UTC DISSEMINATION TO THE REAL-TIME USER: THE ROLE OF USNO

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Abstract

Coordinated Universal Time (UTC) is available worldwide via the Global Positioning System (GPS). The UTC disseminated by GPS is referenced to the U.S. Naval Observatory Master Clock, UTC(USNO), which is regularly steered and maintained as close as possible to UTC(BIPM), the international time scale. This paper will describe the role of the USNO in monitoring the time disseminated by the GPS and the steps involved to ensure its accuracy to the user. The paper will also discuss the other sources of UTC(USNO) and the process by which UTC(USNO) is steered to UTC(BIPM).

INTRODUCTION

The United States Department of Defense (DoD) Instruction 5000.2 charges the U.S. Navy and specifically the U.S. Naval Observatory (USNO) with the requirement to maintain the timing standard for all precise time and time interval (PTTI) operations within DoD. The accomplishment of this task involves a coordinated effort by the USNO and the electronic navigation systems that are synchronized to USNO time. The USNO monitors the time emanating from these systems and reports their offsets with respect to the USNO timing standard. The navigation systems operators then make the necessary adjustments for synchronization with the USNO.

The timing standard or Master Clock (MC) of the USNO is a hydrogen maser which is continuously steered to the USNO time scale. This time scale is based on an ensemble of 50 to 60 cesium frequency standards and 8 to 12 hydrogen masers which are located in environmental chambers throughout the observatory facility in Washington and at the USNO Alternate Station in Richmond, Florida[1]. This is the largest assembly of atomic clocks for any single timing operation in the world. Furthermore, the USNO collection of atomic clocks constitutes nearly forty percent of the International Atomic Time Scale (TAI) which is formulated at the Bureau International des Poids et Mesures (BIPM) in Paris, France. Moreover, to establish a backup MC in a secure facility and to better support GPS timing operations, the USNO will soon have an Alternate Master Clock (AMC) at Falcon Air Force Base in Colorado Springs, Colorado. This AMC will replace the USNO AMC at Richmond, Florida and will be fully integrated into the USNO MC System.

COORDINATED UNIVERSAL TIME (UTC) AND UTC(USNO)

Coordinated Universal Time was revised in 1971 and the new system became effective on January 1, 1972. On that date, UTC was set to be exactly 10 seconds behind TAI. This difference was caused by the divergence of the two time systems from January 1, 1958 when TAI and the time based on the rotation of the Earth (UT1) were set nearly together. During this period variations in the rotation of the Earth which resulted in a longer day, when compared to the more precise atomic time, accumulated to a difference of 10 seconds. Therefore, the more stable atomic time was adjusted to agree on the average with UT1. This adjusted atomic time is UTC.

By international agreement, UTC is maintained within 0.9 seconds of UT1. This is accomplished by making periodic one second adjustments to UTC. These one-second adjustments are referred to as "Leap Seconds" and they can be either positive or negative depending on the variations of the Earth's rotation. Leap seconds are usually added or deleted on June 30 or December 31, but under unusual circumstances the adjustment can be made at the end of any month (Figure 1).

Most timing laboratories that contribute to the TAI steer their reference clocks to UTC(BIPM). However, this is not an easy task and consequently there is always a difference between the reference clocks at each of these laboratories. Therefore, when referring to UTC, it is necessary to define which laboratory clock is being referenced, such as UTC(USNO), UTC(NIST), or UTC(PTB).

STEERING UTC(USNO) TO UTC(BIPM)

The reason steering to UTC(BIPM) is not easy, is because timing reports from the BIPM are usually more than 30 days old. Consequently, timing offsets from the BIPM must be predicted more than one month into the future. This can only be done if a laboratory has a very stable time scale on which to base the predictions. Fortunately, the USNO has such a time scale, due to its large ensemble of state-of-the-art clocks in stable environments with close monitoring, and an optimal mean time scale algorithm.

The USNO predictions of UTC(BIPM) - UTC(USNO) are based on the latest 180 days (18 data points) of data in the monthly Circular T report from the BIPM. These data points are compared to the USNO unsteered time scale and a linear least-squares computation is made for the frequency and drift, with more weight given to the most recent data. Predictions are then made based on the extrapolation of the unsteered time scale in relation to UTC(BIPM) incorporating the computed frequency and drift.

