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Ionospheric Corrections to Precise Time Transfer using GPS

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Abstract

The free electrons in the earth's ionosphere can retard the time of reception of GPS signals received at a ground station, compared to their time in free space, by many tens of nanoseconds, thus limiting the accuracy of time transfer by GPS. The amount of the ionospheric time delay is proportional to the total number of electrons encountered by the wave on its path from each GPS satellite to a receiver. This integrated number of electrons is called Total Electron Content, or TEC. Dual frequency GPS receivers designed by Allen Osborne Associates, Inc. (AOA) directly measure both the ionospheric differential group delay and the differential carrier phase advance for the two GPS frequencies and derive from this the TEC between the receiver and each GPS satellite in track. The group delay information is mainly used to provide an absolute calibration to the relative differential carrier phase, which is an extremely precise measure of relative TEC. The AOA Mini–Rogue ICS–4Z and the AOA TurboRogue ICS–4000Z receivers normally operate using the GPS P code, when available, and switch to cross–correlation signal processing when the GPS satellites are in the Anti–Spoofing (A–S) mode and the P code is encrypted.

An AOA ICS–Z receiver has been operated continuously for over a year at Hanscom AFB, MA to determine the statistics of the variability of the TEC parameter using signals from up to four different directions simultaneously. The 4–channel ICS–4Z and the 8–channel ICS–4000Z, have proven capabilities to make precise, well calibrated, measurements of the ionosphere in several directions simultaneously. In addition to providing ionospheric corrections for precise time transfer via satellite, this dual frequency design allows full code and automatic codeless operation of both the differential group delay and differential carrier phase for numerous ionospheric experiments being conducted. Statistical results of the data collected from the ICS–4Z during the initial year of ionospheric time delay in the northeastern U. S., and initial results with the ICS–4000Z, will be presented.

INTRODUCTION

The ionosphere can be the largest source of error in GPS time transfer, positioning and navigation. Radio waves propagating through the ionosphere suffer an additional time delay

as a result of their encounter with the free electrons in the ionosphere. This total electron content (TEC) is a function of many variables including geographic location, local time, solar ultraviolet radiation, season and magnetic activity. Accurate information on the behavior of TEC is important to satellite navigation and time transfer systems that correct for the time delay effects of the earth's ionosphere.

The GPS dual–frequency system provides the opportunity to measure absolute TEC with a high degree of accuracy. Absolute TEC values are obtained by measuring the differential group delay of the 10.23 MHz modulation on the dual–frequency L–band signals. Relative TEC values are obtained by monitoring the differential phase of the two GPS carriers. By combining both the relative measurements of the differential carrier phase with the absolute TEC obtained from the differential group delay, excellent absolute TEC measurements can be made.

Many ionospheric experiments are currently in operation using this technique. A recent study on the seasonal variability of TEC was conducted at Hanscom AFB, MA. The results of this study will be presented here together with the method used to calculate precise measurements of TEC using the dual frequency GPS system. Ionospheric measurements for this study were made using the AOA 4–channel ICS–4Z Mini–Rogue GPS receiver. It has a high–performance, all–digital design and is capable of tracking four satellites simultaneously using the P codes on both frequencies, L1 and L2, in addition to the C/A code on the L1 frequency. Precise measurements of the L1 and L2 carrier phase are also derived. This paper also will describe some measurements made using the AOA TurboRogue receiver, Model ICS–4000Z. This is an 8–channel receiver that has an improved cross–correlation capability. This allows the receiver to recover sufficiently accurate measurements of TEC when the precision ranging codes (P codes) of the GPS transmissions are encrypted (i.e., with Anti–Spoofing activated).

