Transcontinental and Intercontinental Portable Clock Time Comparison

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***Abstract*—Because of the relatively low transportation costs of the rubidium portable clock, a schedule of relatively frequent comparisons with two of the main counterparts of NBS (Boulder, CO) have been executed: nearly monthly comparisons with the U.S. Naval Observatory (USNO) in Washington, DC, and trips every quarter year to the International Time Bureau (BIH) in Paris, France. The measurement results of the USNO and BIH comparisons are analyzed as a time series using a least squares quadratic fit. The measurements (time readings) yield a standard deviation of about 100 ns and indicate time scale drifts of about 1 × 10^{-13} per year. Comparison with Loran-C data demonstrates the superior time comparison ability of portable clock trips, exceeding that of Loran-C by up to one order of magnitude.**

INTRODUCTION

NBS HAS DEVELOPED and used a small portable rubidium clock, which permits time comparisons with other laboratories at much less cost than possible with the traditionally used cesium clocks [1], [2]. The use of this clock over the past year has shown that time generating clock ensembles perform with stabilities of parts in 10^{14} for time periods of months. National and international precision time comparisons are done today routinely via Loran-C and portable atomic clocks. Satellite links are being explored today and may become the main link of the future. Nevertheless, portable clocks will be needed to calibrate satellite links and to study variations in such transmissions.

DISCUSSION

The use of portable atomic clocks has been limited due to the cost and cumbersome logistics of the clock transport itself. The benefits of the portable rubidium clock include much more frequent and less expensive clock trips and the use of more than one clock on a single trip with greater ease. The NBS portable rubidium clock travels as hand baggage of one person under the seat in an airliner. In contrast, the cesium clock requires two persons as carriers and an additional seat for itself, plus a powered electrical outlet on the airplane. The rubidium clock features a battery pack which powers it typically for a duration of twenty hours which is sufficient to execute intercontinental trips, including airport transportation, with no need to resort to available electrical power. The stability of the rubidium clock and its sensitivity against environmental effects is almost an order of magnitude inferior to that of cesium clocks. However, in successful round trips, using time closure between departure and arrival at the originating laboratory, very acceptable time comparison precision can be achieved. In fact, the timing comparison precision of this clock can be characterized by

$$\Delta t = 2 \times 10^{-12} \times T \qquad (1)$$

where Δt is the timing accuracy in a comparison and T is the one-way travel time. Thus timing precisions of the order of 10 ns are realizable with short trips of the order of $T = 1$ h, and precisions of the order of 100 ns are achievable for intercontinental distances. More frequent portable clock comparisons not only lead to better confidence in the time comparison and more information on the Loran-C link but also to an increased ability to compare frequencies between time generating laboratories even when separated by large distances. In fact, the fractional frequency precision achievable is:

$$\sigma_y(\tau) = \Delta t/\tau \qquad (2)$$

where τ is the time interval between two successive clock trips. Thus with a time accuracy of 100 ns and clock trips spaced three months apart, $\sigma_y = 10^{-14}$ is a very realistic number, and is actually achieved by our series of time comparisons as reported below.

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COMPARISON

An important difference must be noted between these rubidium portable clock trips and trips possible using available cesium clocks. Because of the inferior stability of the rubidium clocks and the greater environmental sensitivity, both almost a factor of 10 inferior as compared to cesium, clock trips must be done as rapidly as possible, as can be realized from (1). If time is to be carried to a remote station which does not have a high-precision timing system on site, an immediate return of the clock and a quick trip are mandatory for good accuracy, because T would indeed be the total time of the whole roundtrip to this remote site (1). However, if the laboratory to be measured or to be compared with is itself a high-precision time-keeping laboratory, a quick roundtrip becomes much less important. Upon arrival of the portable clock at the laboratory, the clock is measured against that laboratory's time signals, monitored during its stay there, and measured *immediately before leaving for its return trip*. Since, for such laboratories, the frequency of its local time scale is *a priori* usually well-known (to better than 10^{-12}), the stay at this laboratory can be quite extensive without noticeable deterioration of the portable clock comparison precision. In fact, the portable clock could remain at such a laboratory for times of the order of one week, if the frequencies are *a priori* known to within 10^{-13}. Despite the advantages in weight, size, ease of handling, etc., it is obvious that the rubidium clock would be much inferior to a cesium clock for a long-term clock transport involving a series of remote sites, each having not very well-known time or frequency signals. For such an application, the portable rubidium clock may be an order of magnitude or more inferior to present day cesium clocks [3], [4].

