RECENT AND PENDING IMPROVEMENTS AT THE U.S. NAVAL OBSERVATORY

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Abstract

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INTRODUCTION

The U.S. Naval Observatory (USNO) Time Service Department has recently made many operational improvements to its clock ensemble, measurement systems, computer systems, timescale algorithms, and time-transfer systems.

HARDWARE

USNO is known for its large number of atomic frequency standards, which provide the basis for a very robust and precise timescale. In the past year we have added to this number by purchasing one additional maser and ordering six more cesium standards, so that soon there will be 50 cesium standards and 11 cavity-tuned masers at our main facility at Washington, D.C., and 11 cesiums plus three masers at our backup site at Schriever Air Force Base, the USNO Alternate Master Clock (AMC).

In order to maximize the benefit from our clocks, we keep them in environmental chambers that control their temperature and humidity. The control system has been improved through better regulation and preventive maintenance on the chambers, and we have also begun preventive maintenance on the clocks themselves by monitoring their digital outputs of health and status information [1]. For protection against electrical power outages, the DC power backup system has been rendered more robust through improved charging systems, batteries, and cabling, while the AC Uninterruptible Power System (UPS) has been replaced by an upgraded system that provides duplicate and interchangeable outputs that are initially powered by batteries but, within a few minutes of a power outage, are powered by diesel generators. So as to protect against catastrophic failure of the UPS system, we are now constructing a second backup power system based upon an independent electrical feed from the outside.

The principle of robustness through duplication extends throughout our operations. Each clock's time (phase) is measured using two different measurement systems, and separate mean timescales are generated using the data from each measurement system. Our operational Digital Acquisition System, used in steering the Master Clock, is our noisiest but most robust; it uses a time-interval counter and switches to measure start/stop time differences of 5 MHz and 1-pps clock signals. As estimated via parallel measurements, the hourly precision of our current system is about 50 ps rms, and the very long-term accuracy is about 1 ns peak to peak. We are in the final process of debugging a new switch-and-counter system which should be quieter, more accurate, and more robust because it has fewer but improved switches, no BNC connectors, phase-stable cabling throughout, and fewer ground loops. The 1-pps measurements will also benefit from the use of pulse regenerators with 400 ps rise times and only 3 ps of jitter.

In addition to our switch system, we also have high-precision measurement systems in each of our two Washington, D.C., clock buildings and at the AMC. These operate on only 5 MHz data, but with an hourly precision of only 20 ps rms, and a system accuracy of 300 ps peak to peak. It is our long-term goal to use the timescales generated from these systems for steering, while the switch system becomes a backup.

For additional robustness, we are improving the ns-level timing ties between our two Washington buildings through the installation of temperature-compensated cables [2], and also maintain ns-level timing ties to the Alternate Master Clock via hourly Two-Way Satellite Time Transfer (TWSTT).

The purpose of maintaining a large and robust ensemble of clocks is to create a timescale which is both precise and robust. This requires an interconnected system of computers to interface with the measurement systems, process data, and distribute our output products. Our computer code and our data are routinely backed up and a base-wide firewall has been partially implemented. Current plans are to have Time Service Department behind the general USNO firewall, as well as behind a secondary department-level firewall, by early next year.

TIMESCALES AND CLOCK STEERING

With our computers secure, and Y2K-compliant, our data analysts will continue to supplement our automatic editing of clock data with visual inspection so as to provide a precise timescale for clock steering, clock characterization, and off-line applications. Our timescale algorithm is best described as a modified Percival algorithm [3,4], and is created by integrating a frequency scale of detrended clocks. The detrending of all our clocks, both cesiums and masers, is for frequency bias and, if significant, drifts, and accomplished by comparison with an unsteered mean of only detrended cesium clocks. A maser-only mean generated from the detrended masers is our most precise timescale, and we are considering switching to that mean for steering. In this plan, cesiums would be used only for the critical function of characterizing maser frequency biases and drifts. For the present, however, we steer via the A.1 timescale, which provides a smooth transition between cesium and maser frequencies by weighting maser frequencies higher in the recent past than in the more distant past [5].