IONOSPHERIC MEASUREMENTS USING GPS

The GPS satellites transmit coherent radio signals at two L–band frequencies, L1, at 1.575 GHz and L2, at 1.228 GHz. Since the ionosphere is a dispersive medium, the two signals experience different amounts of time delay. The difference between the L1 and L2 transmit times is the differential group delay. This differential delay can be related directly to the total electron content along the line of sight between the satellite and the receiver. The value of 1 ns differential group delay represents 2.852 TEC units (1 TEC unit = 10^{16} electrons/meter^2). One ns of group delay at the L1 frequency is equivalent to 1.85 TEC units.

Figure 1a illustrates an example of the differential group delay measurement for one full satellite pass recorded on February 24, 1993. Note that the time delay is given in units of nanoseconds at the L1 frequency; however, the differential time delay is the actual measured quantity in Figure 1a. These measurements represent absolute values of TEC, but they also include the effects of multipath and receiver noise. Multipath is strongly dependent on the local environment and is more evident at low elevation angles, as can easily be seen near both ends of the pass. Note that the approximate elevation and azimuth of the pass are given, for different times during the pass, in Figure 1b.

L1 and L2 signals also experience different carrier phase advances caused by the ionosphere.

The difference between these carrier phase changes, in units of time, is referred to as the differential carrier phase advance. An example of differential carrier phase, expressed in units of nanoseconds of delay at the L1 frequency, is illustrated in figure 1b, together with the approximate elevation and azimuth angles to the satellite. This is a more accurate ionospheric measurement than differential group delay since it is affected much less by multipath and receiver noise. However, it is only a relative measurement because of inherent carrier cycle ambiguities. That is, the number of full phase cycles along the line of sight between the satellite and receiver is initially unknown.

Absolute values of ionospheric time delay (or TEC) generally are determined from these two GPS measurements by using a technique first suggested by Jorgenson (1978). This is accomplished by calculating an arithmetic mean fit of the absolute, but noisy, group delay data, to the relative, but precise, differential phase data. This fitting procedure is done only over the higher elevation portions of the satellite pass, minimizing the error caused by multipath from the differential group delay measurements. Figure 1c illustrates the results of this fitting procedure. There is a possibility of cycle slips in the differential carrier phase, giving potential problems in the fitting of the carrier phase throughout an entire pass to the differential group delay. In practice, however, cycle slips are a relatively rare occurrence with the ICS-4Z receivers, and even rarer with the ICS-4000Z, occurring on the order of less than one cycle slip for each day of data recorded. Nevertheless, a program has been written which finds and corrects for these rare events automatically in virtually all cases.

There are several sources of error in determining the absolute values of ionospheric time delay. The most significant being the additional time delay induced by the receiver hardware and the individual GPS satellites (Klobuchar, et. al. 1993). The receiver hardware is easily calibrated to a fraction of a nanosecond differential delay. The individual space vehicles introduce a much greater error. These errors, or biases in the transmitted time offset between the 10.23 MHz phase of the L2 minus the L1 modulation, are called T_{gd}. They are different for each space vehicle, and they could possibly vary with time, though the evidence for their temporal variations is not compelling. Estimates of T_{gd} indicate that they can be as high as 10 TEC units (3.5 ns differential time delay). A bias this large is intolerable, since it can exceed the maximum TEC observed during solar minimum conditions. These biases have been studied by Lanyi and Roth, 1988; Coco, et. al., 1991; Gaposchkin and Coster, 1993; Wanninger and Sardón, 1993; Wilson and Mannucci, 1993; and others. These studies have revealed many inconsistencies in results of the T_{gd} measurements. A summary of the published T_{gd} values, and the potential problems in deriving them, was given by Klobuchar, et. al, (1993). In this paper, the biases reported by Wilson and Mannucci, (1993), have been applied to the data. Their bias estimates are based on a multi-site fitting technique that exhibits a small day-to-day scatter. The Wilson and Mannucci study of the biases is based on a very extensive data base recorded in March 1993 and is likely the most reliable set of bias estimates available to date.

