The Timing Group Delay (TGD) Correction and GPS Timing Biases

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BIOGRAPHY

Dr. Matsakis received his PhD in Physics from the University of California. Since then he has worked in most aspects of timekeeping, and is the Head of the Time Service Department at the U.S. Naval Observatory.

ABSTRACT

The Timing Group Delay (TGD) is the bias difference between each GPS satellites P-code transmissions at the L1 and L2 frequencies. They are broadcast in the GPS navigation message so that single-frequency users can use them in conjunction with ionosphere delay estimates, such as the Klobuchar ionosphere model, to improve their position determination and to better derive UTC(USNO), which is the U.S. Naval Observatory's realization of Coordinated Universal Time (UTC).

There are at most a few nanoseconds of bias in the TGDs with respect to the official GPS monitor receivers maintained at the USNO. These are within the calibration uncertainties. This paper analyzes the problem, and outlines an approach to a solution.

INTRODUCTION

It is generally recognized that the ionosphere is one of GPS's largest error sources. Because the ionosphere delay is frequency-dependent, GPS Precise Positioning Service (PPS) receivers observe the encrypted P(Y) code on both the L1 and L2 frequencies. The L1-L2 timing difference is used to infer the line-of-site delay due to the ionosphere, subject to the bias difference between the satellite transmissions at the two frequencies. Geodetic receivers do not observe the P(Y) code directly, but by often-proprietary techniques can indirectly infer the L1-L2 differences, subject to the bias between the relevant satellite L1 and L2 transmissions. There are also complications related to the biases between the C/A and P-code transmissions, which are ignored in this work. Single-frequency users relying only on the C/A code are termed Standard Positioning Service (SPS) receivers, and they must use a different means of generating the ionosphere correction. These corrections are in general not subject to the L1/L2 bias. Figure 1 provides an overview of the TGDs as broadcast.

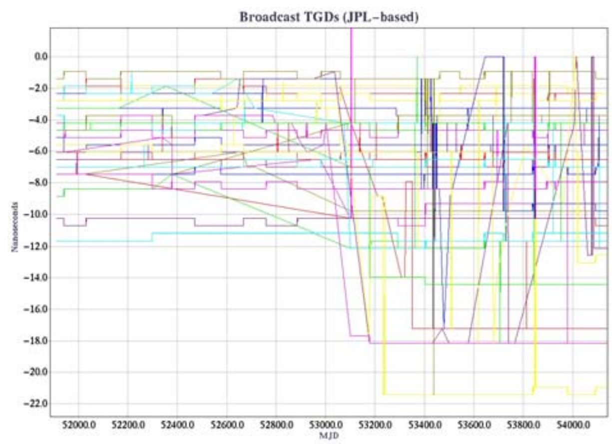

Figure 1. Overview figure of broadcast TGD for each satellite PRN, 1JAN01-11FEB07. Large changes are due to satellite replacement.

The broadcast values are quantized by .46 ns, and based upon data reductions provided by the Jet Propulsion Laboratory (JPL), which uses data from a subset of the receivers reporting to the International GNSS Service (IGS). The TGD corrections are automatically applied to the L1-based pseudorange data by the single-frequency receiver software before generating a position and time fit. The TGD corrections are required because it would be a needless complication for the GPS Master Control Station's Kalman Filter to correct for the L1-L2 biases before deriving the line-of-site ionosphere corrections for the GPS monitor data. It is simpler to let the bias corrections be absorbed into the constant offset in each satellite clock's time. Time is provided to the GPS composite clock by steering to UTC(USNO), and this adjustment also applies to each GPS satellite's realization of the GPS composite clock. So as to provide traceability to UTC via UTC(USNO), the USNO maintains an ensemble of time-monitoring and geodetic receivers, whose calibrations are measured and periodically updated [1,2]. The appropriate corrections for any single-frequency receiver to recover GPS Time and GPS's delivered prediction of UTC(USNO) would include the sum of the ionosphere delay plus the sum of any calibration differences relative to the USNO receivers, along with the TGD corrections. Table 1 summarizes this discussion.

Receiver	L1-L2	Apply TGDs?	Model Ionosphere	Correction Method
Dual Frequency	Measure (bias - corrupted)	No	No	Measurement (bias ignored, because cancels)
Single Frequency	------	Yes	Yes	TGD+Model

Table 1. Difference between single and dual frequency GPS receivers. Ionosphere data measurements include the TGD bias which must be added to the model ionosphere correction in SPS receiver software.