We executed numerous trips from the National Bureau of Standards (NBS) in Boulder, CO to the U.S. Naval Observatory (USNO) in Washington, DC, and several comparisons with the Bureau International de l'Heure (BIH) in Paris, France, during the past year. These trips served to bring about a comparison of the respective time scales with previously unachieved precision. They also served to check the capability of the portable rubidium clock. On several occasions, more than one clock was available simultaneously or near-simultaneously for time comparison. Support for the capability of rubidium portable clocks, as quoted above, is directly given by the data points in Figs. 1 and 2. In January 1977 and April 1977, we carried two rubidium clocks simultaneously on the same trip to the BIH. In fact, it was possible for one person to carry two portable rubidium clocks with no major difficulty to the BIH in Paris. In both cases, the measurements of the two clocks differed by less than 100 ns, indicating that the precision of a single clock on a trip to the BIH with a one-way duration of 14 to 18 hours yields a timing precision of about 100 ns. For trips between USNO and NBS a somewhat better precision appears possible.

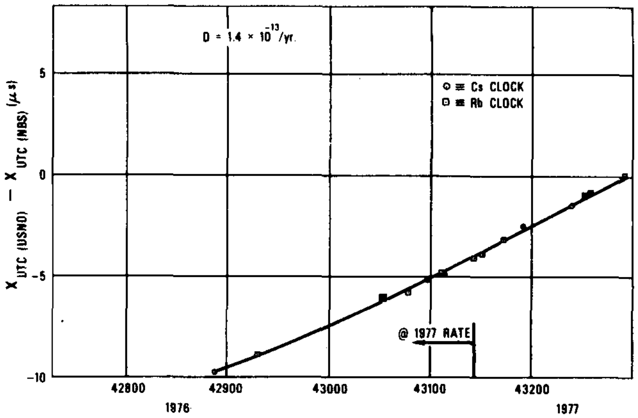

Fig. 1. Portable clock comparisons between USNO and NBS. The curve, $X(n)$, is a least squares, quadratic fit: $X(n) = (16.27\ \text{ps}/d^2)n^2 + (25.60\ \text{ns}/d)n - 4.256\ \mu\text{s}$ where n is 1977 day count. Horizontal axis is the Modified Julian Day (MJD). D is the fractional frequency drift per year. All available rubidium and cesium data are plotted. The rubidium measurement around MJD 43080 is due to simultaneous transport of two independent clocks, yielding agreement to within 50 ns. The data are "normalized" to the 1977 time scale rates; i.e., the 1976 data were adjusted by 72 ns/day for UTC(NBS) [6] and 60 ns/day for UTC(USNO) [7].

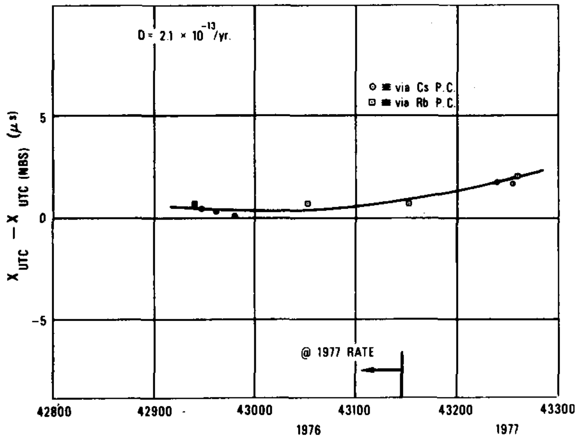

Fig. 2. Portable clock comparisons between BIH and NBS. The curve, $X(n)$, is a least squares, quadratic fit: $X(n) = (22.81\ \text{ps}/d^2)n^2 + (6.64\ \text{ns}/d)n + 0.837\ \mu\text{s}$ where n is 1977 day count. Horizontal axis is the Modified Julian Day (MJD). D *is the fractional frequency drift per* year. All available rubidium and cesium data are plotted. The rubidium measurements around MJD 43150 and MJD 43260 are due to simultaneous transport of two independent clocks each, yielding agreement to within 90 ns for each trip. The data are "normalized" to the 1977 time scale rates; i.e., the 1976 data were adjusted by 72 ns/day for UTC(NBS) [6] and 86.4 ns/day for UTC [6], [7].