DATA BASE

The GPS data used in the TEC variability study was recorded at Hanscom AFB, MA for a full year, from May 1992 through April 1993. Figure 2 illustrates the satellite paths of the various

GPS satellites over Hanscom for one day during this period. Elevation angles of 0 through 60 degrees are represented by the concentric rings centered around the station. Satellite signals received from widely spaced azimuth and elevation angles pass through greatly different regions of the ionosphere. Therefore, simultaneous measurements of ionospheric time delay (or TEC) along different lines of sight generally are not the same.

VARIABILITY STUDY RESULTS

Figure 3 displays the observations recorded on February 24, 1993. The slant absolute delay measurements have been converted to equivalent vertical time delay in ns at the L1 frequency. That is the measurement at the geographic position directly below the point where the satellite intersects the centroid of the electron density distribution with height, typically taken to be at 400 km. In order to display the diurnal variation of ionospheric time delay, the data is plotted versus local time at this sub–ionospheric intersection point. At any local site, the ionization generally peaks in the mid–afternoon local hours, and drops rapidly at night. The differences between measurements made at the same local time are attributed to the ionospheric gradients encountered by satellite paths intersecting the ionosphere at different latitudes.

Ionospheric time delay is also highly variable by season. Figure 4 illustrates the statistics of ionospheric time delay for three seasons during the daytime hours of 1100–1700 local time. The daytime TEC values were computed and grouped together by season, summer (May through August), winter (November through February), and the combined equinox periods of March, April, September and October. The ionospheric time–delay measurements are plotted against their cumulative probability so that the percentage of occurrence above and below certain probability levels can be observed. A straight line on this type of statistical plot indicates a Gaussian, or normal, distribution. The slope of the line is a measure of the standard deviation, and departures from a straight line are simply departures from a normal distribution. This figure indicates that the median daytime values of ionospheric time delay are highest in winter, followed closely by the equinox period. The summer values are the lowest. The winter season exhibits a significant departure from a normal curve above the 99% probability point. Departures like this are often due to the effects of magnetic storm activity.

Figure 5 illustrates the statistics of ionospheric time delay at L1 during the nighttime hours of 2300–0500 local time. Here, it is evident that the summer nighttime values are higher than those for the other two seasons. Winter and equinox have a more nearly normal distribution than summer. Summer begins to depart significantly from a normal distribution above the approximate 95% probability level. The negative numbers below the 1% probability point are probably due to incorrect satellite biases. There is some evidence that the biases vary with time, (Gaposchkin and Coster, 1993), and other evidence that they do not vary with time (Wilson and Mannucci, 1993). Our indications of the apparent "fewer than zero" number of electrons in the ionosphere, seen in Figure 5, for less than 1% of the time during the equinox season and for less than approximately 0.5% of the time during the summer season, are likely due to incorrect values for the T_{gd} for at least some of the GPS satellites.

The ionospheric time delay is primarily a function of solar ultraviolet radiation. A reasonable surrogate measure of the amount of ultra–violet radiation produced by the sun which is

responsible for ionizing the earth's atmosphere, and producing the ionosphere, is the number of sunspots visible on the solar surface. Figure 6 illustrates the last two solar cycles with the period indicated during which the GPS measurements were made. This period was in the declining phase of the current solar cycle, therefore, the ionospheric time delay values measured are approximately half the values expected at the peak of the solar cycle.

The data set used in this ionospheric variability study is the first continuous, well–calibrated, dual–frequency GPS ionospheric data set large enough for statistical research. The TEC parameter, however, has been studied for over twenty years using measurements of the Faraday rotation of linearly polarized radio waves transmitted from geostationary satellites. For comparison with the GPS TEC data study, Figure 7 is included to represent the daytime cumulative probability of equivalent vertical ionospheric time delays at the GPS L1 frequency, as determined from the Hamilton, MA 1981 Faraday rotation data. This data is from a high solar activity year and should represent near–worst–case ionospheric time delays encountered in the mid–latitude region. A comparison of the 1981 results (Figure 7) and the recent GPS daytime statistics (Figure 4) illustrate an agreement in seasonal behavior with summer producing the smallest daytime values and equinox exhibiting the greatest day–to–day variability. It also illustrates the ionospheric time delay dependence on solar activity, with the 1981 data producing median values that are nearly two times those encountered during the 1992–1993 period.

