 Hydrogen Maser. The -hp- 5090A Droitwich Receiver was used as a narrow-band phase-locked oscillator which divides the 200 kHz input, $\nu_6 - \nu_7$, by two. The resulting 100 kHz is measured with a 1000-second averaging time by using the -hp- 5245L and 5214L Counters to measure the time for 10^8 periods to occur. Ten readings taken over a period of slightly less than three hours are shown in Table 1 along with the mean, the standard deviation, and the standard deviation of the mean. The standard deviation of the mean of .78 corresponds to 1.1×10^{-12} for the statistical uncertainty in the measurement of the hydrogen frequency in terms of the cesium frequency. The $\pm$ one count error in the counter is negligible here.

Referring to Fig. 1, it can be seen that

$$10^{-6}\nu_5 = 150\text{K} - 10 - \frac{2 \times 10^7}{\text{N}}$$

$$\text{K} = 9.53737182$$

$$= 1420.6057730000 - \frac{2 \times 10^7}{99{,}999{,}992.1 \pm .78}$$

$$= 1420.6057730000 - .2000000159 \pm .0000000016$$

or $\nu_5 = 1420405772.9841 \pm .0016$ Hz.

Converting to A-1,

$$\nu_{5\,\text{A-1}} = 1420405772.9841 \cdot (1 - 1.5 \times 10^{-8})$$

$$= 1420405751.6780 \pm .0016 \text{ Hz.}$$

This measured frequency must have the corrections applied for magnetic field, second order doppler shift, and wall shift as given in Table 2. These corrections must be subtracted to obtain the final result:

$$\nu_H = \nu_{5\,\text{A-1}} - \Sigma\Delta\nu$$

$$= 1420405751.6780 \pm .0016 + .1032 \text{ Hz.}$$

Rounding off,

$$\nu_H = 1420405751.781 \pm .002 \text{ Hz.}$$

If $\pm 1 \times 10^{-11}$ is allowed for error in the Cesium Standard and $\pm .5 \times 10^{-11}$ for error in the Hydrogen Maser (independent measurements on both the Cesium Standards and Hydrogen Masers indicate these are conservative error estimates), the final result, combining the errors as random, is:

$$\nu_H = 1420405751.781 \pm .016 \text{ Hz}$$

in the A-1 time scale.

This agrees well with the results quoted by the Harvard group[1] and the Neuchatel group.[2]

[1] S. B. Crampton, D. Kleppner, and N. F. Ramsey, **Phys. Rev. Letters** 11, 338 (1963).
[2] Laboratoire Suisse de Recherches Horlogeres Neuchatel Report No. 08-64-02 E.

The ratio desired is:

$$\frac{\nu_{Cs}}{\nu_H} = \frac{9192631770}{1420405751.781}(1 \pm 1.1 \times 10^{-11})$$

$$= 6.471\,835\,078\,444\,(1 \pm 1.1 \times 10^{-11}).$$

These measurements were made at the International Conference on Chronometry held in Lausanne, Switzerland, on June 10, 1964. Dr. J. Bonanomi recognized the possibility and made the suggestion that the measurement could be done and would be useful. Participants in the measurement were Dr. J. Holloway and H. Peters of Varian Associates and A. Bagley and the undersigned of Hewlett-Packard.

—*Leonard S. Cutler*

TABLE I

Data Point No.	-hp- 5214L Reading $N = 10^8 - \Delta$	Δ	Δ^2
1	(10^8-10)	10	100
2	(10^8-11)	11	121
3	(10^8-5)	5	25
4	(10^8-6)	6	36
5	(10^8-7)	7	49
6	(10^8-6)	6	36
7	(10^8-7)	7	49
8	(10^8-5)	5	25
9	(10^8-10)	10	100
10	(10^8-12)	12	144
		$\Sigma\Delta = 79$ $\overline{\Delta} = 7.9$	$\Sigma\Delta^2 = 685$ $\overline{\Delta^2} = 68.5$

$\overline{N} = 10^8 - \overline{\Delta} = 99{,}999{,}992.1 \equiv$ Mean of ten readings.

$$\sigma = \sqrt{\overline{N^2} - \overline{N}^2} = \sqrt{\overline{\Delta^2} - \overline{\Delta}^2} = \sqrt{68.5 - 62.41}$$

$= 2.47 \equiv$ Standard deviation

$$\frac{\sigma}{\sqrt{n}} = \frac{2.47}{\sqrt{10}} = .78 \equiv \text{Standard deviation of the mean}$$

TABLE 2

$\Delta\nu_{\text{wall}} = -.043$ Hz*

$\Delta\nu_{\text{mag field}} = +.0018$ Hz*

$\Delta\nu_{\text{Second order doppler}} = -.062$ Hz (45° Bulb temp.)

