Higher order ionospheric effects on the GPS reference frame and velocities

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Abstract: We describe how Global Positioning System (GPS) time series are influenced by higher order ionospheric effects over the last solar cycle (1995-2008) and examine implications for geophysical studies. Using fourteen years of globally reprocessed solutions, we demonstrate the effect on the reference frame. Including second and third order ionospheric terms causes up to 10 mm difference in the smoothed transformation to the International Terrestrial Reference Frame (ITRF) 2005, with the Z-translation term dominant. Scale is also slightly affected, with a change of up to ~0.05ppb. After transformation to ITRF2005, residual effects on vertical site velocities are as high as 0.34 mm a^{-1}. We assess the effect of the magnetic field model on the second order term and find a time varying difference of 0-2 mm in the Z-translation. We also assess the effect of omitting the third order term. We find that while the second order term is responsible for almost all the Z-translation effect, it is the combination of the second and third order terms that causes the effect on scale. Comparison of our GPS reprocessing with ITRF2005 suggests that GPS origin rates may vary with time period. For example, we find Z-translation rates of -0.76 ±0.17 mm/a (1995-2008) and 0.23 ±0.25 mm/a (1995-2005). If GPS were to contribute to origin rate definition for future ITRFs, higher order ionospheric corrections would need to be applied due to their effect on translation parameters during solar maximum.

1 Introduction

Coordinate time series from GPS are now routinely used to study geophysical signals such as tectonic movement, seasonal loading, glacial isostatic adjustment and vertical displacements at tide gauges [e.g. *Calais et al.*, 2005; *Blewitt et al.*, 2001; *Milne et al.*, 2001; *Wöppelmann et al.*, 2007]. The accuracy of these coordinates, and velocities derived from them, is affected by both the GPS measurement accuracy and the accuracy of the reference frame that the coordinates are realized in. As the magnitude of the higher order ionospheric correction terms is linked to the ~11 year solar cycle [*Fritsche et al.*, 2005], neglect of these terms could potentially lead to spurious trends in coordinate time series over several years. There is uncertainty in realizing the Terrestrial Reference Frame origin as evidenced by the 1.8 mm a^{-1} drift along the Z-axis of ITRF2005 with respect to ITRF2000 [*Altamimi et al.*, 2007]. GPS observations are not yet used in the computation of the ITRF origin but could contribute if shown to be of sufficient accuracy. Long, homogenous, precise and accurate GPS time series [e.g., *Rülke et al.*, 2008] are therefore of substantial interest.

In this paper, we examine the effect of the higher order ionospheric terms on the GPS reference frame and site velocities over a full solar cycle using a series of consistently reprocessed GPS solutions (1995-2008 inclusive). We extend the work of *Fritsche et al.* [2005], which focused on the ionospheric maximum (2001-2003), and that of *Hernandez-Pajares et al.* [2007], which used 21 months of data during 2002-2003, in three important ways. Firstly, we examine the effects of the higher order terms on a much longer time series, covering an entire solar cycle (Figure 1). This allows us to assess the impact on site velocities for the first time and also to gain a more complete understanding of the effects on coordinates and reference frame parameters. Secondly, we examine the impact of different magnetic field models. The second order ionospheric term is strongly affected by the magnetic field. With the exception of *Hernandez-Pajares et al.* [2007] who used the International Geomagnetic Reference Field (IGRF) model, previous GPS studies considering site coordinate effects [*Kedar et al.*, 2003; *Fritsche et al.*, 2005] used a co-centric tilted dipole magnetic field model. As no study has looked at the change in site coordinates or GPS reference frame realization due to the difference in magnetic field model we also investigate the effects on site time series and transformation parameters of changing the model from the IGRF v.10 [*Maus and Macmillan*, 2005] to a tilted co-centric dipole. The percentage difference in magnetic field strength between the two models can be seen in Figure 2. Finally, we investigate the impact of the third order term, as while it has been modeled previously, no study to date has isolated its effect on the GPS reference frame.