IONOSPHERIC MEASUREMENTS USING
THE TURBOROGUE ICS–4000Z

A few weeks of ionospheric measurements using GPS dual–frequency signals were recorded recently at the AOA offices at Westlake Village, California using the TurboRogue Model ICS–4000Z receiver. This receiver has the capability of tracking eight satellites simultaneously. Figure 8 illustrates the equivalent vertical time delay, in ns at L1, measured for one day during that period. This receiver provides much better spatial coverage with up to eight satellites visible simultaneously. In the data collected, a minimum of five satellites were visible at any one time. The passes showing large positive temporal gradients, seen particularly between approximately 0900 and 1700 hours local time were observed from satellites viewed at low elevation angles to the south of the receiver. These are manifestations of the latitude gradients in the ionosphere as viewed from a single station. From a single station the ionospheric time delay can be measured at latitudes up to 15 degrees away from the station.

An advantage of the Rogue–type receivers is their ability to automatically switch to a codeless mode of tracking when the P–code on any satellite is encrypted by Anti–Spoofing (A–S). In this mode, continuous ionospheric measurements are made possible by cross correlating the L1 and L2 signals, (Srinivasan, et. al., 1989). Because of the inherent lower signal to noise ratio obtained by the receiver when the satellites are in the A–S mode there is a higher level of system noise. However, this higher noise level does not greatly affect the normal attempts to measure ionospheric time delay values.

A comparison of P–code and codeless ionospheric measurements is shown in Figure 9. For this comparison, the receiver was set to simultaneously track the same satellite on separate channels

using both the fully coded and the codeless, cross–correlation techniques. Figure 9a shows the differential group delay and phase delay obtained with P–code tracking. The approximate elevation and azimuth angles of the satellite are printed under the curve. Figure 9b shows similar results with data obtained by codeless tracking. Here, system noise provides the greatest error, particularly at elevation angles lower than 30 degrees. However, no difficulties were encountered in fitting the codeless differential carrier phase data to the codeless differential group delay data, despite the obviously much higher noise for codeless group delay case. Ten–second sample rates were used for both the code and codeless channels. Since the receivers make measurements at 50 per second, at a 10–second sample rate a total of 500 measurements are averaged per point.

Figure 9c illustrates the difference in delay between the coded and codeless data. A constant difference of approximately 1.1 nanoseconds at L1 is apparent throughout the pass. That difference is due to the asymmetry in the correlation function, and the difference in the correlator in the code versus the codeless mode in this version (2.8) of TurboRogue firmware. This difference between code and codeless tracking in the TurboRogue has been corrected in receiver firmware versions 3.0 and beyond. The noise in the resultant ionospheric time delay measurement at L1 in the codeless mode is comparable with that found by Meehan, et. al., 1992. It is much less than one nanosecond with ten–second averaging.

CONCLUSIONS

The GPS dual–frequency system provides an accurate source of ionospheric time delay measurements. The general results of the TEC variability study agree with prior studies using the Faraday rotation technique to measure TEC. From this study, it is obvious that reliable GPS measurements greatly depend on the accuracy of the receiver and individual satellite biases. The receiver biases can easily be calibrated, but the GPS satellite T_{gd} biases still have an uncertainty of approximately 1 to 3 differential nanoseconds.

The Mini–Rogue and TurboRogue receivers used in this study proved to be reliable in making highly accurate relative measurements of ionospheric time delay, only limited by the GPS satellite T_{gd} offsets. The receivers ability to automatically switch into cross–correlation mode when A–S is turned on insures continuous ionospheric measurements in the presence of Anti–Spoofing. In this codeless mode, the TurboRogue continued to provide accurate measurements of the ionosphere with ten–second time resolution.

