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ORIGINAL ARTICLE

A new type of troposphere zenith path delay product of the international GNSS service

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Abstract The International GNSS Service (IGS) has been producing the total troposphere zenith path delay (ZPD) product that is based on combined ZPD contributions from several IGS Analysis Centers (AC) since GPS week 890 in 1997. A new approach to the production of the IGS ZPD has been proposed that replaces the direct combination of diverse ZPD products with point positioning estimates using the IGS Combined Final orbit and clock products. The new product was formally adopted in 2007 after several years of concurrent production with the legacy product. We describe here the advantages of the new approach for the IGS ZPD product, which enhance the value of the new ZPD product for climate studies. We also address the impact the IGS adoption in November 2006 of new GPS antenna phase center standards has had on the new ZPD product. Finally we describe plans to further enhance the ZPD products.

Keywords Zenith path delay · ZPD · IGS · Troposphere · GPS antenna phase map · Analysis centers (ACs)

1 Introduction

Spatially well-distributed and continuous measurements of atmospheric water vapor contents are of great interest for numerical weather forecast, climate research, and atmospheric studies. These can be accurately derived from GPS-based estimates of zenith path delay (ZPD) at a ground GPS tracking site, using ancillary measurements of pressure and temperature (Bevis et al. 1992; Rocken et al. 1995; Ware et al. 1997; Bar-Sever et al. 1998). The high spatial and temporal resolution afforded by the vast and ever growing network of GPS tracking sites, and by the continuous nature of the GPS measurements renders the GPS-based estimates of ZPD highly valuable for the above-mentioned disciplines.

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1.1 Legacy products

In 1997 the International GNSS (Global Navigation Satellite System) Service (IGS) started the production of ZPD estimates by combining the contributions of ZPD estimates from several IGS Analysis Centers (ACs). The ACs' ZPD estimates were derived in the course of their routine GPS orbit determination process, which is based on data from a subset of the IGS ground tracking network. However, the ZPD estimation process is highly inconsistent among the ACs, each using different set of ground stations, temporal resolution, elevation angle cutoff, a priori values, and tropospheric mapping functions, to name just a few variants. Therefore, the 'legacy' combination product was restricted to a small (and changing) subset of sites commonly used by several ACs, highly variable in quality, and not conducive to rigorous formal error analysis. Most importantly, the legacy combination was highly suspect for climate studies as it could not guarantee consistent input over time: the ACs ZPD contributions for a given site would vary with changes to the orbit determination process at that ACs, and the mix of AC contributions in the combined product varied from week to week.

There were two types of legacy combined ZPD products: a 'Final' product, with several weeks latency, based on the processing of the Final orbit and clock products at the contributing ACs, and 'Ultra-Rapid' product, with 5–6 h latency relative to the latest measurement, based on the Ultra-Rapid orbit and clock products at the contributing AC. The former was targeted for climate studies, and the latter for weather forecasting. While suffering from the same deficiencies as the Final combined product, the legacy Ultra-Rapid product was too late to contribute to weather forecasting, which typically requires less than 3 h latency, and too unreliable for operational applications.

1.2 The new ZPD product

A new type of ZPD product that offers significant quality and operational advantages was proposed in early 2003 in response to the deficiencies in the IGS legacy ZPD products. The new product is completely independent of individual contributions of ZPD by the ACs. Instead, ZPD values are directly estimated from raw GPS range measurements employing a precise point positioning (PPP) approach (Zumberge et al. 1997), and using the IGS Combined Final orbit and clock product—the flagship IGS product, which is consistently of excellent quality. This new approach enables accurate and reliable generation of ZPD time series for practically all available IGS sites with minimal additional latency, while controlling modeling consistency over time. These are key attributes in increasing the utility of the products to weather modelers, climatologists, and GPS analysts. The new approach is particularly amenable to massive reprocessing in order to establish refined, temporally consistent time series of ZPD, as required for climate studies. This is necessary whenever processing standards evolve and change, for example, upon the introduction of improved tropospheric mapping function.