Throughout, we model the 2nd and 3rd order ionospheric terms after *Fritsche et al.* [2005]. These terms arise when the otherwise complicated expression for the refractive index of the ionosphere is expanded as a series and simplified [see e.g. *Datta-Barua et al.*, 2006]. The first term in the series causes more than 99.9% of the ionospheric effect and is the term eliminated when forming the 'ionosphere-free' linear combination. The remaining terms are not eliminated by this combination. The second order term is affected by both ionospheric electron content and the geomagnetic field, while the third order term is not affected by the geomagnetic field and is much smaller in magnitude. Subsequent terms are negligible at GPS frequencies. Details of modeling the higher order ionospheric terms have been discussed elsewhere [see e.g., *Bassiri and Hajj*, 1993; *Fritsche et al.*, 2005], with an excellent summary of derivations in *Datta-Barua et al.* [2006]. The effects of differential bending of the GPS signals due to the ionosphere [*Hartmann and Leitinger*, 1984; *Brunner and Gu*, 1991; *Hoque and Jakowski*, 2008] have also been noted at the signal level. We agree that these effects should be further investigated in future. However, for this study, we focus on the effects of the second and third order ionospheric terms, following previous authors concerned with coordinate level effects [*Kedar et al.*, 2003; *Fritsche et al.*, 2005; *Hernandez-Pajares et al.*, 2007].

2 Methods and data

2.1 GPS processing

GPS data spanning 1995-2008 from the IGS [*Dow et al.*, 2005] were processed using the GAMIT v10.35 processing software [*Herring et al.*, 2006], modified to include the higher order ionospheric terms discussed here. Daily fiducial-free global networks were formed, consisting of approximately 60 sites out of a pool of 89 sites used in total. Sites were selected to obtain a reasonable hemispherical balance, with a mean of 44% of sites in the southern hemisphere during 1998-2008 (mean 32% for 1995-1997 due to poorer site availability). Where possible, ambiguities were fixed to integers. Satellite orbits and earth orientation parameters were adjusted alongside site coordinates and tropospheric zenith and horizontal gradient parameters. Ocean tide loading was modeled using FES2004 [*Lyard et al.*, 2006] and VMF1 troposphere mapping functions [*Boehm et al.*, 2006] and absolute antenna phase center offsets and variations [*Schmid et al.*, 2007] were used (igs05_1525.atx). Where available, RINEX meteorological files were used to provide pressure and temperature for the a priori zenith hydrostatic delay [*Tregoning and Herring*, 2006], otherwise values from VMF1 were used. Sub-daily atmospheric pressure loading displacements due to solar diurnal and semi-diurnal pressure tides were also modeled [*Tregoning and Watson*, 2009]. To reduce analysis time, only odd days during 1995-2008 were analyzed. The daily GAMIT solutions, generated with only loose constraints applied (e.g. 10m on coordinates), were then used in our subsequent analyses.

2.2 Higher order ionospheric corrections

Four processing runs were performed: one normal (N) run without higher order ionospheric corrections, two runs (IG, ID) both with second and third order corrections modeled and one run (IG2) with only the second order correction modeled. Runs IG and IG2 used the IGRF to model the magnetic field for the second order ionospheric correction, while run ID used a tilted co-centric magnetic dipole. A summary of differences between processing runs is provided in Table 1. To ensure consistency, outlier exclusion in transformation parameter estimation was based on run N and kept identical between the different processing runs.

The second and third order terms were coded into GAMIT at the observation level. The mathematical formulation of the terms was after *Fritsche et al.* [2005], but with the height of the thin ionospheric shell set to 450km and using vertical Total Electron Content (TEC) rather than slant TEC [*Hartmann and Leitinger*, 1984] for the estimation of peak electron density, N_{max}. Ionospheric data was obtained from IONEX files [see *Schaer*, 1999] made available by the Centre for Orbit Determination in Europe (CODE). Current IONEX files contain 13 maps per day but before day 87 1998 they contain one map per day. For run ID, the dipole field was modeled after *Bassiri and Hajj* [1993]. The dipole tilt was varied annually based on the geomagnetic pole values from CODE ION files. For runs N, IG, and IG2 data were processed from

1995 to 2008. For run ID data were processed from 1999 to 2008, as CODE ION files are available from 1999.

