HEWLETT-PACKARD JOURNAL
TECHNICAL INFORMATION FROM THE -hp- LABORATORIES
CORPORATE OFFICES • 1501 PAGE MILL ROAD • PALO ALTO, CALIFORNIA 94304 • VOL. 16 NO. 8, APRIL 1965

Correlating Time from Europe to Asia with Flying Clocks

By means of portable cesium-beam clocks, time has been correlated to 1 microsecond at many of the world's timekeeping centers. A comparison of four of the world's best-known 'long-beam' frequency standards has also been made.

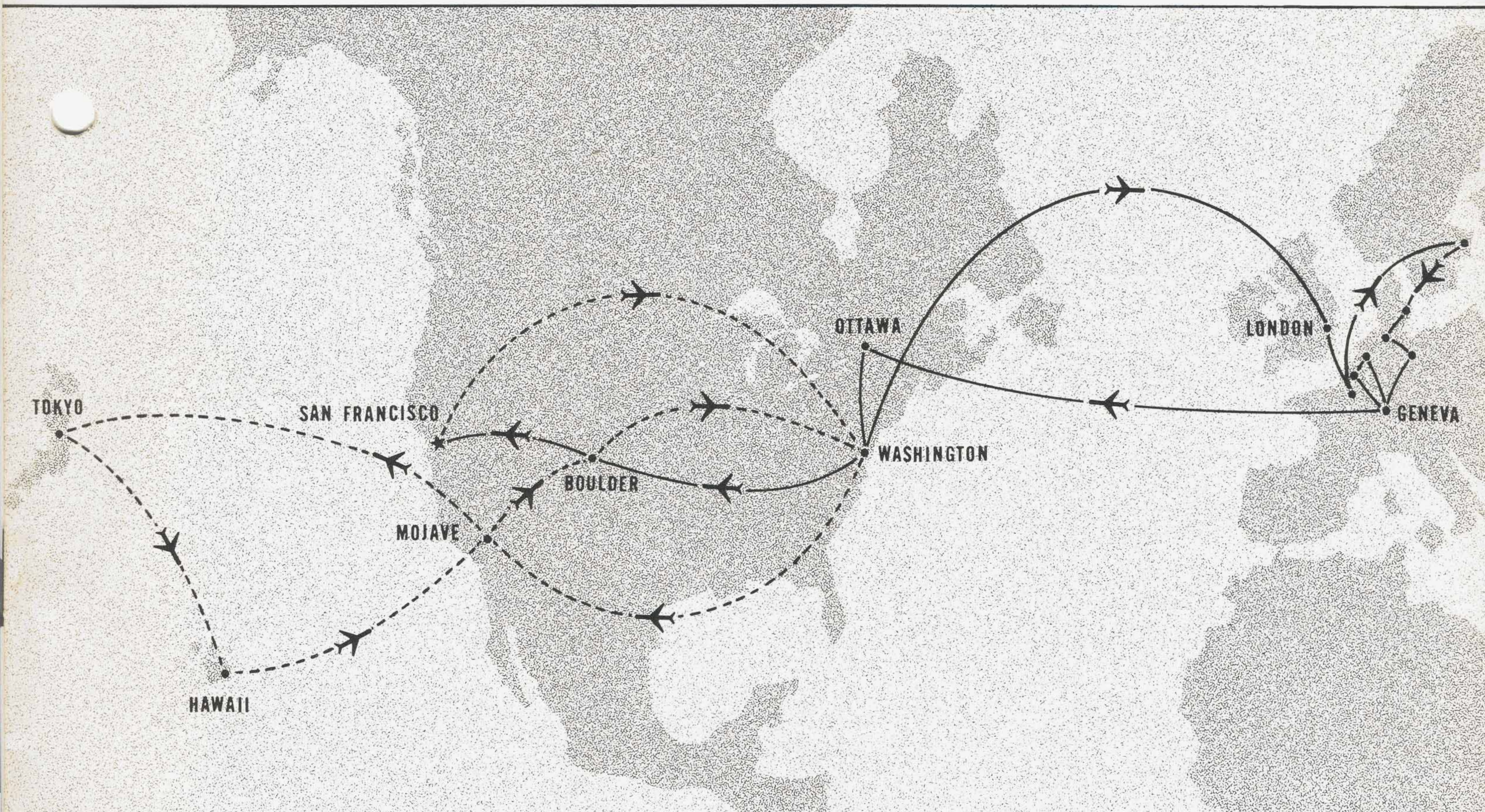


Fig. 1. *Precision 'atomic' clocks were transported to 11 countries in 35 days to correlate time at 21 facilities.*

PRINTED IN U. S. A.

Fig. 2 (at left). *Dr. Yoshikazu Saburi (center) of Radio Research Labs, home of Standards Broadcast Station JJY, Japan, discusses time and frequency measurement results with –hp– engineers Richard Baugh and Lee Bodily.*

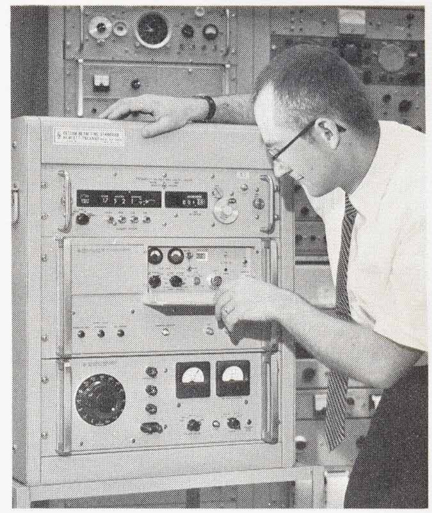


Fig. 3. *Operation of traveling cesium-beam clock is checked by –hp– Engineer Richard Baugh before start of ocean-spanning journey. Cesium-Beam Frequency Standard (middle instrument) has self-checking feature that enables adjustment of cesium-beam resonator for correct operation without reference to any other frequency standard.*