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QUESTIONS AND ANSWERS

Marc Weiss, NIST: How do you know that the noise that you see in the group delay is measurement noise and not actual physical fluctuations of the ionosphere?

R. Snow: Primarily because of the smoothness of the carrier phase. The carrier phase is a much more precise measurement. And that doesn't show that rapid fluctuation. If there were real noise you would see fluctuations in the carrier phase or in the signal to noise ratio, which you do not see. Most of that noise is due primarily to multi-path and measurement noise in the receiver; but primarily multi-path. That is why it grows so much at low elevations.

Claudine Thomas, BIPM: You showed some graphs with vertical delays due to the ionosphere. How did you get these because you are measuring the line of sight to the satellite?

R. Snow: Yes, I'm sorry I didn't go over that. What is done is we convert the equivalent delay that we measure through the line of site to the local vertical delay by using the secant of the angle. The measurement that we are using, we are determining the centroid of the ionosphere which is about 400 kilometers above the earth; so the point with that ray path intersects the centroid of the ionosphere is converted to a local vertical by using a secant of the angle.

Claudine Thomas: Yes, you just choose the elevation of the satellite and nothing else.

R. Snow: Well, we are actually using the angle. Yes, it is a combination of the elevation.

Claudine Thomas: Well, I don't know if it is complete, if this is a complete process to do that. The other point is that I don't know why you need the $T - gd$ with the P–code receiver. I don't think you need the T_{gd}.

R. Snow: T_{gd} tells you the time difference between when the two signals are transmitted. If this is not correct then it will add as an error source to what you measure.

Claudine Thomas: Yes, for sure. But when you use a P–code receiver, like the TTR4P, you don't need the T_{gd} I think.

R. Snow: No, I think you do. You need to know when the L1 and L2 P–codes were transmitted. And the T_{gd} tells you that difference. If you don't know that, it can be off by three ns; that three ns adds to your delay. So you must know the time at which they started the transmission as well as the arrival time. And they are not totally synchronous at the time of the transmission. The offset is the T_{gd}. If they were totally synchronous, if the T_{gd} were zero, we wouldn't have a problem.

Claudine Thomas: Yes, I know about that. Because when we have compared your TTF4P

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with another receiver, we had to deal with that T_{gd}. But I think in the TTF4P there is no values for the T_{gd} which I introduced.

R. Snow: The values are in the navigation message.

Claudine Thomas: Yes, but they are not decoded and introduced.

R. Snow: No, they are not used in real time, that is correct. All of the data which I showed you was done post–mission, not real time.

Dr. Winkler: I have a quick question. In your reduction to the vertical, you are using only elevation but not azimuth. Shouldn't you account for the azimuthal variation also? Wouldn't that be useful?

John Klobuchar, AF Phillips Lab: Well of course you should take into account the azimuth as well as elevation. But you have to know the gradients in order to that. And you in general don't know the gradients well enough. So to first order, we just take into account the thickness parameter which is a function of elevation angle.

I would like to make another comment on the T_{gd}. Perhaps you don't understand what T_{GD} really is. If there were no ionosphere at all, you would measure some "equivalent" ionosphere just because the satellite doesn't transmit those L1 and L2 10.23 MHz modulated signals in phase. So consider the case of no ionosphere where you see a perfectly calibrated receiver would still measure some apparent number of electrons. In fact, sometimes they might measure fewer than zero electrons. And this is the most serious problem; it has nothing to do with the receivers. The receivers are calibrated properly; it has to do with the satellites. And each satellite has a different offset between the L1 minus the L2 modulation phase. It is unknown; it may be changing; it is a difficult thing to measure now that they've been launched; and there is still a lot of question about that down to the last, as Robert said, three to six ns of equivalent delay at 01(?).