The key features of the new processing approach for the IGS ZPD product as currently carried out operationally at the JPL Analysis Center since September 2003 are:

- Software: GIPSY
- Fixed orbits and clocks: IGS Final Combined
- Earth orientation: IGS Final Combined
- Transmit antenna phase center map: IGS Convention
- Receiver antenna phase center map: IGS Convention
- Elevation angle cutoff: 7°
- Mapping function (hydrostatic and wet): Niell (1996)
- A priori: Hydrostatic delay based on altitude (2.3 m at sea level), and 0.1 m for the wet delay
- Data time span: 24 h
- Data rate: 5 min
- Estimated parameters: clock (white noise), station position (constant), wet zenith delay (random walk with variance of 3 cm/h), atmospheric gradients (random walk with variance of 0.3 cm/h), phase biases (white noise) (Bar-Sever et al. 1998)
- Temporal resolution of zenith delay estimates: 5 min

The ZPD estimates derived in this process constitute the new IGS tropospheric product. The process produces a file per site per day. Each file contains a time series of total zenith tropospheric delays with temporal resolution of 5 min (the legacy product had a temporal resolution of 2 h). The file format is nearly unchanged. Since the files are produced daily instead of weekly, the file name convention was changed from sssswwww.zpd to ssssddd0.yyzpd (ssss is 4 letter IGS station id, wwww is GPS week number, ddd is day of year, and yy is year in two digits). Only the 'Final' products, derived from the IGS Final combined GPS orbit and clock solutions are produced. These are currently available at:
ftp://cddis.gsfc.nasa.gov/pub/gps/products/trop_new

In an effort to create a long and consistent time series of tropospheric delay values, back-processing was carried out through October 2000 (prior to this date the IGS did not produce a Combined clock solution). As an additional service to IGS ACs, the ZPD solutions submitted by the ACs are compared to the new IGS product on a regular basis. The resulting comparisons are available at:
ftp://cddis.gsfc.nasa.gov/pub/gps/products/trop_cmp

The naming convention for these files are TROPddd0.yycmp (ddd is day of year, and yy is year in two digits). The internal file format of the legacy product is largely kept here as well. The new ZPD comparison files are available from September 26, 2004.

As an additional service to the contributing ACs, summaries of the inter-comparisons are provided on a weekly basis as both text files and graphics at:
ftp://cddis.gsfc.nasa.gov/pub/gps/products/trop_rpt

The naming convention for these files are TROPwwwwx.rpt and TROPwwwwx.eps, (wwww is GPS week number).

All the ZPD products are available within one day after the relevant IGS orbit and clock products are available.

1.3 Changes in IGS standards

On November 5, 2006 the IGS switched the reference frame for site positions from ITRF2000 to ITRF2005, and implemented new standards for GPS data modeling that included a specific set of antenna phase center variation (PCV) maps for all the GPS satellite transmit antennas, and for most of the ground antennas (Schmid et al. 2007). Prior to that only the phase center offsets of the GPS satellite transmit antennas were standardized, and ACs used a plurality of phase center maps for the ground antennas modeling, including use of no phase maps at all. Complying with the new standard, the new IGS ZPD product has been generated using both receiver and transmitter antenna phase maps since November 2006. Prior to that the new IGS ZPD product was generated without phase maps for ground antennas or for the GPS satellite antennas, and only modeling the conventional phase center offset values for the ground and satellite antennas.

Below we study the effects of the change in modeling standards on the ZPD products. Relative biases induced by this transition are evident in the time series of the new IGS ZPD products as discussed later, and their removal awaits the reprocessing of the IGS Combined Final orbit and clock products. Once this reprocessing is complete, a consistent ZPD time series can be generated within days.

2 Quality assessment

We start by comparing the new and legacy ZPD products side-by-side during a period in which both were generated. We then focus on the later transition to the new processing standard in an effort to assess the impact of this transition on the IGS ZPD product.