The steering philosophy at the USNO is to make very small (1.0×10^{-15}) frequency adjustments to its steered time scale to keep it on time with respect to the predicted UTC(BIPM). Once the steered time scale has been coordinated with UTC(BIPM), UTC(USNO) is steered to this time scale by making daily frequency adjustments of no more than 3.5×10^{-15}. To maintain the stability of UTC(USNO), these adjustments are determined using 10-day averaging and a damping factor of 100. This simple process has proven to be very effective and has maintained UTC(USNO) to within ±20 nanoseconds of UTC(BIPM) for the past year (Figure 2).

GPS TIME AND THE UTC CORRECTION

The Global Positioning System has become the most accurate widely accessible source of UTC throughout the world. With a constellation of 24 satellites, there are at least four satellites in view continuously and a user need only track one of these satellites to obtain precise time, if the users location is known. Otherwise, all four satellites must be tracked to determine location first. Although we take UTC via GPS for granted, it is important to understand how it is disseminated by the satellites.

Even though GPS time originated from UTC, it is not UTC. At 0h on January 6, 1980, GPS time was synchronized to UTC. But unlike UTC, GPS time is not adjusted for leap seconds. Consequently, whenever there is a leap second applied to UTC, the difference between GPS time and UTC changes. While the two time scales may differ by an integral number of leap seconds, they will always be very close at the sub-microsecond level, because GPS time is steered to be in phase with UTC(USNO). However, due to the variations of the two time scales, there will always be a small difference between them. The accumulated leap seconds plus this small phase offset is the correction for UTC.

Leap second adjustments are announced three to four months in advance, so the accumulated leap second correction is clearly defined and easily accounted for. Phase corrections, most often no more than ±20 nanoseconds, are determined at the USNO and sent via secure communications to the GPS Master Control Station (MCS) at Falcon AFB. The data are processed at the MCS and uploaded to the satellites. Page 18 of subframe 4 in the GPS broadcast from the satellites includes the parameters needed to relate GPS time to UTC. User sets must apply these parameters according to the following relationship in order to estimate UTC(USNO). This then becomes a source of UTC referred to as UTC(via GPS):

$$UTC(via\ GPS) = t_{GPS} - \Delta t_{UTC}$$

where $UTC(via\ GPS)$ is in seconds and

$$\Delta t_{UTC} = \Delta t_{LS} + A_0 + A_1(t_{GPS} - t_{RT})$$

Δt_{LS} = delta time due to leap seconds
t_{GPS} = GPS time
A_0 = phase correction
A_1 = the first-order term
t_{RT} = reference time for the UTC data.

Due to Selective Availability (SA) and Anti-Spoofing (A-S) imposed by the GPS, an unauthorized real-time user can experience a time transfer accuracy degradation of 150 nanoseconds (one sigma) or worse, while the user correcting for SA/A-S can expect an accuracy of 28 nanoseconds (one sigma). However, some manufacturers have incorporated smoothing algorithms and other techniques, which have been shown to improve accuracy by a factor of 2 or greater in their uncorrected timing receivers[3].

MONITORING GPS TIME

The USNO monitors GPS system time to provide a reliable and stable coordinated time reference for the satellite navigation system. There are several GPS timing receivers in constant operation in Washington, D.C. and at the USNO Alternate Sites. Each location monitors GPS time using both authorized Precise Positioning Service (PPS) and uncorrected

Standard Positioning Service (SPS) receivers. The receivers are scheduled to track satellites according to a recommended common-view tracking schedule, which is provided by the BIPM, for international time comparisons. Satellite track times are chosen to maximize elevation angles between pairs of stations and open tracking periods are filled with the emphasis on providing a balanced coverage of all satellites.

Data from the SPS receivers are collected and processed on the general purpose computers and, to maintain security, the PPS data are collected and processed on a dedicated computer. Each receiver outputs a measure of GPS time referenced to UTC(USNO) and also the correction for UTC, from individual satellites every six seconds. The six-second data are grouped into thirteen-minute intervals to produce one processed data record. The values within each record are computed for the mid-point of the track and are a measure of the difference between UTC(USNO) and GPS time (Figure 3, column 5) and the difference between UTC(USNO) and UTC(via GPS) (Figure 3, column 14)[4]. The latter is a measure of how well the satellite is disseminating UTC(USNO).