The USNO and JPL are attempting to coordinate the calibration, but the situation is complicated by the 2.5-ns uncertainty of absolute calibrations at each frequency [1,2] and fact that the L1-L2 biases, as observed by the user, depend on the receiver and on the correlator spacing, in convolution with frequency-dependent delays of the filters and other components of the receiver system. These system-dependent effects were recently explored by Hegarty et al. [3], and in this paper we shall borrow extensively from their analysis.

CALIBRATION ISSUES

A completely calibrated dual-frequency receiver system can be used to verify the TGD corrections by fitting to the line-of-sight ionosphere delays measured by the two frequencies. The fit parameters would at a minimum include the TGD value for each satellite, plus the total electron content in the zenith direction (TEC) multiplied by a mapping function that relates the ionosphere path length in the line of site to that in the zenith direction. For an ensemble of N receivers, N-1 receiver-dependent calibration terms could be employed. The issue of overall calibration is often sidestepped by constraining the satellite TGDs so they sum to zero.

A TGD-fit using data taken with the operational GPS time monitor receiver at the USNO, shown in Figure 2, when compared to Figure 1, indicates that the ensemble of receivers used by JPL has a small calibration difference with respect to the USNO monitor receiver calibrations. This difference appears when the TGDs and ionosphere corrections are applied to GPS Time, but it is cancelled in time transfer involving differences between two single-frequency receivers. When corrected with the broadcast TGD values, the USNO's single-frequency receivers show this bias relative to the dual-frequency receivers, even when consistently calibrated at the L1 frequency.

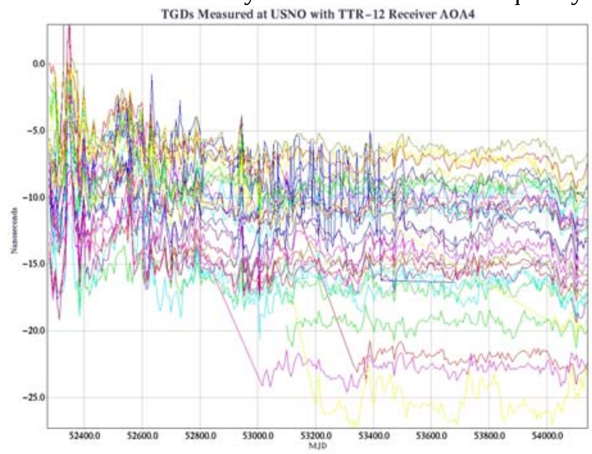

Figure 2. TGDs inferred from USNO monitor data from July 9, 2002 through February 9, 2007. The average value is about 6 ns less than in Figure 1.

Observations of the satellite L1-L2 biases reported by the Center for Orbit Determination in Europe (CODE) are also of interest. These are computed as monthly averages, and in this paper are scaled by a factor of -1.54 so as to be numerically equivalent to the ionosphere correction at the L1 frequency. We refer to them as CODE-measured TGDs. Receiver calibration is not relevant to first order, because the TGDs are normalized so that their average bias is zero [4]. Figure 3 compares the TGDs as inferred from CODE bias measurements with JPL-measured (PS-broadcast) values on November, 2005, and Figure 4 shows the long-term monthly average CODE-measured TGDs for all satellites.

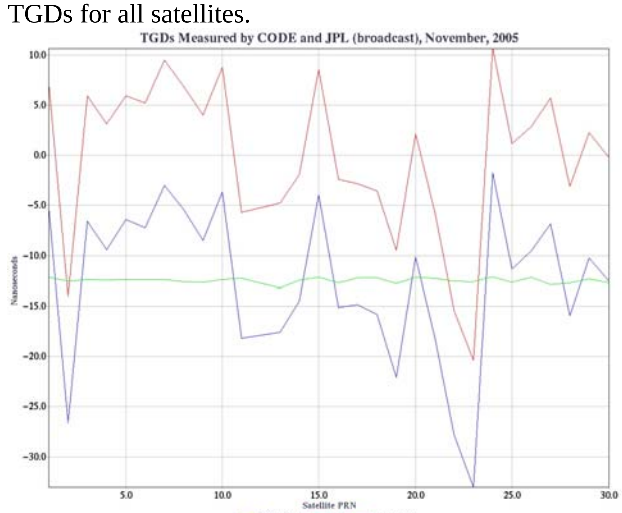

Figure 3. For each satellite, theTGDs as measured by JPL and CODE, and JPL-CODE. GPS TGD broadcasts are periodically updated using the JPL measurements. CODE biases are normalized to 0.

