THE ROLE OF GPS IN PRECISE TIME AND FREQUENCY DISSEMINATION

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This article describes the GPS time and frequency signals, the GPS receiver techniques used to extract those signals, and some of the uses for precise time, time interval, and frequency. Historical background on uses and methods of measuring time and frequency is also provided.

Known primarily as a navigation system, the global positioning system is also used to disseminate precise time, time intervals, and frequency. The GPS carrier signals originate from on-board atomic clocks monitored by ground control stations, as depicted in Figure 1. GPS satellites transmit time signals with each subframe of data modulated onto the carrier. While navigation and survey receivers use GPS time to aid in computation of position solutions, time and frequency receivers use GPS satellite transmissions to control timing signals and oscillators.

TIME, TIME INTERVAL, FREQUENCY

Time and time interval are distinct concepts. *Time* is the marking of an event with respect to a reference origin. A *time interval* is a measurement of duration. The time of an event might be measured by hours, minutes, seconds, and a calendar date, while a time interval might be measured by the number of seconds between two events.

Frequency is the measure of the number of events that occur within a time interval, such as the number of oscillations of a voltage waveform within one second (George Kamas and Sandra L. Howe, *Time and Frequency User's Manual,* National Bureau of Standards Special Publication 559, U.S. Government Printing Office, Washington, DC, 1979).

Coordinated Universal Time (UTC) is a time system adopted by many countries in 1972. UTC is coordinated by the Bureau International des Poids et Mesures (BIPM) in France and is based on the weighted combination of atomic clocks located around the world. UTC occasionally changes by the addition of leap seconds. Other time systems are also used that can be compared with UTC. A system called UT1, for example, is related to the earth's angular rotation rate and is used by navigators.

TIME AND FREQUENCY USERS

Astronomic observatories use time to record celestial events and to perform simultaneous observations at distant locations. Very long base line interferometry uses time-synchronized recordings from widely separated radio-astronomy observatories to map celestial radio sources as though from a single enormous antenna. Electric power companies use frequency standards to maintain the 50- or 60-hertz line frequencies. Computer networks need to synchronize distant nodes for billing and communications switching purposes.

Communications systems use both time and frequency to maintain carrier frequencies and data-bit phase timing. Military and banking communications networks have special timing requirements for synchronization of data encryption and decryption equipment. Frequency standards are required for radio and television stations, as well as for satellite communications transmitters. Tracking deep-space vehicles requires coordinated observations from synchronized ground stations. All of these users require some combination of precise time, time interval, and frequency that attains accuracies measured in nanoseconds (10^{-9} or billionths of a second).

Users of both precise time and precise frequency require precise time intervals as measured by the time between periodic pulse edges or waveform zero-crossings. The relationship of these marks to a reference time is a measure of the phase of the signal. Time and frequency users often have different phase stability requirements for time intervals.

The precise time user may require the time tagging of events to the 100-nanosecond level and maintenance of that accuracy over periods from seconds to years. Modern digital communication networks use time intervals to maintain synchronization between transmitter and receiver clocks so that data frame buffers at the receiver can maintain frame alignment with infrequent "slips" requiring retransmission of the data frame. These users are not affected by pulse-to-pulse jitter (phase noise) on the order of one nanosecond, but they do require that the time intervals maintain a long-term phase stability.

Precise frequency users require short-term phase stability but may not require long-term phase synchronization. Radar and microwave communication systems multiply 5- or 10-megahertz frequency standards up into the gigahertz regions of the spectrum. Any phase noise from the frequency standard is multiplied along with the fundamental frequency and appears as noise in the microwave carrier. Precise frequency users may require time interval signals with phase noise on the order of one picosecond (10^{-12} or one trillionth of a second) to maintain sufficient

