COMMON VIEW TIME TRANSFER USING WORLDWIDE GPS AND DMA MONITOR STATIONS

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Abstract

Analysis of the on-orbit Navstar clocks and of the GPS monitor station reference clocks is performed by the Naval Research Laboratory [1]*using both broadcast and postprocessed precise ephemerides. The precise ephemerides are produced by the Defense Mapping Agency (DMA) for each of the GPS space vehicles from pseudo-range measurements collected at five GPS and at five DMA monitor stations spaced around the world. Recently, DMA established an additional site co-located with the U.S. Naval Observatory precise-time site. The time reference for the new DMA site is the DoD Master Clock. Now, for the first time, it is possible to transfer time every 15 minutes via common view from the DoD Master Clock to the 11 GPS and DMA monitor stations. The estimated precision of a single common-view time transfer measurement taken over a 15-minute interval was between 1.4 and 2.7 nanoseconds. Using the measurements from all Navstar space vehicles in common view during the 15-minute interval, typically 3–7 space vehicles, improved the estimate of the precision to between 0.65 and 1.13 nanoseconds. The mean phase error obtained from closure of the time transfer around the world using the 11 monitor stations and the 25 space vehicle clocks over a period of 4 months had a magnitude of 31 picoseconds. Analysis of the low-noise time transfer from the DoD Master Clock to each of the monitor stations yields not only the bias in the time of the reference clock, but also focuses attention on structure in the behavior of the reference clock not previously seen. Furthermore, the time transfer provides a uniformly sampled database of 15-minute measurements that makes possible, for the first time, the direct and exhaustive computation of the frequency stability of the monitor station reference clocks. To lend perspective to the analysis, a summary is given of the discontinuities in phase and frequency that occurred in the reference clock at the Master Control Station during the period covered by the analysis.*

BACKGROUND

The initial work of transferring time by means of a satellite clock between points widely separated on the Earth's surface was demonstrated by Easton[1], who obtained an average time-transfer

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[1] This work was sponsored by the GPS Joint Program Office.

time-transfer accuracy to 120 nanoseconds between sites in the continental U.S. Easton *et al.*[3], using the TIMATION II satellite, transferred time between the U.S. Naval Observatory and the Royal Greenwich Observatory with an accuracy of 270 nanoseconds. Buisson *et al.*[4], using the Navigation Technology Satellite NTS-1 in a 7500 nautical-mile orbit, obtained in common-view mode for three closely spaced monitor sites a closure with a mean phase error of 9 nanoseconds and an rms phase error of 43 nanoseconds. Time was also transferred to England and to Australia with an accuracy of 240 and 700 nanoseconds respectively. Allan *et al.*[5], using four Navstar satellites in 10000 nautical-mile orbits and three timing centers in Boulder, Colorado, in Braunschweig, Germany, and in Tokyo, Japan, transferred time in a common-view mode over a 3-month period and obtained a mean phase error upon closure of 5.2 nanoseconds. Using measurements of ionospheric delays, precise ephemerides from DMA, and a consistent set of antenna coordinates, Lewandowski *et al.*[6] achieved time transfer over intercontinental distances by the GPS common-view method with a precision of 2 nanoseconds by averaging several measurements over a day. Around-the-world closure using three intercontinental links was verified to within a few nanoseconds.

INTRODUCTION

Prior to establishment at the U.S. Naval Observatory (USNO) of the new DMA monitor station, time transfer via the common-view method[7] from the DoD Master Clock to a GPS monitor station, for use in analysis of the performance of the monitor station time reference, was limited by a number of factors. For example, measurements [2]of the offset of the space vehicle clocks from the DoD Master Clock were obtained from a linear least-squares fit to 13 minutes of six-second phase-offset measurements, and these measurements were nominally timed according to a schedule issued by the Bureau International des Poids et Mésures (BIPM) for establishment of International Atomic Time (TAI). Although this schedule was adequate for the purpose intended, the number of measurements was sparse compared to those taken by the other monitor stations, which made observations every 15 minutes during each pass of the space vehicle. Moreover, these measurements utilized the broadcast ephemeris, and the receiver operated for some period of time on a single frequency requiring use of the ionospheric model broadcast in the navigation message. Measurements made by the monitor stations, on the other hand, were synchronized to GPS system time and were scheduled every 15 minutes. The phase offset was obtained using post-fit precise ephemerides supplied by DMA, and the receivers operating at dual frequencies measured the ionospheric delay. The dissimilarity in the nature of the measurements made by the Naval Observatory compared to those made by the ten monitor stations and the lack of synchronization of the Naval Observatory measurements with those made by the other monitor stations introduced significant error. But most limiting was the sparse number of measurements made by the Naval Observatory, resulting in a single raw estimate of the time transfer at a given time.

TIME TRANSFER

While the time reference for both the DMA site in Washington, D.C., and the Naval Observatory precise-time site is the DoD Master Clock, as expected there is considerable difference in the time transfer from each of these sites. Figure 1 is a plot of the time transfer from the Naval Observatory to the Colorado Springs monitor station for the first ten hours of Thursday, 1 June 1995. Immediately obvious is the lack of multiple estimates of the time transfer at the

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[2] All measurements utilized in this study were corrected for Selective Availability.

measurement times even though, during the ten hours shown, there were between five and seven Navstar space vehicles in common view. So sparse was the measurement schedule that as few as two measurements were made from 0500 to 0600. In addition to the paucity of the estimates, there is considerable scatter in the measurements, as evidenced by a standard deviation of 11 nanoseconds.