We have improved our Master Clock steering through adoption of a faster time constant (25 days) for steering our maser to a steered mean, which is the A.1 steered to predictions of UTC(BIPM). This was justified by an improved ability to predict UTC(BIPM)-UTC(USNO)[6], and has allowed UTC(USNO) to stay within 8 ns of UTC(BIPM) over the past year (Figure 1). Starting July, 1999, we began steering using the "gentle mean" concept [7], which steers UTC(USNO) to UTC(BIPM) with the mathematically minimum amount of control, given the constraints of the problem. Figure 2 shows the stability of the USNO Master Clock, when referenced to our unsteered maser mean, for four 1-year periods. The stability has been less than 3×10^{-15} over periods from 8 hours to 30 days. As expected, our switch to a more aggressive steering strategy has not affected our frequency stability over periods less than a few days, but the price we have paid for adhering closer to UTC(BIPM) has been a decrease in our stability over 10-30 day sampling times. We expect that our timescale will be more stable in the near future, when our cesium atomic fountain (Figure 3) becomes operational and when JPL delivers its mercury-based LITE [8]. We also anticipate that the use of TWSTT data in trans-Atlantic time transfer for the computation of UTC(BIPM) will improve its stability as well.

TIME TRANSFER

As important as time generation is time transfer, which at the USNO and in most laboratories takes many forms. Our coarsest means, via telephone, has about 787,000 users per year, while almost a million users download the time electronically using modems on telephone lines. We also e-mail timing information weekly to all who request it in our Series 4, and provide anonymous Web-based FTP and ADS services which generate over 100 million requests per year. You may want to visit our Web pages at http://tycho.usno.navy.mil.

Our largest number of users access the time via the Internet using Network Timing Protocol (NTP). Figure 4 shows that the number of NTP packet requests has almost tripled last year – and these amount to over a billion requests from at least 430,000 separate IP addresses. Our NTP program has recently been added to the SIPRNET [9], and we are working with the Defense Information Systems Agency (DISA) on extending that service.

We have continued to monitor LORAN transmissions, and upgraded our systems at Flagstaff, Arizona, and Elmendorf, Alaska, as part of our Y2K preparations with rubidium-based GPS receivers.

Every PTTI user knows that we monitor GPS time so that it can be steered to UTC(USNO), to serve a large and semi-anonymous set of users [10], but it is less well known that we run a GPS receiver calibration service that has assisted military users. In order to improve GPS monitoring, we have ordered and received the raw materials to construct a multi-path reducing structure on our main building, and we are also developing improved time-transfer receivers [11].

Our work in GPS carrier phase time transfer will be reported in two papers here [2,12], but we also have improved our TWSTT operations through the introduction of better X-band low-noise amplifiers, improved up- and down-converters, and the replacement of travelling wave tubes with solid state power amplifiers. TWSTT is currently the most accurate means of long-distance time transfer, and we know this because our periodic calibrations generally indicate only subnanosecond shifts. The importance of our TWSTT program is shown by the many users willing to help contribute to its costs.

CONCLUSION

I want to close by acknowledging the important contributions made by all members of the Time Service Department and the chain of command leading up to and including DoD PTTI manager Captain Larsen. Specifically, this is Jeff Beish, Bill Bollwerk, Lee Breakiron, Eric Burt, Harold Chadsey, Jim DeYoung, Chris Ekstrom, Jim Eler, Steven Hutsell, Nicolette Jardine, Kenneth Johnston, Wendy King, Anthony Kubik, Ed Lukacs, George Luther, Phu Mai, Dennis McCarthy, Angela McKinley, Mihran Miranian, Ed Powers, Lara Schmidt, Richard Schmidt, Kenneth Senior, Tom Swanson, Minh Tran, Francine Vannicola, and Paul Wheeler.

