# TIME TRANSFER BY SATELLITE

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## ABSTRACT

Time transfer by satellite provides a reasonable means of time dissemination and synchronization for any location which can accommodate a satellite receiver. Several satellite systems have been used to perform time transfer, and commercial receivers are available that provide the link between the user and the satellite. Different methods of time transfer by satellite are described and related to commercially available user equipment. Relative cost and accuracy of the methods are compared and presented. Special emphasis is given to time transfer methods using the NAVSTAR Global Positioning System.

## INTRODUCTION

There have been many applications of time transfer by satellite which have evolved as a result of experiments performed almost two decades ago.[1] The Naval Research Laboratory was one of the pioneers in time transfer by satellite with the experimental TIMATION and Navigation Technology Satellites (NTS), which preceded the present operational NAVSTAR Global Positioning System (GPS). Table 1 shows the evolution of these satellites and their characteristics.

The accuracy of time transfer by satellite can be largely dependent on the stability of the spacecraft clock. The technology has advanced from a quartz clock with 300 parts in $10^{13}$ stability over a day to an atomic cesium clock with 2 parts in $10^{13}$ stability over a day. The clock stability indicates how well satellite time can be predicted when the spacecraft is not in view and measurements cannot be performed. This is an important factor in several applications of time transfer by satellite which will be described later. The ability to predict satellite time over a one day period has improved from 3.66 $\mu$sec to 25 nsec, as demonstrated by the NRL satellites.

Naval Research Laboratory
Technology Satellites

| | TIMATION | | Navigation Technology Satellite | |
|---|---|---|---|---|
| | T-I | T-II | NTS-1 | NTS-2 |
| launch date | 5/31/67 | 8/30/69 | 7/14/74 | 6/23/77 |
| altitude | 500 n.mi. | 500 n.mi. | 7400 n.mi. | 10,900 n.mi. |
| inclination | 70 deg. | 70 deg. | 125 deg. | 63 deg. |
| eccentricity | .0008 | .002 | .007 | .0004 |
| weight | 85 lbs. | 125 lbs. | 650 lbs. | 950 lbs. |
| power | 6 watts | 18 watts | 100 watts | 445 watts |
| frequency | UHF | VHF/UHF | UHF/L | UHF/L,L1/L2 |
| modulation | sidetone | sidetone | sidetone | sidetone, PN code |
| clock | Qtz | Qtz | Qtz,Rb | Qtz,Cs |
| stability ($pp10^{13}$,avg time=1 day) | 300 | 100 | 5-10 | 2 |
| prediction (nsec/day) | 3660 | 1220 | 60-125 | 25 |

Table 1.

There have been many other satellites used to perform time transfer applications. Each system has its own particular techniques, but the methods can be described in few general cases. Some basic methods will be described which apply to the systems that are available to users today.