Using the DMA site in Washington, D.C., which made synchronized measurements every 15 minutes, produced the raw estimates of the time transfer to the Colorado Springs monitor station shown in Figure 2. Here the number of simultaneous measurements—indicative of the number of Navstar space vehicles in common view—varied between five and seven. If the noise in the raw measurements for a specified measurement time were white, the optimum estimator of the time transfer at that time would be the sample mean. Figure 3 is a plot of the sample mean at each of the measurement times over the 10-hour time span. If the sample mean in Figure 3 is subtracted from the raw measurements in Figure 2, the plot of the measurement noise shown in Figure 4 is obtained. Doing this for the 4 months from 1 June 1995 to 1 October 1995 results in the time transfer and the corresponding measurement noise shown in Figures 5 and 6. In Figure 5 the frequency offset of the Colorado Springs time reference from the DoD Master Clock has been removed to emphasize the detailed behavior of the reference clock. An appreciation for the stability of the time transfer using the DMA site in Washington, D.C., can be had by examining the comparison in Figure 7 of the time transfer to Colorado Springs from both the DMA site in Washington, D.C. (dark trace) and the Naval Observatory (scattered dots) for the same 4 months.

MEASUREMENT STATISTICS

The histogram in Figure 8 shows the measurement noise for the Washington, D.C., to Colorado Springs link to be predominantly normal. In Figure 9 the normalized integrated periodogram of the measurement noise lies well within the 95 percent Kolmogoroff-Smirnov[8] confidence interval, supporting the hypothesis that the noise is white, or uncorrelated.

To estimate the precision of the time-transfer measurement requires computation of the standard deviation of the distribution of the sample mean—the sample being the 5–7 raw time transfer measurements made during the same 15-minute interval. If the measurements in the sample are independent and identically distributed random variables, the standard deviation of the sample mean will be the standard deviation of the population from which the sample was taken reduced by $1/\sqrt{n}$, where n is the number of measurements in the sample. The number of noise measurements (n_{noise}) in Figure 6 was 59497. The number of estimates (n_{mean}) of the time transfer obtained by taking the mean of each sample of raw measurements at the measurement times was 10364. Dividing the two yields $n_{sample} = 5.74$ for the average size of the samples for which the mean was found. With the standard deviation of the measurement noise $\sigma_{noise} = 2.67$ nanoseconds, the standard deviation of the sample mean is

$$\sigma_{mean} = \frac{\sigma_{noise}}{\sqrt{n_{sample}}} = 1.1\ ns.$$

The same analysis was performed for the other ten links and the results summarized in Table 1. It is interesting to note that the two links involving Colorado Springs show the least precision even though the reference clock at Colorado Springs was an HP5071 high-performance cesium beam tube. In addition, the reference clock at the DMA Washington site was a hydrogen maser steered by a very large ensemble of atomic clocks. The fact that the noise on the Washington-to-Quito link is considerably lower establishes Colorado Springs as the problem.

Of the 11 links, eight had subnanosecond measurement precision. The link between Hawaii and Kwajalein Island showed the greatest precision at 650 picoseconds.

Table 1

SUMMARY OF TIME TRANSFER BETWEEN ADJACENT PAIRS OF MONITOR STATIONS
1 June 1995 to 1 October 1995

Link	n_{noise}	n_{mean}	n_{sample}	σ_{noise} (ns)	σ_{mean} (ns)
CSP--WAS	59497	10364	5.74	2.67	1.11
HAW--CSP	49470	10554	4.71	2.46	1.13
KWJ--HAW	60369	10688	5.65	1.40	0.65
SMF--KWJ	47509	10633	4.47	1.49	0.70
DGI--SMF	33268	9717	3.42	1.52	0.82
BAH--DGI	49671	9928	5.00	1.86	0.83
ENG--BAH	47884	10766	4.45	2.12	1.01
ASC--ENG	40855	10234	3.99	1.55	0.78
ARG--ASC	49258	10852	4.54	1.43	0.67
QUI--ARG	57927	11348	5.10	1.81	0.80
WAS--QUI	53269	11149	4.78	1.66	0.76

The time transfer links listed in the table utilized the five GPS monitor stations in Colorado Springs (CSP), Hawaii (HAW), Kwajalein Island (KWJ), Diego Garcia Island (DGI), and Ascension Island (ASC), and the six DMA monitor stations in Washington, D.C. (WAS), Smithfield, Australia (SMF), Bahrain (BAH), England (ENG), Argentina (ARG), and Quito, Ecuador (QUI).

ANOMALY DETECTION

Previous to the availability of the uniformly sampled database of 15-minute low-noise time transfer measurements between the DoD Master Clock and a monitor station, analysis of an anomaly in the behavior of the monitor station time reference relied upon the 15-minute measurements made during a pass of a Navstar space vehicle over the monitor station. While voids between passes could be filled in with observations from other space vehicles, always the analysis was hampered by the behavior of the less stable Navstar clock.