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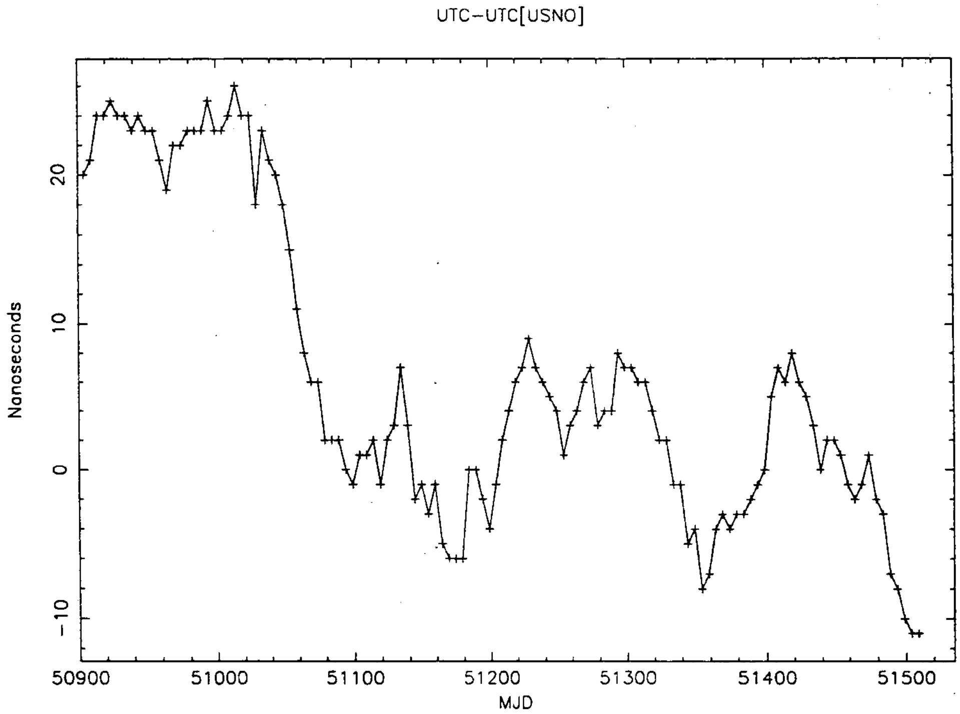

Figure 1. UTC(BIPM) minus UTC(USNO) from March, 1998 to November, 1999. The improvement beginning MJD 51200 is due to the implementation of a tighter steering algorithm.