THE FEASIBILITY of transporting compact 'atomic' clocks in continuous operation to distant points by commercial airliner or other conventional transport was established by a flying clock experiment performed in the summer of 1964.[1] That experiment correlated the time of day within a microsecond between the Observatoire de Neuchâtel in Switzerland and both the U. S. Naval Observatory and the National Bureau of Standards in the United States. It also established within 200 microseconds the propagation time of radio timing signals from Beltsville, Md., to Neuchâtel, and it provided an opportunity for intercomparing laboratory-constructed 'long-beam' cesium frequency standards by way of the traveling cesium-beam standards.

A new flying clock experiment has now been performed with the traveling cesium-beam clocks, an experiment that involved more time-keeping centers than any clock correlation experiment conducted so far. Standards facilities in Japan, Hawaii, Canada, and most of the countries of western Europe were visited in the experiment. In all, time and frequency were correlated at 21 different facilities in 11 different countries.

As a result of the experiment, time scales maintained by widely-separated timekeeping laboratories have been correlated within a microsecond, an accuracy far higher than that possible by high-frequency radio broadcasts of time signals which, at intercontinental distances, have only been able to achieve accuracies in time comparisons of about 1 millisecond at best. Indicative of the accuracy achieved in the latest flying-clock experiment, one of the portable clocks changed less than 10 μsec during the 29 days between two measurements made with respect to the Master Clock at the Naval Observatory, which establishes Universal (Earth rotational) time in the United States. The other clock changed *less than 1 μsec* in a 23-day period with respect to the NBS UA Time Scale, a time scale based on Atomic time but offset slightly to approximate Universal time.

The experiment repeated the comparison made last summer between time scales in the United States and that maintained by the Observatoire de Neuchâtel in Switzerland, but in so doing, it provided further information by disclosing any relative drift in the time scales. As described later, the comparison shows excellent agreement between the time scales of the Observatoire de Neuchâtel and the National Bureau of Standards in Boulder, Colorado, the two scales being within 50 microseconds of the first comparison made eight months ago. This is equivalent to an average frequency difference of 2.1 parts in 10^{12}.*

Another accomplishment of the experiment was the verification of results obtained in a U. S. Navy time synchronization experiment conducted by way of the satellite Relay II. The experiment was conducted between the Minitrack Radio Tracking Station at the Goldstone tracking site in the California Mojave Desert and the tracking station operated for NASA at Kashima, Japan, by the Japanese Radio Research Laboratories. Preliminary results from the U. S. Naval Observatory indicate that the experiments, which also used VLF transmissions from NLK/NPG, Jim Creek, Washington, confirm that communications satellites may be used to synchronize clocks to high precision at facilities equipped with satellite tracking antennas.[2]

The experiment provided an opportunity for frequency comparisons between the traveling standards and four laboratory-constructed "long-beam" cesium standards, five commercially-built cesium-beam standards, and also one hydrogen maser. The intercom-

[1] Alan S. Bagley and Leonard S. Cutler, "A New Performance of the Flying Clock Experiment," **Hewlett-Packard Journal**, Vol. 15, No. 11, July, 1964.

* To place this in perspective, it is noted that 2 parts in 10^{12} is equivalent to a length of one foot in the 93,000,000 miles between Earth and Sun.

[2] W. Markowitz and C. A. Lidback, "Clock Synchronization via Relay II, Preliminary Report," Proceedings of the 19th Annual Symposium on Frequency Control, 1965, to be published.

parisons of cesium-beam standards — standards that were independently designed and constructed at widely-separated points of the globe — provided further evidence that cesium-beam resonators are primary frequency standards of extreme accuracy. For instance, the results of a frequency comparison between the cesium-beam standard in one of the traveling clocks and the 4-meter cesium-beam standard of the Swiss Horological Research Laboratory (Laboratoire Suisse de Recherches Horlogères) in Neuchâtel, considered to be one of the most accurate frequency standards in the world, agreed within 1 part in 10^{11} with a comparison between the same traveling standard and one of the long-beam cesium standards (NBS II) at the National Bureau of Standards in Boulder, Colorado. Two separate comparisons made 29 days apart between the traveling standard and NBS II agreed within 1 part in 10^{12}. This performance attests to the stability and reliability of portable cesium standards in a traveling environment, as well as confirming the fundamental accuracy of cesium resonators.

CESIUM-BEAM CLOCKS

Clocks driven by quartz crystal oscillators have been used in many traveling-clock time synchronization experiments. Higher accuracy is obtained with clocks controlled by atomic resonators, however, because the microwave spectral lines characteristic of certain atoms are fundamental physical constants that can be reproduced by independent means anywhere on earth without reference to another primary standard. Most of the world's frequency standards now use cesium-beam resonators as an absolute reference since a certain cesium spectral line at present provides the most practical means for controlling frequency by a fundamental atomic constant. The International Fundamental Unit of Time (the Atomic Second) is based on this particular cesium transition frequency.

Until recently, however, atomic clocks required the use of cargo planes for air transportation because of their size and power requirements. Newly-developed compact cesium-beam frequency standards, because of their relatively small size and modest power requirements, now make it possible to transport atomically-controlled clocks by conventional carriers. The clocks used in the experiment described here were each controlled by an -*hp*- Model 5060A Cesium-Beam Frequency Standard, a relatively small, lightweight (65 lbs.) instrument requiring minimum power (40W at 26 V dc) but nevertheless capable of high accuracy ($\pm 2 \times 10^{-11}$) and long term stability ($\pm 1 \times 10^{-11}$).*

The traveling clocks each used an -*hp*- Model 115BR frequency divider to integrate frequency and display time. The Model 115BR also generates a 25-μsec pulse once per second for measurements of the time correspondence between it and another clock.