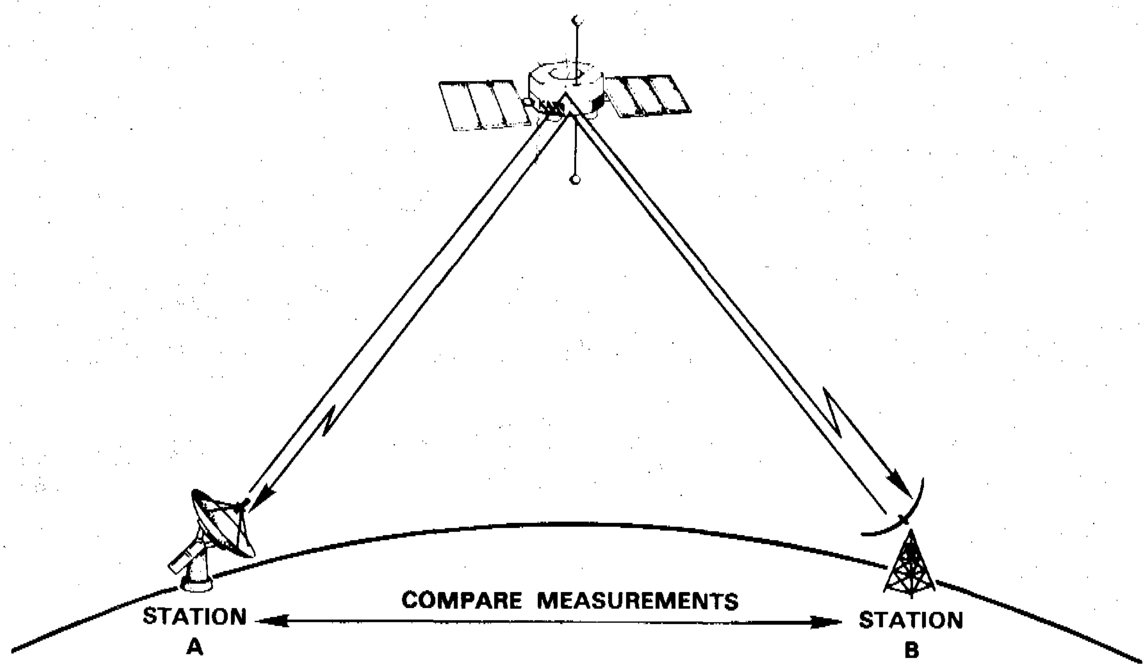
## METHODS OF TIME TRANSFER

In each method described, a time transfer is to be performed between the reference clocks of two ground stations with the use of a satellite. Restrictions on the distance between stations, requirements of the ground receiving equipment, and satellite capabilities are addressed for each case.

### Two-Way

Two-way time transfer is an active process that requires a transmitter at each of the ground stations and a satellite with a relay transmitter or transponder. Fig. 1 describes this method.

## TWO WAY TIME TRANSFER




$$2\Delta T_{A\text{-}B} = [\,T_A - (T_B + \Delta T_{BA})] - [\,T_B - (T_A + \Delta T_{AB})]$$

$$= 2(T_A - T_B) \qquad \text{for } \Delta T_{AB} = \Delta T_{BA}$$

Figure 1.

Both stations are required to be in view of the satellite at the same time. Station B transmits a time marked signal through the satellite to station A. Station A makes a measurement between its own reference and the signal, $T_A-(T_B + \Delta T_{BA})$, where $T_A$ is the time from station A, $T_B$ is the time from station B, and $\Delta T_{BA}$ is the time delay in the signal path from station B to station A. Station B makes a similar measurement from station A, $T_B-(T_A + \Delta T_{AB})$. The measurements are exchanged by the two stations and compared. An assumption is made that the two time delays in the signal path are equal and the result is twice the difference between the clock at station A and the clock at station B. This method has been employed in many time transfer experiments and applications using different satellite systems.[2,3,4]

Non-Simultaneous Measurements

In this method, the stations may be separated by any distance and the satellite must be in an orbit that is visible to each station. However, there is no restriction that the satellite be in view of both stations simultaneously. The satellite must have an onboard clock and transmit a time marked signal. The quality of the clock will influence the accuracy of the time transfer. The NRL satellites described earlier used this method in several experiments.[5,6] Fig. 2 describes the method.