2.1 Comparison of the new and legacy product

We have selected a subset of 30 globally distributed sites as shown in Fig. 1 to illustrate the qualitative differences between legacy ZPD products and the new product. (Other than ensuring broad distribution and completeness of available data the sites were selected randomly). Figures 2 and 3 contrast the formal error of the legacy and new ZPD products in 2003.

The formal error for the legacy product was derived from the standard deviation of the AC-contributed values, and is highly dependent on the number of ACs submitting ZPD for a given site. Zero formal error indicates sites-days for which not enough ACs contributed solutions. The formal error for the new product is produced by the estimation process employed by the PPP approach, and is largely dependent on the amount and distribution of carrier phase measurements for any given site. Note that this formal error does not account for systematic errors in the GPS orbit and clock product, and is therefore underestimating the actual error. Overall, the formal errors of the new process are far more uniform across sites. Figure 4 depicts the RMS differences in ZPD values between the legacy and new products for each site over the year 2003. Only legacy solutions with non-zero formal errors were used in the difference. The RMS difference is largely consistent with the inherent uncertainties of the two ZPD products as expressed by their formal errors.

The new IGS ZPD product is produced for all available IGS sites for every day for which RINEX files exist at any of the IGS data centers. Thorough search of the IGS data centers CDDIS, IGN, and SIO retrieves more than 300 RINEX files per day. Figure 5 depicts the number of sites for

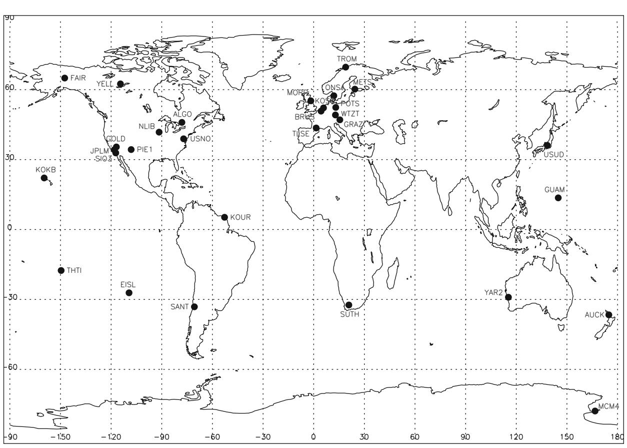

Fig. 1 The subset of global IGS stations used for comparing the new and legacy ZPD

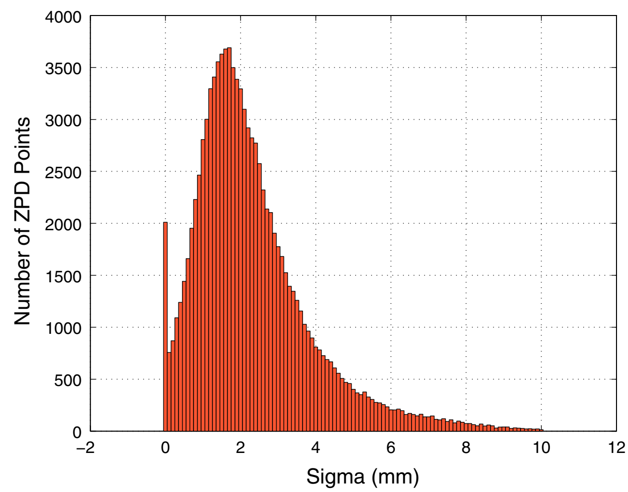

Fig. 2 Histogram of the formal errors reported for the legacy combined final troposphere solutions. The histogram was generated using 30 site solutions for year 2003. Zero sigma is reported when only one AC contributed a solution for a given site