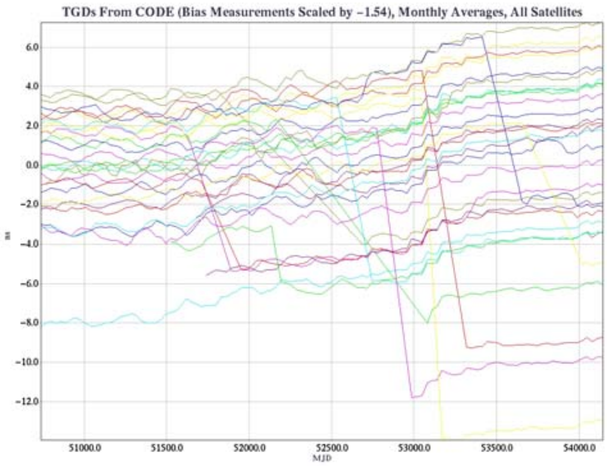

Figure 4. TGD monthly averages s reported by CODE, OCT97-FEB07. We have chosen to retain the CODE sign-convention, which in their format is opposite to that of the broadcast TGDs. Because CODE sets the average TGD to zero, an individual satellite's replacement by one with a lower TGD would raise the reported TGD of all other satellites.

Observations at any one laboratory must be used with care, because it is well known that GPS receivers can exhibit spontaneous frequency-dependent calibration changes, which could either be sudden or long-term[5]. In order to remove the first-order effects of these variations, the GPS satellite constellation is shown relative to a single satellite, SV4, in Figures 5-7. The TGD differences should be independent of overall receiver calibration variations, and such analyses could be used to quantify the variability of the satellite TGDs.

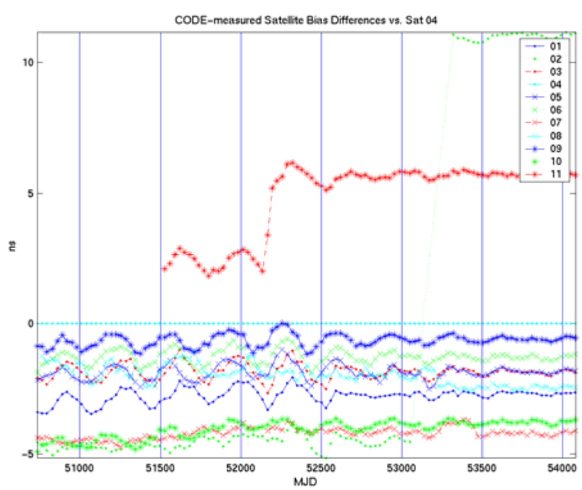

Figure 5. CODE-reported TGDs of GPS satellites 1-11 differenced with the TGD of Satellite 4.

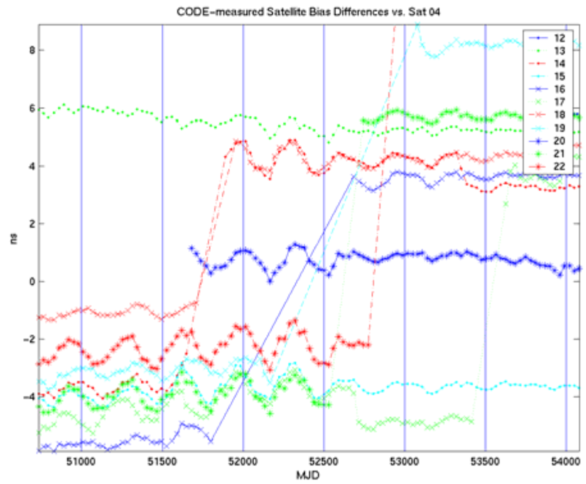

Figure 6. CODE-reported TGD of GPS satellites 12-22 differenced with TGD of Satellite 4. The author has not investigated the cause of the apparent oscillations in the first half of the data, and notes that several explanations are plausible.

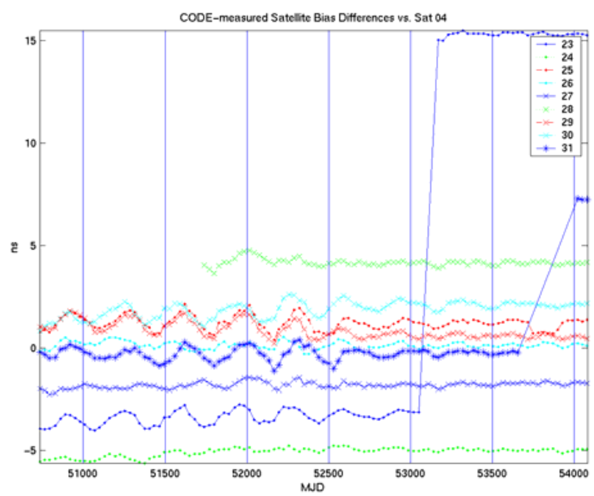

Figure 7. CODE-reported TGD of GPS satellites 23-31 differenced with the TGD of Satellite 4.