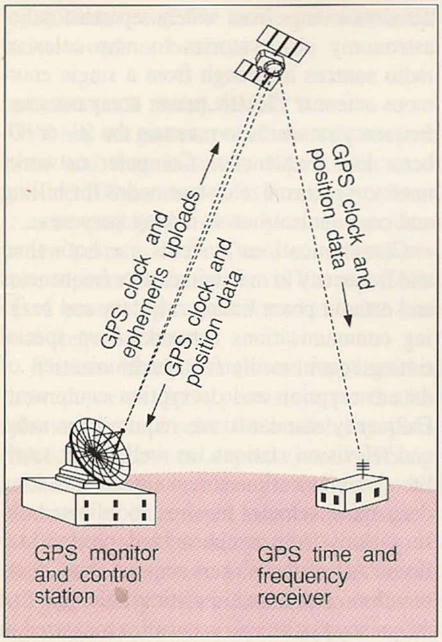

Figure 1. GPS time and frequency transfer

spectral purity and low noise in their transmitted signals.

TIME AND FREQUENCY IN HISTORY

People have marked time by the movement of the sun and other stars, by phases of the moon, by the changing of seasons, and by the passing of generations. Time intervals have been measured by sand-filled hour glasses, water clocks, and mechanical devices. The frequencies of musical instruments are tuned by comparison to tuning forks and pitch pipes.

History has recorded inventive examples of time, time interval, and frequency measurement. As early as 1000 B.C., the Chinese made frequency standards by counting the number of bean kernels that filled the pipe of a wind instrument. For pipes of the same diameter, the frequency (pitch) was specified by the number of kernels required to fill the pipe. Time intervals were measured in 13th-century Spain by burning candles on lever arms that lost weight as they burned, moving the arm to display the passage of time.

The Chinese burned incense clocks that marked time by changes in the scent given off by layers of incense impregnated with different oils. Cassini's tables of predicted eclipses of the moons of Jupiter were used to provide position-independent time measurements, accurate to a few minutes, for the mapping of France in 1679. Harrison's chronometer, perfected in 1759, allowed time transfers aboard ship with accuracies in the 10-second range over periods of weeks.

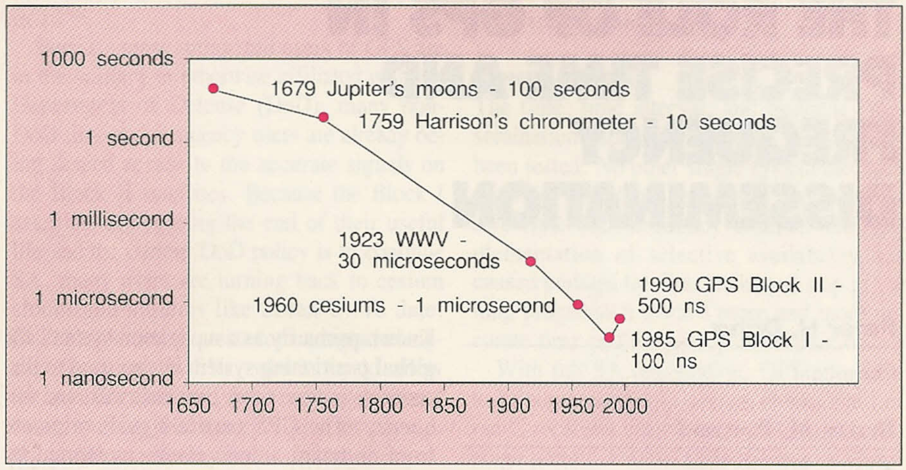

Figure 2. Time dissemination techniques

The simple sundial provides examples of time and time-interval measurement problems for different users. If a user wants to mark local noon at the same location each day, the sundial will serve this purpose well. Because users at different locations do not mark the same moment as noon, however, they cannot synchronize events using the sundial without performing extensive calculations from position and orbital data. The sundial can measure local time and time interval periods of 24 hours but is not well suited for linking two events at distant locations.

TIME, FREQUENCY DISSEMINATION

For the most part, the history of time dissemination has been a steady advancement toward more accurate time transfer between distant locations, as illustrated in Figure 2. Current time and frequency dissemination technologies in wide use include atomic standards and both high- and low-frequency radio services.