The Frequency Standard and Clock were powered by special power supplies, designed for the clock experiment, which contain rechargeable nickel-cadmium batteries capable of powering the instruments for several hours. The power supplies can also power the instruments and recharge the batteries when operating from ac sources ranging from 100 volts to 280 volts at any frequency from 50 to 400 c/s, or from 6 or 12-V dc sources. The

* These Standards use a compact cesium-beam tube developed especially for them by the Quantum Electronics Division (Bomac) of Varian Associates, under contract to Hewlett-Packard.

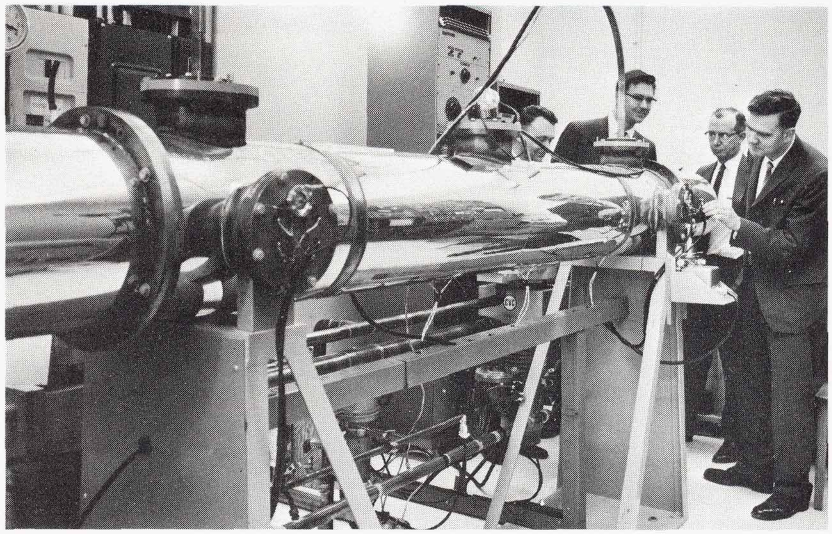


Fig. 4. *"Long-beam" cesium resonator at National Research Council, Ottawa, Canada, is typical of high-precision, laboratory-constructed frequency standards intercompared during flying-clock experiment. Cesium-beam standards in both traveling clocks agreed with this standard to better than 1 part in 10^{11}.*

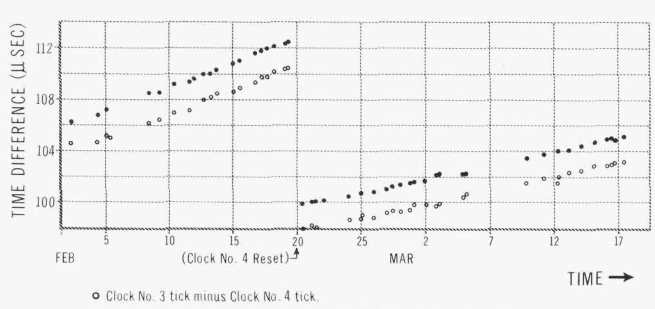


Fig. 5. *Time displacement between once-per-second "ticks" produced by flying clocks as measured during trip. Phase displacement between 100-kc/s outputs of Cesium Beam Frequency Standards was also measured to provide correction factor for any phase shifts in clock frequency dividers. Discontinuity on Feb. 20 results from restart of Clock No. 4 (see text). Slope of graph during March indicates that clocks agreed within 2.4 parts in 10^{12}. During February, slope is equivalent to 4 parts in 10^{12}, well within specified accuracy of clocks.*

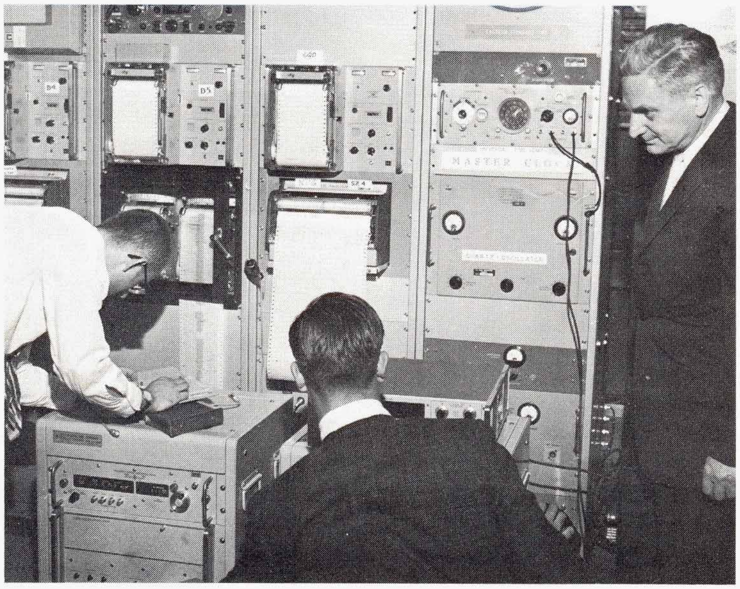


Fig. 6. *Time kept by traveling clocks is compared to Master Clock at U. S. Naval Observatory, which establishes time in United States, by –hp– engineers Baugh and Bodily and by William Markowitz, Director of Time Service Division of U. S. Naval Observatory. Time of once-per-second ticks of traveling clocks, which had been set according to –hp– House Standard three days earlier, differed from time of Naval Observatory ticks by less than 80 μsec.*

instruments may also operate, without recharging the batteries, from 24-V dc sources. Thus it was possible to power the clocks from the aircraft on which they were flown, from storage batteries or automobile electrical systems, from commercial power lines anywhere in the world, or, when necessary, from the internal batteries.