The USNO has adopted what it calls the "melting pot" technique for data reduction. With this technique, the thirteen-minute data from all satellites are grouped into running two-day intervals and a filtered linear least-squares solution is made, solving for the beginning of the second day. These daily values are a very good gauge of the time dissemination performance for the entire GPS constellation. The smooth data in Figure 4 shows that GPS time is most often maintained to within ±10 nanoseconds of UTC(USNO). It also shows that on rare occasions there can be a large divergence. However, Figure 4 also shows that, during periods when GPS time runs off, UTC(via GPS) can remain stable because the USNO reports the magnitude of the run-off to the MCS so that the UTC correction can be adjusted accordingly.

OTHER SOURCES OF UTC(USNO)

There are many ways in which UTC(USNO) is disseminated to the real time user. These range from a simple telephone call to a voice announcer at the USNO to specialized receiving equipment for tracking Earth-orbiting navigation satellites. With accuracies ranging from ±0.05 seconds to less than ±100 nanoseconds, users can select the system that best fills their requirements. Figure 5 lists the principal sources of UTC(USNO) and the accuracy a user can expect when using one of these systems. It should be noted that while all of the systems provide a reference for making phase comparisons, Loran-C and Omega do not provide the time of day.

The USNO Time Announcer, Computer Time via modem, and Network Time Synchronization (NTP) satisfy the needs of most users and are relatively inexpensive. In fact, with the possible exception of GPS, NTP is the most accessed source of UTC(USNO), with over 500,000 requests daily. The NTP is a free service and the software is available via anonymous FTP from "louie.udel.edu". All three of these services provide UTC(USNO) to an accuracy of ±0.05 seconds or better. In addition, the commercial Leitch system has a direct link to the USNO Master Clock and provides UTC(USNO) to subscribers via its time dissemination system.

For those who need time in the microsecond range, the Navy Transit Satellite System and the Omega navigation system are synchronized to UTC(USNO) via GPS and can provide a time reference which is accurate to less than ±25 microseconds. However, both of these systems will stop operations in the near future. The Transit system will discontinue its service at the end of 1996 and Omega will stop transmitting at the end of 1997.

As a service to the U.S. Coast Guard (USCG), the USNO has been monitoring the timing of the Loran-C system since the mid 1960s. This is in compliance with Public Law 100-223, which requires that all USCG controlled Loran-C master stations shall be synchronized to UTC. The monitoring of Loran-C transmissions by the USNO has made it possible for the USCG to control the timing of the Loran-C signals to within ±300 nanoseconds of UTC(USNO)[2]. Therefore, a user can obtain UTC(USNO) to an accuracy of ±500 nanosecond from Loran-C, allowing for errors in the computation of the propagation path of the signal. The USCG recently relinquished control of all foreign Loran-C stations to the host nations. Consequently, we cannot guarantee that these stations will continue to be synchronized to UTC. Therefore, it is recommended that users only monitor USCG-controlled Loran-C transmissions for the purpose of time transfer. But even this will not last long, because the USCG has announced that Loran-C transmissions controlled by them will be turned off by the year 2000, and replaced with differential GPS.

CONCLUSION

The USNO plays an important role in the formulation and dissemination of UTC. As the major contributor to the TAI, the USNO clocks have become a critical ingredient in the formulation of the International Atomic Time Scale. This is an important responsibility which the USNO will continue to meet in its support of the world timing community. The GPS now provides continuous accessibility to UTC throughout the world. As the primary reference to UTC for the GPS, UTC(USNO) has been steered to within ±20 nanoseconds of UTC(BIPM) for the last 400 days and within ±10 nanoseconds for the last 150 days (Figure 2). By maintaining UTC(USNO) as close as possible to UTC(BIPM), the USNO will ensure that all time dissemination systems that are synchronized to UTC(USNO) will also be synchronized to UTC.

REFERENCES

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[4] M. Miranian, and W.J. Klepczynski 1991, *"Time transfer via GPS at USNO,"* Proceedings of ION GPS-91, 11-13 September 1991, Albuquerque, New Mexico, pp. 215-221.

