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Time Transfer through GPS, and the Harmonization of GPS, GLONASS and Galileo for Timing

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Abstract
The Global Positioning System (GPS) has become a key component of the world technology, and one measure of its success is that it has inspired enhancements and similar systems. GPS can therefore be considered the prototype of several existing or planned Global Navigation Satellite Systems (GNSS), with which term we also include supporting satellite-based enhancement systems. This paper briefly describes how GPS derives its timing, how GNSS systems are used for several means of precise time transfer, how carrier phase can assist time transfer, and how GNSS systems can cooperatively create improved products. Significant benefits in terms of robustness and precision can result from combining GNSS systems. Applications which may require them are situations involving interference, limited reception as in urban canyons or indoors, or where there is limited time to acquire a signal.

I. GPS Operations and Constellation Timing

Although operationally managed by the United States Air Force, GPS has evolved from a military system to one intended for both civilian and military users. Initially, satellites broadcast spread-spectrum coded information at 1575.42 MHz (L1) and 1227.6 MHz (L2). The L1 transmissions include a publicly available coarse acquisition (CA) code. The C/A code is a satellite-specific digital code of 1023 bits, called chips, of duration 1 microsecond, which is repeated every millisecond. The values are set so that a receiver can process the signal from any satellite in view without any prior information as to the positions or clock states of the satellite or receiver. Once the receiver can identify a satellite's signal, the navigational message can be extracted in 12.5 minutes from a superimposed signal whose bits are 20 ms long. The navigational message contains information about the satellite orbit, clock parameters, health status, etc. The L1 and L2 transmissions also include a classified precise code (P1 and P2) whose 100 ns chip length is ten times less than the C/A code, resulting in a correspondingly higher reduction of multipath and other errors. The P-code is available only to designated users; however, in September of 2005 a GPS satellite was launched that broadcasts the publicly available C/A code on both L1 and L2. All future satellites will include this feature, and in 2007 the first satellite launch is scheduled that will broadcast a code for a third civil signal, L5. These new satellites will also include other signals such as the M-code, which is for military use only.

The GPS constellation is officially monitored at 11 sites, which send their data to the GPS Master Control Station (GPSMCS) for processing by the GPSMCS Kalman Filter (MCSKF). The data consist of arrival times of the GPS signals, as measured by

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the monitor site clocks. Every 15 minutes, the MCSKF uses these data to produce estimates of the monitor and satellite clock time and frequencies, the orbital positions of the satellites, ionosphere corrections, and other parameters.

The inputs provided directly to the MCSKF enable it to generate a time-like quantity, but do not provide a means to reference it to Coordinated Universal Time (UTC). UTC is provided by the U. S. Naval Observatory (USNO), which monitors satellite transmissions and reports the difference between their broadcast time (GPS Time) and UTC(USNO), which is the USNO's realization of Coordinated Universal Time (UTC). GPS Time is often confused with UTC because it is steered to UTC(USNO), modulo 1 second. However, GPS Time is a timescale provided for navigational purposes, and it is not adjusted for leap seconds. The (predicted) difference between UTC(USNO) and GPS Time is provided digitally in the satellite navigation messages, with an observed precision of 1.5 ns when averaged over a day. GPS Time is steered by a simple acceleration algorithm [1] which results in quasi-periodic oscillations of up to 10 ns, with durations of 10-20 days.

The parameters and corrections computed by the MCSKF are uploaded to each individual satellite approximately once a day, but are uploaded more frequently when necessary. As a result, the broadcast orbital and clock estimates can differ by the equivalent of up to a few 10's of ns from their true values, as measured inside the MCSKF. Until 2000, the timing of the GPS transmissions was intentionally distorted by the addition of pseudo-random noise of up to 100 ns RMS, which was termed Selective Availability (SA). The magnitude of SA was set to zero in 2000, and it is widely anticipated that SA will be completely removed in the near future.

Although not part of the official operations, the International GNSS Service (IGS, *http://igscb.jpl.nasa.gov/*) can contribute to civilian use of GPS in many ways. The IGS was founded in 1993 in order to make improved use of GPS, and it has since expanded its mission to add GLONASS and other satellite systems. The IGS currently uses carrier phase data (described below) from over 300 stations to generate highly precise measurements of GPS and GLONASS satellite orbits and clock states as well as Earth rotation parameters, troposphere delay, and ionosphere maps.

2. GPS Time Transfer

2.1 Calibration

In order to carry about the most accurate time transfer, it is essential that the factory-provided calibration be measured and improved upon. This section reports recent GPS satellite maintenance activities conducted by NPLI, which revealed some unusual characteristics of certain types of GPS time-transfer receivers. Some GPS receivers do not sample the GPS navigation message subframe of health information nearly as often as they should. It has been noted that the average time produced by many GPS timing receivers can vary over a range of a few hundreds of nanoseconds [2,3], which suggests that GPS timing receivers should be calibrated before being used.

As an example, the calibration of two receivers of different types is discussed here, using the setup in Fig.1. Receiver type 1 is a 12 channel L1 / C / A code GPS receiver, and receiver type 2 is a combined GPS and GLONASS receiver with 12 channels for each. Receivers of type 2 may be operated in a GPS only, GLONASS only, or combined GPS and GLONASS mode. The antennas of GPS receivers are fixed at locations whose relative coordinates must be determined to within a few cm. The 1pps from GPS receiver is compared with 1 pps of the master clock of NPLI through a precision time interval counter (TIC), whose measurement resolution should be at least one order better that the best specification of GPS Time. In our example, the TIC(HP 53131) has the resolution of 500ps. The reference 1pps was a realization of UTC(NPLI), and measurements were recorded through the computer's RS232 port. Since the calibration of UTC(NPLI) was previously determined by the BIPM, this process calibrates the receiver relative to all BIPM-calibrated receivers, which is consistent with the absolute calibrations performed by the USNO and the Naval Research Laboratories (NRL).