$\Sigma\Delta\nu = -.1032$ Hz

$\Delta\nu$ is the shift from the free atom frequency ν_H

i.e.: $\Delta\nu = \nu - \nu_H$, where ν is the measured frequency.

*Data supplied by Varian Associates.

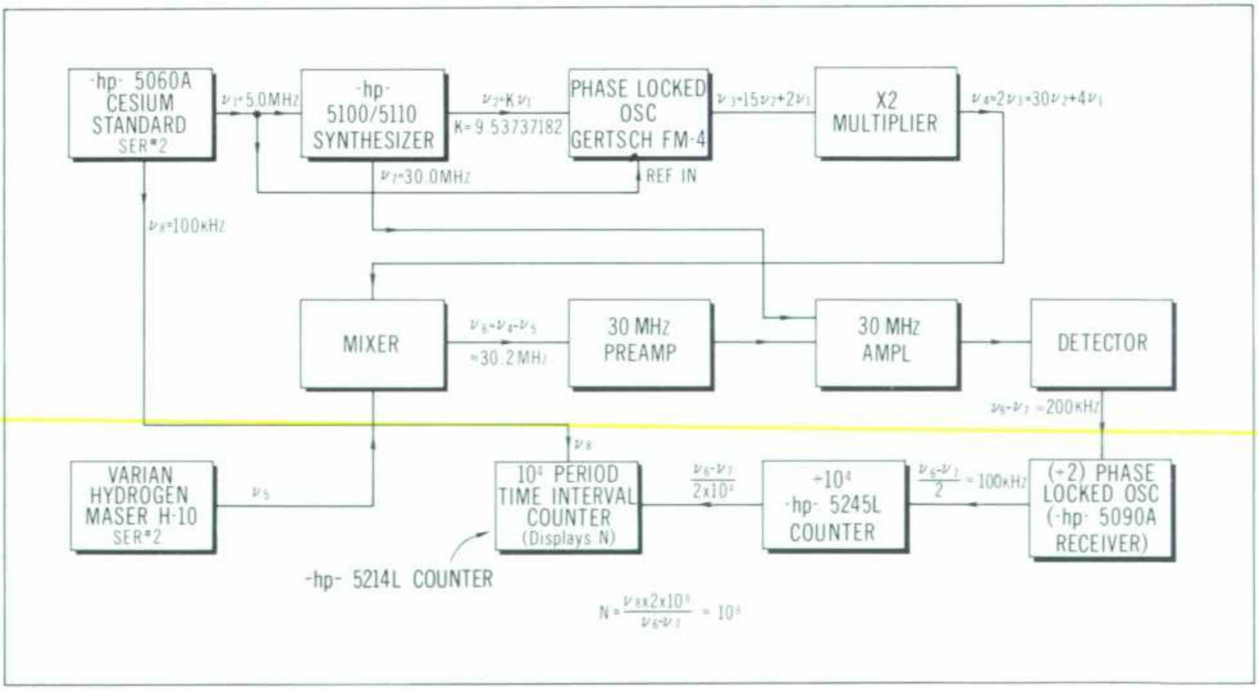


Fig. 1. *Block diagram of equipment arrangement used to measure ratio of output frequencies of Cesium Beam Frequency Standard and Hydrogen Maser.*

Fig. 7. *Front view of Cesium Beam Frequency Standard. Cesium beam standards utilize a quantum-mechanical effect to produce ultra-stable frequencies. Two standards were combined with electronic clocks and power supplies to form an "atomic" clock with stabilities of a few parts in 10^{12}.*

cesium-beam standards and found to be in agreement with them within a few parts in 10^{12}, the second series of measurements being made after a trip of ten thousand miles and an elapsed time of some 13 days.

(d) The two –*hp*– standards agreed with one another within a few parts in 10^{12} after the full trip.

(e) A measurement to high precision was made to compare the frequencies of a hydrogen maser and a cesium beam standard.