Atomic clocks are based on the natural atomic oscillations of gases in resonant cavities. When isolated from magnetic fields, rubidium and cesium gases will resonate at specific frequencies under controlled conditions. These frequencies are so accurate that since 1967 the length of the second has been defined as the frequency of a specific resonant mode of the cesium atom, producing 9,192,631,770 oscillations in one second. The frequency accuracies of cesium clocks are on the order of 2×10^{-12}. (This notation is simply a way of expressing the percentage of accuracy: 1×10^{-2} is the equivalent of 1.0 percent error.)

Time and frequency are transferred from reference standards using portable cesium clocks that are compared with the reference clock, transported to the remote location, and compared with the remote station clock. Although time-consuming and expensive, this method does provide time transfer in the one-microsecond (10^{-6} or one-millionth of a second) range.

High-frequency radio time services are maintained by more than two dozen countries. Time, frequency, and time interval data can be derived from these signals with time accuracies ranging from 1 to 10 milliseconds and fractional frequency accuracies from 1×10^{-10} to 5×10^{-12}. The United States National Institute of Standards and Technology (NIST), formerly the National

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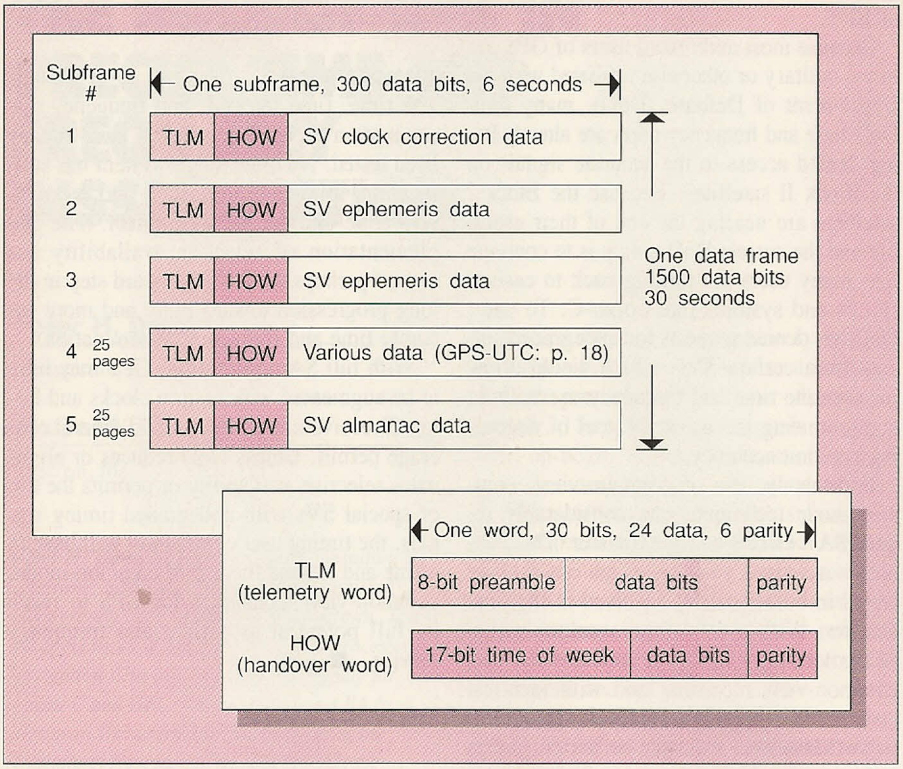

Figure 3. GPS data format

Bureau of Standards operates the WWV and WWVH stations that broadcast continuous time and frequency signals at 2.5, 5, 10, and 15 megahertz (and 20 megahertz on WWVH).

Omega navigation and VLF (very low frequency) communication signals cover much of the globe and can, with careful attention to ionospheric variations and modal interference, be used for time and frequency determination in the 2- to 10-microsecond range. These systems can also help us determine frequency to several parts in 10^{-11}. The diurnal effect on both signals due to the ionosphere limit the accuracy of these low-frequency systems.

Loran-C is another method used to disseminate both time and frequency information. Designed primarily as a navigation system, Loran-C signals use a 100-kilohertz carrier modulated by precisely controlled pulses that propagate as groundwaves with stable phase over distances of thousands of kilometers. Those Loran-C stations that are monitored by the U.S. Naval Observatory (USNO) can provide frequency accuracies of 1×10^{-12}. Time intervals can be obtained from Loran-C, and UTC can be derived with accuracies of several microseconds using published corrections. Loran-C stations with varying time and frequency accuracy control are available over much of the northern hemisphere.