Figure 10 is a plot of the residuals of a linear fit to the phase offset of several Navstar clocks from the Colorado Springs reference clock and the Colorado Springs reference clock from the DoD Master Clock. The bottom trace was obtained from time-transfer measurements. A 7-nanosecond break is clearly visible in the low-noise time-transfer measurements. The break in the time transfer was traced to initialization of the Colorado Springs monitor station. The break was not detectable in the measurements from Navstar 13 and Navstar 29 because it occurred between passes of the space vehicles over the monitor station. The break, on the other hand, occurred during the time the Navstar 20 and the Navstar 36 space vehicles were in view of the monitor station. While the evidence of a break in the time-transfer measurements is compelling, such a small break in the phase offset of the Navstar clocks from the monitor station reference clock is much more difficult to detect. It was only a review of these time-transfer measurements that revealed the anomaly.

Figure 11 presents the time-transfer measurements—the mean of the raw measurements at each measurement time—between the time reference at the Hawaii monitor station and the DoD Master Clock for the month of August. The abrupt changes in the slope of the phase reflect repetitive breaks of 2 $pp10^{13}$ in the frequency of the Hawaii time reference, which was an HP5061 cesium beam tube. Such breaks in the frequency of an HP5061 are not unusual, and a review of the operations log for the monitor station revealed no switching of frequency standards during this time.

In Figure 12 is plotted the behavior of the Colorado Springs time reference for 5 days in July. The data were smoothed by a moving average filter to reduce the short-term noise. Immediately apparent is a 12-hour periodic component. It needs to be emphasized that the peak-to-peak variation of 2 nanoseconds would have been difficult to detect in the observations by the monitor station of any of the Navstar space vehicle clocks.

DATA CORRECTIONS

A summary is given in Table 1 of the corrections that were made to the data from the Colorado Springs monitor station during the period covered by the analysis. That there were no breaks in the frequency is not surprising, since the time reference for the entire period was never switched from the single HP5071 cesium clock. Each of the breaks in phase requiring correction were confirmed to have been the result of actions taken by the Master Control Station. The corrected data, except for a constant bias, represent what would have been the unperturbed behavior of the reference clock.

Table 2

DATA CORRECTIONS
Colorado Springs Monitor Station
1 June 1995 to 1 October 1995

(date)	Time (hour)	(MJD)	Phase (*ns*)	Frequency ($pp10^{14}$)
06 JUN 95	1607	49874.67188	94	0
14 JUN 95	1700	49882.70834	-446	0
12 JUL 95	1707	49910.71354	-238	0
25 AUG 95	1552	49954.66146	-155	0
25 AUG 95	1800	49954.75000	-7	0
14 SEP 95	1622	49974.68229	-10	0

FREQUENCY STABILITY

The time transfer provides a uniformly sampled database of 15-minute measurements, which makes possible for the first time the direct and exhaustive computation of the frequency stability of the monitor station reference clocks. Figure 13 is a plot of the frequency-stability profile for the time reference at Colorado Springs for sample times of 15 minutes to 12 days. By exhaustive calculation is meant that the frequency stability is calculated for every multiple of the basic sample interval of 15 minutes up to the maximum sample time. The maximum sample time is limited to one-tenth of the time spanned by the measurements to ensure meaningful confidence limits on the estimates of the stability.

Superimposed on the plot is a solid line corresponding to the Allan deviation of simulated white phase noise with a standard deviation of 1 nanosecond, which was approximately the estimated deviation of the sample means (Figure 5) of the raw time-transfer measurements. This might be expected to represent a floor below which the estimates of the stability would not fall. That the stability for 15 minutes does fall slightly below this line suggests that the estimate of 1 nanosecond for the precision of the time-transfer measurements without smoothing is a conservative one.

The stability for a sample time of one day is 3 pp10^{14} which is the upper bound on the specification[9] of the HP5071A high-performance cesium beam tube. While the specified upper bound on the flicker floor for this frequency standard is 2 pp10^{14}, at 12 days the Colorado Springs time reference had a stability of 5 pp10^{15} and had not yet reached the flicker floor.

Of particular interest is an oscillation with a period of 3 hours which is clearly visible in the stability profile. The oscillation was only visible in the stability profile for the reference clocks at the Colorado Springs and the Smithfield, Australia, monitor stations. The source of the oscillation is under investigation.

CLOSURE

The path indicated in Figure 14 for calculating closure of the time transfer was chosen to minimize the distance between station pairs. Figure 15 is a plot of the time transfer from the DMA site in Washington, D.C., to the same site using the ten intervening GPS and DMA monitor stations and the 25 Navstar space vehicle clocks over a period of 4 months. The periods of missing data are the cumulative effect of outages at the various monitor stations. No smoothing of the data was done. While there were almost one million measurements in the analysis, only five were purged as statistical outliers. The magnitude of the mean phase error obtained from closure of the time transfer around the world measured 31 picoseconds. Figure 16, which is a history of the magnitude of the mean phase error of closure for time transfer around the world, shows an almost linear trend with time.

