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CONSTRUCTION AND PERFORMANCE CHARACTERISTICS OF A PROTOTYPE NBS/GPS RECEIVER

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Summary

The National Bureau of Standards (NBS) has proposed a particular application of the clear access channel C/A of the Global Positioning System (GPS) signal utilizing the fact that the location of two earth stations may be known. Hence, if one has common-view of a single satellite from these two earth stations, excellent time transfer capability exists. NBS has developed a prototype receiver featuring extremely high time transfer accuracy and low cost. Even though one may not know the absolute delays through the receivers, one can do absolute time transfer by knowing the differential delay between two receivers.

The received satellite signals gave an RMS time fluctuation of the receiver output as good as 3.5 nanoseconds for an omni antenna using 15 second averages. The noise was characterized as white noise phase modulation, which can be averaged below the systematics, which are about 1 nanosecond over a thermal range of several degrees about ambient. The day-to-day time fluctuations, when measuring the time difference between the NBS Boulder and U.S. Naval Observatory (USNO) Washington, D.C. were about 5 ns.

The software and the receiver are configured to be fully automatic with a Z80A microprocessor setting the amplitude for the lock loops of the receiver and setting the synthesizer which corrects for the nominal Doppler shift. The receiver also has a unique feature of using the microprocesser to calibrate a 0.1 ns built-in time interval counter. All that is required on the part of the user is a local 1 pps tick and a 5 MHz signal, plus his local coordinates.

Key Words: Automatic time comparison; deep space network; differential time transfer; frequency transfer; international time comparison; primary frequency standards; SI second; Global Positioning System.

Introduction

The advent of GPS has opened other doors besides navigation for applications using this system. In particular, the staff at the Time and Frequency Division of NBS have capitalized on the idea of using a single GPS satellite signal in common view at two fixed and known coordinate locations on the surface of the earth, e.g., NBS in Boulder, CO, USNO in Washington, DC, National Research Council (NRC) in Ottawa, Canada, Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, West Germany, or the Bureau International de l'Heure (BIH) in Paris, France. Since navigation is not necessary, this system can be turned into a pure time transfer technique for achieving a significant amount of common-mode cancellation of errors. In particular, any satellite clock errors disappear when the difference is taken between the received times at the two sites; the ephemeris errors for the satellite might be reduced by an order of magnitude or more depending upon the size and direction of the ephemeris errors, and upon the baseline distance between the two earth stations. If convenient times are chosen, there may be significant amounts of common-mode cancellation in the ionosphere of the two paths from the satellite to the two ground stations. A previous paper has been published showing the estimated effects of these various error sources, the results of which gave significant encouragement to pursue this type of approach.[1]

Over the course of about the last 1½ years, a few of the staff of the Time and Frequency Division at NBS have vigorously pursued the design, construction, and testing of a receiver to accomplish these goals. The basic design goals were high accuracy and low cost so that hopefully some industry could capitalize on the research and development effort and make the same available on the open market to a significant number of interested users. On 4 May 1981, the prototype receiver at NBS was locked to a GPS satellite signal on the first attempt. The results of the received data thereafter will be presented in part in the body of the paper.

One of the cost-cutting aspects that has been incorporated is to use the C/A signal only, since preliminary studies showed that it would have adequate accuracy to meet the design goal of better than 10 ns worldwide time transfer using the common-view approach.

Receiver Configuration

Hardware Configuration. The system consists of three rack-mounted chassis, 13.3 cm (5¼ in.) H x 40.6 cm (16 in.) D. A separate low-noise amplifier and down-converter are mounted at the antenna. One rack-mounted chassis contains the receiver processing circuitry, the second contains the the microprocessor-counter and the third is a fail-safe (battery-backup) power supply.

The system is controlled by a Z80A processor operating with a 4 MHz clock. The processor card, which is designed for this application, includes 32 k-bytes of RAM, 16 k of EPROM, 2 serial UARTs (1 for RS-232 and 1 for tape), 9 eight-bit parallel ports, a memory-mapped video display generator and an eight-level priority interrupt structure. Total power consumption of the processor card is eight watts.