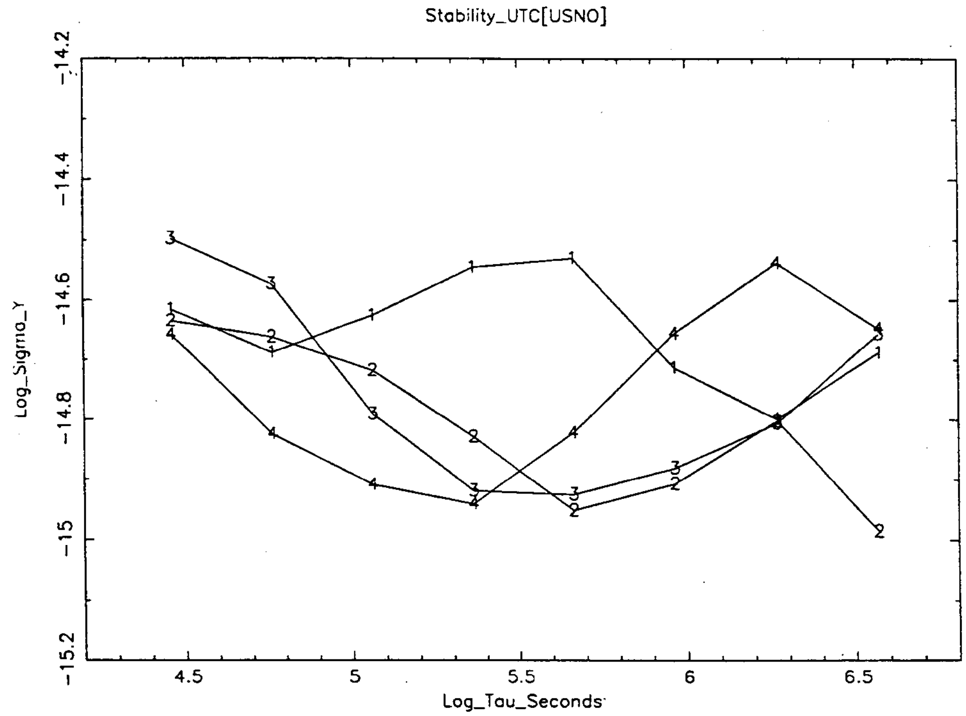

Figure 2. Frequency stability (σ_y) of the USNO Master Clock as measured by the USNO unsteered maser mean timescale over four successive 1-year periods. The curves are numbered chronologically from MJD 50070-550435 (19 Dec. 1995-18 Dec 1996) to MJD 51165-51530 (18 Dec. 1998-18 Dec. 1999). Because the unsteered maser mean has accumulated a frequency drift compared to UTC, a parabolic term was removed from the raw data before the statistics were computed.