CONCLUSIONS

Now, for the first time, it is possible to transfer time every 15 minutes via common view from the DoD Master Clock to the 11 GPS and DMA monitor stations. The estimated precision of a single common-view time-transfer measurement taken over a 15-minute interval was between 1.4 and 2.7 nanoseconds. Using the measurements from all Navstar space vehicles in common view during the 15-minute interval, typically 3–7 space vehicles, improved the estimate of the precision to between 0.65 and 1.13 nanoseconds. With the uniformly sampled database of 15-minute measurements afforded by the time transfer, it is also possible for the first time to directly and exhaustively calculate the stability of the time reference for each of the monitor stations—the exhaustive calculation in one case leading to detection of systematics that would otherwise have been missed. The uniformly sampled database of low-noise time-transfer measurements provides a very sensitive analysis tool for detecting anomalous behavior in the monitor station clocks. Finally, closure of the time transfer around the world was achieved with an error of 31 picoseconds.

REFERENCES

[1] R.L. Easton 1972, *"The role of time/frequency in Navy navigation satellites,"* Proc. IEEE, **60**, pp. 557-563.

[2] J.A. Buisson, D.W. Lynch, and T.B. McCaskill 1973, *"Time transfer using the TIMATION II satellite,"* NRL Report 7559 (Naval Research Laboratory, Washington, D.C.).

[3] R.L. Easton, D.W. Lynch, J.A. Buisson, and T.B. McCaskill 1974, *"International time transfer between the U.S. Naval Observatory and the Royal Greenwich Observatory via the TIMATION II satellite,"* NRL Report 7703 (Naval Research Laboratory, Washington, D.C.).

[4] J.A. Buisson, T.B. McCaskill, T.B., H. Smith, P. Morgan, and J. Woodger 1977, *"Precise worldwide station synchronization via the Navstar GPS Navigation Technology Satellite (NTS-1),"* Proceedings of the 8th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 30 November-2 December 1976, Washington, D.C., pp. 55-84.

[5] D.W. Allan, D.D. Davis, M. Weiss, A. Clements, B. Guinot, M. Grandveaud, K. Dorenwendt, B. Fischer, P. Hetzel, S. Aoki, M. Fujimoto, L. Charron, and N. Ashby 1985, *"Accuracy of international time and frequency comparisons via Global Positioning System satellites in common-view,"* **IEEE Trans. Instr. Meas., IM-34,** pp. 118-135.

[6] W. Lewandowski, G. Petit, and C. Thomas 1992, *"Accuracy of GPS time transfer verified by closure around the world,"* Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, pp. 331-339.

[7] D.W. Allan, and M.A. Weiss 1980, *"Accurate time and frequency transfer during common-view of a GPS satellite,"* Proceedings of the 34th Annnual Symposium on Frequency Control, 28-30 May 1980, Ft. Monmouth, New Jersey, pp. 334-346.

[8] G.M. Jenkins, and D.G. Watts 1968, **Spectral Analysis and Its Applications,** (Holden-Day, San Francisco), pp. 234-237.

[9] *"Operating and programming manual HP 5071A primary frequency standard,"* 1st ed., September 1993, Manual Part No. 05071-90025 (Hewlett-Packard Company, Santa Clara Division, 5301 Stevens Creek Boulevard, Santa Clara, California 95052-8059), p. 6-2.

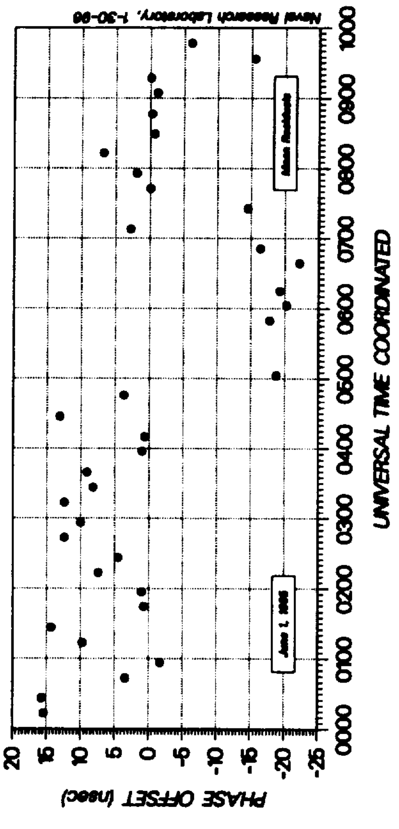
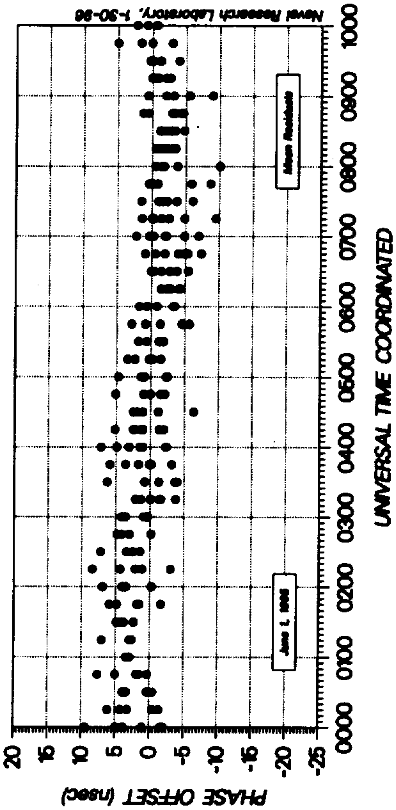