The calibration mismatch shown in Figures 1 and 2 is reflected in the Circular T, which is published by the International Bureau of Weights and Measures (BIPM). The Circular T provides the difference between UTC and GPS Time, along with the difference between UTC and its realization at contributing laboratories, such as the USNO (Figure 8). The BIPM's estimate of UTC-GPS is based upon a dual-frequency GPS carrier-phase receiver located at the Observatory of Paris (OP), whose data were corrected using broadcast TGDs and IGS orbit and clock products. Note that the difference between the USNO's measurement of UTC(USNO)-GPS and that reported in the Circular T was greatly reduced on MJD 54045 (November 6, 2006); this was coincident with some changes made by the IGS in their data processing procedures. An additional bias change occurred when the USNO adjusted its PPS GPS receiver's calibration by approximately 2 ns on MJD 54069 (November 30, 2006).

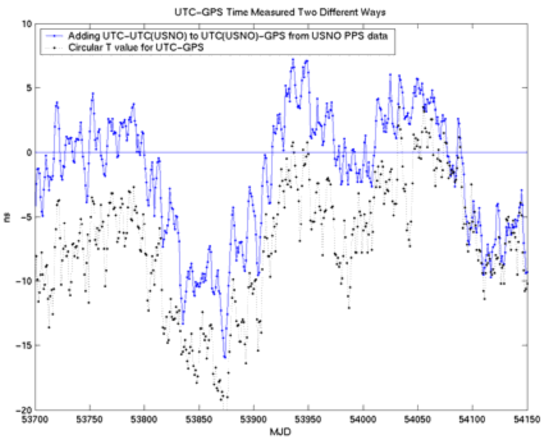

Figure 8. Circular T data showing UTC(USNO)-GPS as reported in the Circular T and as inferred by direct measurements at the USNO, from 26NOV05 to 28FEB07. IGS procedures were changed on MJD 54045, and data from MJD 54045-54099 were adjusted as specified in Circular T 229.

Although the GPS data reported in the Circular T are extracted from the GPS receiver at the OP, that receiver's biases would be irrelevant if the link from OP to the other laboratories were through the same GPS receiver. This is because any bias in that receiver's processed data would be cancelled in the double differencing between GPS-UTC(OP) and UTC-UTC(OP). If all links used in TAI were computed with GPS, the Circular-T derived bias would reflect the difference between the TGD-corrected, and otherwise corrected, data from the operational SPS receiver at the USNO and the data from the dual-frequency PPS receiver at the USNO which is used for steering GPS Time [6]. However, when the USNO and/or OP are linked to TAI entirely via Two Way Satellite Time and Frequency Transfer (TWSTFT) to the PTB, then the relevant biases are a subset of the biases of the USNO-PTB and OP-PTB TWSTFT links, and the biases of the GPS receiver at the OP (particularly if GPS links are by All-in-View instead of Common-View [7]). Under the current configuration wherein TWSTFT is used for both of the PTB links, the relevant bias is between the sum of the PTB-USNO and the PTB-OP TWSTFT links and the All-in-View difference between the USNO dual-frequency PPS receiver data and the as-corrected data from the OP GPS receiver. When TWSTFT was used for only the USNO-PTB link, the relevant bias was between the USNO-PTB TWSTFT link and All-in-View link between the PTB's GPS receiver and the USNO dual-frequency PPS receiver. No matter what configuration of links is used by the BIPM, any bias between the calibration implied by the broadcast TGDs and the calibration of the USNO's GPS monitor receivers would have an effect.

RECEIVER-SATELLITE EFFECTS

Along with the overall biases discussed above, biases could be associated with each combination of receiver configuration and satellite. Figure 9 suggests that the difference between the CODE and herein reported USNO TGD measures are a function of the satellite. All other satellites fall within the extremes shown in the figure. We speculate that this supports a minor extension of the analysis of Hegarty et al. [3], by implying that the TGD biases are a function of both satellite and receiver. This hypothesis could be verified by TGD-fits to data from individual receivers of different makes, or from direct measurements with GPS simulators.