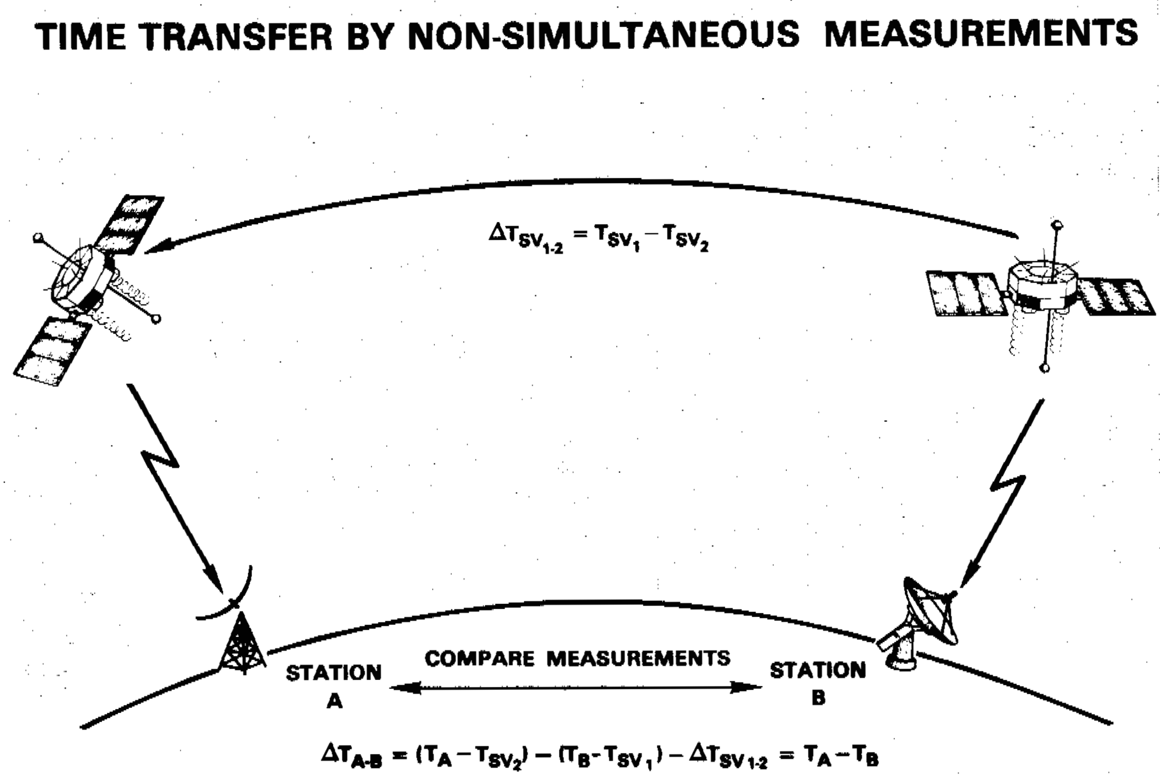



Figure 2.

Station B makes a measurement between its own reference and the satellite signal. With this measurement and given satellite position information, a clock difference between B and the satellite at position 1, $T_B - T_{SV1}$, is determined by correcting the measurement for the signal path delay. Station A performs a similar measurement some time later when the satellite becomes in view at position 2. A prediction is made of the change in the satellite clock between position 1 and position 2, $\Delta T_{SV1-2} = T_{SV1} - T_{SV2}$. The measurements taken at A and B are compared, and when the satellite clock correction is subtracted, the difference is the time transfer between station A and station B.

The accuracy of this method depends heavily on the ability to predict the satellite clock and position. Also, one station is usually designated as a master and keeps track of the satellite clock relative to its own reference. The master station determines the satellite clock correction for the other users.

Simultaneous Measurements

The dependency of the time transfer on satellite clock stability is significantly reduced in this method which is described in Fig. 3.

## TIME TRANSFER BY SIMULTANEOUS MEASUREMENTS

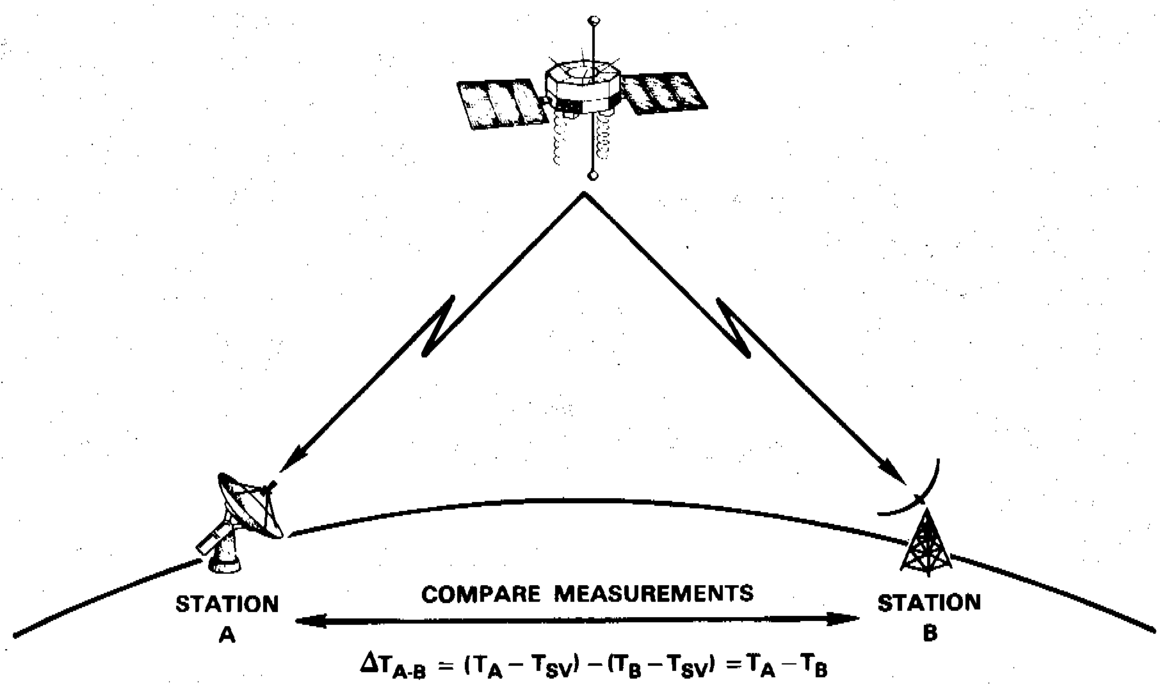



Figure 3.