Local I/O is provided through a parallel input keyboard and video display. The video display provides "warm feelings" to the user by continuously displaying system status. Local hard copy is available through the RS-232. Two systems can communicate with each other through a dedicated auto-answer/auto-originate modem.

A "micro-cassette" tape drive in the processor chassis is used to load/save programs and data. Each cassette has a capacity of approximately 50 k-bytes.

The time interval counter card in the processor chassis helps keep system cost low with no compromise in performance. The counter is a start-stop interpolator type and is calibrated by the processor before each satellite pass measurement begins. Counter resolution is 0.1 ns. Absolute accuracy is better than 1 ns (3 σ).

Since the ultimate goal is to provide differential time transfer capability with maximum accuracy, we have paid particular attention to those factors in the receiver design that can result in delay variations. For example, receiver bandwidth (RF and IF) is much larger than necessary if the goal were simply to optimize signal/noise performance. Also, special attention was given to the correlation loop servo to minimize the effect of temperature. Although we have not performed exhaustive tests up to this time, it appears that the receiver systematics are less than ±2 ns in a normal room environment where temperature variations are on the order of ±5 °C.

The software and hardware are capable of providing analog azimuth and elevation outputs to steer a high-gain (16 dB) antenna if this option appears desirable to minimize the effects of multipath on timing accuracy. (This option is certainly not necessary from the standpoint of S/N, since in 10 minutes we can average down to the 1-2 ns level of the receiver systematics with the present quad spiral omni antenna wound on a 2.5 cm diameter x 6 cm long cylinder with a 7 cm ground plane. We are able to track satellites down to a 1° elevation angle with the omni antenna.)

Software Configuration. The key element in the performance of this "stand-alone" GPS time transfer system is in the integration of the hardware and software. Since all control and computation is performed by a single Z80A processor, the software is required to be very efficient in execution time, especially the interrupt-driven routines that must perform a return from interrupt within 500 µs. A key "number-crunching" requirement is sufficient numeric accuracy to compute satellite position to 1 cm.

We chose to start from scratch, with the deveopment of a 15 decimal digit floating point package with hex interpreter for number crunching and a unique interrupt implementation in Z80 assembly language for the interrupt-driven programs. The total software package presently stands at approximately 20 k-bytes of object code. This represents about 1 man-year of programming time.

There are 7 interrupt-driven programs, plus the interruptable "number cruncher." The interrupt-driven programs are:

Priority	Name	Interrupt Rate	Function
1	Receiver	50Hz/1kHz	Lock Rcvr-Track
2	Tape	75Hz/200Hz	Read/Write Tape Files
3	RX	150Hz	Receive RS-232 Data
4	Spare	---	---
5	Keyboard	30Hz	Read Kbd-Display-Video
6	Counter	30Hz	Make Counter Measurements
7	TX	150Hz	Transmit RS-232 Data
8	1Hz	1Hz	Run Real Time UTC Clock

The interrupt-driven programs represent a processor overhead time of from 5% to 15%, depending upon what is happening at any instant of time.

One crucial point is that all 7 interrupt-driven programs and the interruptable number cruncher are "alive" at all times (naturally in a time-slice context). It is possible that at a given second, the receiver program is loading the serial data from a satellite and running the GPS clock, the tape program is in the process of writing a data file, the RX program is decoding an operator command, the counter program is making a pseudo-range measurement, the TX program is printing the hard copy results of passes for the previous 10 days, and the 1 Hz program is updating the UTC clock and has determined that this is the second to stop tracking the current satellite. Meanwhile, the interruptable program is in the process of computing the x,y,z coordinates of the satellite now being tracked.