MEASUREMENT TECHNIQUES

Time scales were correlated by measuring the time displacement between the one-second electrical "ticks" generated by the two clocks being compared. Electronic counters were used to measure the time interval between ticks with a resolution of approximately 0.1 μsec.

Frequency comparisons were made in some cases by measuring the phase difference between waveforms produced by the two standards being compared. A plot of many of these measurements over a period of time showed the relative frequency drift of the two standards.

TABLE 1. OVERSEAS FACILITIES VISITED DURING FLYING-CLOCK EXPERIMENT

PLACE	FACILITY	COMPARISONS TIME	COMPARISONS FREQUENCY
Koganei, Japan	Standard Broadcast Station JJY	x	x
Kashima, Japan	RRL Tracking Station	x	
Maui, Hawaii	Standard Broadcast Station WWVH	x	
Herstmonceux Castle, Eng.	Royal Greenwich Observatory	x	
Teddington, England	National Physical Labs	x	x
Bagneux, France	National Center for Communication Studies (CNET)	x	x
Paris, France	Paris Observatory	x	x
Stockholm, Sweden	Swedish Nat'l Defense Research Institute	x	x
Copenhagen, Denmark	Royal Danish Air Force Calibration Centre	x	
Hamburg, Germany	German Hydrographic Institute (DHI)	x	
Braunschweig, Germany	National Bureau of Physics and Technology (PTB)		x
Neuchâtel, Switzerland	Swiss National Observatory	x	x
Neuchâtel, Switzerland	Swiss Horological Research Lab		x
The Hague, the Netherlands	Post Telephone and Telegraph	x	
Brussels, Belgium	Royal Observatory of Belgium	x	
Ottawa, Canada	National Research Council		x

In other cases, a beat note was derived from the outputs of the two standards, after the outputs had been multipled to higher frequencies for greater measurement resolution. Repeated measurements of the period of the beat note provided data which were analyzed statistically to show the nature of short term frequency deviations as well as the frequency offset between the two standards.

INITIAL ADJUSTMENTS

The experiment actually started on Feb. 2, 1965 at Palo Alto, California, where the Cesium-Beam Standards in the two clocks which made the trip were aligned independently of one another. The cesium-beam "C" field, the weak magnetic field that splits up and separates cesium microwave spectral lines into groups of extremely narrow lines,[3] is adjusted by an alignment procedure that uses the cesium-beam tube to check on its own performance. Each Cesium-Beam Frequency Standard was thus aligned independently, by adjustment of the "C" field to the exact value required, without reference to any other standard.

The internal frequency synthesizers, which derive the 9192-Mc/s cesium resonance frequency from the servo-controlled 5-Mc/s oscillator output, were set to introduce a frequency offset of -150×10^{-10}. Thus, the 0.1, 1, and 5-Mc/s outputs of the Cesium-Beam Standards, and therefore the Clocks themselves, were offset −150 parts in 10^{10} with respect to Atomic Time. The Clocks were thereby set to an approximation of UT2 time, a time scale based on the rotation of the earth and the time scale maintained by most time-keeping institutions.

The clocks were then set to the WWV-referenced time maintained by the *–hp–* Standards Lab. The once-per-second time ticks generated by the clocks were, however, offset 100 microseconds with respect to each other to simplify time interval comparisons between the clocks themselves. (The clocks are referred to as Clocks No. 3 and No. 4 to distinguish them from

[3] Leonard S. Cutler, "Examination of the Atomic Spectral Lines of a Cesium-Beam Tube with the –hp– Frequency Synthesizer," **Hewlett-Packard Journal,** Vol. 15, No. 4, Dec., 1963.

Clocks Nos. 1 and 2 which were used in the previous experiment.)

THE JOURNEY

The route of the recent flying-clock experiment is diagrammed in Fig. 1 and the overseas facilities visited are summarized in Table I. The clocks were flown on Feb. 5, 1965 to the U. S. Naval Observatory in Washington, D. C., for a measurement of the difference between time as kept by the traveling clocks and the time kept by the master clock at the Naval Observatory, which defines time in the United States. The cesium-beam standards were also compared in frequency to a hydrogen maser maintained by the Naval Research Laboratory.

The clocks then traveled to the tracking station in the Mojave Desert for a time comparison and thence to Japan. Frequency and time comparisons were made at JJY, the Japanese Standards Broadcast Station, and one clock was taken to the Kashima tracking site for a time comparison.

On returning from Japan, a stop was made in the Hawaiian Islands for a time comparison with NBS standard broadcast station WWVH. The clocks were then returned to the Mojave tracking station.