The satellite must be in view of both stations at the same time. Station A and Station B make simultaneous measurements between their own respective clocks and the satellite transmitted time marked signal. Each measurement is corrected for the signal path delay and clock differences are obtained between each station and the satellite, ($T_A - T_{SV}$) and ($T_B - T_{SV}$). Since the satellite time, $T_{SV}$, is the same for both stations, it is removed when the results at station A are compared to those at station B, and the time difference between A and B is obtained, $T_A - T_B$.

Direct Measurement

A method used quite often is that of direct measurement because it requires no coordination between stations. The satellite transmits a time marked signal and data which references the satellite clock to a master clock reference. Any station can make measurements from the satellite and obtain the difference between its own clock and the master clock reference whenever the satellite is in view. This method is described in Fig 4.

Any time the satellite is in view, station A makes a measurement between its own clock and the time marked signal from the satellite. Signal path delay and satellite clock offset from the master clock are computed from data received in the satellite signal. The measurement is corrected for the signal path delay to obtain the difference between the station clock and the satellite clock, $T_A - T_{SV}$. Finally, the satellite clock offset from the master reference is added to obtain the resulting difference between the station clock and the master clock. Several operational satellite systems use this method today, and commercially available receivers exist for users with time transfer applications.

# TIME TRANSFER BY DIRECT MEASUREMENT

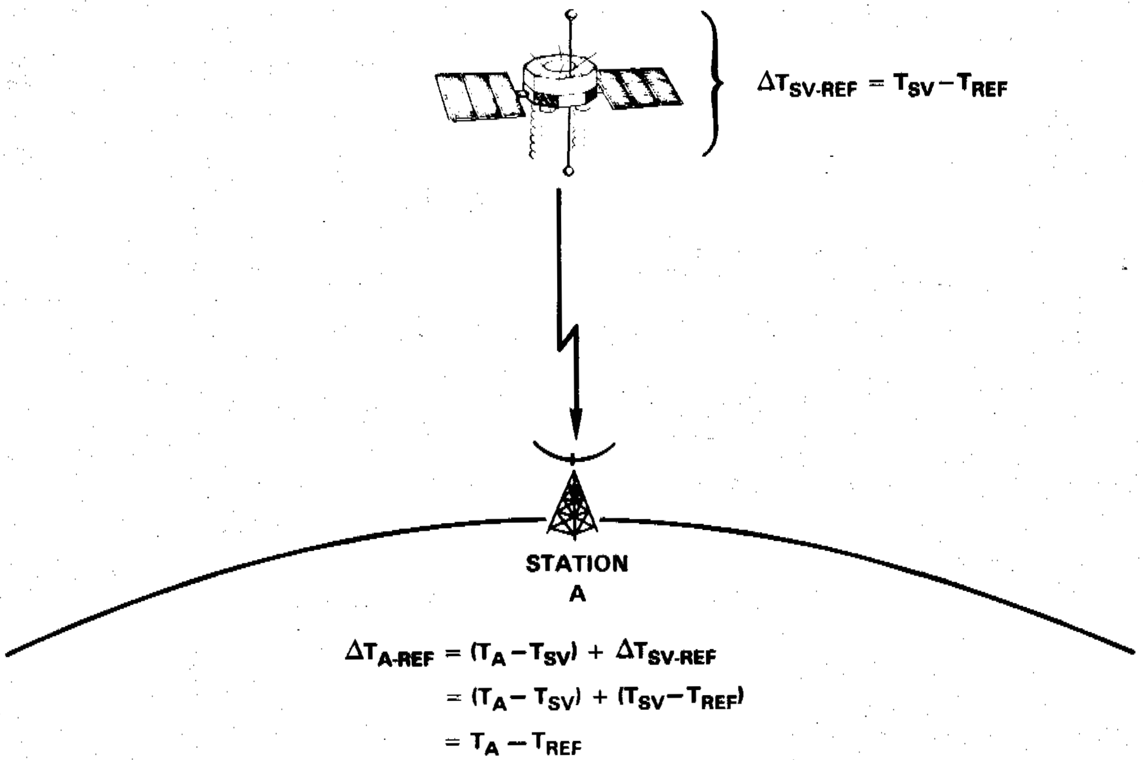



Figure 4.

COMPARISON OF CHARACTERISTICS OF AVAILABLE SATELLITE TIME TRANSFER SYSTEMS

The salient features of three satellite systems that provide the capability of time transfer by direct measurement are given in table 2.