Table 1 shows the results of several consecutive calibration runs. The receivers of type 1 were operated in normal and hold-over modes, and an initial calibration bias estimate of order 10 μs was removed. Receivers of type 2 were operated in their three available modes: GPS only, GLONASS only, and combined GPS and GLONASS. The timing bias was determined by averaging satellite data over the

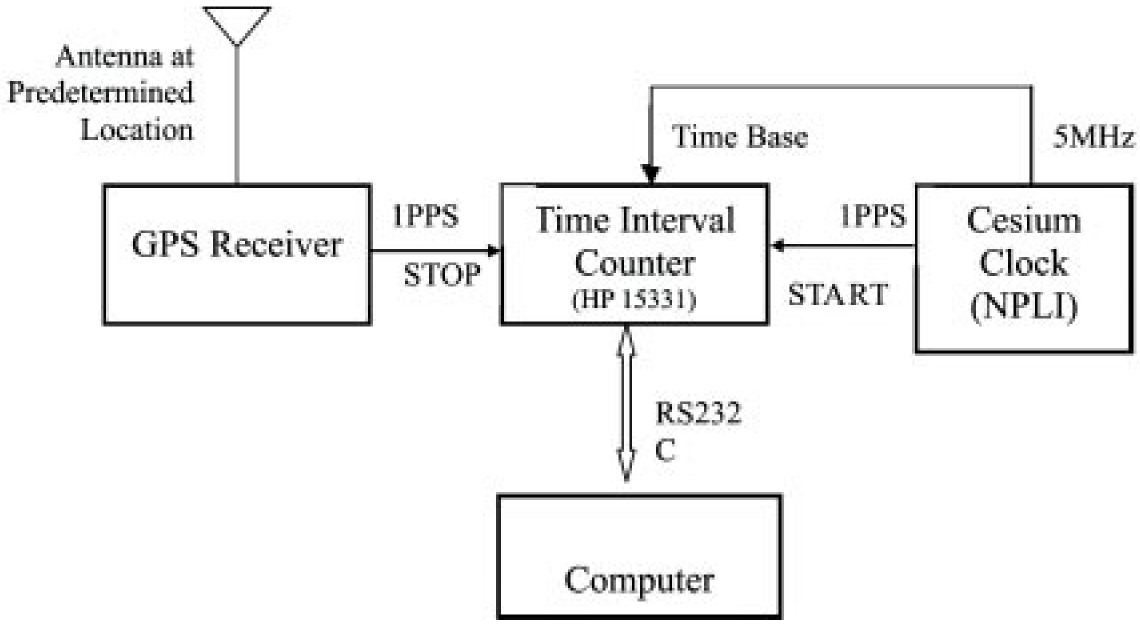


Fig. 1. Block Diagram of Experimental Set-up

Table 1
Consecutive few-minute calibration measurements for two receivers of known antenna positions

Data Bin (~15 min)	Receiver of type 1 (12-channel single-freq SPS)		Receiver of type 2 (Combined GPS, GLONASS)		
	Bias	RMS	Bias	RMS	Mode
1	-136.52	51.58	1830.67	19.63	GPS
2	n / a	n / a	1775.33	13.17	GPS
3	124.62	325.18	1815.24	10.47	GPS
4	-129.11	57.47	1771.69	21.44	GPS
5	-113.31	40.22	1733.96	37.36	GPS
6	-71.73	46.65	1757.31	46.68	GPS
7	-74.47	51.9	1790.77	21.36	GPS
8	-71.65	48.08	1799.63	15.28	Mixed
9	70.65	52.23	1216.1	22.69	Glonass
10	-81.76	55.52	1242.95	66.63	Glonass
11	-103.43	53.8	1807.32	10.12	Mixed
12			1181.88	9.95	Glonass
13			1812.74	14.91	GPS
14			1760.39	44.86	Mixed
15			1175.13	8.13	Glonass

period of the solution, and correcting for GPS-UTC(NPLI) using data available in the Circular T. Note that the GLONASS only differences differ systematically from the other modes involving receiver of type 2. This is evidently indicative of a 600 ns bias difference in the receiver's handling of GLONASS data. The bias does not appear in the combined solutions, and this is either due to lack of GLONASS satellites or perhaps to their exclusion by the receiver software, as outliers.

The overall calibration bias would be an average of the individual solutions, taking into account systematic differences between any receiver modes. The large scatter in the bias measurements of the receiver of Type 1 is most likely a measure of the quality of that unit.

2.2 Time Transfer via Direct Access (DA)

The simplest way to extract time from GPS, termed direct access, is to use GPS's delivered prediction of UTC(USNO). This can then be referenced to any other standard desired, using the BIPM's Circular T or other means. The bottom half of Fig. 2 shows one year's GPS performance; the top half shows the corresponding performance of GPS