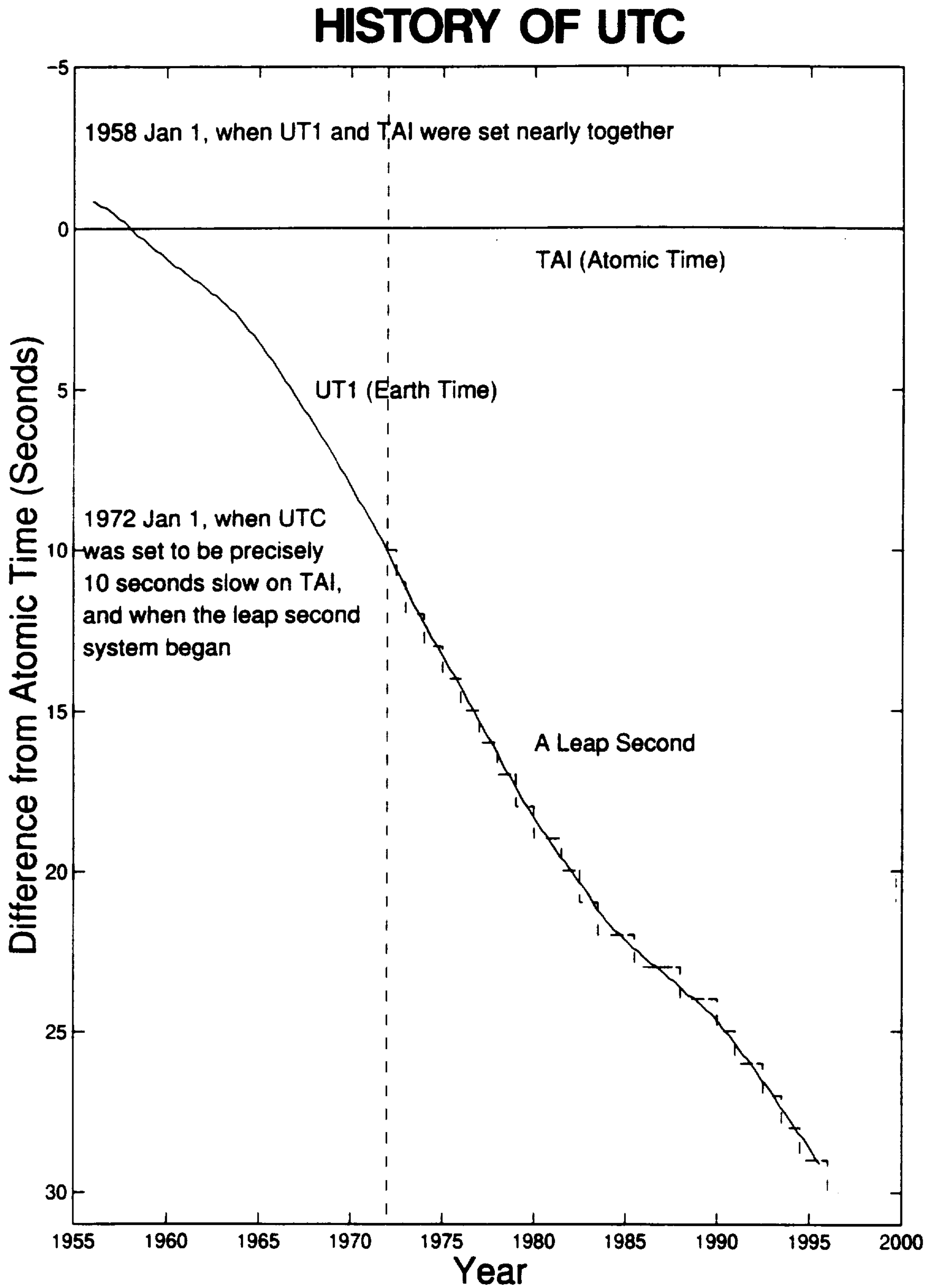
HISTORY OF UTC
1958 Jan 1, when UT1 and TAI were set nearly together
TAI (Atomic Time)
UT1 (Earth Time)
1972 Jan 1, when UTC was set to be precisely 10 seconds slow on TAI, and when the leap second system began
A Leap Second
Difference from Atomic Time (Seconds)
-5
0
5
10
15
20
25
30
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year