Receiver Results

Shown in figure 1 are the time deviations between the space vehicle clock and the NBS reference clock. The space vehicle clock is a cesium onboard NAVSTAR-5 and, of course, the deviations include propagation fluctuations as well. One observes over the 10½ minute segment of data an rms time fluctuation of 3.5 ns. Each point is a 15 s average. In figure 2 is plotted $\sigma_y(\tau)$ fractional frequency stability and a new method (see Ref. 2) of frequency stability measurement called "modified" for Mod $\sigma_y(\tau)$ vs. the sample time, τ, for the data shown in figure 1. The resulting analysis indicates that the random noise process involved is commonly referred to as white noise phase modulation. The implication of this kind of noise is that one could average the time reading down to an uncertainty of better than 1 ns for averaging times longer than 3 minutes. Shown in figure 3 is a similar analysis for a rubidium standard onboard NAVSTAR-3, denoted space vehicle 6 vs. the reference clock at NBS and one sees similar performance. Also plotted on this $\sigma_y(\tau)$ diagram is the inferred stability of the onboard rubidium clock. The inference here is that one would be able to see the clock instabilities for averaging times beyond about 3000 s (roughly 1 hour).

Shown in figure 4 are the elevation angles vs. UT time for 15 June 1981 as observed from Boulder, Colorado and figure 4b is a similar plot as observed from Washington, DC. It is evident that there are several times over which the common-view, common-mode cancellation technique can be used to do time transfer between Boulder and Washington, DC. Advantage was taken of this to compare the clocks between NBS and USNO. Figure 5 is a plot of those time differences utilizing the average of the two rubidiums and the two cesiums onboard NAVSTAR-3, 4, 5, and 6, respectively. Since the differential delay between the two receivers was not known, a portable clock trip over 25-30 May 1981 was used to calibrate the differential delay before plotting the results in figure 5.

The time difference as obtained across the four satellites as compared to that by portable clock differed by approximately 335 ns. The reason for this difference is not known. It is possible that it is in how time is defined in the pseudo-random code by the designers of the receiver used at USNO vs. the NBS design. The next obvious step, of course, is to build two identical receivers, and compare them side-by-side. It is fully believed and expected that this difference will disappear, or at least be reduced to the order of a few nanoseconds.

The agreement, when taken across the satellites, in the measure of the time difference UTC(USNO) - UTC(NBS) on any day on the average was 6.5 ns, which would yield a standard deviation of the mean of about 3 ns. This is very close to the clock noise for a sample time of only one day! The frequency difference averaged over 15 days between UTC(USNO) and UTC(NBS) was measured independently using each of the above four satellites and the values were as follows:

NAVSTAR	$y_{\mathrm{UTC(USNO)} - \mathrm{UTC(NBS)}}$
3	-4.0×10^{-14}
4	-4.0×10^{-14}
5	-3.7×10^{-14}
6	-4.4×10^{-14}
Average	-4.0×10^{-14}

The standard deviation of the mean is 0.14×10^{-14}. This is at least two orders of magnitude better than the results that can be obtained using Loran-C.

Conclusions

We have preliminarily demonstrated that a low-cost, high-accuracy GPS C/A receiver can be built, taking advantage of simultaneous common view of the same satellite. This appears to potentially allow time transfer with accuracies of the order or or less than 10 ns for baselines as large as 3000 kilometers, and frequency can be measured to better than 1 part in 10^{14}. With further studies of the propagation delays, this level of accuracy should be able to be extended on an international basis. It is fortunate that many of the key laboratories involved with accurate time and frequency are at high latitudes. This affords simultaneous common view between such sites as NBS, Boulder and New Delhi, India and USNO, Washington, DC and Radio Research Laboratories (RRL), Tokyo, Japan. This seems suprising at first, but upon calculation becomes obviously doable. This level of national and international time transfer accuracy, of course, affords also excellent frequency transfer accuracy at nominal state-of-the-art levels. These results have potentially significant impact on assisting the monitoring stations for GPS, on syntonizing the tracking stations for the Jet Propulsion Laboratory (JPL) Deep-Space Network, and for doing fundamental time and frequency comparisons for the international time scale and between primary frequency standards laboratories. Any future applications like the above, of course, depend on GPS remaining operationally available at better than the current levels of accuracy. At the present time, we do not know whether this will or will not be true.