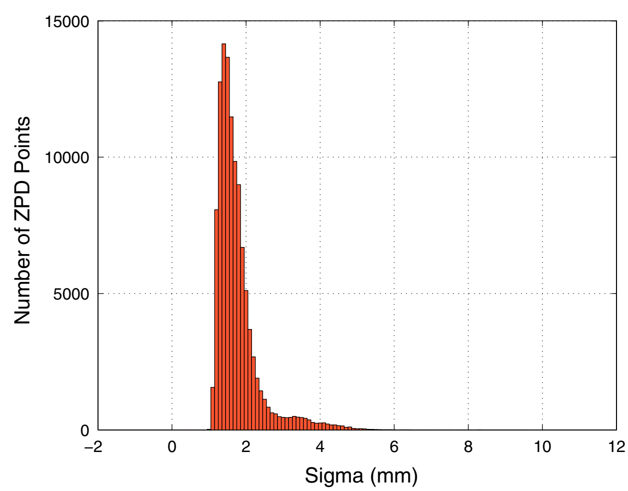

Fig. 3 Histogram of the formal errors reported for the new Final troposphere product. The histogram was generated from daily precise point positioning for a set of 30 globally distributed sited for year 2003

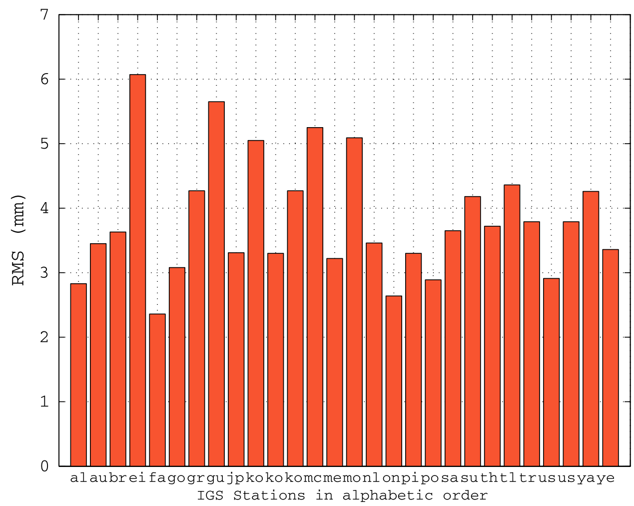

Fig. 4 The RMS of ZPD differences between the new and legacy strategies for each site selected for the comparison. x-axis denotes the station list in alphabetic order; y-axis denotes the RMS of the ZPD differences in mm