A *disciplined frequency standard* is a microprocessor-controlled system that locks an oscillator to an external source while "learning" the offset and aging rate — or drift — of the internal oscillator. When the external reference is removed or fails, the disciplined frequency standard continues to apply these "learned" corrections to the internal oscillator. A system using Loran-C monitored by the USNO as the frequency standard and a cesium atomic clock as the disciplined internal oscillator can maintain accuracies of a few parts in 10^{-12} (Robert F. Ellis, *Austron Timing Reference Handbook,* Austron, Inc., Austin, TX, 1988).

GPS CAPABILITIES

GPS is capable of global time and frequency dissemination 24 hours a day. The frequency accuracies from the system can rival the best Loran-C stations, and the timing accuracies can be in the 100-nanosecond range. No previous system has provided this potential combination of accuracy and availability. GPS has proven to be so successful that GPS receivers are now used to help control some Omega and Loran-C transmitters.

GPS time is a precise time standard that is related to UTC. The major difference is that GPS time is a continuous time usually measured in weeks and seconds from the GPS time zero point of midnight, January 5, 1980. Controlled by UTC, GPS time is not corrected with leap seconds, and so is currently ahead of UTC by six seconds (1990). With the exception of the integer number of leap seconds, GPS time is steered to within one microsecond of UTC with the difference reported in the GPS navigation message to a precision of 90 nanoseconds.

Signal and data processing. To set a GPS receiver to GPS time, the receiver must first track a GPS satellite, or space vehicle (SV), on one or both of the L-band carriers. After locking on to the spread spectrum carrier by applying the local pseudorandom noise (PRN) code at the correct time, the 50-hertz data stream containing the navigation message can be decoded. SV time — the time as given by an individual satellite's clock — can be recovered by noting the start time of the PRN code necessary to achieve lock.

Time intervals at the receiver can be produced by the 1-millisecond repetition rate of the coarse acquisition (C/A) PRN code. Time tagging of each millisecond in SV time is accomplished by extracting the week number (WN) and time of week (TOW) count from the navigation message (ICD-GPS-200, Navstar GPS Space Segment/Navigation User Interfaces, 1987). Figure 3 shows part of the data frame format of the GPS navigation message.

No prior system has provided this potential combination of GPS accuracy and availability.

A 300-bit subframe of data bits is transmitted every six seconds by a satellite. Each subframe is marked by a preamble and parity bits in fixed locations. For each subframe, a space vehicle transmits a TOW count that increments by one six-second unit. The time of applicability for that TOW is the

THE TIMING SUBCOMMITTEE OF THE CIVIL GPS SERVICE STEERING COMMITTEE

The Timing Subcommittee of the Civil GPS Service Steering Committee has been working for several years to determine the requirements and needs of the civilian timing community for GPS information, the availability of GPS timing information and how it can be disseminated. The subcommittee is chaired by David W. Allan of the Time and Frequency Division of the National Institute of Standards and Technology in Boulder, Colorado, and co-chaired by Wlodzimierz Lewandowski of the Time Section of the Bureau International des Poids et Mesures (BIPM) in France. Other frequent participants in subcommittee meetings are representatives of the U.S. Naval Observatory, the Naval Research Laboratory, the Jet Propulsion Laboratory (JPL) and private sector companies such as AT&T, DunsNet, and the power industry.

Timing experts believe GPS offers a much improved means for taking advantage of high accuracy atomic clocks around the world. The subcommittee's work is in support of communicating time and frequency between national and international timing cemters, the JPL's Deep Space Network, the timing for millisecond pulsars, and several other industrial calibration laboratories and service organizations.