(f) Lastly, it is understood that the results of the time measurements will be used to obtain better synchronization by the various agencies in the United States and Europe.

The standards operated without flaw for the full trip, although one associated circuit suffered an electronics failure and momentary loss of power. This invalidated the clock reading of that unit but did not affect the accuracy of the cesium-beam tube, as indicated by the final frequency readings made at NBS, Boulder.

Many people contributed generously of their efforts to the experiment. These include Dr. George E. Hudson, David Allen, and James Barnes of the Bureau of Standards, Boulder; Dr. Wm. Markowitz and C. A. Lidback of the U. S. Naval Observatory, Washington; Dr. Jacques Bonanomi, Director of the Observatoire de Neuchatel; and Dr. Peter Kartaschoff of the Laboratoire Suisse de Recherches Horlogeres Neuchatel. LaThare N. Bodily of the –*hp*– Frequency and Time Division made many measurements on the Washington-to-Palo Alto portion of the experiment. Appreciation is expressed to –*hp*–'s Frequency Standard Group in preparing the equipment needed for the experiment.

Special thanks are also given to the people of United Air Lines and Swissair who made the needed arrangements.

— Alan S. Bagley and Leonard S. Cutler

Copies of the paper, "A Modern Solid State Portable Cesium Beam Frequency Standard," presented to the International Conference on Chronometry, are available from the editor, **Hewlett-Packard Journal.**

AUTHORS

Alan S. Bagley

Al Bagley became affiliated with –hp– while earning his MS degree at Stanford University in 1949. His first project was the development of a high-speed scaler, and he subsequently became project leader on a program applying the scaler circuitry to a frequency counter, leading to the industry's first high-speed counter, the –hp– Model 524A. He has been project leader on many of –hp–'s first generation of counters and also on the well-known –hp– 560 series digital recorders. In 1958, he was appointed engineering manager of the electronic counter group in the –hp– R and D Department and later became manager of the –hp– Frequency and Time Division when that activity assumed divisional status.

Leonard S. Cutler

Len Cutler joined Hewlett-Packard in 1957, following several years of experience in development supervision of frequency-measuring instruments. At –hp– he has been section leader of the frequency standards group and was responsible for development of the –hp– high frequency counter time bases. He was also responsible for the development of the –hp– Models 103, 104, 106, and 107 Frequency Standards and the –hp– 5060A Cesium Beam Standard. At present, he is director of quantum electronics in –hp–'s Physics Research and Development Group. He holds a BS and MS in physics from Stanford University and is presently completing work on his doctorate in physics.

PLANT DISTRIBUTION OF A ONE-VOLT DC STANDARD

DC test voltages accurate to within ±10 microvolts for calibrating precision digital voltmeters are supplied to production lines by a dc voltage distribution system.

DIGITAL voltmeter accuracy has improved to the point that laboratory precision is a necessity during final production checkout of these instruments. Voltage sources for production line checkout now must have accuracies that are within about 10 parts per million if they are to be sufficiently more accurate than the voltmeters themselves. To maintain voltages of this accuracy at test stations on the DY-2401B Digital Voltmeter production line, the Dymec Division of Hewlett-Packard has developed a highly precise reference voltage distribution system that is of particular interest.

A separate voltage source on each production line is satisfactory so long as the voltage sources are an order of magnitude more accurate than the voltmeter specifications. With accuracies of 10 parts per million now being called for, however, the maintenance of separate voltage standards on the production line becomes difficult. Loading problems, temperature variations, and other variables in normal day-to-day handling all affect the accuracy of highly precise voltage standards.