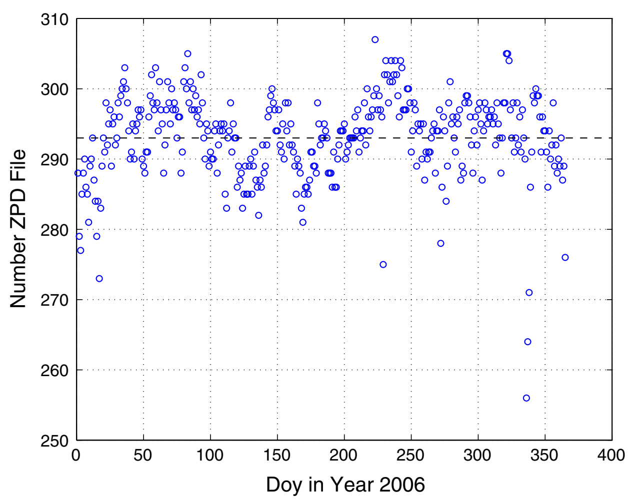

Fig. 5 The number of IGS troposphere ZPD files for each day in year 2006

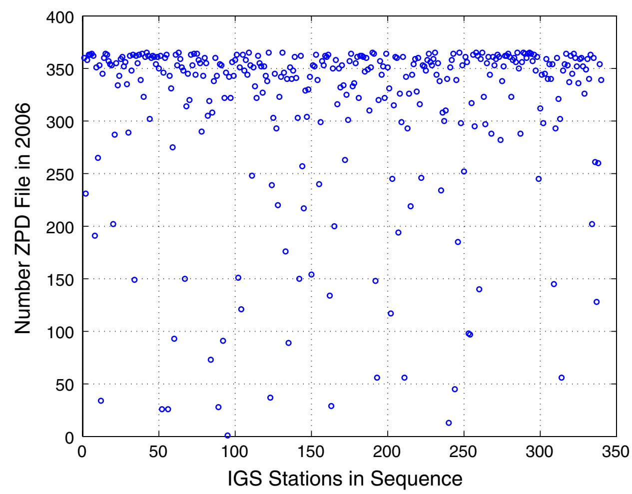

Fig. 6 The number of IGS troposphere ZPD files for each IGS ground station in year 2006

Table 1 The internal quality metrics comparison of the IGS ZPD product generated by using IGS Final orbit and clock

	No-PCV	PCV
Post-fit res.	8.55	8.59
ZPD discon.	8.59	8.74
Sta. Rept. E	3.68	4.29
Sta. Rept. N	2.79	2.73
Sta. Rept. V	6.97	7.38

The numbers are derived from all available stations during two distinct 1-year periods. The no-PCV modeling was employed in the year leading to November 5, 2006, and the PCV modeling was employed in the year following November 5, 2006. All units are in mm

which ZPD estimates were produced for each day in 2006. The fluctuations in the number of ZPD files are strictly due to fluctuations in the availability of RINEX files from the sites in the IGS Data Centers. Figure 6 depicts the availability of daily ZPD files from each site in the year 2006.

This constitutes a significant improvement in ZPD coverage over the legacy product which only provided about 180 stations per day by counting the products generated with non-zero formal errors (two or more ACs contributing).

2.2 Impact of changes in IGS modeling standards

Some aspects of the IGS ZPD product prior to the introduction of the new antenna PCV standards in November 2006 were described in (Byun et al. 2005; Byun and Bar-Sever 2006). In this section we revisit some of the key quality metrics with more recent data, and focus on ZPD quality changes that may have been induced by the introduction of IGS GPS antenna phase map and the switch to ITRF2005 reference frame. We do that by inspecting internal quality metrics with and without antenna PCV maps, such as the post-fit residual values of the ionospheric-free carrier phase measurements (LC); the apparent discontinuities in ZPD value across day boundaries (ignoring the 15-min gap at day boundaries caused by the 15-min temporal resolution of the IGS orbit product); and the site position repeatabilities after removing a secular trend. These metrics can be indicators for the relative quality of the ZPD product with different estimation strategies with different orbit and clock inputs.

Surprisingly, these quality metrics exhibit slight degradation when we look at 2 years of data spanning the transition date of November 5, 2006 (with one full year of no PCV modeling just before the transition, and one full year of PCV modeling just after the transition) as shown in Table 1. Because the no-PCV modeling period and the PCV modeling period

Table 2 The internal quality metrics comparison of ZPD product generated by using two different JPL Final orbit and clock product as input

	No-PCV	PCV
Post-fit res.	8.33	7.73
ZPD discon.	7.09	6.83
Sta. Rept. E	2.86	2.75
Sta. Rept. N	1.98	1.91
Sta. Rept. V	6.08	5.84

The numbers are derived from all available stations during the same 6-month period from November 11, 2007 to May 03, 2008. All units are in mm