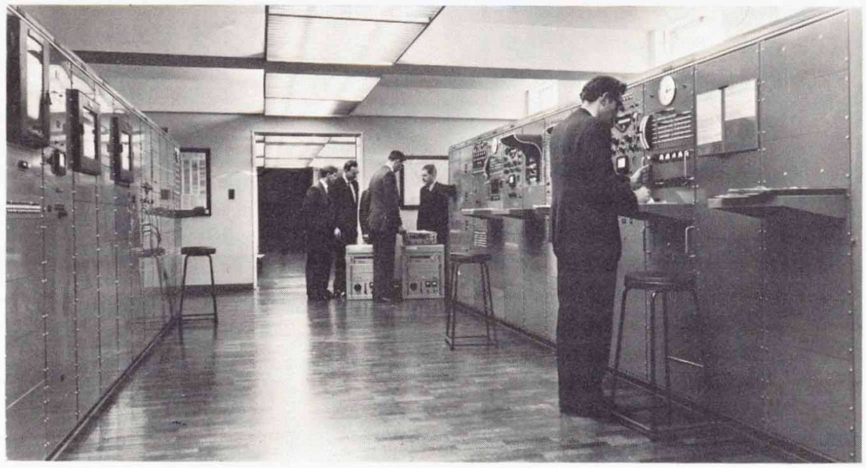
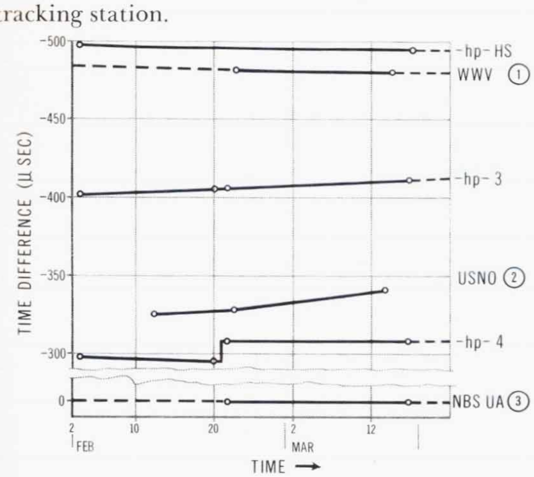


Fig. 8. *Traveling clocks arrive at Royal Greenwich Observatory, Herstmonceux Castle, England, home of Greenwich Mean Time.*

From the Mojave Desert, the clocks were taken to Boulder, Colorado, for time and frequency comparisons at the National Bureau of Standards. During transfer, however, Clock No. 4 experienced a transient condition which activated a warning lamp in the monitoring circuitry. Unfortunately, a defect in the lamp circuit shorted out the circuit and shut down the clock. This required a restart, including readjustment of the "C" field, after the malfunction was corrected, but, since time and frequency comparisons were made



① Offset about 500µ sec from NBS UA to facilitate measurements.
② Maintained with respect to Universal Time by astronomical observations.
③ Controlled by atomic transitions but with offset that approximates Universal Time.

Fig. 7. *Time displacement between clock times as determined by traveling clocks. Vertical scale shows time relationship of once-per-second "ticks" of indicated time standard with respect to "ticks" of NBS UA, which was arbitrarily selected as reference time scale. As described in text, –hp– House Standard (–hp– HS) is maintained in close agreement with WWV and traveling clocks (–hp– 3 and –hp– 4) initially were offset 100 and 200 µs respectively with respect to –hp– HS.*

TABLE II. COMPARISONS BETWEEN TIME SCALES AND ARBITRARILY SELECTED REFERENCE (NBS UA)

DATE	TIME (UT)	FACILITY	COMPARISON
2 Feb.	1906	–hp– House Standard	−498 µsec
12 Feb.	0251	U. S. Naval Observatory	−326 µsec
17 Feb.	0710	Radio Research Lab	+1001 µsec
17 Feb.	2340	WWVH	−231 µsec
21 Feb.	1608	Traveling Clock No. 3	−406.3 µsec
21 Feb.	1609	Traveling Clock No. 4	−308.2 µsec
22 Feb.	1333	U. S. Naval Observatory	−329 µsec
22 Feb.	1743	WWV	−483 µsec
24 Feb.	1302	Royal Greenwich Obs.①	+5019 µsec
25 Feb.	1428	Nat'l Physical Labs②	+705 µsec
26 Feb.	1012	Centre Nat'l d'Et. Tele.	−242.198 ms
26 Feb.	1454	Paris Observatory	−752 µsec
27 Feb.	2246	Swedish Nat'l DRL	−883 µsec
2 Mar.	1243	Royal Danish AF Cal. Lab	+115.952 ms
3 Mar.	0817	Deutsche Hydro Inst.	−398.228 ms
5 Mar.	1027	Standard Broadcast HBN	+1353 µsec
11 Mar.	1630	Nat'l Res. Council③	+6 µsec
13 Mar.	1513	U. S. Naval Observatory	−342 µsec
14 Mar.	1603	WWV	−481 µsec
16 Mar.	1545	Traveling Clock No. 3	−411.9 µsec
16 Mar.	1544	Traveling Clock No. 4	−308.9 µsec
17 Mar.	0611	–hp– House Standard	−495 µsec

Results, determined by flying clocks, have been adjusted to account for constant time drift of traveling clocks, as determined by time closure at NBS, Boulder. Time scale differences, which may be as much as tenths of seconds, have been made large in many cases to facilitate measurements. In all cases, time differences have been known for some time but are now known more precisely because of flying-clock measurements.

[1] Maintained with 5-ms offset with respect to internationally-coordinated time signal broadcasts.
[2] Maintained on Atomic time.
[3] Clock set according to traveling clocks.