To overcome these problems, the technique of distributing a single

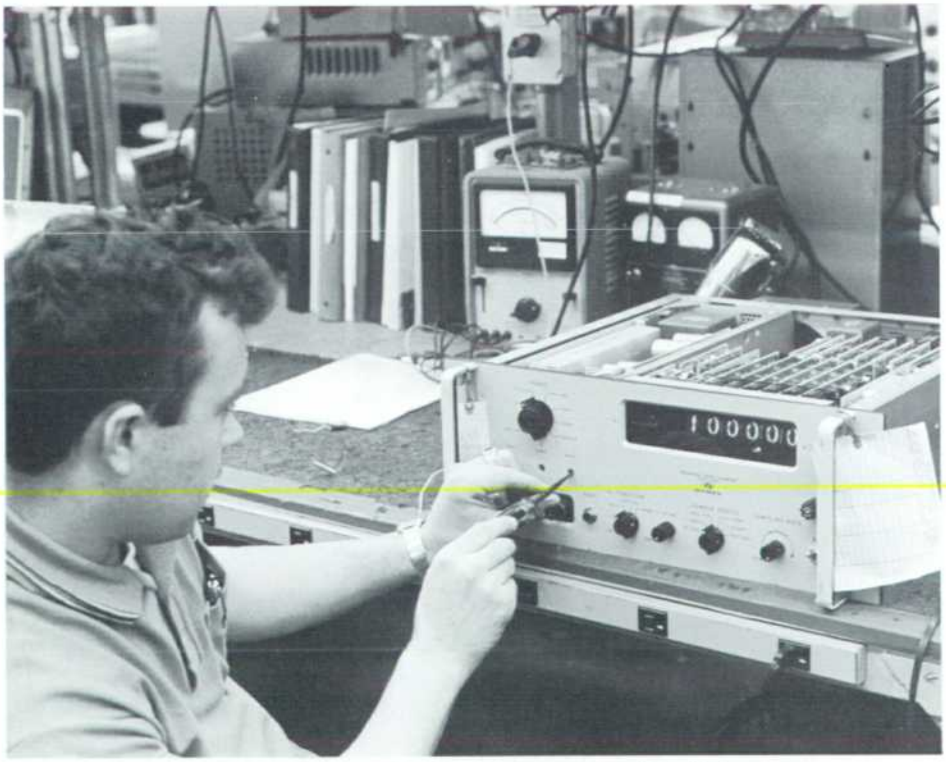


Fig. 1. *Standard voltage distribution system makes high accuracy standard voltages available to each test station on digital voltmeter production line.*

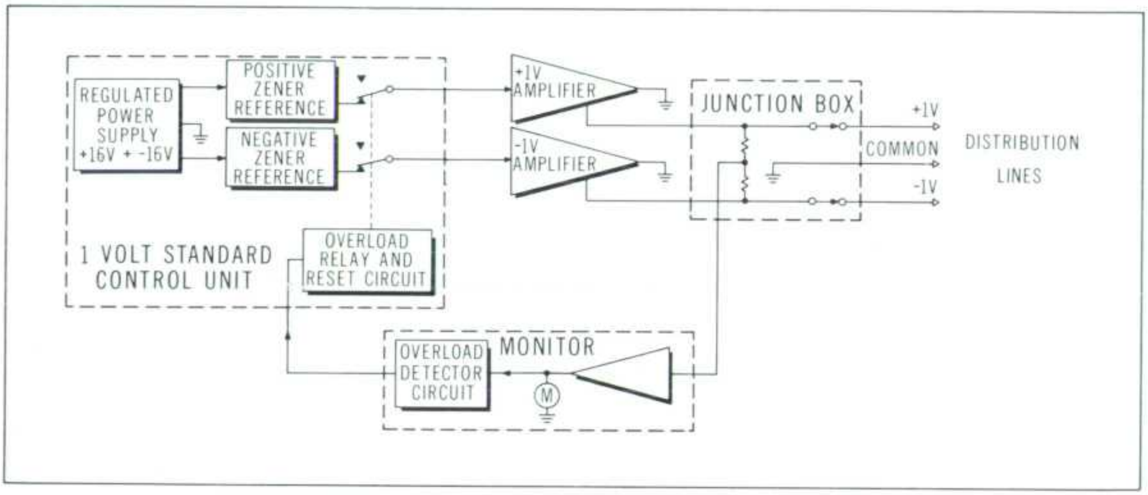


Fig. 2. *Block diagram of ±1 v driving source of standard voltage distribution system.*

reference through cables was borrowed from the widely-used method of distributing standard frequencies. With such a distribution system, all test stations can be supplied from a single high-precision voltage standard which is maintained within the controlled environment of a standards laboratory.

Successful operation of such a system requires assurance that voltage accuracy is not degraded by the distribution system. This assurance was made possible by the Dymec 2460A DC Amplifiers,[1] which are used as the distribution amplifiers. The 2460A amplifiers are highly stable operational amplifiers that drift less than 1 μv/week at a constant temperature and have a temperature coefficient of only 0.5 μv/°C referred to the input summing point. These amplifiers, when used with the isolation plug-in feedback network that provides a gain of +1 (the Dymec M4 gain unit), have an output impedance of less than 50 milliohms. Loading of the distribution lines therefore has negligible effect upon the amplifier output voltage. At the same time, the amplifier input impedance is over 10,000 megohms. The amplifiers therefore do not load the nominal 8,000 ohm impedance of the zener diode voltage reference sources.