A major concern of the panel is the extent to which selective availability (SA) and anti-spoofing (A-S) will degrade the accuracy of the GPS system and create common-view time-transfer errors. A recent study by William Klepczynski, deputy director of the Time Service Department of the U.S. Naval Observatory, states that for at least 80 percent of the timing community, the negative effects of S/A can be drastically reduced by daily averaging ("smoothing"); even greater accuracy can be achieved with three-day "smoothing." Accuracies of 50–100 nanoseconds are acceptable for most purposes such as earthquake monitoring, mineral research, and general navigation. To benefit from this smoothing, an atomic clock is needed as a reference.

However, the high precision users in the timing community remain concerned about the impact of SA on the GPS signal. This includes those involved with the JPL's deep space network, millisecond pulsar timing, and the accurate time and frequency transfer from NIST to other government laboratories, among others. Allan recently conducted a test using one of the Block II GPS satellites to compare the clocks between NIST and USNO and between NIST and the Paris Observatory in the common-view mode in which the satellite clock errors cancel. He measured only two nanoseconds and seven nanoseconds, respectively, on the residuals over the three-month test period with SA turned on.

Regardless of these very encouraging results, Allan believes that SA can have a major impact on nanosecond-level accuracies, and is participating in an international effort to test all GPS Block II satellites in this regard. The Timing Subcommittee is collaborating with the National Geodetic Survey to obtain precise ephemeris data with only a two-week delay to help reduce errors introduced by SA to better than could be obtained with the Block I satellites if used in the common-view mode.

Because time-transfer issues are international in scope, Allan as chairman of the Timing Subcommittee is calling on Dr. Bernard Guinot, director of the Time Section of the BIPM, to set up a committee of experts to study questions related to international time accuracy. One task of this group is to prepare standards for GPS receiver software and the consistent use of fundamental constants. The BIPM is working on developing an accurate coordinate reference frame for GPS. Lewandowski reported at the last CGSSC meeting that the ITRF (international terrestrial reference frame) is more accurate than the current reference system used by the Department of Defense, WGS 84. Following the suggestion of the BIPM, all national timing centers contributing to International Atomic Time (TAI) and to UTC changed their GPS receiver coordinator from WGS84 to ITRF on June 12.

Because of the effects of SA on GPS, some have suggested the use of the Soviet Union's GLONASS system. At an April meeting in Paris, the Consultative Committee for the Definition of the Second decided to use GPS and GLONASS to communicate frequency and time from a primary standard laboratory near Moscow (VNIIFTRI); this would tie Moscow into the international time network using GLONASS in the common-view mode between VNIIFTRI and the University of Leeds and GPS in the common-view mode between Leeds and the BIPM.

For more information about the activities of the Timing Subcommittee, contact Karen Van Dyke at (617)494-2131.

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C/A code start time that occurs on the final data bit transition at the start of the next 300-bit subframe. The number of seconds represented by a TOW starts at zero on the GPS time Saturday midnight and continues to a full week of 604,799 seconds before being reset to zero.

To set precise time, the three-dimensional position of the receiver must be known. A position error of one meter translates to about three nanoseconds of time error and about a millihertz of frequency error. Most special-purpose time and frequency receivers require some independent position estimate to achieve the full potential of GPS. Once receiver position is established, the orbital ephemeris in the navigation message is used to compute the SV position at the moment in time when a particular C/A code millisecond start time was transmitted.

SV time. The time of transmission from a particular space vehicle is known as SV time. SV time at the receiver must then be corrected for the errors in the SV clock with respect to GPS time and for periodic relativistic effects. The SV clock error is transmitted in each data frame by a set of polynomial coefficients. The relativistic correction is computed from the SV orbital parameters normally used for SV position determination. The true GPS time of transmission is the result.