Acknowledgments

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References

1. David W. Allan and Marc Weiss, Proc. 34th Annual Symposium on Frequency Control, 334 (1980).
2. David W. Allan and J. A. Barnes, Proc. 35th Annual Symposium on Frequency Control (1981), to be published.

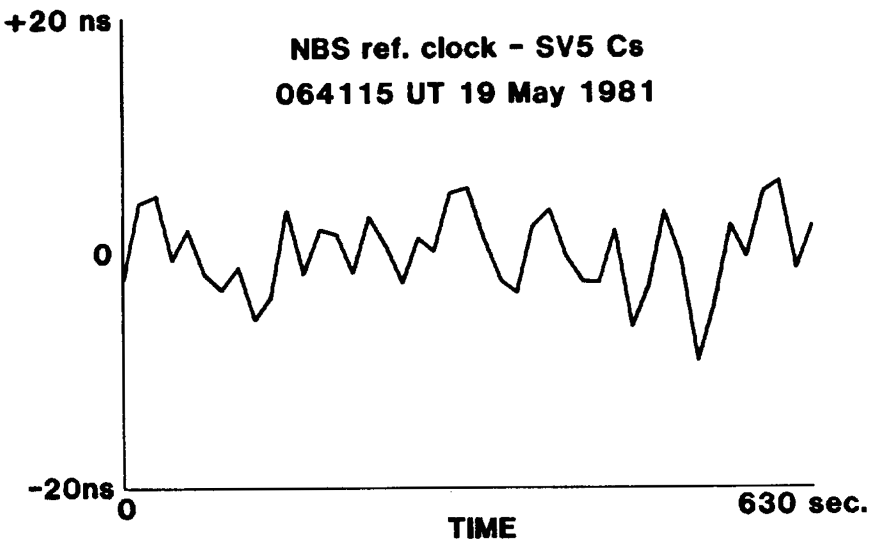

Fig. 1. A plot of the time deviations between a cesium clock onboard the GPS satellite, NAVSTAR-5, vs. the NBS reference clock. Each point is a 15 s average. The rms across the data set was 3.5 ns.

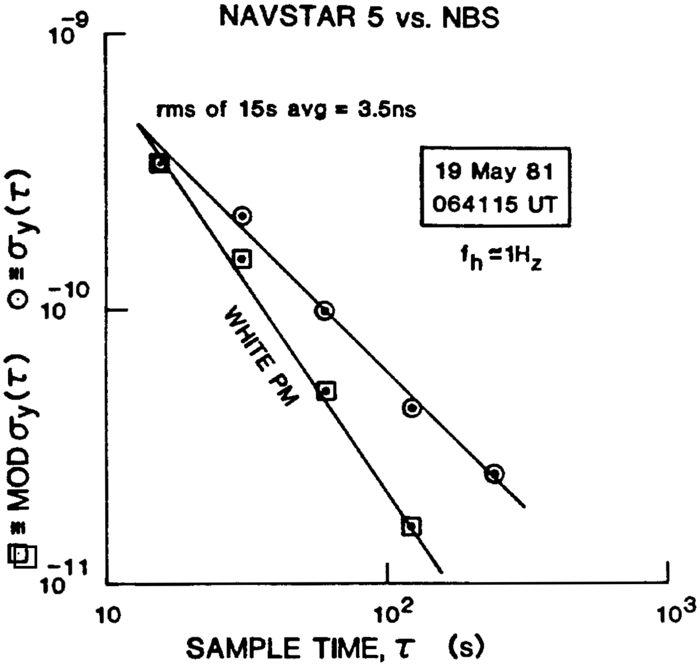

Fig. 2. A plot of the fractional frequency stability of the data shown in Fig. 1. Namely of the cesium in Space Vehicle No. 5 of the GPS constellation. The ordinate is double-valued for both $\sigma_y(\tau)$ and Mod $\sigma_y(\tau)$ as explained in Ref. 2. The noise is well-modeled by white noise PM at a level of 3.5 ns for 15 s averages. This noise is consistent with a meaningful usage of the standard deviation of the mean, which for this data set is 0.5 ns.