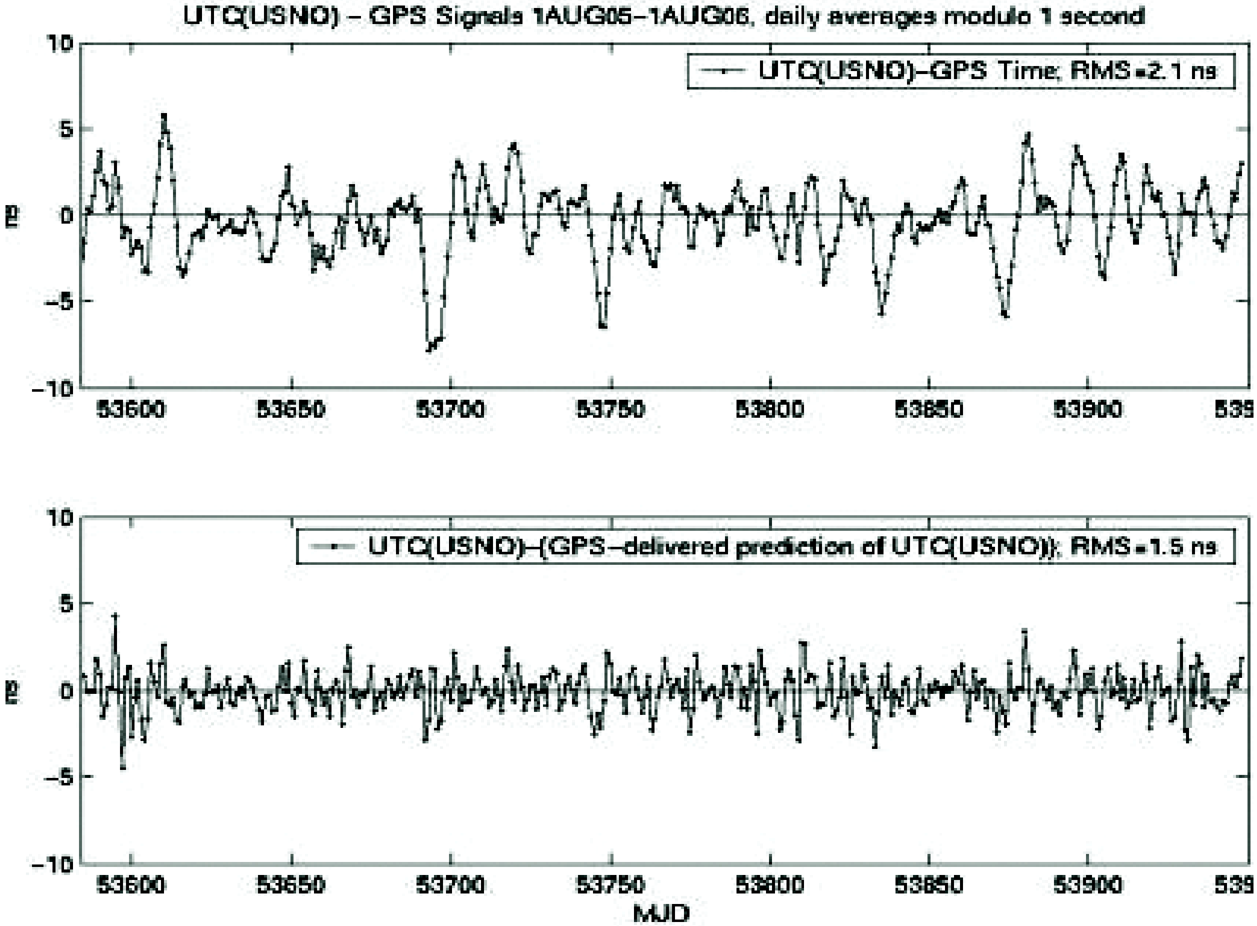


Fig. 2. One year's GPS timing performance. Upper plot shows the navigational timescale modulo 1 second, while UTC(USNO) is shown in the lower plot

time modulo 1 second.

2.3 Common View and All-in-View Time Transfer

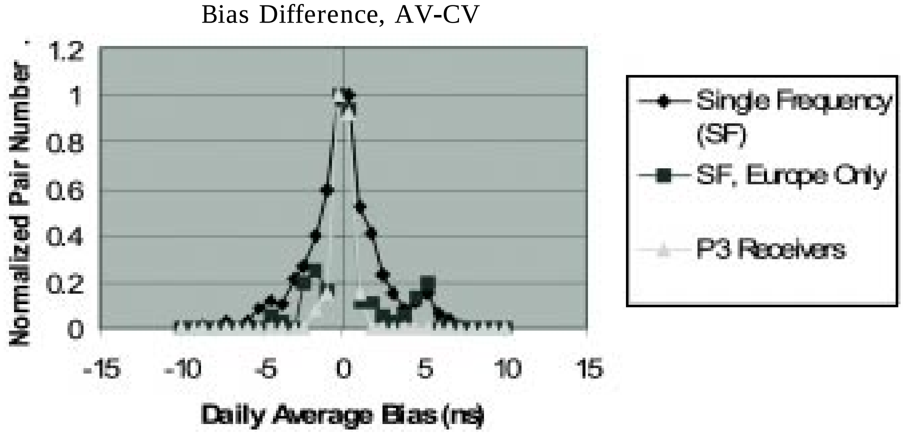
All-in-View (AV), also termed Melting Pot, can be considered an extension of the direct access technique. To transfer time between two sites, each site independently averages the corrected visible satellite times against its own clocks, and then those two averages are differenced. Common View (CV) is achieved by first differencing the corrected data of those satellites in view at both sites, those differences are then averaged. For extremely short baselines, AV and CV should yield identical values because the associative property of arithmetic requires that the average of a set of differences equals the difference of the associated averages. For longer baselines, the number of satellites that are jointly visible at both sites for CV decreases, and this decrease in the number of satellites degrades CV precision relative to AV. However, systematic errors can affect both techniques as well. AV is sensitive to satellite clock modeling differences as applied to the two sites. For example, if GPS Time (or any correction applied to it) is realized differently in northern satellites compared to southern satellites, AV between Australia and Japan would yield an incorrect value. Conversely, CV between Australia and Japan would preferentially use southern observing directions from Japan and northern observing directions from Australia. Any systematic north / south multipath difference at either site would lead to an incorrect value. With longer baselines, CV tends to preferentially use satellites at lower observing elevations, leading in general to increased multipath errors of all forms.

In order to study this problem, ionosphere and orbit-corrected GPS time transfer data made publicly available by the BIPM were analyzed for the year 2005, and taken from [4]. Figs. 3 and 4 show the biases and mean-removed RMS of the averaged daily differences between AV and CV for all pairs of laboratories. To generate the figures, CV and AV time transfer points were computed for every pair of laboratories with corrected GPS data. Data were averaged by day, and then the difference between CV and AV was computed for each day and pair of laboratories. These differences are independent of clock variations and receiver calibration errors. In the figures, P3 receivers are geodetic two-frequency receivers whose code data are contributed to the BIPM for a special project [5]. In the Figs. 3 and 4, the largest bias and RMS deviations are often associated with observations from India, South America, and South Africa. This is due to lack of CV observations but may also be in part due to long distances between them and other laboratories contributing to TAI, which leads to the question of direction-dependent effects.

In order to study the direction-dependent effects, the corrected GPS data were also analyzed by site.

Daily averages of all the GPS data observed from satellites in one hemisphere (of direction north, south, east, or west from the antenna) were averaged over a day. Also computed were site averages of all GPS data taken from satellites above 30 degrees elevation, and between 10 and 30 degrees elevation. Then data from opposing directions were differenced to generate daily north-south, east-west, and hi-low elevation differences. The reason for this approach is to mimic the difference between AV and CV. CV is based upon a subset of the data used for AV, because CV is sensitive to only those satellites that are geometrically situated at a position observable by both laboratories. Figs. 5a and 5b are histograms of the average difference, and Figures 6a and 6b are histograms of the mean-removed RMS of those daily differences. The hemispheric differences are independent of clock variations and receiver calibration, but they reveal the direction-dependent site-specific effects that are the root cause for CV being systematically different from AV, as shown in Fig. 3 and 4. The effect is more pronounced between widely-separated laboratories because directions of satellites are more selectively sampled. For example, observations between NPLI and NICT would exclude almost all GPS satellites that are to the west of New Delhi or to the east of Tokyo. At very high and very low latitudes, we have a further complication that northern observations tend to be of low-elevation.