3 Results

3.1 Effect of higher order ionosphere modeling on transformation parameters

Seven parameter Helmert transformations were estimated from the daily GPS solutions to ITRF2005. A threshold of 3σ was used to exclude sites from the daily transformation estimation. The translation (TX,TY,TZ) and scale parameters are plotted in Figure 3a. Rates estimated from these parameters are given in Table 2. The rates were estimated together with annual and semi-annual components and outliers >0.2 m were excluded. The IG scale rate is within the uncertainty of the ITRF2005 scale rate (estimated at 0.08 ppb/a) [*Altamimi et al.*, 2007]). However, it appears that the translation rates are dependent on the time period sampled (Table 2). For comparison with previous reprocessed GPS results, the results of *Rülke et al.* [2008], using data between 1994 and 2005, are also shown in Table 2. Our results for a similar time period (1995-2005) are closer to ITRF2005 than those of *Rülke et al.* [2008], except for the TX rate. Our uncertainties are larger, possibly because we processed only every second day, used a much smaller set of stations and because our results are from daily solutions rather than the weekly solutions and alternative strategy of *Rülke et al.* [2008]. However, the time dependence shown by our translation rates once later data is included, while not related to the higher order ionospheric corrections, is worthy of future investigation.

The higher order ionospheric corrections affect the realization of the frame origin and in particular the Z-translation to ITRF2005 by up to ~30 mm dependent on ionospheric conditions. Performing 90 day Gaussian smoothing reveals the worst systematic effects during solar maximum are ~10 mm. The other translation parameters and scale show much smaller effects (see Figure 3b). The difference in the Z-translation was analyzed using the Lomb-Scargle method [see *Scargle*, 1982] applied as by *Press et al.* [1992] (see Figure 3d). There is an indication of the expected peak at ~11 years, though the data span is insufficient to define it. A peak was also found with a period of 58.4 days. Periodograms of TEC at different individual sites were performed, but no strong 58.4 day peaks were found. A double of the 27 day solar rotation cycle giving a 54 day period in electron density has previously been found [*Liang et al.*, 2008], but the 58.4 day peak is well defined. However, 58.4 days is approximately a sixth of the GPS orbital repeat period (~351.4 days, [*Ray et al.*, 2008]). As the GPS satellites are arranged in six orbital planes, it is possible that there is an effect on the loosely constrained solar radiation pressure parameters when the Sun is in a particular orientation with respect to one orbital plane (pers. comm., T. Herring, 2009). The solar radiation pressure parameters are known to be a sink for incorrectly modeled errors [*Ziebart*, 2004], so this would be a potential explanation for the 58.4 day peak.

3.2 Effects on transformation parameters of alternative models: influence of the magnetic field model and of the third order term

There is a time varying difference of 0-2 mm in the Z-translation (Figure 3c) between the frame using the IGRF to model the magnetic field for the second order ionospheric effect (IG) and that using a tilted dipole (ID). As the IGRF more closely represents the magnetic field of the Earth, we suggest that this equates to the ID frame being 0-2mm in error as compared to the IG frame.

To investigate the impact of the third order term, we compare the results from runs N, IG and IG2. Most of the Z-translation effect seen in Figure 3d can now be seen to come from the second order term (Figure 4a). There is a small time varying effect from the third order term of ~ 0-3mm. For the scale, however, the effect originates from both the second and third order terms (Figure 4b). The impact on the scale of modeling the third order term is limited to less than 0.05 ppb.