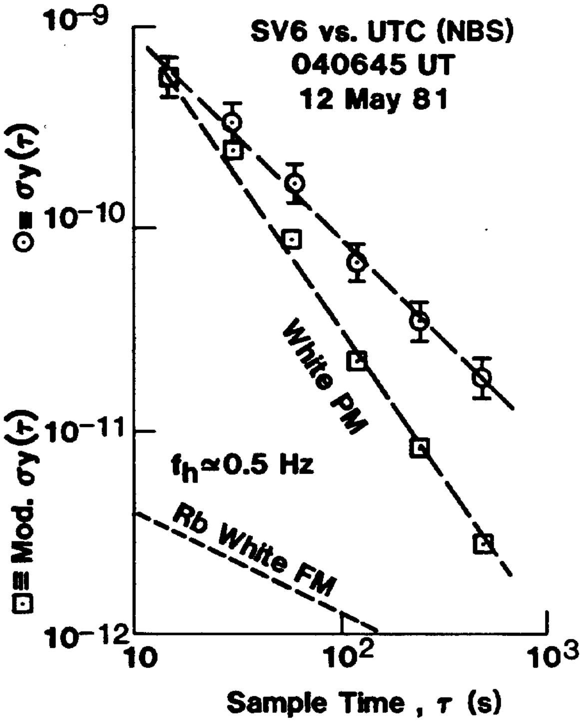

Fig. 3. Fractional frequency stability plot for $\sigma_y(\tau)$ and Mod $\sigma_y(\tau)$ of a rubidium clock in Space Vehicle 6 onboard NAVSTAR-3 as a function of sample time, τ, as explained in Ref. 2. Note also the estimated level of noise of the rubidium clock.

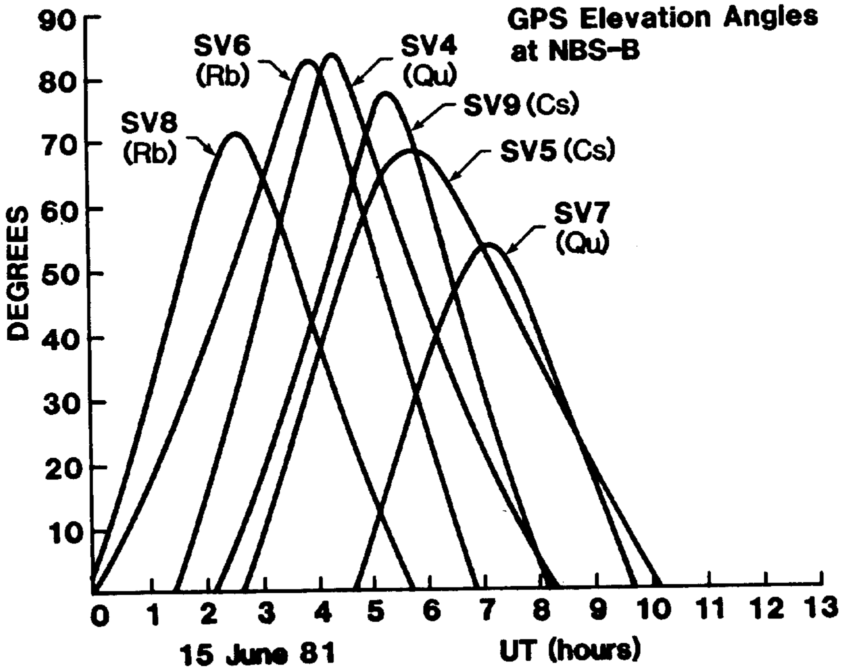

Fig. 4a. A plot indicating the elevation angles for the various satellites in the GPS constellation as a function of hours UT on 15 June 1981 as observed in Boulder, Colorado.