The first consideration in choosing a satellite system for time transfer applications is the system coverage. The Geostationary Operational Environmental Satellite (GOES) system consists of two satellites in synchronous orbits that provide coverage from $0^{\circ}$–$210^{\circ}$ west in longitude[7]. The Navy Navigation Satellite System (NNSS), commonly referred to as Transit, consists of five satellites in lower 600 n.mi circular polar orbits that provide global

Characteristics of Satellite Systems Used in Time Transfer

| SYSTEM | OWNER | SATS | FREQ | ORBIT | COVERAGE | REFERENCE | ACCURACY | COST $ |
|---|---|---|---|---|---|---|---|---|
| GOES | Dept of Commerce (NOAA) | 2 | 468 MHz | synchronous, stationary | western hemisphere, continuous | UTC(NBS) | 1ms-100us | 3-5k |
| NNSS Transit | Dept of Navy | 5 | 150 MHz, 400 MHz | circular,polar, 600 n. miles, non-repeating ground track | global, 15min-2hrs possible wait for sat | UTC(USNO) | <25us | 10-15k |
| NAVSTAR GPS | Dept of Defense | 7 now, 18 final config | 1242 MHz, 1575 MHz | circular, 55 deg incl, 10,900 n. mi., repeating ground track | global, continuous in final config | UTC(USNO) | <100ns | 20-30k |

Table 2.

coverage[8]. Depending on the time and location, the user may be required to wait as long as two hours for a satellite to come into view. A typical transit satellite visibility lasts fifteen minutes. The Global Positioning System (GPS) final constellation will consist of eighteen satellites in circular, 55$^{\circ}$ inclination, 10,900 n.mi orbits that will provide constant global coverage[9]. Currently, there are seven operational GPS satellites providing global coverage. A user now may have to wait up to five hours for a GPS satellite to come into view. A typical GPS satellite visibility may be from two to six hours.

Another important consideration in choosing a satellite system for time transfer is the accuracy requirement. The accuracy values shown in table 2 were obtained from published literature and manufacturer's specifications of available receiving equipment. The table points out a direct trade-off between cost and accuracy. Less expensive hardware has been projected to be available for GPS applications.

## GLOBAL POSITIONING SYSTEM

The time transfer by satellite methods that have been described previously apply to many satellite systems. The Global Positioning System has been chosen as an example to be presented in more detail. The receiving equipment described is a time transfer receiver that was designed by NRL in 1980. Today, receivers are available from several commercial manufacturers. Each manufacturer has a design that is unique, but all designs process the GPS signal in a similar manner to perform a time transfer. The example described here applies in a general sense to all GPS time transfer receiver applications.

Each GPS satellite transmits on two L-band frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz [10]. The ground receiving system described here uses only the L1 frequency. The second frequency is transmitted for users to measure and correct for the ionospheric delay. Single frequency users may use an ionospheric correction model for which parameters are transmitted in the satellite navigation message. The L1 frequency consists of two carrier components in phase quadrature with each other. One component is biphase modulated with a 1.023 Megabit/sec (Mbps) coarse/acquistion (C/A) pseudorandom noise (PRN) code and the other is biphase modulated with a 10.23 Mbps precise (P) code. The C/A code repeats every millisecond allowing quick acquisition, and the P code is a long code sequence which is truncated to repeat every 7 days but whose higher rate allows more precision, primarily for military users. Each satellite transmits on the same L1 and L2 frequencies, but each has a unique C/A and P code which provides discrimination between satellites. Each L1 carrier component is also biphase modulated with 50 bit/sec (bps) data which contains the navigation message. The final modulated L1 frequency is of the form:

$$2A\, G_i(t)\, D_i(t) \cos \omega_{L1}t + A\, P_i(t)\, D_i(t) \sin \omega_{L1}t$$

where A is the amplitude, $G_i(t)$ is the C/A code sequence, $P_i(t)$ is the P code sequence, $D_i(t)$ is the data sequence, and $\omega_{L1}$ is the carrier frequency. The C/A code component is 3db higher in amplitude than the P code component. The time transfer receiver described here uses only the C/A code component of the L1 signal [11]. All modulating and carrier signals are derived from the onboard spacecraft reference oscillator.

The general format of the 50 bps data is shown in Fig. 5.

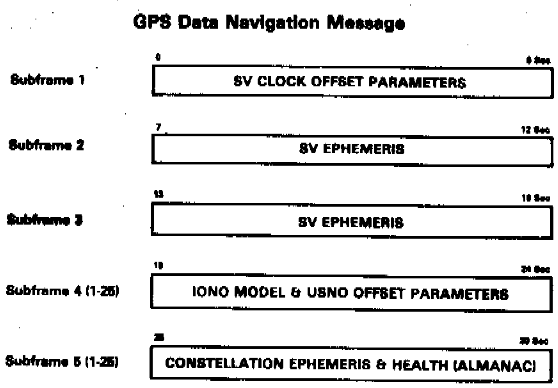



Figure 5.