Path delay computations. The total signal path transmission delay computation begins with the range from the SV to the receiver. Using the speed of light, one can convert the range to a time delay. This delay is then corrected for the ionospheric delay using a model provided in the navigation message, for the "Sagnac" effect (the result of transmission in a rotating inertial reference system), and for hardware delays in cables and receiver circuitry. The difference between the computed and measured millisecond time marks will give the relationship between the receiver

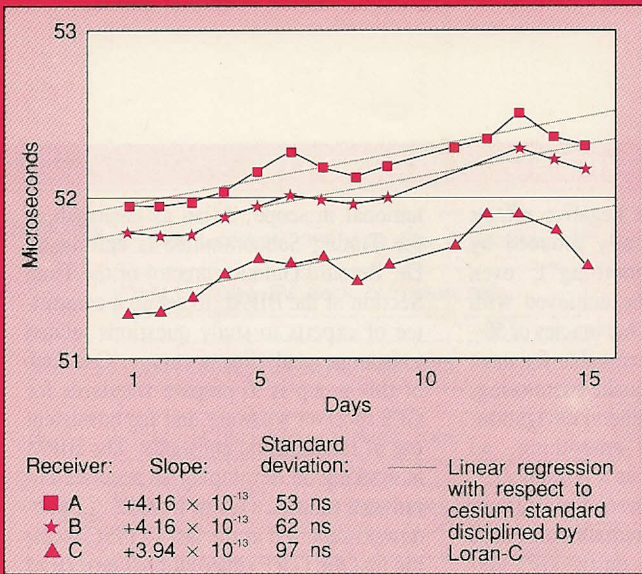

Figure 4: GPS 1PPS phase control

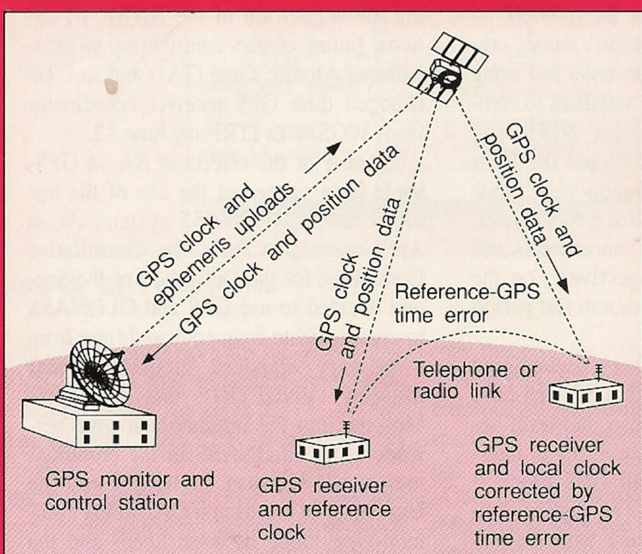

Figure 5: GPS common-mode common-view time transfer

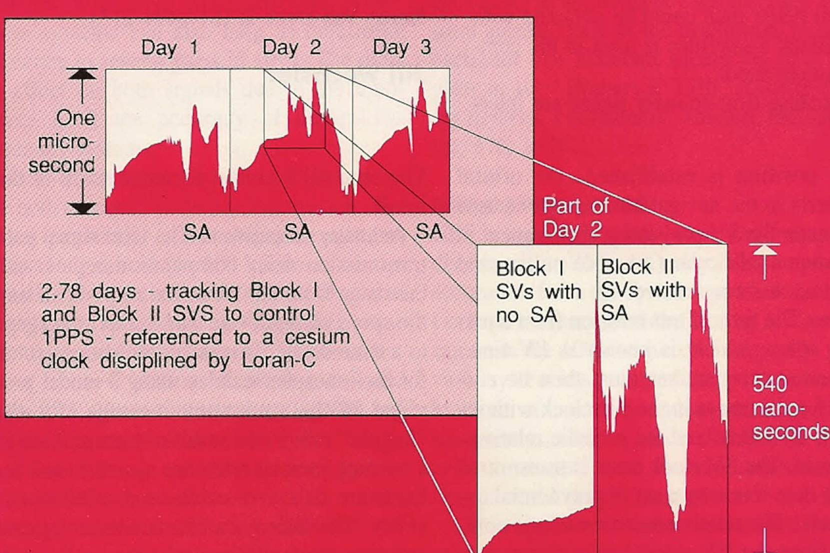

Figure 6: Selective availability effect on 1PPS control

clock and GPS time.