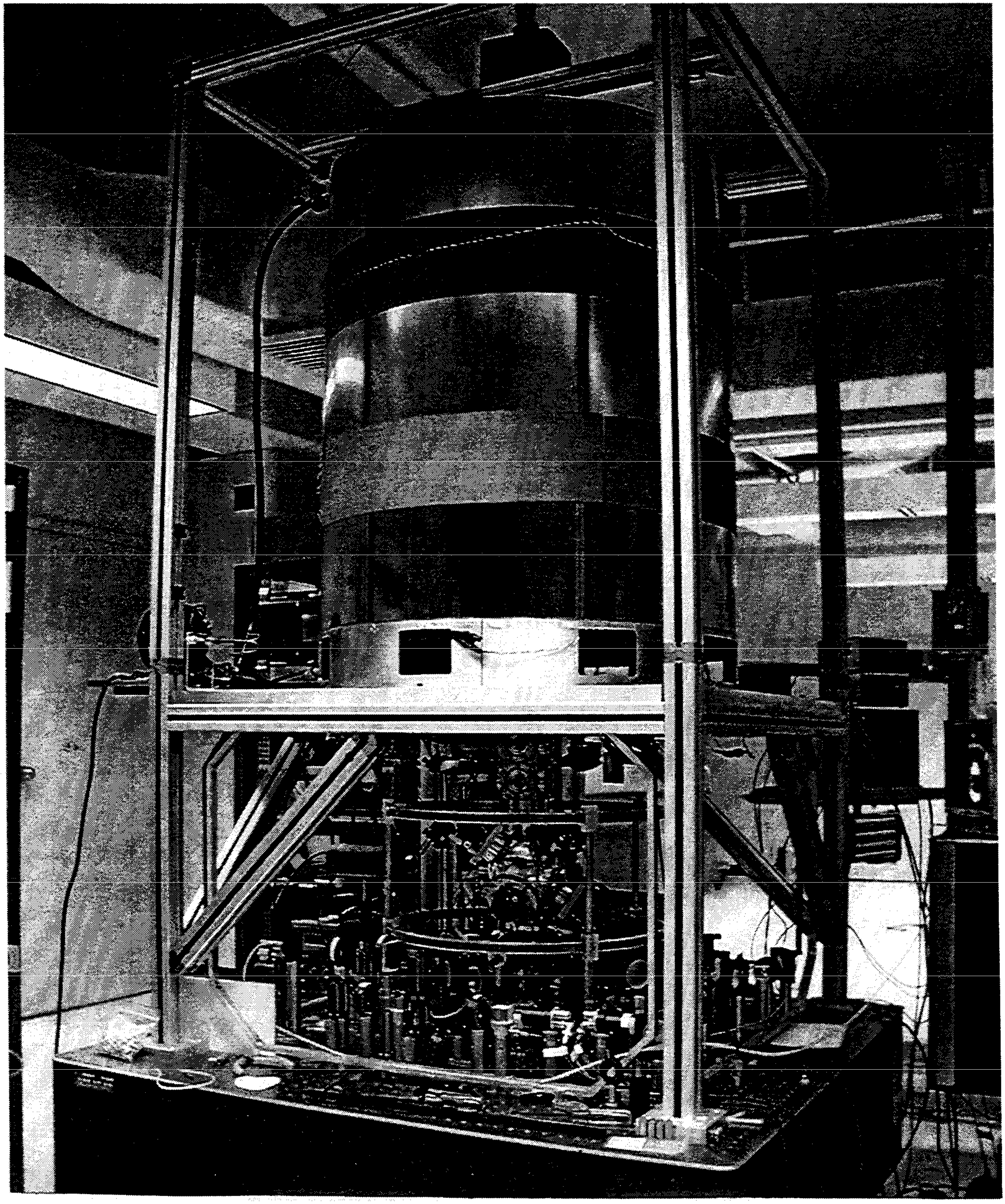

Figure 3. Cesium Fountain in its current state of development, which can trap and launch atoms, but not state-select them yet. Much of the hardware is within the magnetic shield.

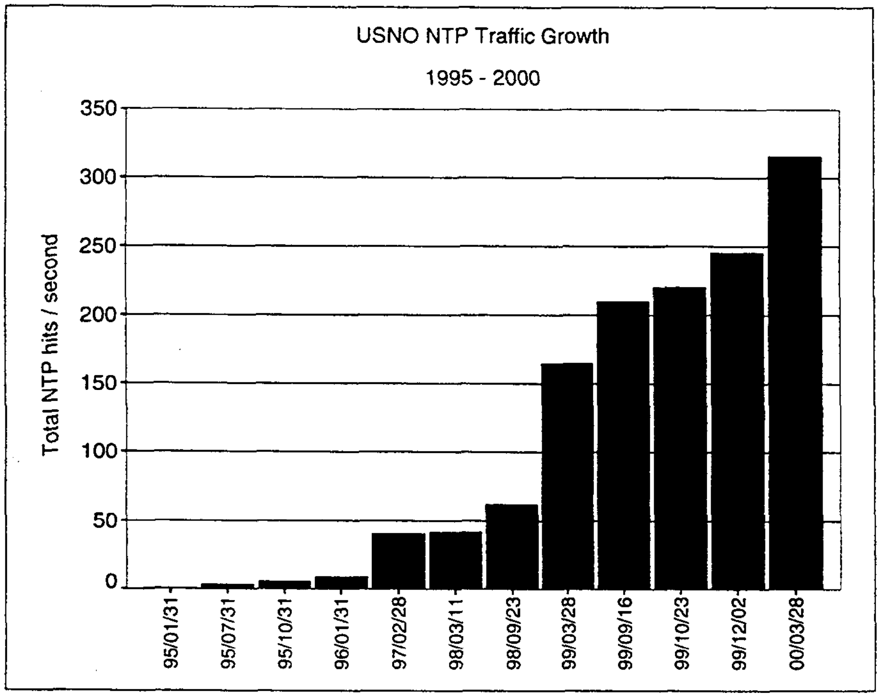

Figure 4. Growth of Network Timing Protocol (NTP), as measured in number of packet requests per second.

Questions and Answers

CAPTAIN MICHAEL RIVERS (USAF 2SOPS): What user is driving the need for the 20-nanosecond synchronization between UTC (USNO) and UTC?