Figure 1



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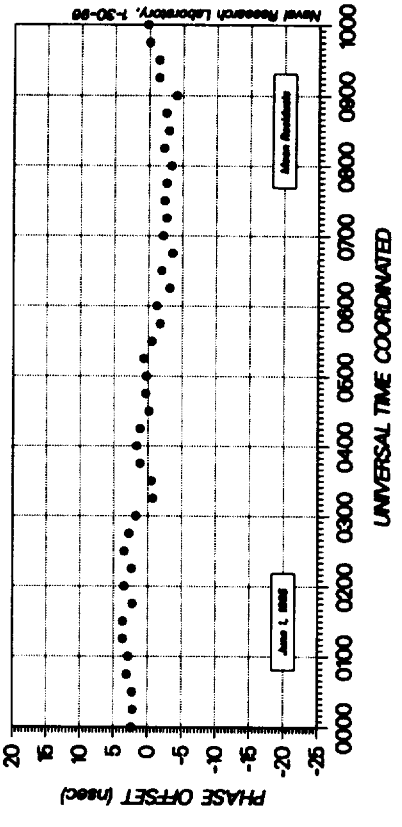

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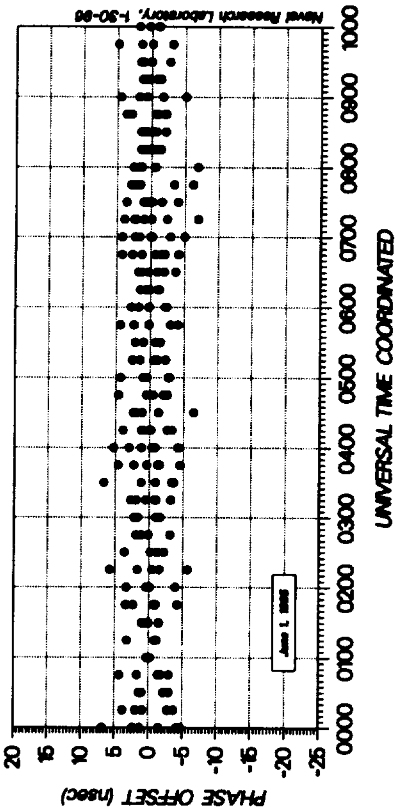

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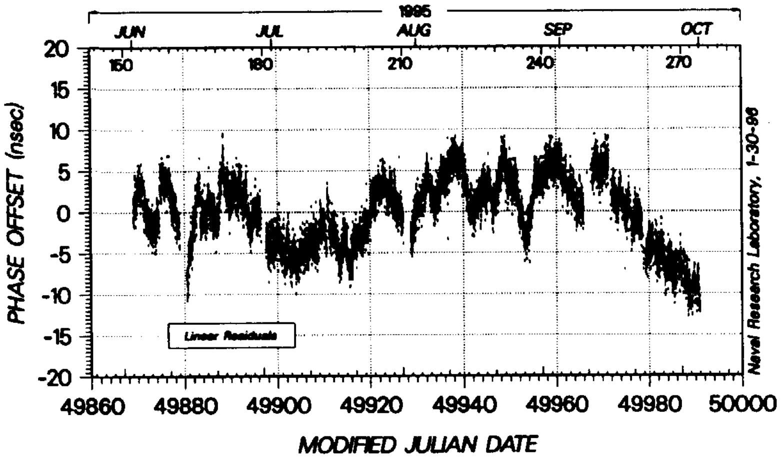

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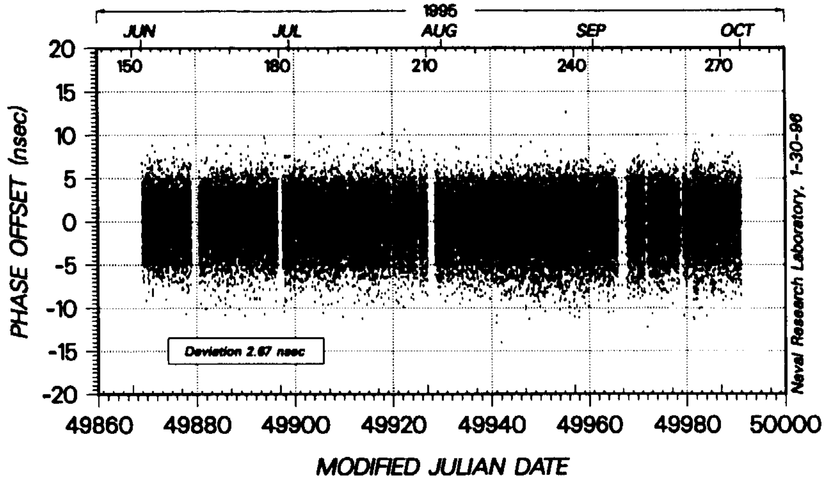