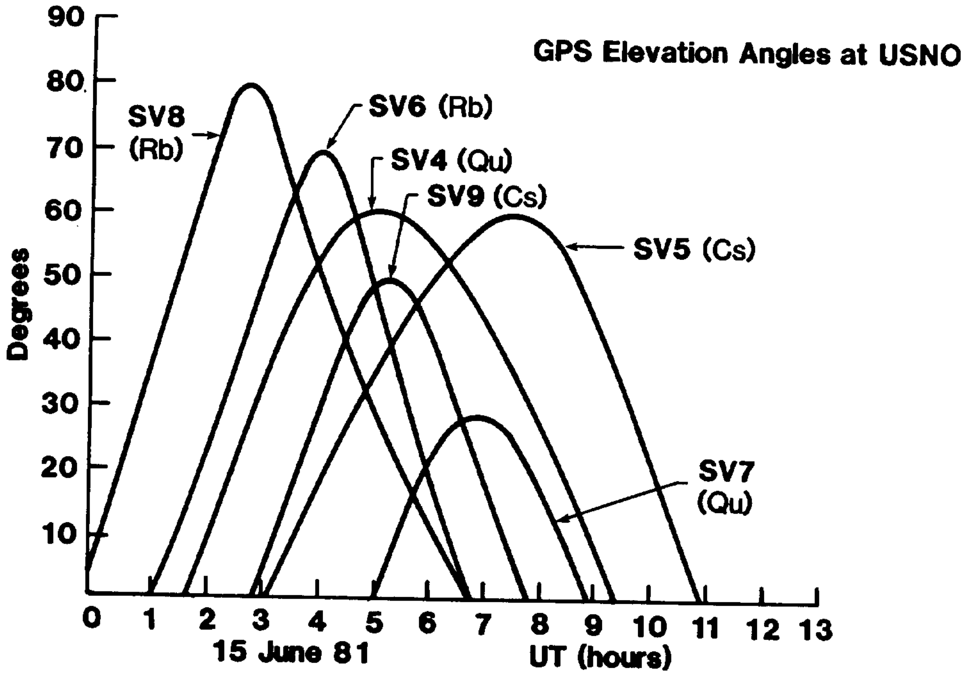

Fig. 4b. A similar plot to Fig. 4a only as observed from Washington, D.C.

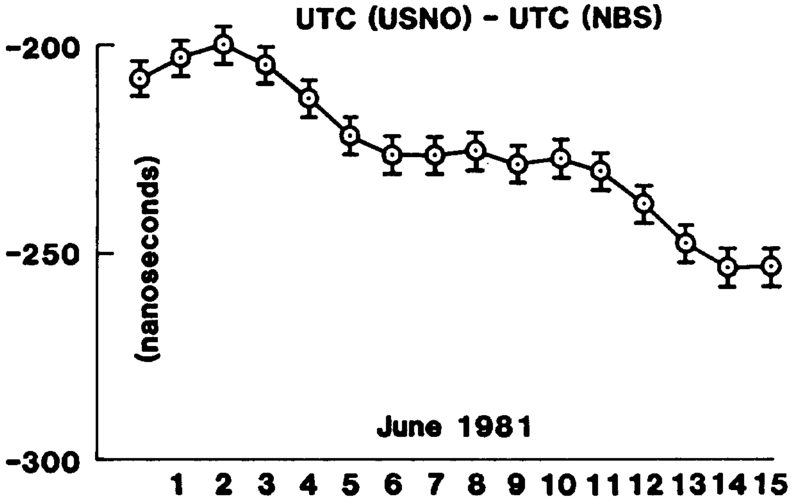

Fig. 5. A plot of the time difference between UTC(USNO) and UTC(NBS) via an average of the four GPS satellites NAVSTAR-3, -4, -5, -6. The error bars are the average standard deviation taken across the four satellites.