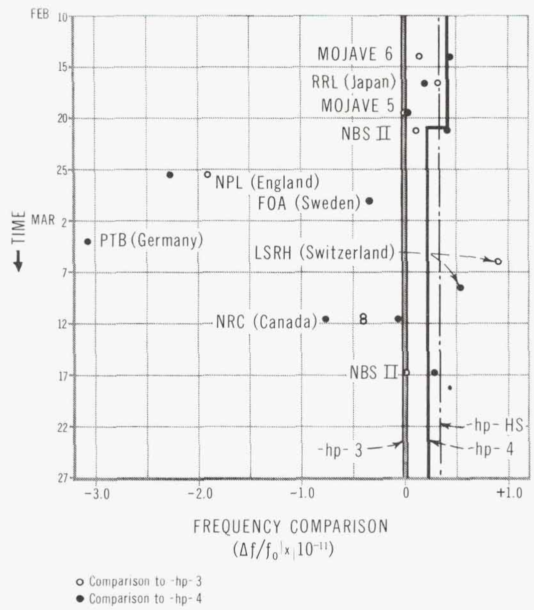


Fig. 9. *Frequency comparisons between traveling clocks and other cesium-beam standards are plotted here as frequency differences in parts per 10^{11}. Offset of -150×10^{10} of standards operating on Universal Time has been removed to show only fundamental frequency differences. Results of measurements on all standards shown are well within known accuracies of individual standards.*

between the clocks and NBS standards following restart, the shutdown did not affect subsequent measurements. The clocks were then returned to the U. S. Naval Observatory for a time closure. The clocks were also compared to time as maintained by the master clock at NBS station WWV.

The clocks then proceeded to London for a time comparison at the Royal Greenwich Observatory and a frequency comparison at the National Physical Laboratory. From London, the clocks were taken to the continent for time and frequency comparisons in the cities and facilities listed in Table I.

On returning from Europe, the clocks were taken to Canada for time and frequency comparisons at the National Research Council in Ottawa. They then returned to Washington for another time closure with the U. S. Naval Observatory and with WWV. The clocks then went to Boulder for yet another time closure and frequency comparison with NBS.

From Boulder, the clocks were returned to Palo Alto, California, to complete the loop for the entire journey. Comparisons were made once more with the Hewlett-Packard House Standard — 42 days after the clocks had been set prior to the start of the trip.

RESULTS

Measurements of the time displacement between the one-second ticks of an arbitrarily selected reference time scale and the time scales of various time-keeping centers are summarized in Table II. The figures given are determined from the actual time displacement measured with the traveling clocks as corrected for the known difference between the flying clocks and the reference scale at the time of measurement. Assuming a constant drift rate for the traveling clocks, this difference is known to high accuracy because of the time closure that was made with the reference scale, in this case the NBS UA time scale.

Frequency comparisons are summarized in Table III and diagrammed in Fig. 9. As was true of the traveling standards, those standards denoted in Table III as being maintained with respect to UT2 time were arranged to generate standard frequencies offset —150 parts in 10^{10} with respect to

TABLE III. COMPARISONS BETWEEN CESIUM-BEAM FREQUENCY STANDARDS AND TRAVELING CLOCKS

Date (1965)	Local Standard	Type	Comparison Results† vs. –hp– Clock No. 3	Comparison Results† vs. –hp– Clock No. 4	Measurement
Feb. 13	Mojave No. 6*	12.4 cm Commercial	-1.5×10^{-12}	-0.3×10^{-12}	11-hr phase comparison at 100 kc/s
Feb. 19	Mojave No. 5*	12.4 cm Commercial	0×10^{-12}	$+3.8 \times 10^{-12}$	6-hr phase comparison at 100 kc/s
Feb. 16–17	RRL (Japan)*	12.4 cm Commercial	-3.3×10^{-12}	$+2.2 \times 10^{-12}$	28-hr phase comparison at 100 kc/s
Feb. 20	NBS II (Boulder)	164 cm Lab type	$-(150.012 \pm .018) \times 10^{-10}$	$-(150.018 \pm .012) \times 10^{-10}$	29 samples (with –hp– Clock No. 3) 33 samples (with –hp– Clock No. 4) 200 seconds each
Mar. 16	NBS II (Boulder)	164 cm Lab type	$-(150.002 \pm .013) \times 10^{-10}$	$-(150.005 \pm .011) \times 10^{-10}$	57 samples (with –hp– Clock No. 3) 58 samples (with –hp– Colck No. 4) 200 seconds each
Feb. 25	NPL (Teddington)	277 cm Lab type	$-(149.81 \pm .03) \times 10^{-10}$	$-(149.75 \pm .03) \times 10^{-10}$	1-hr. phase comparison via Rb transfer standard
Feb. 28	Swedish Nat'l Def. Res. Lab.*	12.4 cm Commercial		$+5.1 \times 10^{-12}$	Via Rb transfer standard
Mar. 3–4	PTB (Germany)	90 cm Commercial		-149.67×10^{-10}	12-hr. phase comparison
Mar. 5–6	Swiss Horological Research Lab	408 cm Lab type	$-(150.09 \pm .04) \times 10^{-10}$		7-hrs averaging
Mar. 8	Swiss Horological Research Lab	408 cm Lab type		$-(150.03 \pm .08) \times 10^{-10}$	2-hrs averaging
Mar. 11	Nat'l Res. Council (Canada)	200 cm Lab type	$-(149.96 \pm .05) \times 10^{-10}$ $-(149.96 \pm .04) \times 10^{-10}$	$-(149.97 \pm .045) \times 10^{-10}$ $-(149.91 \pm .045) \times 10^{-10}$	20 samples 20.6 seconds each
Feb. 2–Feb. 19	–hp– Clock No. 3	vs. –hp– Clock No. 4	-4.14×10^{-12}		
Feb. 20–Mar. 17	–hp– Clock No. 3	vs. –hp– Clock No. 4	-2.4×10^{-12}		

* These standards are maintained with respect to UT2 time.
† Frequency offset $= (f_t - f_l)/f_l$, where f_t is frequency of traveling standard and f_l is frequency of local standard.