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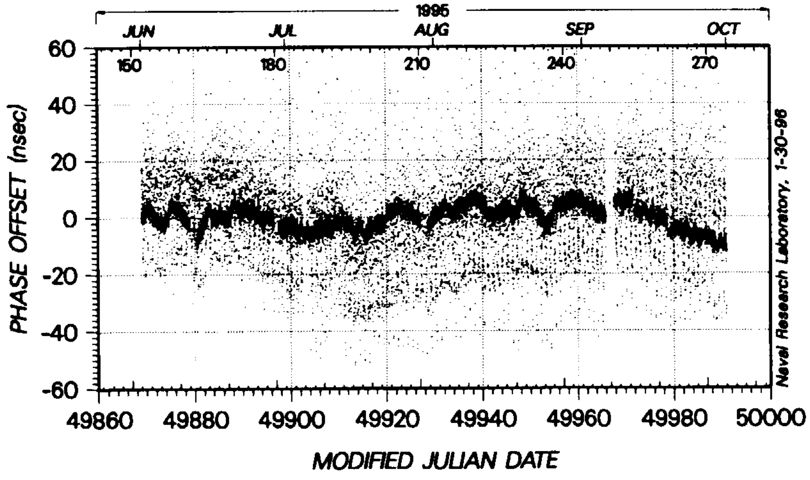

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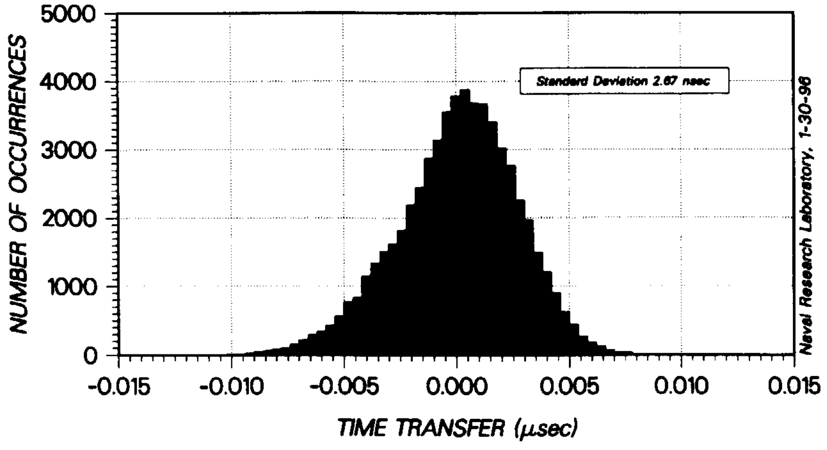

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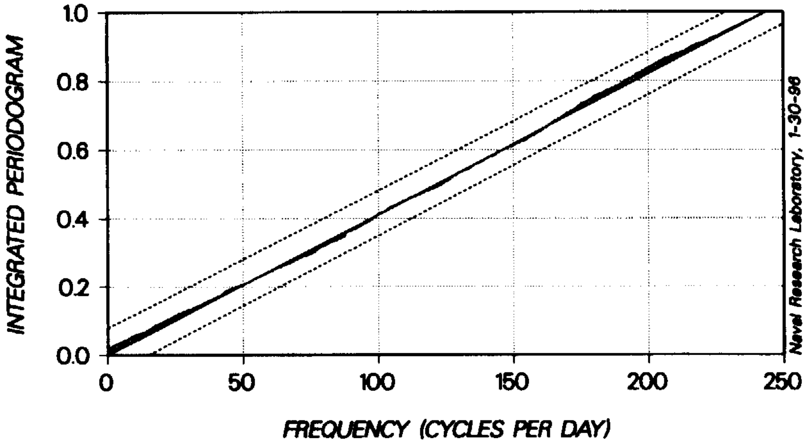

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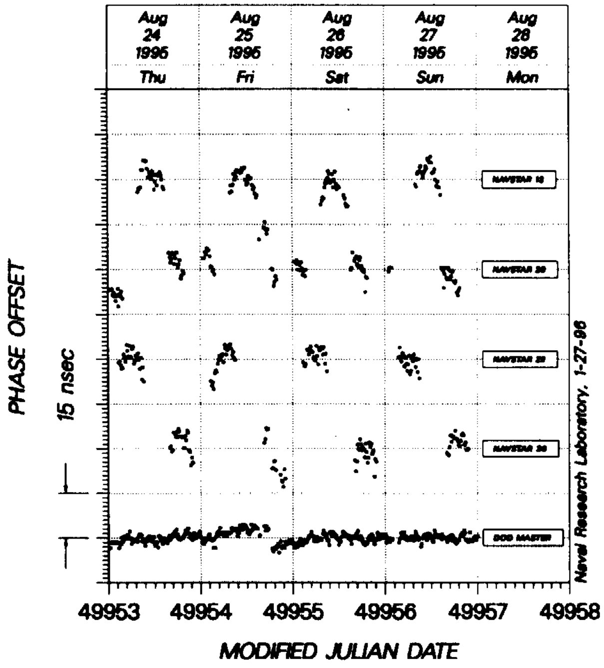

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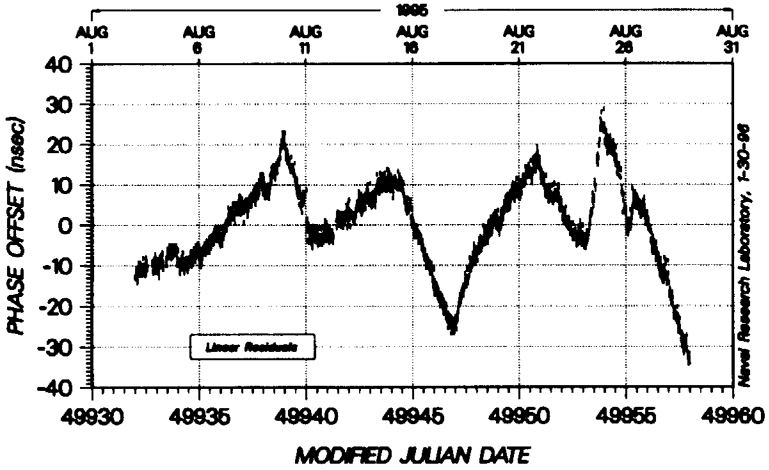