Figure 1

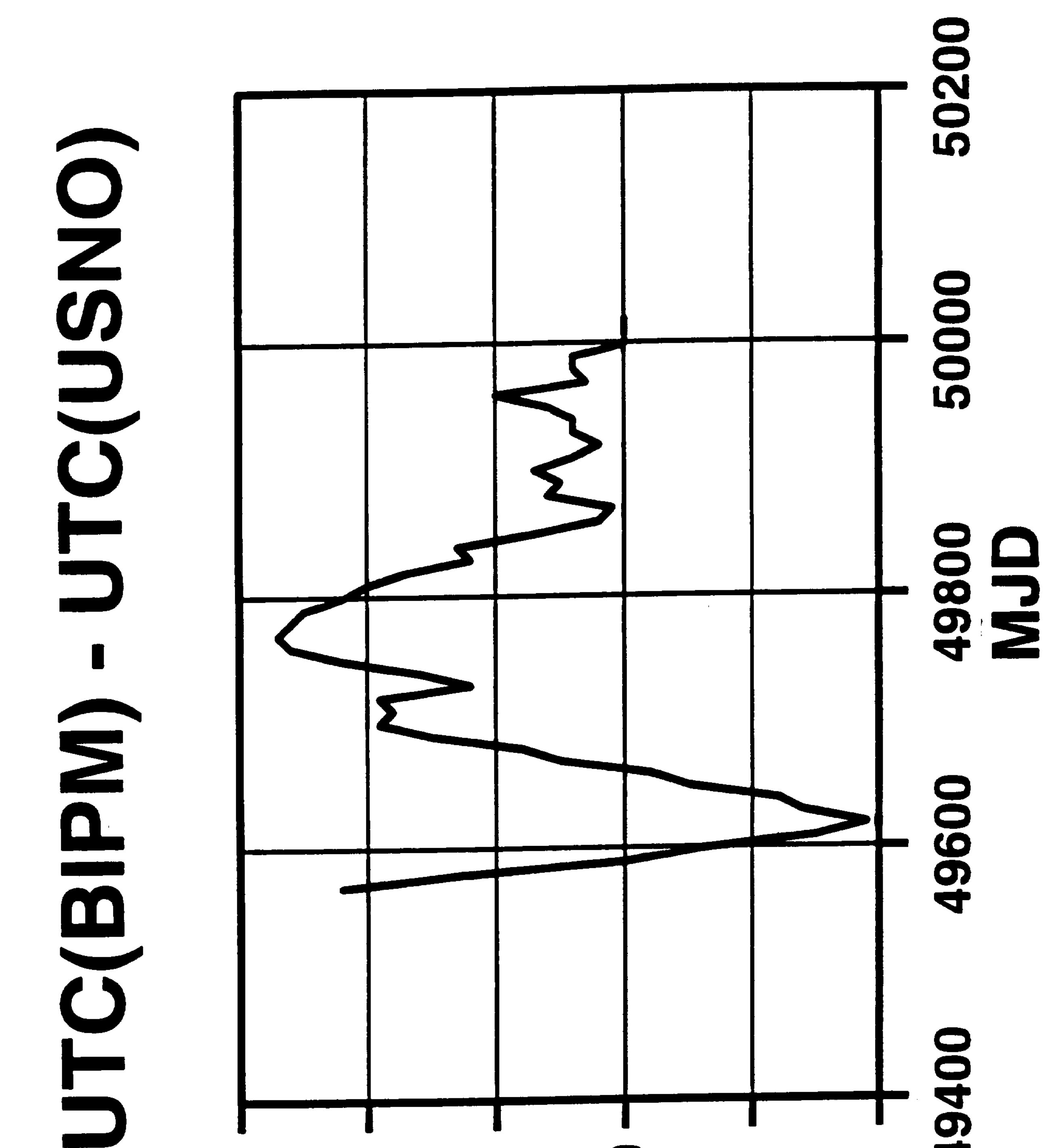
UTC(BIPM) - UTC(USNO)
Nanoseconds
30
20
10
0
-10
-20
49400
49600
49800
50000
50200
MJD