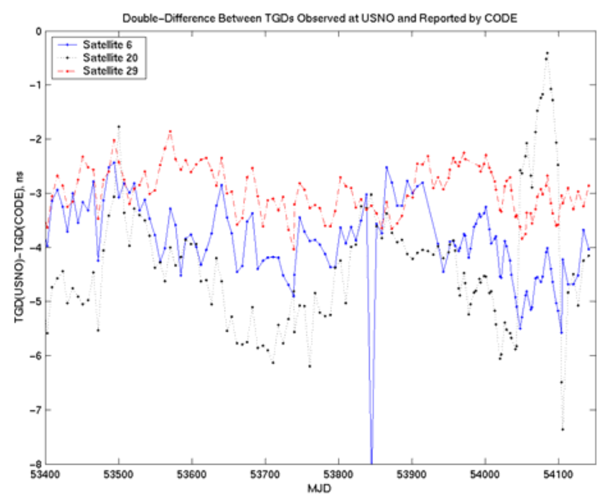

Figure 9. Double-difference between TGDs as measured by the primary USNO PPS receiver and those reported by CODE, for three satellites. CODE-reported biases were scaled by -1.54 so as to be TGD-measurements.

Hegarty et al. [3] considered the effect of frequency-dependent delays upon GPS timing measurements. Figure 10, taken from their figure 2, shows the spectral decomposition of a C/A code signal superimposed upon a typical receiver filter.

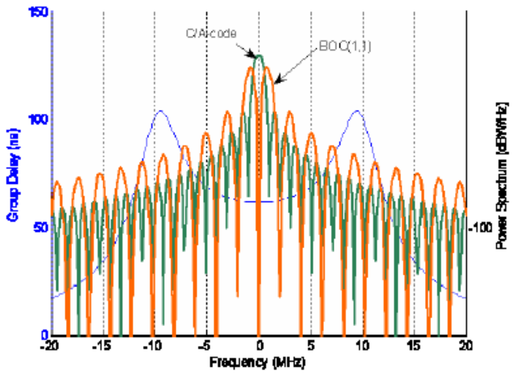

Figure 2. Example Group Delay Response for the RF/IF Filtering within a GPS-Galileo Receiver and Power Spectra of the GPS L1 C/A-code Signal and BOC (1,1) Modulation Planned for the Galileo L1 OS Signal.

Figure 10. Spectral dependence of filtering within a GNSS receiver superimposed upon broadcast signal spectra. This is also figure 2 of Hegarty et al.

Hegarty et al. noted that user receiver systems frequently can have a delay variation of up to 150 ns across the signal passband. The authors simulated a typical spread-spectrum GPS signal to study the effect of such delay variations. This can be understood as decomposing the signal into its Fourier components, applying the filter-related delay pattern shown in Figure 10, Fourier-transforming the signal back into its time-domain representation, and simulating the inferred time delay in an early-late correlator. They observed unequal changes in the group and phase delay which lead to ns-level receiver-dependent biases. The observed effect may result from GPS satellite signals having different frequency-dependent delays or amplitudes in their passbands, which will convolute with the receiver system electronics in a non-linear fashion. Different ensembles of receivers will then observe the satellite change differently.

EXPECTATIONS FOR THE FUTURE

While the problem of receiver-satellite combination effects will remain, the first-order effects of the TGD biases should eventually be minimized in the future because GPS satellites are now being launched with unencrypted L2C code, which provides L2-based timing information to all worldwide. Later generations of GPS satellites will have three universally accessible frequencies, and Galileo satellites will provide signals at two frequencies in its Open Service. Therefore, the generic problem of biases will be even more serious as the number of GNSS signals, and receiver types, continues to grow.

One solution to the TGD first-order problem would be to ensure that all GPS receivers are calibrated consistently with each other, and in particular with those that are used to monitor GPS. This requires greater attention to the details of absolute calibration, including the publishing and establishment of recommended procedures. The more general problem of biases between and within GPS and all other GNSS systems would best be approached by ensuring that all GNSS systems are consistently calibrated, with possibly different values for each combination of satellite signal, receiver type, antenna or external filter, and receiver correlator spacing. It is possible to do this through common-clock, short baseline time-transfer, although tables from manufacturers could prove useful.

SUMMARY

TGD biases exist at the several ns level, and have observable effects. These effects are understood, and can be minimized through consistent calibration practices. Following such practices will become increasingly important as the number of GNSS signals, and GNSS receiver types, increases.

ACKNOWLEDGMENTS

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