[1] Robert J. Strehlow, "A Solid-State Operational Amplifier Of High Stability," **Hewlett-Packard Journal**, Vol. 14, No. 3-4, Nov.-Dec., 1962.

Fig. 3. *Dymec Model 2401B Integrating Digital Voltmeter has internal calibration source with stability of ±0.01% per six month period to match voltmeter's high accuracy. Programmable voltmeter has five ranges, from ±0.1 to ±1000v full scale, with 300% overranging on four most sensitive ranges for increased resolution and sensitivity on 1-to-3 readings. Guarded, floating input provides high common mode noise rejection; integrating operation averages out superimposed noise and completely eliminates effect of power line hum to retain high accuracy in presence of noise. Overall instrument common-mode rejection is 140 db (10 million to 1) at all frequencies, including dc.*

Fig. 4. *Standard voltage driving source is installed in controlled environment in standards laboratory.*

THE DISTRIBUTION SYSTEM

The complete reference voltage distribution system is shown in the block diagram of Fig. 1. Both +1 volt and —1 volt references are supplied to the test stations through conductors in steel electrical conduit.

The resistance of the conductors was recognized as a possible source of inaccuracies. Loop resistance of either channel to the most remote outlet, however, was found to be only about 0.2 ohm. This means that as many as 10 DY-2401B Digital Voltmeters (on the 1-volt range) connected in parallel to the system for simultaneous testing would not affect the voltage at the output terminals by even as much as 0.0003%.

Thermal voltages (Seebeck and Thomson effects) in the distribution system have been found to be negligibly small. To check this, the standard was disconnected, the lines were short-circuited at the supply end, and the voltage measurements were made at several places in the test area. The measurements showed all thermal and galvanic voltages to be less than 2 microvolts. The uniform temperature of the air-conditioned plant undoubtedly helps to keep this figure low.

System capacitance was measured and found to be near .003 microfarads. This distributed capacitance, along with the shielding provided by the steel conduit, holds transient effects and pickup noise to negligible levels. Furthermore, to eliminate ground loops, the neutral wire is connected to the ground point only at the distribution box located in the Dymec Standards Laboratory.

OVERLOAD DETECTOR

System performance is monitored continuously by an overload detector. The +1 v and —1 v amplifier outputs are connected together through a pair of equal-value resistors, as shown in the block diagram. The summing point at the resistor junction is at ground potential when both voltage references are operating satisfactorily. Should either reference voltage change, because of accidental shorts or ground loops or equipment malfunctions, the summing point voltage moves off the ground, and this voltage change is amplified by another dc amplifier which in turn drives the overload-reset circuit. Circuit parameters are such that a 10-microvolt change in either reference voltage with respect to the other activates the overload relay. The relay disconnects the amplifiers from the laboratory reference and illuminates an overload indicator. A thermal delay then restores system operation after one minute, unless the fault remains.

STABLE REFERENCE SOURCES

The reference voltages are supplied by 3-stage zener-stabilized voltage dividers driven by a 16-volt regulated voltage supply. The dividers employ selected zener diodes of the same type used in the 1-volt reference of the Dymec 2401B Digital Voltmeters. These diodes are low temperature coefficient devices that have been aged for approximately 1,000 hours. During aging, diode breakdown voltages are monitored to determine the degree of voltage stability for selection purposes.