Time and time interval signals. Once the relationship between the receiver clock and GPS time is established, time or time interval signals can be produced by the receiver. Synchronization between receivers at different locations can be established and maintained using GPS time. If time signals are required to maintain synchronization with UTC, the UTC correction in the navigation message can be applied, and time and time-interval signals, such as one-pulse-per-second (1PPS) signals, can be set and maintained to UTC. Figure 4 compares 15 days of 1PPS control by three different GPS receivers. The receivers were measured against a reference cesium clock disciplined by a Loran-C timing receiver.

The accuracy of GPS time signals is related to the ability of the receiver to accurately track the received C/A PRN code. Accuracies in the 100-nanosecond range are possible with undegraded GPS signals and correct receiver position.

Frequency control. Users can establish frequency control by steering an oscillator using integrated code-phase measurements or by directly measuring the SV carrier frequency. Carrier tracking is accomplished by phase locking to the de-spread carrier and by making accurate frequency measurements of the received carrier.

The transmitted carrier signals are controlled by on-board atomic clocks. A Doppler shift in the received carrier results from the changing range to the receiver from the moving SV. The difference between predicted and measured Doppler frequencies in a stationary receiver is the result of the receiver oscillator error. A direct computation of the error in the receiver clock can be made and used to adjust the oscillator or to report the oscillator frequency error to the user. Frequency accuracies of a few parts in 10^{-12} are possible with undegraded signals.

Common-mode, common-view time transfer. Another very useful technique is the method known as common-mode, common-view time transfer that was pioneered by NIST in the early 1980s. This method requires that two receivers track a satellite at the same time, as shown in Figure 5. It is assumed that the path-delay corrections and SV signal and data message errors are common to both received signals. If one receiver is compared to a master clock, such as those maintained by the U.S. Naval Observatory, the error in SV time seen at the reference location can be transmitted to the other location and used to adjust the clock at that location. Successful tests over paths of thousands of kilometers have shown that time transfers, under certain conditions, can be made to within 25 nanoseconds or better.

SELECTIVE AVAILABILITY

GPS has the proven potential to disseminate time and time intervals with accuracies of around 100 nanoseconds. Frequency control can be established globally to accuracies of a few parts in 10^{-12}. The Block I satellites, placed in orbit during the 1970s and 1980s, gave promising results for worldwide time and frequency users.

The new Block II satellites being launched now, however, have provisions for the implementation of selective availability (SA). SA is the intentional degradation of GPS signals and navigation messages to limit the full accuracy of the system to authorized users.

Implemented last March, SA seriously affects both the time and frequency accuracies of GPS. Early tests indicate that accuracies are degraded from errors of approximately 100 nanoseconds to errors of approximately 500 nanoseconds. Figure 6 shows actual results of selective availability on timing accuracies during a three-day period. Frequency control accuracies are reduced to a few parts in 10^{-10}.

Because most authorized users of GPS are in the military or otherwise affiliated with the Department of Defense (DoD), many non-DoD time and frequency users are already being denied access to the accurate signals on the Block II satellites. Because the Block I satellites are nearing the end of their useful life and the current DoD policy is to continue SA, many users are turning back to cesium clocks and systems like Loran-C. To date, DoD has denied requests for undegraded signals from certain SVs, which would allow for accurate time and frequency use without compromising the agency's goal of degrading position accuracy.

Fortunately, use of common-view, common-mode techniques can considerably reduce SA's effects on time transfer. The technique assumes that SA produces similar errors in both receivers involved in the time transfer. With careful time synchronization of the viewing window at the reference and common-view receivers, and with identical code phase-averaging techniques, the corrections transmitted from the reference station will remove most of the SA errors at the remote receiver site.

CONCLUSION

The time, time interval, and frequency dissemination capabilities of GPS have already been tested. No other single system has such potential for global, accurate, and inexpensive time and frequency control. The implementation of selective availability has caused perhaps the first backward step in the long progression toward more and more accurate time and frequency dissemination.

With full SA degradation, GPS may have to be augmented with cesium clocks and Loran-C receivers when costs and Loran-C coverage permit. Unless DoD reduces or eliminates selective availability or permits the use of special SVs with undegraded timing signals, the timing user community will have to refine and expand the use of common-mode, common-view techniques for GPS to reach its full potential as a time and frequency service. ■

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