Figure 2

13-MINUTE PPS DATA RECORDS

PRN	MJD MID-POINT	START TIME UTC	TRK TIME s	USNO MC-GPS ns	SLOPE ps/s	RMS ns	N	EL	AZ	MEAS IONO CORR ns	USNO MC-SVCLK ns	SLOPE ps/s	USNO MC-UTC(via GPS) ns
17	50007.71705	1706	780	-18	-5	7	78	46	315	15	95466	0	4
17	50007.72608	1719	780	-17	2	3	78	66	316	19	95470	6	5
9	50007.75316	1758	780	-24	14	7	77	40	138	19	12682	17	-3
9	50007.76219	1811	780	-23	-12	5	78	45	132	20	12684	-9	-2
12	50007.78233	1840	780	-26	5	8	78	26	51	27	-236089	55	-5
17	50007.79483	1858	780	-22	19	8	78	57	181	20	95487	22	-1
9	50007.80663	1915	780	-22	0	4	78	56	84	15	12694	2	-1
21	50007.81844	1932	780	-29	31	5	75	49	314	18	5481	32	-8
23	50007.83927	2002	780	-20	-9	2	78	70	88	17	-2624	-9	2
23	50007.84830	2015	780	-21	7	3	78	66	103	16	-2625	7	1
21	50007.87260	2050	780	-24	1	1	69	84	331	10	5498	-8	0
21	50007.88157	2103	770	-22	0	4	77	88	152	10	5501	4	0
5	50007.89407	2121	770	-14	12	8	77	32	74	15	-4151	10	8
15	50007.90524	2137	780	-19	-12	9	78	19	309	24	-233545	-14	2
15	50007.91427	2150	780	-17	9	17	78	21	303	22	-233544	10	5
20	50007.93927	2226	780	-22	14	3	78	46	80	16	-29963	4	-1
20	50007.94824	2239	770	-20	-7	6	77	45	71	14	-29968	-17	1
1	50007.96080	2257	780	-29	-15	6	78	57	80	13	-607994	-13	-7
14	50007.97260	2314	780	-25	11	7	78	22	317	19	-11324	11	-3
25	50007.99621	2348	780	-19	33	11	78	71	8	9	-793	33	3

Figure 3

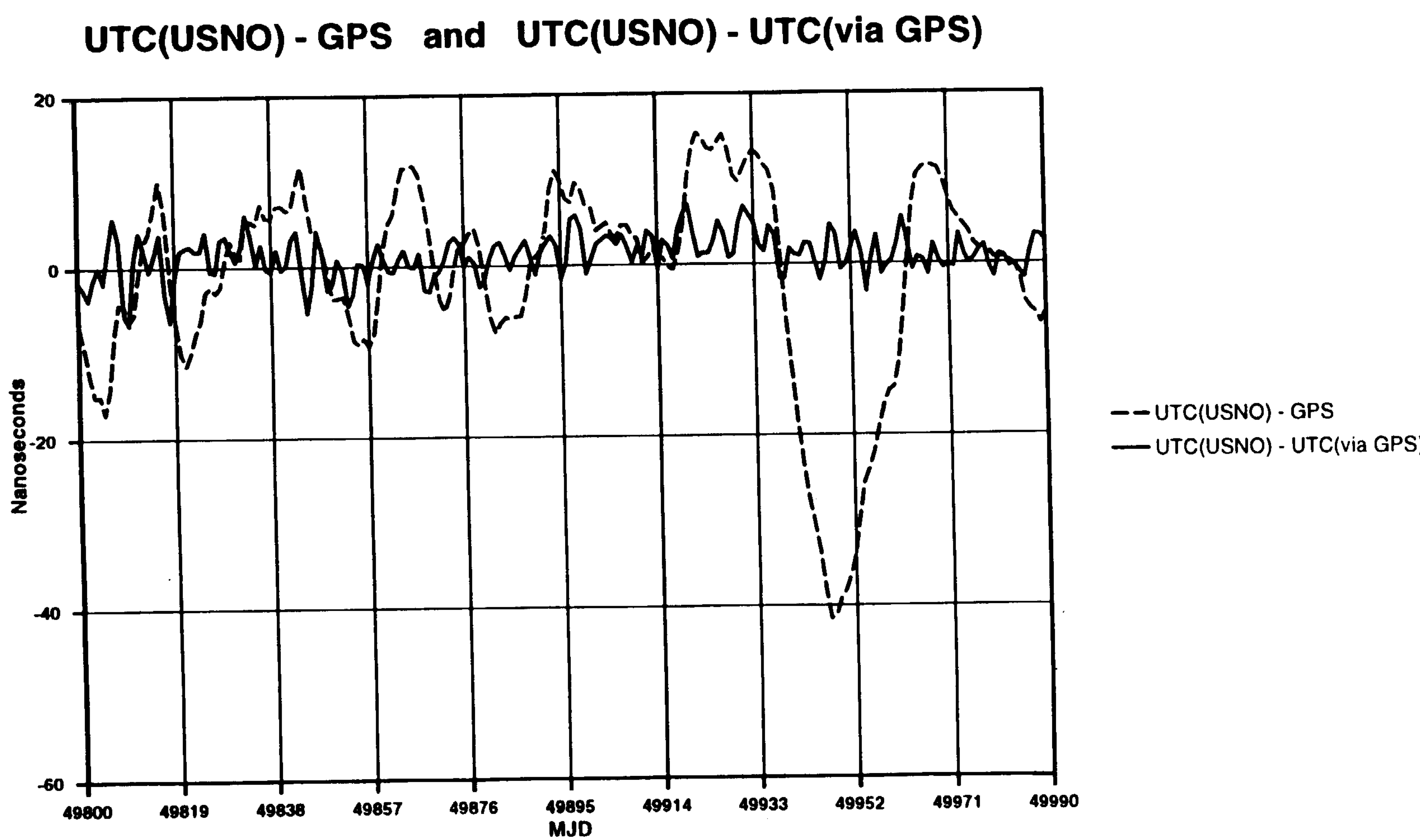
UTC(USNO) - GPS and UTC(USNO) - UTC(via GPS)
20
0
-20
-40
-60
Nanoseconds
49800
49819
49838
49857
49876
49895
49914
49933
49952
49971
49990
MJD
UTC(USNO) - GPS
UTC(USNO) - UTC(via GPS)