Atomic time. The diagram of Fig. 9 has been adjusted to account for the difference in time scales and reflects only the difference in the cesium-beam excitation frequencies.

The frequency comparisons at the National Physical Laboratories, England, were made at a time when improvements being made to the long-beam standard there were not yet complete. It is interesting to note, however, that the frequency comparisons show all the cesium-beam standards to be well within their present specified accuracy. Those of recent design are quite close, indicating a continuing improvement in the accuracy achieved by atomic beam frequency standards.

COMPARISON OF SWISS OBSERVATORY AND NBS TIME SCALES

As mentioned earlier, time between the Observatoire de Neuchâtel in Switzerland and the National Bureau of Standards in Boulder, Colorado, was correlated during this experiment as a continuation of the measurement conducted during the flying clock experiment in June, 1964.[1] The results of the earlier measurement are summarized as follows:

June, 1964

Flying Clock No. 1 leads NBS UA Time Scale by	1150 μsec
Station HBN* time ticks lead Clock No. 1 by	440 μsec
Neuchâtel Observatory Time Scale leads HBN time ticks by	170 μsec
Neuchâtel Observatory Time Scale leads NBS UA by	1760 μsec

* Swiss Standards Broadcast Station

The recent experiment provides information for comparing the two time scales over the elapsed time between experiments. The results of the 1965 comparison are as follows:

5 March, 1965

Clock No. 3 lags NBS UA Time Scale by	−409 μsec
HBN time ticks lead Clock No. 3 by	1762 μsec
Neuchâtel Observatory Time Scale leads HBN time ticks by	358 μsec
Neuchâtel Observatory Time Scale leads NBS UA by	1711 μsec by Clock No. 3
Clock No. 4 lags NBS UA Time Scale by	−309 μsec
HBN time ticks lead Clock No. 4 by	1662 μsec
Neuchâtel Observatory Time Scale leads HBN by	358 μsec
Neuchâtel Observatory Time Scale leads NBS UA by	1711 μsec by Clock No. 4

A comparison between the experiments on the two dates yields 1760 − 1711, or 49 μsec. Agreement within 49 μsec of the previous measurement 273 days earlier is equivalent to an average frequency difference of 2.1 parts in 10^{12}, certainly a remarkable result but in view of the fact that none of the frequency standards involved are judged to be this accurate, it can best be considered a fortuitous circumstance at the present time. Many more experiments will be required to establish the time correspondence with the potential accuracy of the measurement technique.

To provide the data necessary for time correlations on a long-term basis, Hewlett-Packard plans to repeat the flying clock experiments periodically.

CHECK ON VLF PHASE COMPARISONS

The Flying Clock Experiment also confirmed the usefulness of VLF Phase Comparisons[4] for maintaining accurate time, once that time between stations is definitely established. During August of 1964, the *-hp-* Standards Clock was set to agree very closely with WWV time by means of another flying clock. Since then, phase comparisons between the crystal oscillator which drives the clock, and the VLF standard frequencies broadcast by NBS stations WWVL and WWVB, have provided information for periodic readjustments of the oscillator, thus maintaining the clock in agreement with WWV time.

A measurement at Beltsville, Md., on Feb. 21, 1965 showed that traveling Clock No. 3 was 77 microseconds ahead of WWV-referenced time. From the known time drift of *-hp-* Clock No. 3, it was known that No. 3 was 90 microseconds ahead of the Hewlett-Packard Standards Clock on that date. The difference between the *-hp-* Clock and WWV on Feb. 21 is therefore 90 − 77 or only 13 microseconds. This close correlation, which was maintained over a 6-month period since establishment of time on the *-hp-* Standards Clock, was achieved by occasional readjustment of the clock oscillator according to information supplied by VLF phase comparisons. This demonstrates the usefulness of VLF phase comparisons for maintaining accurate time, once a time correlation is established.

[4] Dexter Hartke, "A VLF Comparator for Relating Local Frequency to U. S. Standards," **Hewlett-Packard Journal**, Vol. 15, No. 2, Oct., 1964.

TABLE IV. TIME CLOSURES

Comparisons derived by time closures performed in the recent flying clock experiment are shown in the following. The frequency difference is determined from time difference by the relationship: $\Delta f/f_o = -\Delta t/T$.

Traveling Clocks vs. U. S. Naval Observatory Master Clock

Feb. 22	Clock No. 4 leads U. S. N. Observatory by	20.4 μsec
Mar. 13	Clock No. 4 leads U. S. N. Observatory by	33.4 μsec
19 days		−13.0 μsec

−13.0 μsec/19 days = 7.9×10^{-12} average frequency difference.

Feb. 12	Clock No. 3 leads U. S. N. Observatory by	−78.5 μsec (A)
Feb. 22	Clock No. 3 leads U. S. N. Observatory by	−77.6 μsec (B)
Mar. 13	Clock No. 3 leads U. S. N. Observatory by	−68.7 μsec (C)

(A) − (B) = −0.9 μsec in 10 days = 1.0×10^{-12} average frequency difference

(B) − (C) = −8.9 μsec in 19 days = 5.4×10^{-12} average frequency difference

Traveling Clocks vs. NBS UA (Boulder) Time Scale*

Feb. 21	Clock No. 3 leads NBS UA by	−406.3 μsec
Mar. 16	Clock No. 3 leads NBS UA by	−411.9 μsec
23 days		5.6 μsec

5.6 μsec/23 days = −2.8 parts in 10^{12} average frequency difference.

Feb. 21	No. 4 leads NBS UA by	−308.2 μsec
Mar. 16	No. 4 leads NBS UA by	−308.9 μsec
23 days		0.7 μsec

0.7 μsec/23 days = −3.4 parts in 10^{13} average frequency difference.