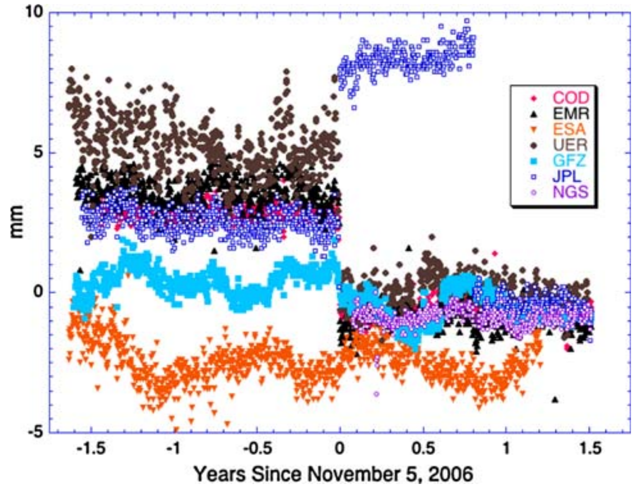

Fig. 7 The daily bias between ZPD product produced by each AC and the IGS ZPD product. For each day the bias is averaged over all sites and epochs

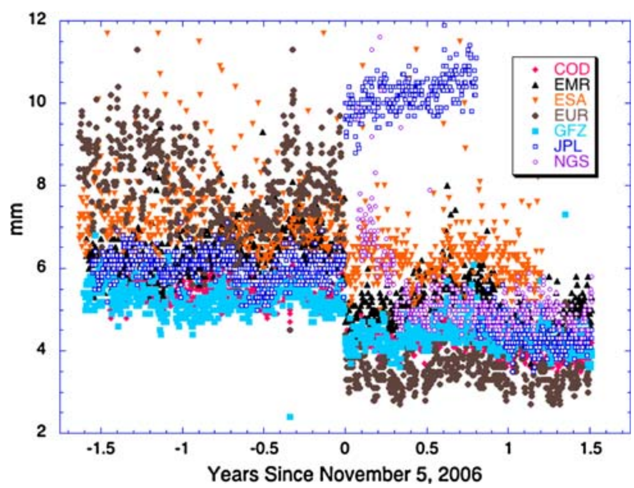

Fig. 8 The daily standard deviation for the ZPD product from each AC relative to the IGS ZPD product. For each day the standard deviation is computed from all sites epochs

in this comparison are not coincident, one cannot conclude that the introduction of PCV degrades the quality of PPP solutions. In fact, this is in contradiction to common experience at JPL and elsewhere with co-temporal comparison of PCV-based and non-PCV-based products. The JPL's orbit and clock product generated with the IGS antenna PCV maps is submitted to the IGS for Final combination, and the solution generated with only IGS antenna offset values is used internally to facilitate continuity in geodetic analysis. When the two JPL orbit and clock products are compared, we observe clear benefits from employing the IGS PCV models as shown in Table 2. Some of the improvements can be considered significant. For example, the post-fit residual noise was reduced by 3 mm in quadrature. This comparison was performed by using all available IGS sites (nearly 300) during 6 months, from November 11, 2007 to May 03, 2008. Note that JPL started producing PCV-based orbit and clock products only in August 2007 (The artifact of this late compliance are evident in Figs. 7 and 8).

We conclude that the IGS PCV maps do appreciably improve the key metrics of the PPP solutions when used with the JPL orbit and clock products. Since we trust the PCV modeling in GIPSY we suspect that the input to the IGS ZPD product, namely, the IGS combined orbit and clock product, may be the reason for the degradation in the internal quality metrics of the PPP process. This hypothesis is examined further in Sect. 2.3.

Since the same software, GIPSY, is used to generate the JPL orbit and clock products and to generate the IGS ZPD product, it is necessary at this point to address the question of the so-called 'software bias', namely, the potential tendency of a given software to perform better with its own products. While we cannot completely discount the presence of software bias in this case, we note that there is no evidence of it in the inter comparison of ZPD estimates from the ACs. Figures 7 and 8 show the bias and standard deviation of each AC and the IGS ZPD product from August 2007. As can be seen in these figures the JPL contributions do not exhibit the lowest bias or the lowest standard deviation relative to the GIPSY-generated IGS ZPD product.

2.3 IGS GPS clock product

In an effort to further investigate the root cause for the slightly worse performance (in terms of our key PPP quality metrics) of the IGS Combined orbit and clock products relative to the JPL orbit and clock products, we examined the IGS Final Combined clock product, and noticed that it had deteriorated, in some aspects, since November 2006.