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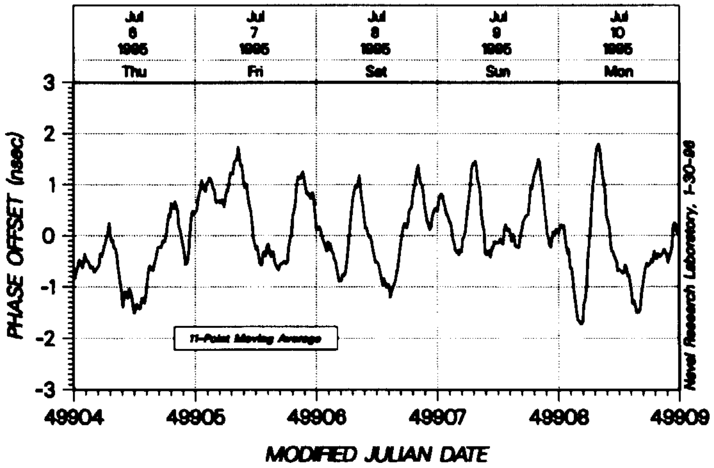

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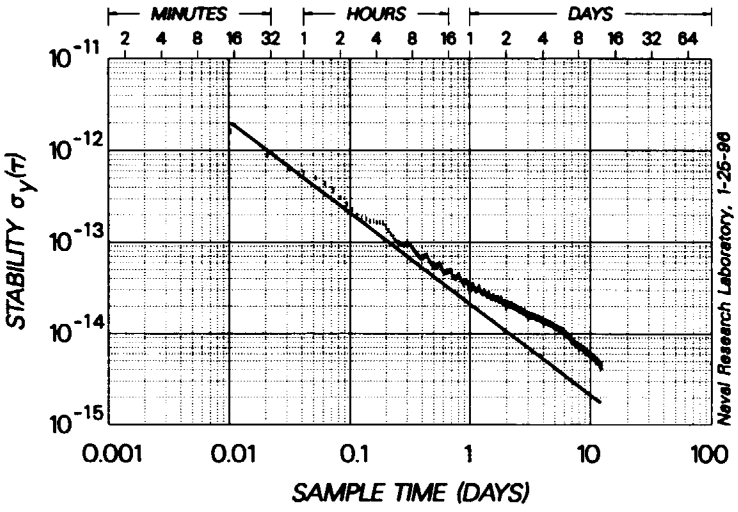