In Figs. 1 and 2, we give the measurement results of a series of portable clock trips between NBS and USNO and NBS and BIH, respectively. Removed are the intentional frequency changes of January 1, 1977 in the time scales of the laboratories which were done both for coordination purposes and to bring the scale unit of TAI into agreement with the SI second. Plotted in Figs. 1 and 2 are the new 1977 rates; i.e., the actual rate changes were used to modify all data prior to January 1, 1977. All data on rubidium clocks are based on NBS records; all data on cesium clocks are based on USNO records.

When using portable clock data to compare the time and frequency of two time scales remote to each other, it is profitable to consider the general character of the instabilities involved which may limit the comparison. In Fig.

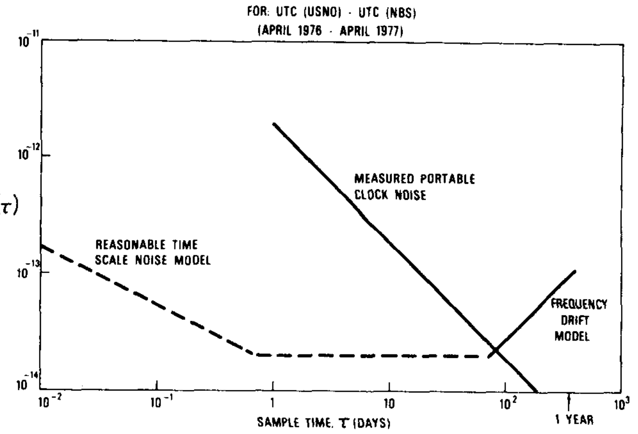

Fig. 3. Noise performance of time scales and portable clock comparisons. The time scale noise model is derived from internal measurements at NBS and believed to be typical for today's high performance time scales. The portable clock noise and the time scale rate drift are calculated from the data of Fig. 1; therefore, they only apply to the USNO/NBS comparison.

3 we illustrate graphically an estimate of the current instabilities in the USNO and NBS time scales, including the effect of the linear frequency drift apparent in Fig. 1 on $\sigma_y(\tau)$ (the two-sample deviation). We assume that other time scales have instabilities of the same order. Also plotted in Fig. 3 is the portable clock comparison measurement noise achievable from repeated portable clock trips; we use an rms time error for each trip of 90 ns, which was obtained from Fig. 1. Therefore, the noise-model of Fig. 3 is applicable only to the USNO/NBS comparison of time scales.

From Fig. 3 it appears that for the most part the predominant "signal" process between two time scales is frequency drift; whereas the predominant measurement limitation is the accuracy achievable with repeated portable clock trips. This limitation may be well modeled by a white phase (or time) noise process, hence a good estimate of the comparison of two time scales via repeated portable clock measurements is a least squares quadratic fit to the time difference measurements. The curves in Figs. 1 and 2 are a result of such a fit in the comparisons between UTC–UTC(NBS) and UTC(USNO)–UTC(NBS). The rms error of departure of the actual measurements from the curve is only 0.09 μs for the USNO/NBS data. We estimate the uncertainty in all three coefficients of the least squares quadratic fit at about ±20 percent for Fig. 1 and ±50 percent for Fig. 2. We also note that the least squares fit appears to be an adequate model for the given sets of data; however, we caution against applying any conclusions (especially on drift) drawn from our data to past or future sets of similar data. If one analyzes these measurements as departures from the fit due to random instabilities other than the assumed linear frequency drift between the time scales involved, then one obtains the very impressive stability $\sigma_y(\tau \sim 3 \text{ months})$ between the scales of 1.5×10^{-14}. The error and stability for the BIH/NBS link is not as good as can be seen from Fig. 2.