For example, we note that the number of days for which a GPS satellite was present in the orbit product but for which no clock was available jumped from 28 days in the year before November 6, 2006 to 115 in the year following November 5,

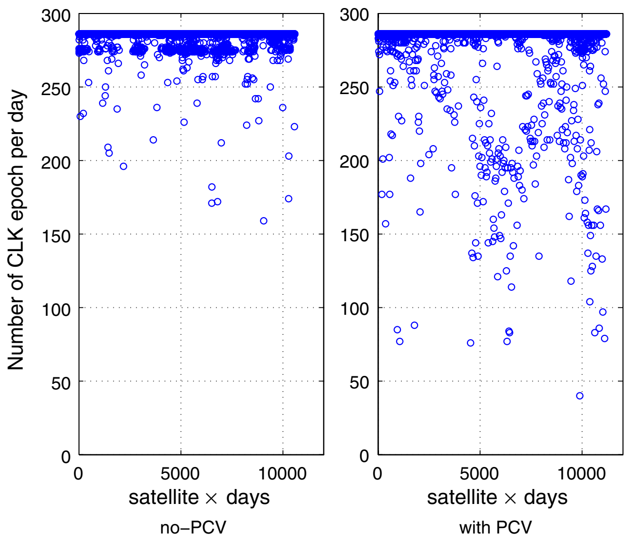

Fig. 9 The number of clock epochs in the IGS clock files for each satellite, during 1 year before November 2006 (no-PCV) and 1 year after November 2006 (with PCV). The x-axis denotes the satellite × day ordinal number during the 1 year time span ($365 \times 30 \approx 11000$); Note the significantly increase in number of missing epochs after the transition to PCV modeling

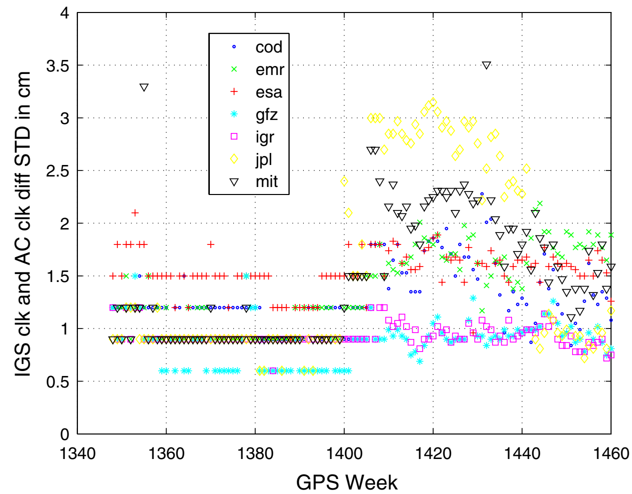

Fig. 10 The standard deviation value of difference between IGS combined clock solution and each AC's clock solution are extracted from IGS summary files from GPS week 1348 to 1460. This period spans 2 years with GPS week 1400 at the center. The x-axis denote the time in GPS week and the y-axis denote the standard deviation of clock difference in cm