Bias Difference, AV-CV



Daily Average Bias (ns)

Fig. 3. Histogram of daily bias between CV and AV techniques, over all laboratory pairs. Differences are consistent with the directional differentials present in CV that are not present in AV

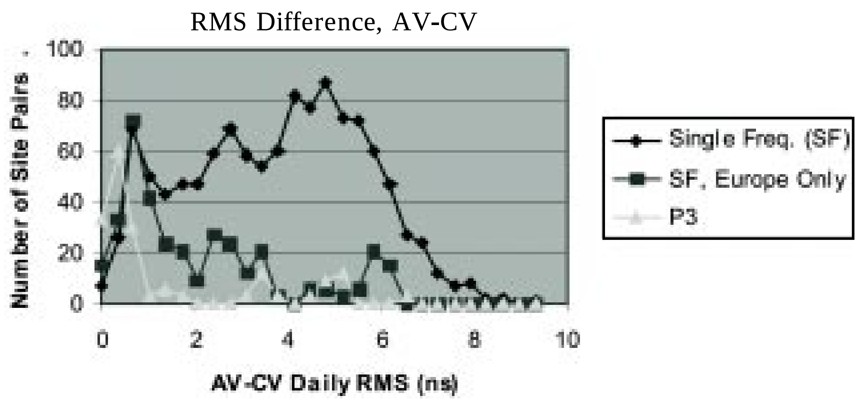


Fig. 4. Histogram of RMS of daily difference between AV and CV techniques, over all laboratory pairs

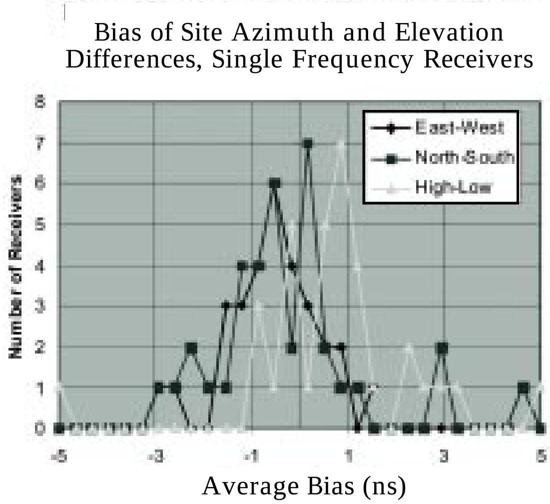


Fig. 5a. Histogram of difference between daily averages of all GPS observations at different elevations or opposing cardinal directions, for all single-frequency receivers

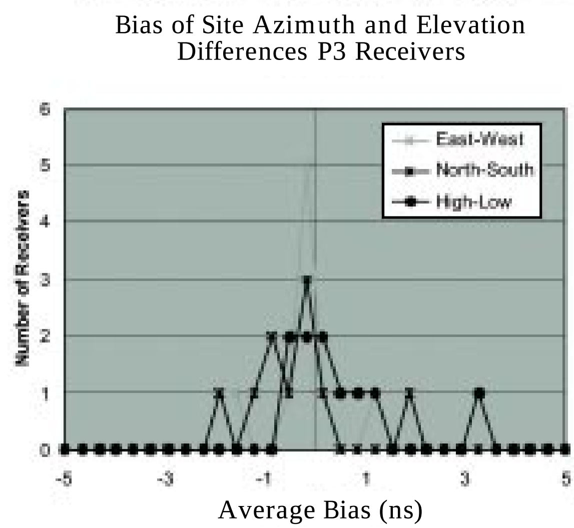


Fig. 5b. Histogram of difference between daily averages of all GPS observations at different elevations or opposing cardinal directions, for all P3 receivers

Because multipath, atmosphere, and ionosphere are stronger at low elevations, their unmodelled effects would tend to make the north / south differences of non-equatorial sites more similar in character to hi / low elevation differences than to east / west differences. This is roughly supported by the non-zero values of the (yearly) average biases in Figs. 5 and the RMSs shown in Fig. 6.

Figs. 3-6 show a consistent pattern that suggests CV results in calibration biases and daily scatters at the level of a few ns in single frequency receivers. Inter-European CV data are of higher quality because CV link-based noise increases in long baselines, such as those involving geographically isolated sites. In general, P3 data show less bias and RMS scatter than the single frequency (SF) receivers; this is likely due to better multipath rejection. However, the geodetic receivers used in the P3 experiment can show sudden calibration jumps at the ns level [6].

2.4 Carrier Phase Techniques

Time and frequency transfer using GPS carrier phase measurements [7,8] is currently a widely accepted method for high precision applications. The GPS carrier frequencies are pure tones and hence cannot provide timing information. However they

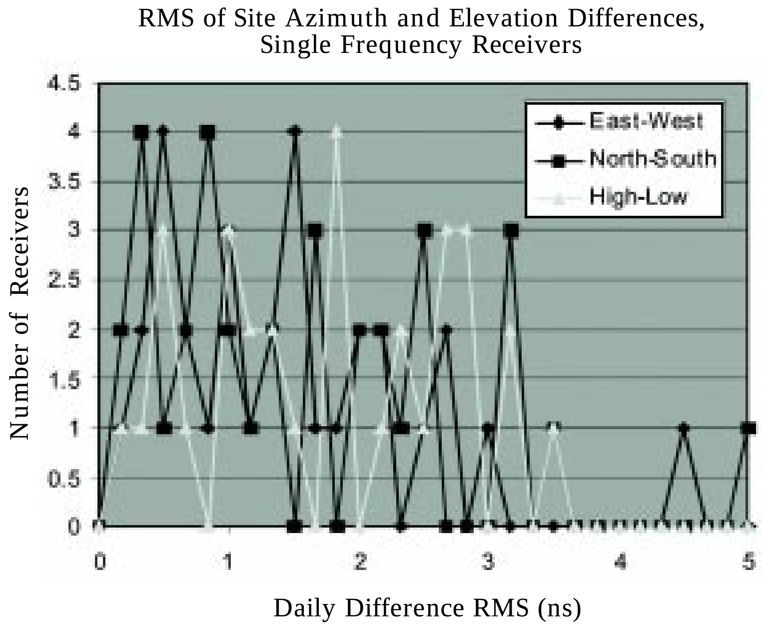


Fig. 6a. Histogram of RMS of daily difference between averages of all GPS observations at different elevations or opposing cardinal directions, for all single-frequency receivers