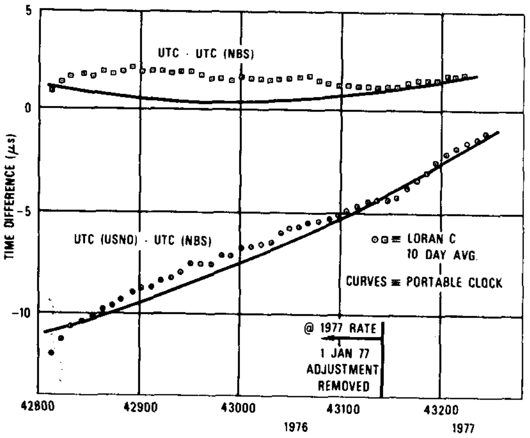

Fig. 4. Comparison of Loran-C data and portable clock data for the links USNO/NBS and BIH/NBS. The curves are identical to those of Fig. 1 and Fig. 2. The Loran-C data are taken from the BIH Circular *D*. As in Fig. 1 and Fig. 2, the plotted rates are those of 1977; i.e., the 1976 data are adjusted. In addition, the 1976 data are also modified to remove a Loran-C time-step adjustment by the BIH on January 1, 1977 (−0.4 μs for UTC(USNO) and −0.2 μs for UTC(NBS) [8]). Horizontal axis is the Modified Julian Day (MJD).

The time differences as given by Loran-C measurements are plotted in Fig. 4. The error and stability associated with the Loran-C data are significantly worse than those achievable by repeated portable clock trips. In fact, one observes significant departures of the Loran-C measurements from the least squares quadratic fit over the course of a year of almost 1 μs for the USNO/NBS data and 1.5 μs for the BIH/NBS data. Also, the data strongly suggest seasonal variations in both Loran-C links.

CONCLUSION

In summary, we submit that we have shown that time scales can be compared in frequency to parts in 10^{14} via repeated portable clock trips and that the corresponding capability of the Loran-C links is about 1×10^{-13}. The data also indicate, that time scales show drifts of the order of 1×10^{-13} per year. It appears futile to attempt scientifically sound explanations of such drifts. However, their presence illustrates the importance of a steering of TAI (and UTC) using data from primary standards. This steering is being implemented [5] by the BIH. Our data show that, at present, Loran-C links would not be sufficient to relate the data needed for the steering from the contributing primary standards laboratories to the BIH and to compare primary standards in these laboratories. Portable clocks must therefore be used for these purposes until it is demonstrated that a substitute system such as a satellite based system has equal or better performance. Therefore, we intend to extend portable clock trips to other laboratories in addition to the USNO and the BIH. We hope that both small rubidium and cesium portable clocks will become commercially available so that laboratories involved in time-keeping and coordination can take advantage of the available time comparison accuracy.

ACKNOWLEDGMENT

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REFERENCES

[1] H. Hellwig and A. E. Wainwright, "Sub-microsecond time transport with a rubidium portable clock," in *Proc. 29th Annu. Symp. Frequency Control* (Atlantic City, NJ), pp. 384–386, May 1975.

[2] ——, "A portable rubidium clock for precision time transfer," in *Proc. 7th Precise Time and Time Interval* (PTTI) *Planning Meeting* (Washington, DC), pp. 143–159, Dec. 1975.

[3] J. C. Hafele and R. E. Keating, "Around-the-world atomic clocks: Predicted relativistic time gains; Observed relativistic time gains," *Science*, vol. 177, pp. 166–170, July 1972.

[4] G. M. R. Winkler, "Recent experiments with flying atomic clocks, Loran-C, Omega, and VLF for clock synchronization," Rep. to XVII General Assembly, Warsaw 1972, of the International Union of Radio Science.

[5] 8th Session of the Consultative Committee for the Definition of the Second, Sevres, France, Apr. 26–27, 1977, Recommendation S1.

[6] NBS Time and Frequency Services Bulletin, No. 230, p. 7, Jan. 1977.

[7] USNO Time Service Announcement Series 14, No. 21, 27 Oct. 1976.

[8] Bureau International de l'Heure Circular D124, Mar. 3, 1977.