The navigation message is transmitted in five subframes. Each subframe lasts six seconds and contains 300 bits of information. The primary information is contained in subframes 1,2, and 3 and requires a maximum of 30 seconds to receive after locking onto the data. Secondary information is contained in subframes 4 and 5 which commutate 25 different subframes of information each. Twelve and one half minutes may be required to receive the desired information in these subframes. Subframe 1 contains the information required for the user to compute the SV clock offset from GPS time. Subframes 2 and 3 contain the necessary information to compute the SV position. For time transfer, it is assumed that the user position is known, and along with the computed SV position, the range delay of the signal from the satellite can be determined. Subframe 4 contains the ionospheric correction model parameters and the USNO MC time offset from GPS parameters. Subframe 5 contains a shortened version of the SV ephemeris and a health summary for each satellite in the GPS constellation. This data is referred to as the almanac and is used to compute satellite visibilities, satellite search frequency offsets due to doppler shift, and satellite tracking priorities according to satellite health and geometry with respect to the user.

Each of the GPS satellites transmits signals that are derived from frequency standards. The NRL designed receiver determines time from the GPS satellite signals in the following manner. The six second repeating subframes in conjunction with the one millisecond repeating C/A code is viewed as a clock signal. The C/A code is tracked to a fraction (3%) of a one microsecond chip width, deriving a 1 kilopulse/sec (kpps) clock which counts time in milliseconds. The 1 kpps is divided by one-thousand in a milliseconds counter to provide a satellite 1 pps. The milliseconds counter is synchronized to the proper count by using the epoch of the six second subframe. A time interval measurement is made between the satellite clock 1 pps and the station clock 1 pps to get a measured Δt. This basic measurement is refered to as pseudorange and must be corrected to obtain the actual difference between the ground clock and the satellite clock. These corrections are described later. First, consider the link of the satellite clock to GPS time and UTC (USNO MC) time as shown in Fig. 6.