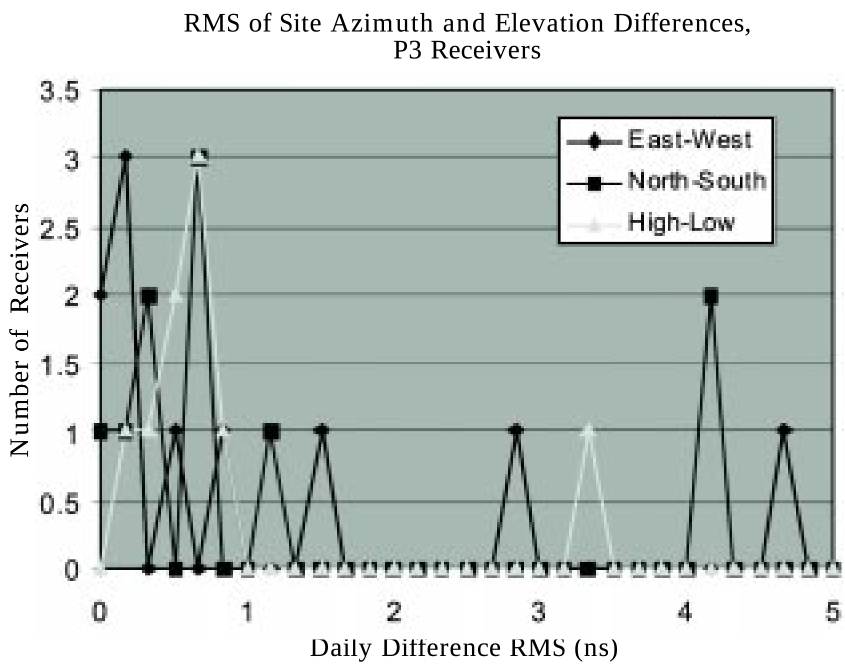


Fig. 6b. Histogram of RMS of daily difference between averages of all GPS observations at different elevations or opposing cardinal directions, for all P3 receivers

can provide frequencies, which can be integrated to achieve "uncalibrated time transfer". Their precision is approximately 100 times better than available from true timing information derived from the GPS pseudorandom code signals. Carrier phase timing consists of using the code to provide the average time (or equivalently the initial time, or the calibration constant), and the carrier phase to provide the rest. This technique provides consistent, precise clock information with a high temporal resolution in large networks. The method can also be applied for frequency comparisons without reference to the code.

The IGS, and other institutions, currently provide time transfer between contributing receivers using independent daily time-transfer solutions. These can show discontinuities of up to 1 ns at the day-boundaries due to noise in the code (pseudorange) data. The GIPSY GPS software (developed by JPL) can mitigate day-boundary discontinuities by applying a continuous Kalman filter across consecutive days [9]. Such continuous techniques are currently employed by several real-time systems [10]. Recently, extensions of the Bernese GPS Software package (developed by AIUB) have been developed that remove day boundary discontinuities through the method of ambiguity stacking [6], which passes ambiguity information across day boundaries by reconnecting the phase ambiguity parameters of consecutive days.

Carrier phase time transfer can attain a precision of 20 ps for 5-minute data points, although ns-level jumps have been observed and frequency stabilities below 1.E-15 at a day have not been consistently demonstrated. Improvements in GPS receiver technology may lead to greater long-term accuracy, while improvements in precision are certain to follow from the additional GPS frequencies and Galileo.

2.5 Scintillation and GPS data

Scintillation is singled out in this paper because it is a significant source of error for single-frequency receivers, particularly at the equatorial regions, as shown in Fig. 7 and described in [11-13]. GPS signals are delayed while passing through the ionosphere, and also fluctuate in amplitude. Large irregularities in the electron density distribution cause severe fluctuation in the signal strength known as scintillation. The Indian subcontinent extends from the magnetic equator, touching the tip of the Peninsula, to the mid-latitude zone in the north. Thus, nearly whole of India lies within the region prone to scintillation. It has also been well established that the strength and frequency of scintillation is highly correlated with 11-year cycle of sunspot number.

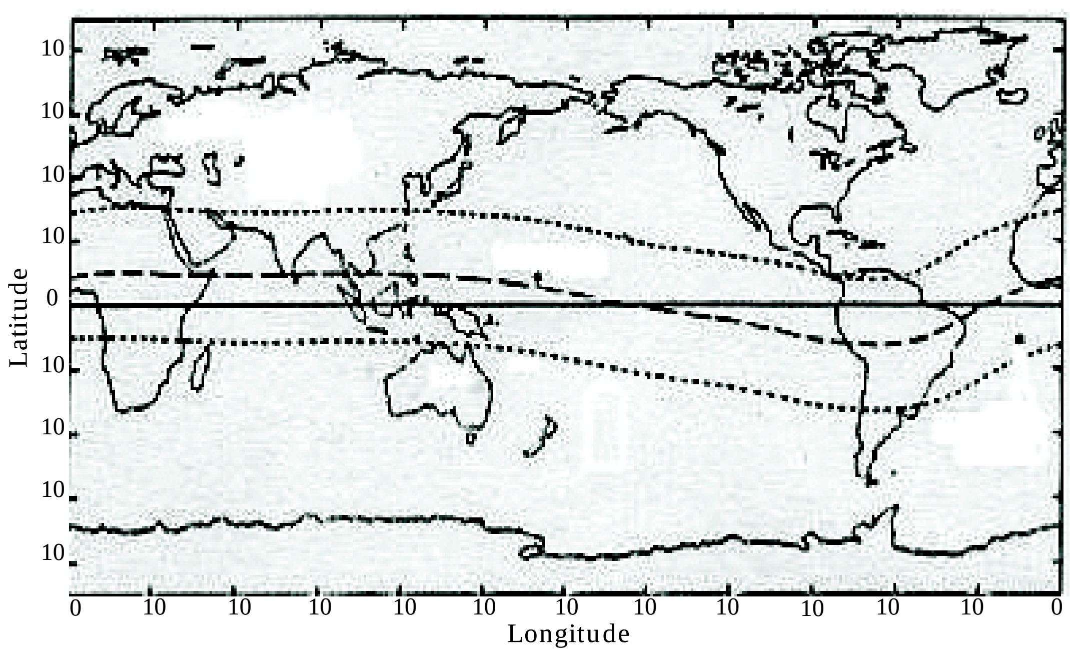
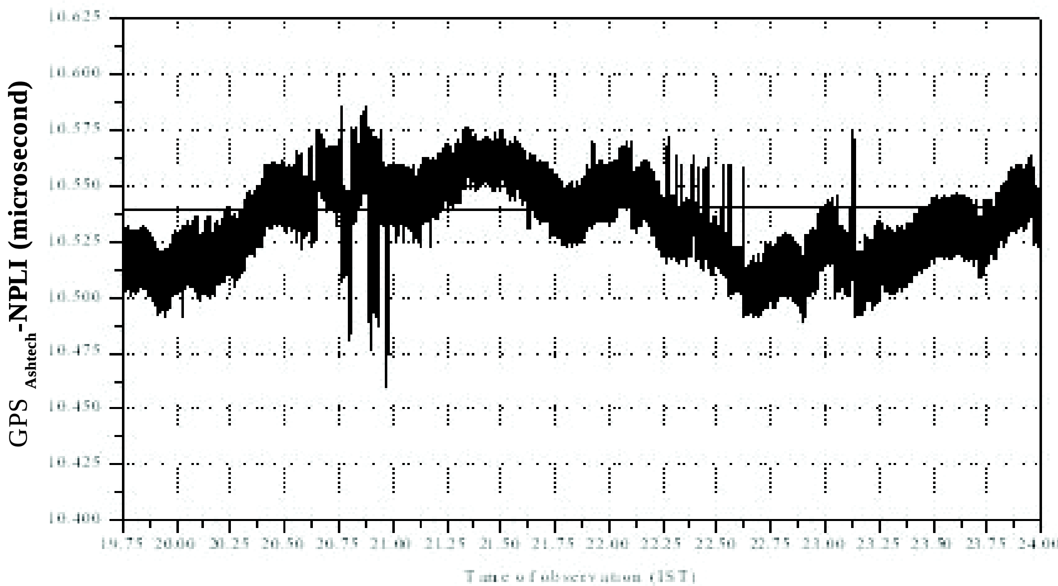