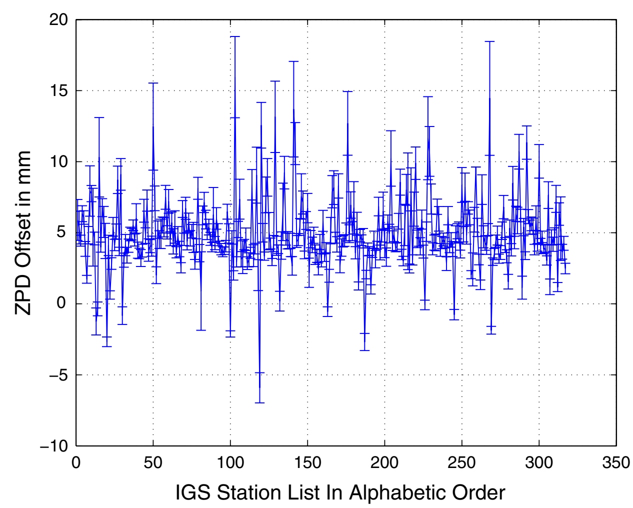

Fig. 11 The ZPD values from PCV case were subtracted from those of no-PCV case at matching time tags, and the daily mean values of ZPD differences are computed for each IGS ground station. Then, the mean and sigma of daily mean differences are computed for the period from November 11, 2007 to May 03, 2008. The x-axis denote the IGS ground stations in alphabetic order. The y-axis denote the mean and sigma value of the daily mean differences. A consistent bias between the two cases can be easily noted from this figure

2006. Similar degradation can be observed in the number of epochs per satellite per day for which a clock solution is available. Optimally, the IGS clock file contains the clock corrections for each GPS SVN every 5 min, thus 288 epochs per day. If the number of clock epochs is less than 288 it implies that clock solutions are unavailable at some epochs. Figure 9, illustrates the significant increase in missing clock epochs after November 2006.

We have also examined the clock differences between the IGS combined clock and each AC's submitted clock solution by looking at IGS summary files from 2 years spanning GPS week 1400. As shown in Fig. 10 the clock solutions submitted by ACs show increased variance relative to the IGS combined clock. Nearly coincident to the transition to the new standard, the IGS has also changed its clock combination strategy incorporating high rate clock submissions from some ACs into the combination. This may have been a factor in causing the observed symptoms.

2.4 The ZPD bias due to the IGS processing change

Due to the correlation between PCVs, vertical position, and ZPD, it is expected that the November 2006 switch to new PCV standard has induced a systematic bias in the estimated ZPD value. This is also strongly indicated in Fig. 7. To quantify this bias we have again used the co-temporal JPL orbit/clock products produced with and without antenna PCV maps. We computed the daily mean difference in ZPD values for each ground station during the 6-month period from November 11, 2007 to May 03, 2008.

Figure 11 shows the daily mean differences in ZPD values between the no-PCV and PCV cases, together with the formal errors; 5–7 mm bias is evident for nearly all sites. This large bias must be addressed before long time series of the IGS ZPD product can be used in climate studies. We await the completion of the back-processing of the IGS orbit and clock products so that we can reprocess the ZPD values and provide a long and continuous time series of ZPD values. Luckily, the new ZPD production process is amenable to rapid reprocessing.

3 Discussion

The motivation and many advantages of the new approach in generating the new IGS troposphere ZPD product have been presented. The key advantages include the ability to generate ZPD products for all available IGS stations, improved temporal consistency of the ZPD time series, and greater agility in implementing new modeling standard and regenerating long and consistent time series of ZPD values.

The new ZPD product is shown to possess typical formal errors of 1.5–5 mm. Actual error are higher, due to systematic error in the GPS orbit and clock products.

We have found that the implementation of new IGS processing standards in November 2006 (primarily new transmitter and receiver antenna PCV maps) have led to a much higher agreement between the ACs ZPD products significantly reducing the relative bias and standard deviation. However, the IGS combined final clock product seem to have degraded in some aspects after the November 05, 2006 transition to the new IGS processing standard, potentially degrading some quality metrics of PPP solutions with the IGS combined final orbit and clock products, such as post-fit LC residuals, suggesting an increased level of noise. However, noticeable improvement due to the new PCV maps was evident with orbit and clock products from the JPL. We speculate that the root cause of this behavior is an increased level of incompatibility between the IGS orbit and clock products.

Planned future improvements to the IGS ZPD product include using tropospheric mapping functions that are based on information from numerical weather models (Boehm and Schuh 2004; Niell 2001), using weather models to derive better a priori value of the hydrostatic delay, and using 30 h arcs to reduce day boundary effects.

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