3.3 Effects on velocities and coordinates

We difference the site time series from runs N and IG and we estimate the velocity bias in the vertical component caused by higher order ionospheric effects to be in the range 0.0 to 0.29 mm a^{-1} over the period 1996-2000, while over the period 2001-2005 the bias is in the range -0.34 to 0.0 mm a^{-1} (Figure 5). The bias seen in the vertical velocities is entirely positive for the first period and negative for the second period. This corresponds to increasing ionospheric activity for the first period and decreasing activity during the second period. Although it should be noted that the formal errors of the velocity biases exceed their magnitude we suggest that the results do not support random scatter about zero. Full variance-covariance matrices were propagated and used in the velocity bias estimation. The largest effects appear in the equatorial regions, where the ionospheric electron content is highest. Examples of differenced equatorial site time series (IG-N) demonstrating effects on the north coordinate component are shown in Figure 6.

If the mean coordinate shifts (as opposed to rates) due to modeling the second and third order ionospheric terms are plotted for the three years of the last ionospheric maximum (2000-2002), a pattern of high latitude sites shifted north and equatorial sites shifted south is seen. The pattern is similar to that found in the study by *Hernandez-Pajares et al.* [2007] though not clearly seen in *Fritsche et al.* [2005] or *Steigenberger et al.* [2006]. The pattern is also present in the data over the whole period (Figure 7a). For shorter periods, the mean difference depends on the ionospheric activity during the period. For the three years representing the last ionospheric maximum (2000-2002), the maximum mean coordinate differences are larger than those averaged over an ionospheric cycle (see Table 3). Considering the period 2001-2003 for a comparison with the co-centric dipole study of *Steigenberger et al.* [2006], we find slightly reduced mean coordinate differences (see Table 3 and Figure 7d). To clearly demonstrate the effects of using the IGRF rather than a dipole model, we also plot IG mean coordinate differences for the same period (Figure 7b) and the difference between the two (Figure 7c). If Figure 7c is compared to Figure 2, showing the percentage difference in magnetic field strength, it becomes apparent that the areas with the largest coordinate differences match those areas with differences in magnetic field strength.

If the mean of the North residual coordinate time series of all sites after the transformation to ITRF2005 is formed, it contains a quasi-annual oscillation (Figure 8a). A similar effect has also been noted by the IGS analysis centers, and it had been considered that the effects of the higher order ionospheric terms could be a candidate to explain this oscillation (pers. comm. from J. Ray 2008). However, the oscillation is seen in the mean North time series from both the N and IG runs. If the difference of the two mean time series is taken, the smoothed difference is no more than 0.2 mm (Figure 8b), considerably smaller than that seen by the IGS analysis centers.

The coordinate results suggest that when aiming for millimeter level coordinate precision, higher order ionospheric effects should be considered, particularly in equatorial regions and over periods of ionospheric maximum.

4 Discussion and Conclusions

Our results are the first estimation of GPS velocity biases caused by not modeling the second and third order ionospheric terms (Figure 5). The velocity biases are small (< ~0.35 mm a^{-1}), but are important when correcting, for example, the vertical rates of tide gauges, where 0.35 mm a^{-1} is over 10% of the observed mean sea level change using tide gauges for the period 1993-2007 [*Prandi et al.*, 2009]. As many continuous GPS sites have been introduced at tide gauges since the last solar maximum, their vertical velocities may be systematically biased by up to several tenths of a millimeter if higher order ionospheric corrections are not taken into account.

Looking at mean coordinate differences (Figure 7), we reproduce the pattern of equatorial sites moving south and high latitude sites moving north found by *Hernandez-Pajares et al.* [2007] though this pattern is not clearly seen in the work of *Fritsche et al.* [2005] or *Steigenberger et al.* [2006]. However, we suggest that the reason for the difference of the results of *Hernandez-Pajares et al.* [2007]) to the results of *Steigenberger et al.* [2006] and *Fritsche et al.* [2005] is the northern hemisphere bias of the Fritsche/Steigenberger network rather than the computation of TEC, as we follow the Fritsche/Steigenberger method of estimating TEC from IONEX files. We agree that the method of estimating TEC directly from the GPS signals used by *Hernandez-Pajares et al.* [2007] has the potential to be more accurate in isolated areas and also before 1998 (when there is only a single daily TEC map per IONEX file). However, we consider that obtaining TEC from IONEX files is a reasonable approach that appears to produce similar results.