Fig. 7. Regions of high ionosphere activity. Latitude and Longitude are expressed in degree

Scintillation becomes a major issue for applications of GPS network because fluctuations present additional stresses to the GPS receiver tracking loops and can induce cycle slips or even complete loss of signal. The degradation of time and position solutions due to suboptimal geometric arrangement of observable satellites is termed dilution of precision (DOP). The loss of signal from a particular satellite, which is equivalent to the absence of that particular satellite for that location, may temporarily increase the DOP value and therefore reduces the precision of GPS timing.



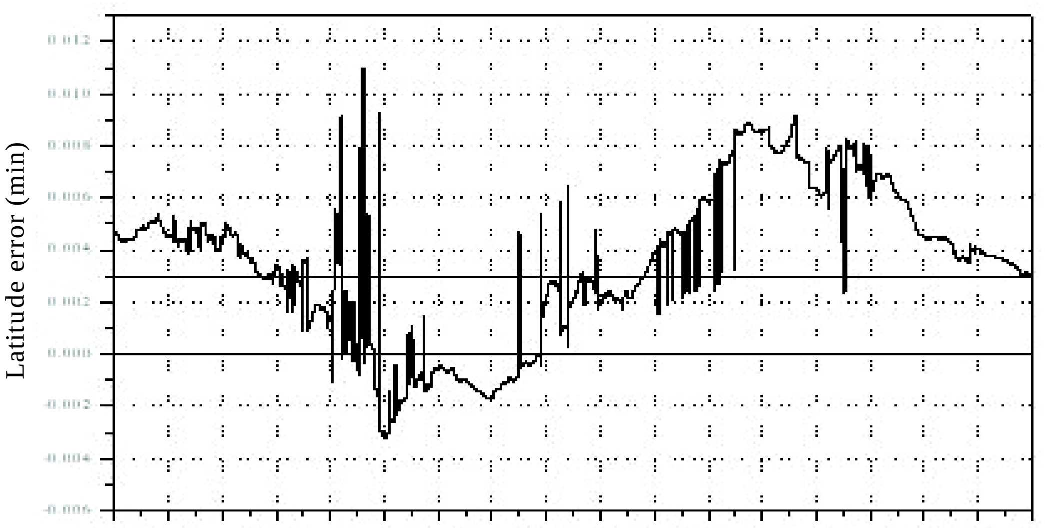


Fig. 8. GPS-determined position and timing offsets in the presence of scintillation. The upper plot depicts solutions for time, and the lower plot depicts a solution for latitude, in units of arcminutes Data are not corrected for the bias (calibration error) of the GPS receiver, which was inferred to be 1.7 ms . At the time of the observations, UTC-UTC(NPLI) was roughly 12.2 ms. Horizontal units are hours Indian Standard Time

To study this effect, GPS satellite observations were taken in the month of November, 2001, with a single-frequency multi-channel receiver whose antenna position had been pre-determined and whose time was referenced to UTC(NPLI). This was a peak period of the solar cycle, when scintillation events are most intense, frequent, and of longest duration. As scintillation normally occurs in the post-sunset period, the observations were started well before sunset and continued until early morning of the next day.

Fig. 8 shows receiver-generated values for time and latitude using a stationary single-frequency receiver with the standard Klobuchar model. The upper plot is the receiver's solution for time, as realized by its 1-pps output and referenced to UTC(NPLI). The lower plot is the latitude component of the receiver's solution for position. Fig. 9 shows the values after removal of long-term trends. The strong and rapid fluctuations seen in both kinds of solutions are not unusual in the presence of intense