Figure 13

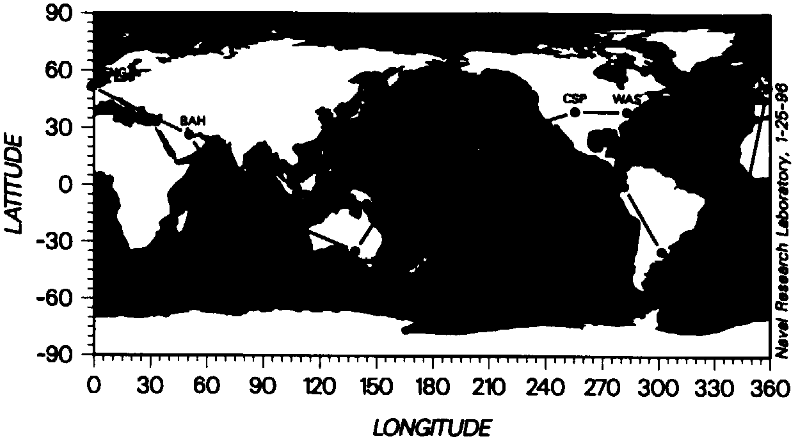

Figure 14

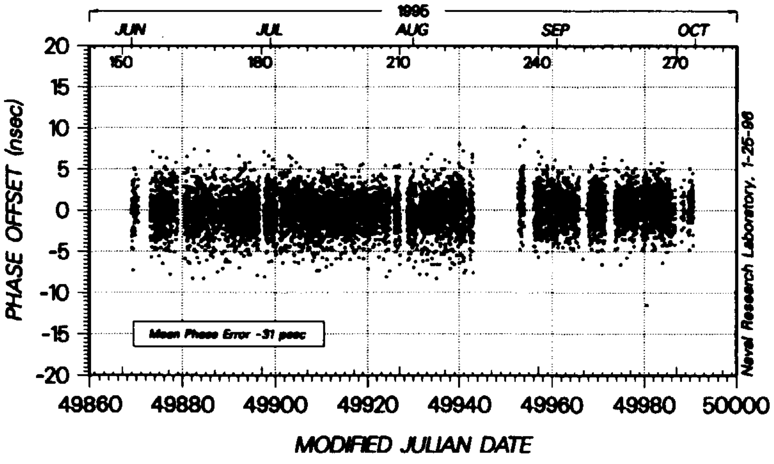

Figure 15

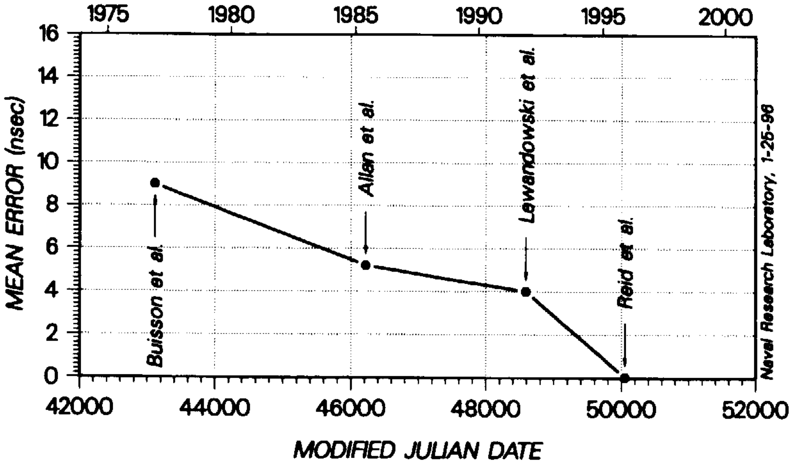

Figure 16

Questions and Answers

CAPT. STEVEN HUTSELL (USAF): If you could, could you put up the plot of the Diego Monitor Station, rather the Hawaii Monitor Station? No, the plot that led you to conclude that there were frequency standard swaps being performed at Hawaii Monitor Station.

WILSON G. REID (NRL): You mean Kwajalein. Right here?

CAPT. STEVEN HUTSELL (USAF): Yes. I'm trying to find out if you have any additional information that would lead you to believe that there are actually frequency standard swaps occurring. Because, I can tell you that unless the site folks are doing something they're not telling us about, we did not swap any frequency standards at Hawaii that often, let alone that many times, over the course of the summer.

My conclusion, or I surmise from this that we've actually had a very chronic problem over this past year, not with Hawaii, but also – in fact, the reason why I said "Diego" earlier – with very huge changes in frequency which we can't absolutely pinpoint because we're not out at the site. We do know that Diego, for example, has experienced temperature changes within the timing rack on the order of tens of degrees. Whether it's a very good performing cesium frequency standard or not, that 25-degree temperature change will affect the frequency output. I'm wondering if you would agree that that would be the most likely cause of this.

WILSON G. REID (NRL): As I go back and look, if we examine the file that we've been sent in the past of special events which affect what we see, sometimes for these monitor sites we would switch to Frequency Standard One, switch to Frequency Standard Two; and then again switch to Frequency Standard Two, which indicates that maybe in the log the switching back to One was left out.

So I don't know. Sure, you do. So if you tell me that no switches were made, I believe you. But without having that information, I assume that they might have been clock switches.

CAPT. STEVEN HUTSELL (USAF): Oftentimes those logs will include times when the operator will re-select the frequency standard that it's intended to be on. Oftentimes, when we perform an initial program load, what we call an "IPL," of the site, sometimes the Series I computer will automatically switch to One. In many cases, the operator will need to immediately re-select the frequency standard that we desire it to be on. And I can safely say we have not had any scheduled frequency standard swaps nearly that often over that time period. If there were any frequency standard swaps, they were unauthorized.

DR. GERNOT WINKLER (USNO, RETIRED): Can I make a comment to that? This is a 5061 standard?

WILSON G. REID (NRL): Yes, I believe so.

DR. GERNOT WINKLER (USNO, RETIRED): Some of those standards have a very great environmental sensitivity. It is entirely possible that it is due to environmental shocks.

Let me ask a question. Monitor station receivers, is it correct that DMA stations all have the Ashtech-12 channel?

WILSON G. REID (NRL): I believe that's what they have.

DR. GERNOT WINKLER (USNO, RETIRED): But the GPS monitor stations have the S-TEL monitor receiver.

WILSON G. REID (NRL): I think so.

DR. GERNOT WINKLER (USNO, RETIRED): So they are different receivers. In addition, you have the tremendous difference in performance between the 5071 in Colorado Springs and the 5061 in Hawaii.

WILSON G. REID (NRL): Oh, yes.

DR. GERNOT WINKLER (USNO, RETIRED): That is exactly the point, because you have been trying to preach for a number of years that they should be replaced.

DAVID ALLAN (ALLAN'S TIME): I would like to follow up on what Dr. Winkler said in terms of the environmental sensitivity of the 5061s. In fact, all commercial cesiums we studied when I was back at NIST, they all have temperature and humidity coefficients. And given the length of time over which you are seeing these frequency shifts, one would wonder about storm systems and humidity; that if in fact you plotted the humidity during that period, you might see a correlation with those frequency steps. Because, the humidity coefficients for the 5061, along with all other commercial standards, except for the 5071, are quite high.

WILSON G. REID (NRL): That's a good suggestion. We don't get that data, and I'm not sure – did I hear this morning that there's a problem with the sensors on the environment? I think that was mentioned this morning. So, it might be difficult to get that data, but it would certainly be useful.