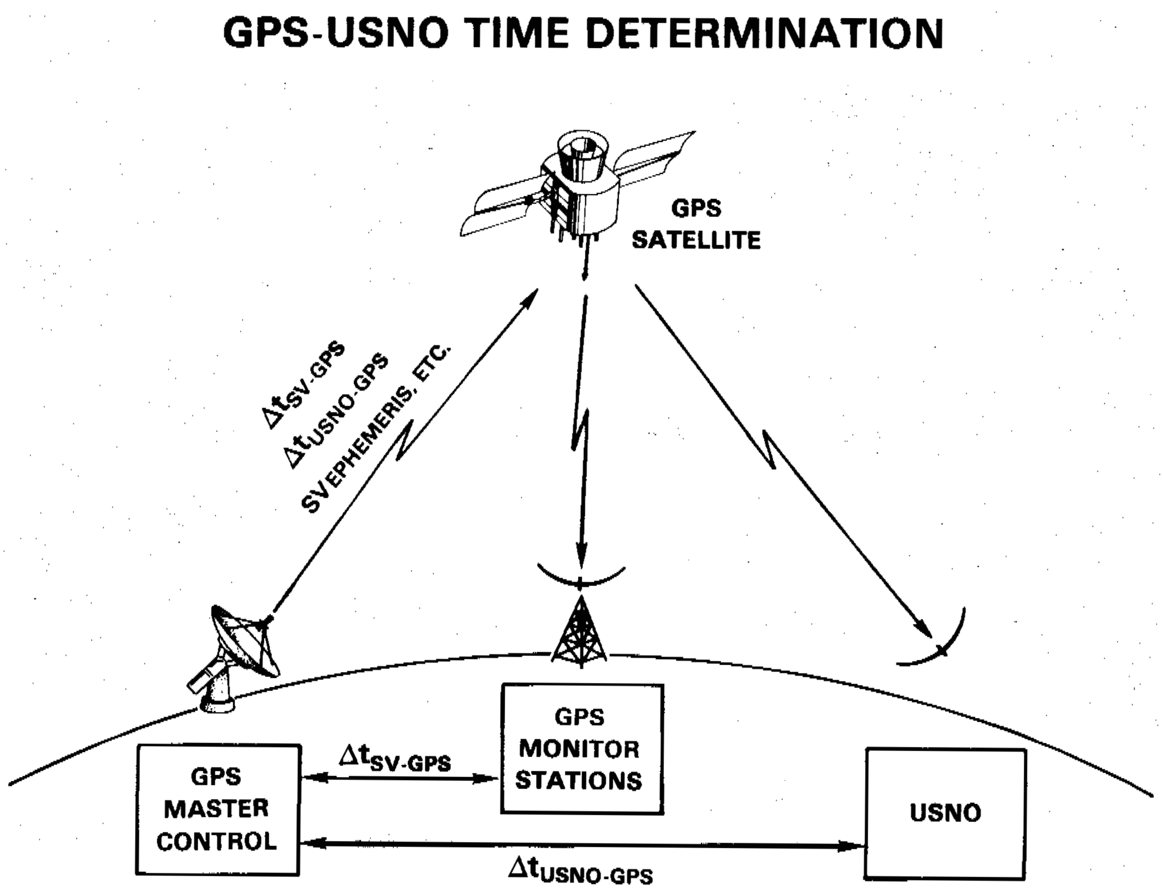



Figure 6.

The GPS Monitor Stations make measurements from each satellite and transmit them by ground link to the GPS Master Control Station. These measurements are used to determine the orbit of each satellite and the difference of each satellite clock from the GPS master clock. The U.S. Naval Observatory makes measurements from the GPS satellites and determines the difference between GPS time and UTC (USNO MC) time. This difference is transmitted to the GPS Master Control Station. The Master Control Station models each satellite clock difference from GPS time with a second degree polynomial, and models the difference between GPS time and UTC (USNO MC) time with a first degree polynomial. The coefficients of these polynomials are uploaded into each respective satellite along with the ephemeris of the satellite. The satellites transmit this information to the user in the navigation message [12].

A user performs a time transfer from a GPS satellite by the process shown in Fig. 7.

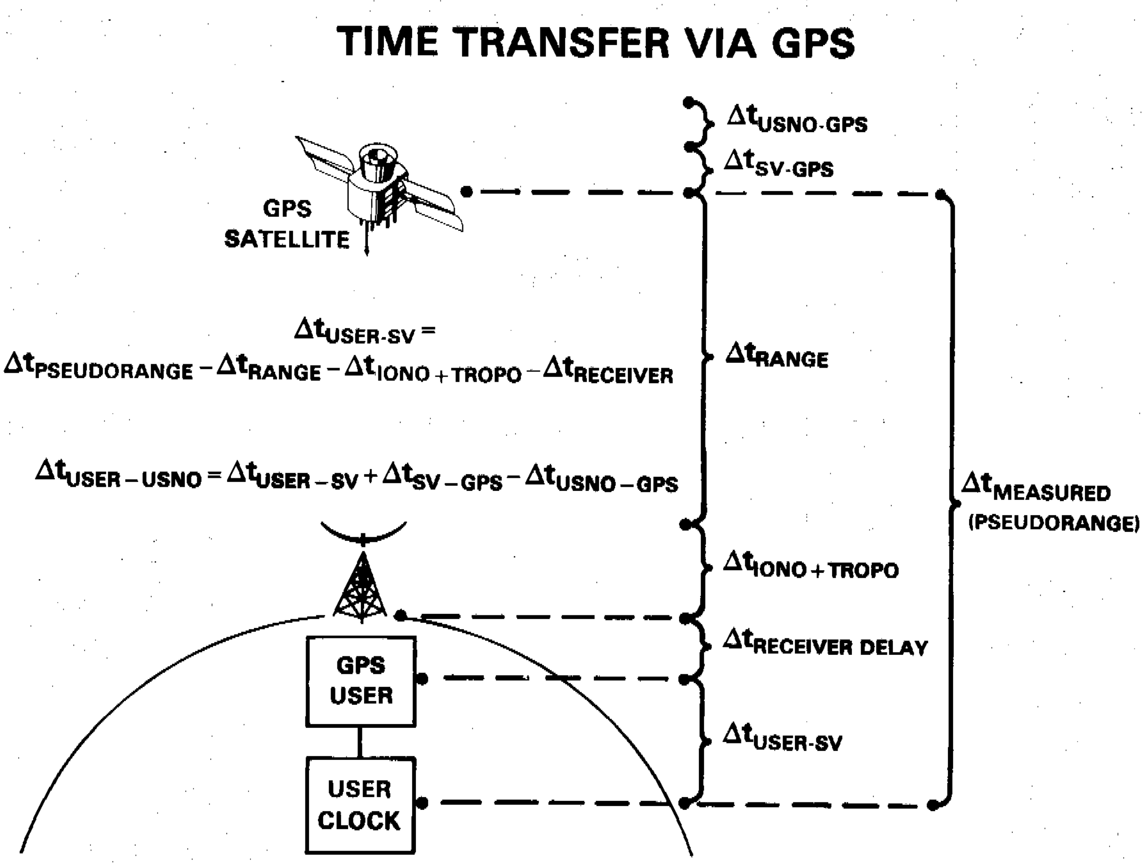



Figure 7.