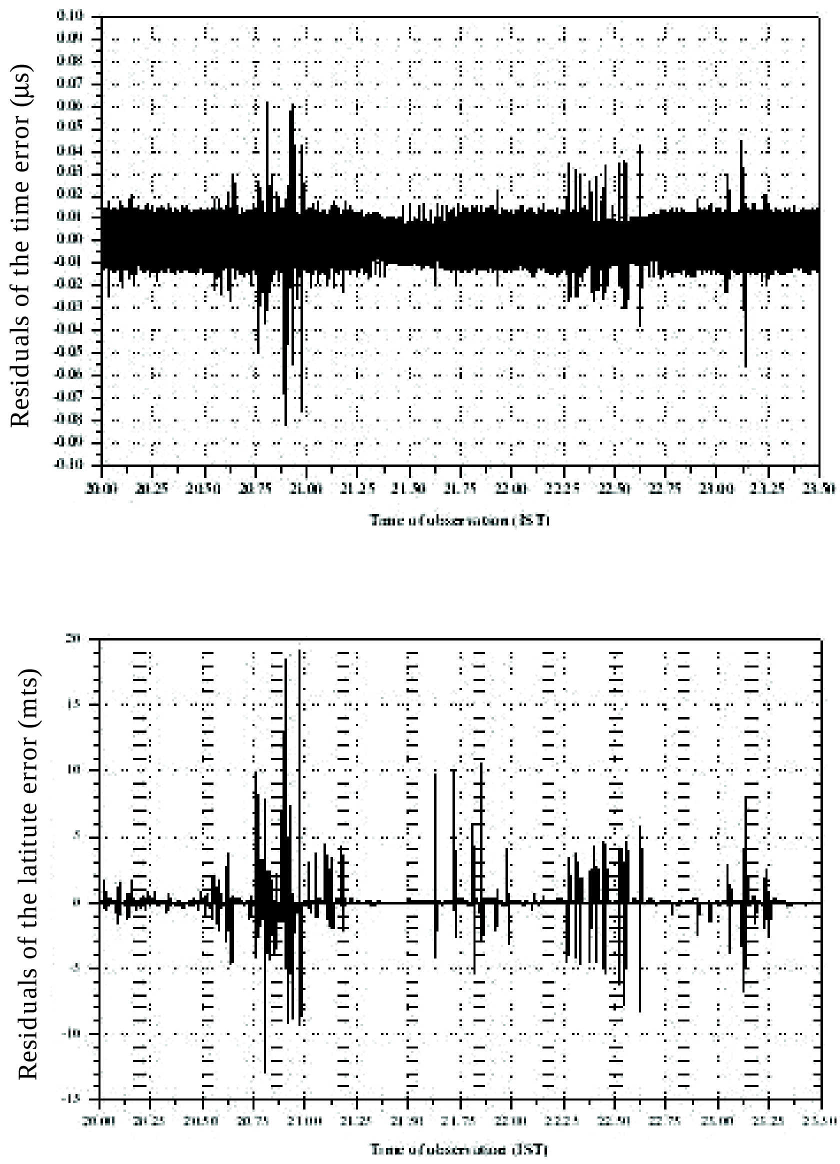


Fig. 9. High-pass filtered versions of corresponding plots of Fig. 8, which reveal effects of scintillation. Latitude errors have been converted to meters

scintillation [14]. It is not surprising that the large fluctuations of time error and those of position error occur simultaneously because they are due to corrupted single-satellite observations that are not removed by the receiver's internal consistency checks. When scintillation is absent, the fluctuations of the residuals of the time errors remain within ± 10 nanoseconds, but they become as high as 60 nanoseconds in the presence of scintillation. Similar events were observed on many other days during the month of Nov. 2001, and the degradation of solution precision is almost proportional to the intensity of the scintillation.

The hourly variations in Fig. 8 are most likely due to ionospheric mismodeling, which is the source of the correlations between the three fitted position components for this period (Fig. 10). The altitude measurement is anticorrelated with the time measurements of Fig. 8. This is because the receiver was in fact stationary, so that a high fitted altitude would imply that the receiver was actually lower in altitude than the fitted value and therefore the satellite signal arrived at the antenna later than projected by the fit. This would cause the value of UTC(NPLI)-GPS would be inferred as more positive than it really was, consistent with the more negative value of UTC-UTC(NPLI) in Fig. 8. A dual-frequency receiver that uses a measured ionosphere correction would not show such long-term effects.

The study was in New Delhi, at approximately 28.6^0 N latitude, where the scintillation is expected to be strong. At places where the scintillation is expected to be even more intense (such as around the S. American anomaly, -30 degrees latitude), the deterioration of the solutions would be more pronounced. This effect is not cancelled even in Common View, because the time of occurrence and the intensity of the scintillation vary unpredictably depending on the geographical location.

To reduce the deteriorating effect of scintillation on GPS time, some on-line remedial measures are