Traveling Clocks vs. WWV (Beltsville) Master Clock

Feb. 22	Clock No. 3 leads WWV by	76.7 μsec
Mar. 14	Clock No. 3 leads WWV by	70.1 μsec
20 days		6.6 μsec

6.6 μsec/20 days = −3.8 parts in 10^{12} average frequency difference.

Feb. 22	Clock No. 4 leads WWV by	174.9 μsec
Mar. 14	Clock No. 4 leads WWV by	172.4 μsec
20 days		2.5 μsec

2.5 μsec/20 days = −1.4 parts in 10^{12} average frequency difference.

Traveling Clock vs. −hp− House Standard

Feb. 2	Clock No. 3 leads −hp− Standard	96.1 μsec
Feb. 17	Clock No. 3 leads −hp− Standard	82.9 μsec
42 days		13.2 μsec

13.2 μsec/42 days = −3.6 parts in 10^{12} average frequency difference.

* Measurement actually made against NBS Working Standard No. 8 then corrected to NBS UA

WORLD TRAVELERS

The trip covered some 35,000 miles by air and 2,300 miles by car. Nine airlines and eight different kinds of aircraft were involved. The clocks usually traveled ½-fare as "children" (230 lbs. each) and occasionally as excess baggage or cabin freight. Electrical power was usually obtained from the galley,

Fig. 10. *Dr. L. Essen, who developed world's first Cesium^{133} atomic-controlled frequency standard at National Physical Laboratories, examines compact cesium-beam frequency standard that controls traveling clock.*

or from the self-contained batteries if the trip was short.

The inherent ruggedness of the traveling clocks was demonstrated by the trip from Tokyo to the tracking station at Kashima, which occurred without mishap. The 100-mile route was over a tortuous, unimproved road that required five hours to negotiate each way. The time closures which included this part of the trip show that the clock was unaffected by the journey.

The time taken to travel to the remote tracking site, incidentally, required an overnight stay at a non-American-oriented Japanese inn, a rather pleasant, other-worldly experience for the American engineers accompanying the clocks.

The use of the word "atomic" to describe the nature of the clocks had unfortunate repercussions even though the clocks had nothing fissionable within them. Curious fellow passengers on the aircraft often changed to seats further away when they learned what those space-age-looking machines were. The flight from London to the continent was delayed because the airline which was to transport the clocks had heard about the devices being "atomique" and balked at transporting devices that might affect the safety of their passengers. (A second airline, however, was more understanding and flew the clocks from London to Paris only slightly later than originally planned.)

Otherwise, the reaction of lay personnel to the instruments in some cases was nothing short of spectacular. In London, for instance, the police had been informed that the instruments contained "atomic" material and since the police wished to take no chances, the voyagers found themselves accompanied by a motorcycle escort from the airport to the first night's stop.

Disaster nearly befell the expedition during the overnight stop at the English hotel, however, despite all the solicitations of police and others. Although the engineers had brought an assortment of adapters for the variety of electrical outlets they expected to encounter, they did not have one that fit the wall outlets in the vacant conference room where the clocks were to be lodged. This required a dismantling of one of the light fixtures to permit attachment to the power cord. During the night, however, a bellboy let himself into the locked room to clean the ashtrays — and he conscientiously turned out the lights upon leaving. The clocks continued to operate on their internal batteries, of course, but these had already been partially discharged during the transfer from the aircraft and there was barely enough charge left the next morning to keep the clocks running during the transfer to the Royal Greenwich Observatory at Herstmonceux Castle. Although the British personnel at Herstmonceux had prepared tea as a proper inaugural to the proceedings, protocol had to be ignored long enough to rush the clocks into the building and get them operating on ac power once more.

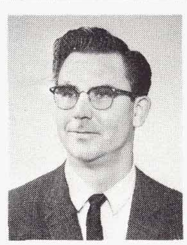
All in all, the people in the various laboratories that were visited were most hospitable and cooperative, willing to give up free evenings and Sundays to make measurements if the travel schedule so required. Most were keenly interested in the experiment being performed and requested a return visit so that long-term variations in time scales may be determined. As mentioned earlier, such return visits are planned for the future.

ACKNOWLEDGMENTS

We at Hewlett-Packard wish to express our appreciation to the many scientists — too numerous to mention individually — at all the overseas facilities listed in Table I, and at the U. S. Naval Observatory, the Goldstone Tracking Station, and facilities of the National Bureau of Standards, whose wholehearted support made this experiment possible. We acknowledge with gratitude their encouragement and valuable assistance, which contributed immeasurably to the success of the experiment.

—LaThare N. Bodily

AUTHOR



LaThare N. Bodily

Lee Bodily graduated from Utah State University with an EE degree in 1956 and directly joined -hp- as a development engineer. He later earned an MSEE at Stanford in the -hp- Honors Cooperative Program and has done further graduate study toward the degree of Electrical Engineer.

At -hp- Lee's first assignment was with the group developing the -hp- Model 560A Digital Recorder but since that time he has been concerned with precision oscillator development, first on the time bases for the 524C/D 10-Mc/s Electronic Counters and then as project leader for the 100E Frequency Standard, the 101A 1-Mc/s Oscillator, the 106A and 107A Precision Quartz Oscillators, and the time base in the 5245L 50-Mc/s Counter. He developed the quartz oscillator "flywheel" in the 5060A Cesium-Beam Frequency Standard and also contributed to the 103A and 104A Quartz Oscillator development. Since mid-1964 he has been section leader of the frequency standards group, now having responsiblity for both quartz oscillator and cesium-beam frequency standard development.