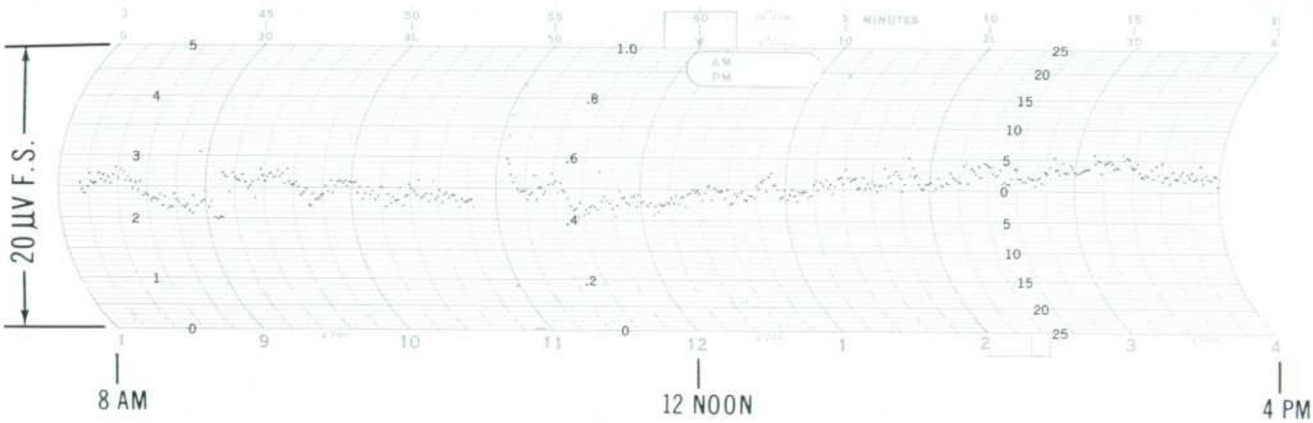


Fig. 5. *Graph plots voltage at resistive summation point between +1v and −1v outputs to show stability of standard voltage system during typical working day. Chart scale is 20 µv from edge to edge. System overload trips whenever voltage moves ±10 µv from center of chart. Overload shown at 10:50 am was caused by ground loop formed when guard shield of voltmeter under test was accidentally shorted to chassis ground.*

The resistors in the zener diode reference also have low temperature coefficients and they were aged artificially to achieve stability. Any residual long term drift can be corrected by small trimming resistors in the output circuit and the controlled temperature of the Dymec Standards Laboratory further minimizes temperature effects. The maximum output voltage deviation caused by component drift has been found to be less than 3 microvolts over a one-month interval.

The reference voltages at the amplifier outputs are calibrated daily to a resolution of better than ±1 microvolt against a standard cell in the Dymec Standards Laboratory. The standard cell likewise is calibrated daily against a bank of saturated cells which are traceable directly to NBS.

With the frequent calibration, and the inherent long term stability of the entire system, overall accuracy of the Dymec 1-volt distributed standard during normal usage is well within the stated design goal of ±10 PPM.

ACKNOWLEDGMENTS

The original design of this system was conceived by Dale F. Ridenour, Wiring, Assembly and Test Manager, and George Brown, Engineer. The overload detection and reset circuitry was developed by James L. Robertson, Senior Test Engineer.

—Richard Bean
Dymec Quality
Assurance Manager

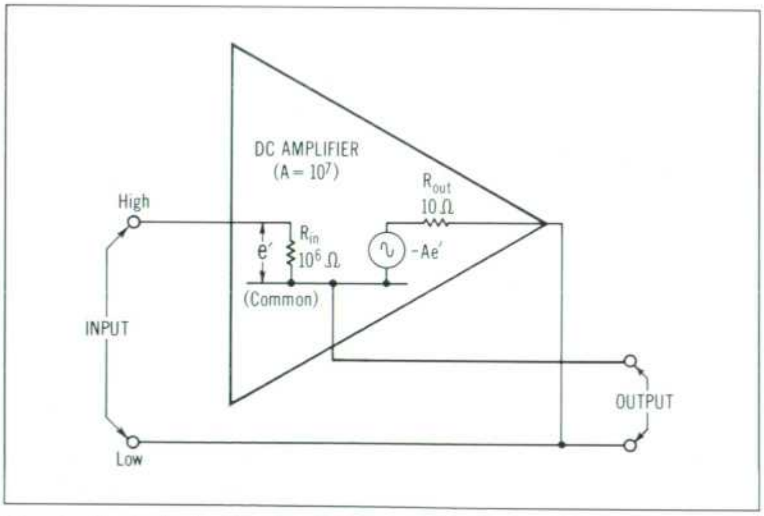


Fig. 6. *Equivalent circuit of Dymec 2460A Amplifier with isolation plug-in (M4). Plug-in converts amplifier to "amplifier-follower," analogous to cathode-follower, with exceptionally high input impedance and very low output impedance. Any change of voltage e′ results in equivalent generator voltage change of −Ae′ so that amplifier "Common" bus follows input voltage closely. Resistor R_{in} therefore draws negligible current and appears to be greater than 10,000 Megohms to input.*