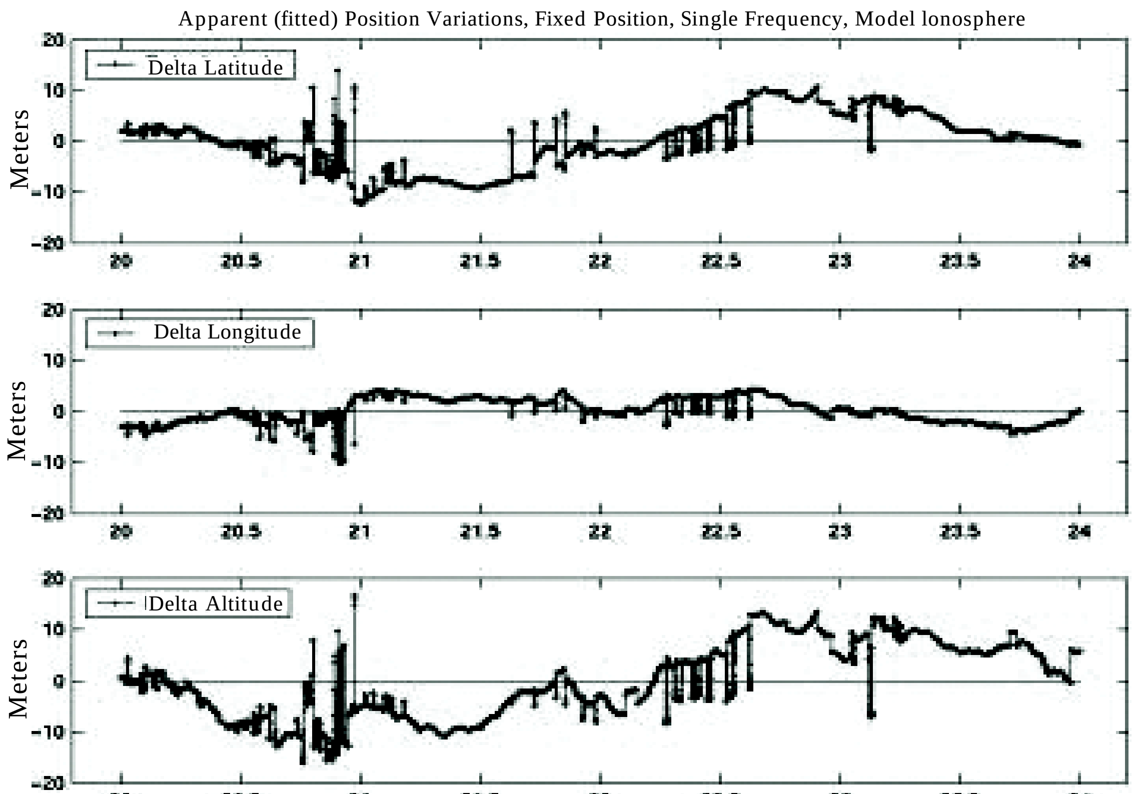


Fig. 10. Position components estimated bythe stationary single-frequency receiver. Effects of ionosphere include the rapid spikes and the long-term varitions in the position. The altitude variations are anticcorrelated with the timing variations of Fig. 8

available. The semi-empirical model [15, 16] which makes use of the instantaneous position error to improve the GPS time accuracy may be useful. Also, application of Kalman filter may help to partially reduce the effects of unexpected sudden fluctuations.

3. GLONASS Time Transfer

The GLONASS satellite system is operated by Russia, and differs from the GPS system in several ways. The most significant design difference is that each GLONASS satellite operates at its own two frequencies, which for timing implies that separate receiver bias corrections must be applied for each satellite. Also, since the number of satellites and observing stations are fewer, IGS orbital information is not as precise. On the other hand, the more precise P-code is available to all, and CV time transfer precisions of 1-3 ns have been reported after careful analysis [17]. Unlike GPS, GLONASS system time is UTC, and there is no special timescale created for navigational solutions.

4. Compatibility and Interoperability of GNSS Systems

A number of GPS-enhancing systems are being prepared for implementation. In the United States, the Wide Area Augmentation System (WAAS) has two satellites broadcasting in test mode. The European Geostationary Navigation Overlay Service (EGNOS) is under development [18], and the Japanese Quasi-Zenith Satellite System (QZSS) is steady approaching the launch stage [19].

Following the model of GPS and GLONASS, a largely European effort is underway to field a GNSS system named Galileo. Galileo will follow the GPS system in that all satellites will broadcast at the GPS L1 frequency, and its navigational system time will also be offset 19 seconds from TAI. The enhancement systems are designed to work with GPS, while Galileo has a stand-alone capability. In a series of meetings between the United States and Galileo, ways to share the GPS L1 frequency were agreed upon, so that transmissions from the two systems would not interfere with each other [20]. Galileo will also broadcast at the planned GPS L5 frequency, and in addition will solely use the E6 frequency.

Interoperability can be defined as the ability to enhance performance by combining data from different systems. The augmentation systems do this by providing real-time corrections to the broadcast navigational message, so that users would have better estimates of the satellite positions and clock status. A key issue is speed of identification and tagging of satellites that have developed problems and are malfunctioning.

The combination of GNSS systems can lead to significant improvements in other ways. While four satellites are required to form a solution giving user location in space and time, for safety-of-life and other applications a minimum of five would be needed so as to provide redundancy and identification of malfunctioning satellites. Under most situations it is common to have about eight satellites in view, but there are times when fewer than four are in view even from an undisturbed vantage point. Such situations can occur in "urban canyons", or in the presence of interference or jamming. Galileo, in combination with GPS, would roughly double the number of satellites available to users, and local augmentation system satellites could add an extra satellite or two, which may prove to be just enough for the situation. For this reason, the QZSS system is designed so there will always be at least one satellite lingering at a high elevation over Japanese cities.

Malfunctioning satellites can also be identified directly, by augmentation systems designed to provide such information in real-time. In the United States, and other countries, a requirement for mobile telephones, termed "E-911", has been established. This requirement states that users of a mobile phone should be able to make an emergency telephone call to the police and, in analogy to dialing 911 with a normal telephone in the USA, that the phone unit would be able to provide its location to within 50 meters for 67% of the calls using handset-based solutions, even inside buildings where GPS signals may be very weak. Use of augmentation systems and Galileo would make it much easier for manufacturers of mobile telephones to meet this requirement.

In order to optimize the compatibility of GNSS systems and their augmentations, it is essential that all systems share a common time. If the two systems do not have a common time, then the receiver would have to add a time-offset parameter to its solution, which is equivalent to removing one satellite from a combined solution. Under such conditions it would require six satellites to improve upon the solution derived from four satellites of a single GNSS system.

For all the above reasons, plans are under way to synchronize GPS with QZSS and Galileo [19,20]. One way to achieve this is to install GNSS receivers that simultaneously observe both GPS and the cooperating system's signals, so that the average time differences can be observed. A second method is to use a complementary time-transfer technique, Two Way Satellite Time Transfer [21], to directly measure the offset between the system times at one or more monitor stations of each GNSS system.

5. Combination of GNSS systems by the users

Compatibility of the transmitted signals of different GNSS systems is technically attainable, although any calibration errors would limit time-transfer performance. Therefore, individual users or manufacturers will need to make careful adjustment of any residual biases in their systems. Such biases are evident in the calibration example given in section IIa above. Another such bias is the effect of the receiver's correlator spacing on instrumental timing [22], which can be different for each satellite-receiver pair.

For precision applications, the combination of GNSS systems can lead to new benefits. The Galileo transmissions will be less vulnerable to multi-path than those of GPS, and this can be used to study and improve the multipath environment of receivers. The additional frequencies and presence of the C / A code on the GPS L2 frequency will allow enhanced ambiguity resolution for carrier phase applications. Use of multiple systems will allow identification of systematic biases and other error sources.

6. Conclusion

As more GNSS systems and their augmentations are fielded, there will be improved performance in time transfer. The increased basic performance will lead to secondary improvements through the detection and reduction of systematic or system-specific error sources. The technical efforts have been made possible by political cooperation, for the mutual benefit of all parties.

7. Disclaimer

We cannot endorse any commercial product, and therefore have not identified most of the key components whose behavior is described. We also note that none of the systems described here were studied under controlled conditions, and that past performance as reported herein may not be characteristic of models currently marketed by any manufacturer.

Dr. Matsakis wishes to state that this paper reflects his personal viewpoints, which are not necessarily those of the U.S. Naval Observatory, the United States Department of Defense, or the government of the United States.

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