Figure 4

SOURCES OF UTC (USNO)

(Real Time)

SOURCE	TIME	PHASE	ACCURACY
			>
Voice Announcer	X	X	0.05 seconds
Computer Time	X	X	0.01 "
Leitch	X	X	0.01 "
Internet (NTP)	X	X	0.01 "
Transit Satellite	X	X	25 microsec.
Omega		X	2 "
Loran-C (US only)		X	500 nanosec.
GPS SPS	X	X	300 "
GPS PPS	X	X	50 "

Figure 5

Questions and Answers

SAMUEL STEIN (TIMING SOLUTIONS CORPORATION): Mihran, I was wondering if it would be possible for you to put some numbers to the bullets you had on your conclusion graph. For example, if I'm in an industrializing nation and I'm setting up a time and frequency laboratory to provide calibrations for local industry, and I want to establish frequency accuracy using GPS, I go through UTC, USNO; and the frequency accuracy I get is determined by the maximum steering rate that USNO will ever use in order to keep its time close to UTC. Do you publish that maximum rate?

MIHRAN MIRANIAN (USNO): The maximum rate – let's see – that we're using right now is about 3×10^{-15}. That's a maximum. But it's usually not that much; it's no more than about one part daily. So it's pretty stable.

SAMUEL STEIN (TIMING SOLUTIONS CORPORATION): The other question I had was that I think you gave a very conservative specification of 300 nanoseconds for the performance an SPS commercial receiver, but more commonly, people bandy about approximately 100 nanoseconds. Can you comment on that?

MIHRAN MIRANIAN (USNO): Yes. There are a number of techniques that are being used. I think the HP receiver, the new HP receiver, we just tested one for a short time at the Observatory. It's amazing what it can do. It's performing around 50 to 70 nanoseconds.

The Motorola receiver – I just showed you that one – there are a number of receivers. There are a lot of techniques that are now being used for averaging. Actually, maybe Dave could talk about that, Dave Allan. I know you're involved with that. Do you want to, Dave?

DAVID ALLAN (ALLAN'S TIME): The idea of averaging is a little different because, of course, these receivers are built for telecom, and they have to be real time. So you're not really averaging, you're looking at the SA spectrum and reducing its effects; looking at the clock spectrum and designing a filter so that you can do a real-time estimate of what is UTC. The rms numbers on the HP receivers are about 20 nanoseconds. Peak-to-peak will go up to like 70 each day.

So one can do very well. That's with a quartz-phase simple receiver. So once you understand the SA, it goes extremely well.

The question I had, Mihran, I know there's legislation for LORAN to be within 100 nanoseconds. How is that proceeding?

MIHRAN MIRANIAN (USNO): Yes, there is a public law that says that LORAN is supposed to be within that specification, but they never defined what. And we think they mean 100 nanoseconds rms. But it was never clearly defined. So I don't know what to tell you. But I can tell you that when you look at our Series Four, where we published the offset between LORAN stations – most of them are within about 100 nanoseconds.

But again, to the user – and I'm going to the real time user now – what can he expect? I'd say it's safe to say 500 nanoseconds.