The GPS user first performs a measurement between its own reference clock and the received satellite time marked signal. This measurement is $\Delta t_{measured}$ and is commonly referred to as pseudorange. The difference between the user clock and the satellite clock is determined by correcting the pseudorange measurement for signal path propagation delay, $\Delta t_{range}$, ionospheric and troposheric delay, $\Delta t_{iono+tropo}$, and the propagation delay in the receiver itself $\Delta t_{receiver}$. The path delay is determined by computing the position of the satellite relative to the receiving station using the ephemeris transmitted in the navigation message. The ionospheric and tropospheric delays are computed from models, and the receiver delay is used as calibrated, and provided with each unit. The satellite clock difference, $\Delta t_{user-sv}$, is then calculated, as shown in Fig. 7. The satellite clock offset from GPS time, $\Delta t_{SV-GPS}$, is determined by using the second degree polynomial coefficients which are transmitted by the GPS satellite in the navigation message. Similarly, the difference between GPS time and UTC (USNO MC) time $\Delta t_{USNO-GPS}$, is computed from the first degree polynomial coefficients transmitted in the navigation message. Finally, the difference between the user clock and UTC (USNO MC), $\Delta t_{user-USNO}$, is determined.

The example described above is time transfer by direct measurement. There need be no communication between the user and USNO to obtain the final desired result. The system also can be used to perform time transfer by the simultaneous measurement method. The USNO tracking schedule and measured values of GPS data are published for users who wish to implement this method. Time transfer by satellite has become a commonly used method of synchronizing remote stations over global distances. As the cost of user equipment continues to decrease, it is replacing the older methods which employed the transporting of portable clocks from station to station.

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## QUESTIONS AND ANSWERS

JIM WRIGHT, EASTERN TEST RANGE:
There are two communities that I am aware of that have different ideas about where the GPS system should go as far as the users are concerned. The military was concerned at one time that you could get too great an accuracy from the GPS system and they were interested in degrading the L1 system so that you could not get as good a time transfer as you can now. The FAA was concerned that they could get a much better collision avoidance system if the L2 channel were declassified. Do you know if either of these two factions are going to win out? How good is the time synchronization from GPS going to be in the future for the non-classified user?

MR. OAKS:
I don't have a specific answer, but I can tell you a little about the capabilities. What I showed was the current transmission of the L2 channel which had the P code. GPS does have the capability of transmitting the CA code on the L2 channel. As to answering the question about what direction they are going, I don't have the answer to that. Maybe someone from GPS has the answer.

MR.BEARD:
As to which faction is going to win out, that's anybody's guess. The FAA is concerned about the capability of navigating for collision avoidance. They are not too concerned about time transfer.

MR. WRIGHT:
I believe that the answer that we are getting is that we don't expect any change from what we have right now, in the near future.

MR.BEARD:
In the Block 2 operational constellation, there will be a change in the operation of the satellites that will affect the performance.

MR. WRIGHT:
Can you elaborate on what that change is going to be?

MR. BEARD:
For a military user there shouldn't be any problems.

MR. WRIGHT:
We are not a military user.

MR. BEARD:
Then you might have some problems. They are encoding some of the data messages that have some of the clock correction terms in them and they introducing other things that will degrade the performance for the civilian user. Dr. Winkler will tell you all about it.

MR. WINKLER:
I am not going to say anything except be advised to look into the program book. The classified session has some discussion on that.

MR. BEARD:
That would be a better place to discuss this. I have a question. Is there a comparative difference between the two way and the common view or simultaneous measurement with GPS? Are they roughly comparable in precision?

MR.OAKS:
Recalling the results that have been published, the common view has resolution or accuracy on the order of a nanosecond and the two way time transfer would be using Hermes or a Symphony. Does anyone have an answer on that?

MR. ALLAN:
The common view approach we feel is, world wide, more like ten nanoseconds. Sometimes better, sometimes worse, depending on conditions. On the two way stability, we have seen experiments and numbers reported as low as 100 to 200 picoseconds. The accuracy, the best number I am aware of is the result published by the Radio Research Laboratory, which is six nanoseconds on an absolute sense.

MR.BEARD:
Is that global?

MR. ALLAN:
This was an experiment conducted in Japan, using higher frequencies in the 30GHz band as I recall. It was published in CPEM 1982, I think. That is the best accuracy number that I am aware of.