DEMETRIOS MATSAKIS (USNO): That number is what we heard yesterday from two different speakers. And I guess I have a question to present, too, of what is driving that need. You have to distinguish between two questions also. One is the online synchronization. UTC is not defined for the present; UTC only comes out 15 days to 1 month late. So is the requirement to be within 20 nanoseconds of a realization of UTC, of which UTC (USNO) is one, or is it to have been accurate to 20 nanoseconds a month ago? And that was not clear yesterday either.

The question of what user requirements really are is one that we're very interested in. The Master Clock is a very powerful thing; we can optimize it for time, we can optimize it for frequency or for any compromise in-between. And we're always interested in finding out from users what they need.

SIGFRIDO LESCHIUTTA (IEN): I'm taking, Mr. Chairman, this opportunity to make an announcement, with your permission. Since the topic of timescale formation and timescale algorithm is an important one for a number of applications, we are planning to organize in Torino at the end of 2000 and beginning of 2001 a special seminar devoted to the timescale algorithms in cooperation with the USNO and BIPM. It will be the third seminar on this topic. Thank you, Mr. Chairman.

TOM McCASKILL (NRL): Could you please give us your best estimate of the stability of the DoD Master Clock at a 1-day sample time?

MATSAKIS: I actually have some plots comparing that, but I left them in my hotel room. I can show you later, and they will appear in the published version.

What we now do is we steer a maser once a day to our average of clocks. So in less than 1 day, the stability is given by a single maser. And longer than 1 day is given by our steering of that maser, but it's a very smooth transition if you go from one point to the other. When we get into the gentle-mean concept and introduce the low-noise measurement systems, we will be able to do much better on the short term because we will be able to do a better average on all our masers in the short term with lower noise and steer more carefully to it.

STEVEN HUTSELL (USNO AMC): I thought I would sort of add on to Captain Rivers' question. Having worked both sides of the hallway, so to speak, in the operations center at 2SOPS and in the Alternate Master Clock, I think it's safe to say that from the time I've worked in both, GPS – if we're talking about user requirements for synchronization between USNO and BIPM, I want to just hit home on what I commented yesterday with the golden foot stomp. GPS is not, repeat, not a driver for any such synchronization. And also to hit the point home, that's not to suggest that the steering be relaxed to the point of oblivion or turned off, but just as long as people understand as far as customers or users, GPS really cannot be considered the driver for that.

I think Mike was sort of alluding to that. We haven't heard of any users from the ones we've talked to who've levied any such requirement, and certainly in the MCS we don't have that requirement. Thank you.

DAVID ALLAN (Allan's Time): Kind of a complementary statement to Steve Hutsell's comment. From an international perspective, having been involved with that community for many years, even though GPS is not a driver, it is an incredible support structure for tons of folks who pay nothing. We have this free service which is so wonderful. And, in fact, if UTC (USNO) does track UTC which, as Demetrios says is a month after the fact, then this provides a tremendous service to the world community. So even though there's no funds driving it, its utility is really pretty great.

MATSAKIS: I can add more comment. It's an area where I'm not a hundred percent certain because I've started working on it, but ran into some trouble getting old data to play with. If you're interested in the interaction between UTC (USNO) and GPS time, UTC (USNO) is only part of the question. The other issue is how does GPS time steer to UTC (USNO), and that's relevant for people who don't download the correction until they can get UTC (USNO) out.

UTC (GPS) time is steered to optimize frequency stability. So there's a coupled system between something the USNO and GPS. You have to take both of those into consideration. It would be very simplistic to say UTC (USNO) should be optimizing phase because GPS is optimizing frequency. It has to be looked at together.

The problem I ran into is that the Composite Clock information has not recorded all the time at GPS, so it's a little hard to get to the historical information to do detailed simulations. I actually had a paper in the last ION meeting about it, and when I faxed it to the ION people they lost it. And it was less work for me.