The IG to ID Z-translation of up to 2 mm indicates that for high precision applications the choice of magnetic model could be significant. While the magnitude of the coordinate shifts is similar for run ID and IG (Figure 7b,c,d), there are differences, particularly around the South Atlantic and in South East Asia, where the contrast in magnetic models is largest (Figure 2). This confirms earlier suggestions based on work at the signal level and simulation [*Hernandez-Pajares et al.*, 2007; *Hawarey et al.*, 2005] that using the IGRF or other similar magnetic model would be advisable for such applications. The IGRF model is not particularly complex to implement.

Our GPS reprocessing shows reasonable agreement with ITRF2005 for scale and translation rates though the rates are time variable (Table 2, Figure 3a). We also find that during the period of solar maximum the IG origin is closer along the Z axis to the ITRF origin than the N origin. When higher order ionosphere corrections are not applied (solution N) the 90 day smoothing indicates the origin can be systematically displaced by up to 10mm in the negative direction along the ITRF Z axis (Figure 3b). This finding is consistent with the findings of *Fritsche et al.* [2005]. The effect is much smaller outside the solar maximum period and along the X and Y axes. There is also a small effect on the scale (~ 0.05ppb). The majority of the Z-translation effect is due to the 2nd order term, while the scale effect is due to both the 2nd and 3rd order terms (Figure 4). Due to the way that absolute phase centers for the GPS satellites are estimated, using them means that GPS scale and scale-rate becomes aligned to the ITRF2000 scale and are no longer independent [*Schmid et al.*, 2007], see also IGS information at: ftp://igscb.jpl.nasa.gov/igscb/station/general/antenna_README.pdf.

GPS as a technique has the possibility of contributing to the definition of the terrestrial reference frame origin. The time-variability in our GPS origin compared to ITRF2005 means further investigation would be needed in this case. However, if GPS is to contribute to origin definition in future, higher order ionospheric corrections would need to be applied due to their effect on translation parameters during solar maximum.

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Run	2^{nd} order ionospheric term modeled?	3^{rd} order ionospheric term modeled?
N	No	No
IG	Yes : IGRF v.10 used	Yes
ID	Yes: dipole used	Yes
IG2	Yes: IGRF v. 10 used	No

Table 1. Summary of differences between processing runs

Parameter	**Run IG (1995-2008)**	**Run N (1995-2008)**	***Rülke et al.* [2008] (1994-2005)**	**Run IG (1995-2005)**
TX rate, mm/a	0.61 ± 0.04	0.62 ± 0.04	0.41 ± 0.00	0.52 ± 0.05
TY rate, mm/a	0.11 ± 0.04	0.13 ± 0.04	0.61 ± 0.00	0.35 ± 0.06
TZ rate, mm/a	-0.76 ± 0.17	-0.88 ± 0.17	0.41 ± 0.00	0.23 ± 0.25
Scale rate, ppb/a	-0.001 ± 0.001	0.001 ± 0.001	-0.04 ± 0.00	-0.010 ± 0.002

Table 2. Rate comparisons to ITRF2005. Standard deviations for the results from this study are estimated from the residuals to the fit.

Direction of shift	Sites with min. 10 years data: 1995 - 2007	Ionospheric maximum: 2000 - 2002	2001-2003
North	-0.9 to 0.4 mm	-0.9 to 1.3 mm	-0.8 to 1.2 mm
East	-0.2 to 0.2 mm	-0.3 to 0.3 mm	-0.3 to 0.3 mm
Up	-0.3 to 0.5 mm	-0.8 to0.5 mm	-0.8 to 0.4 mm

Table 3. Range of mean coordinate differences for different sites over selected time periods (IG – N).

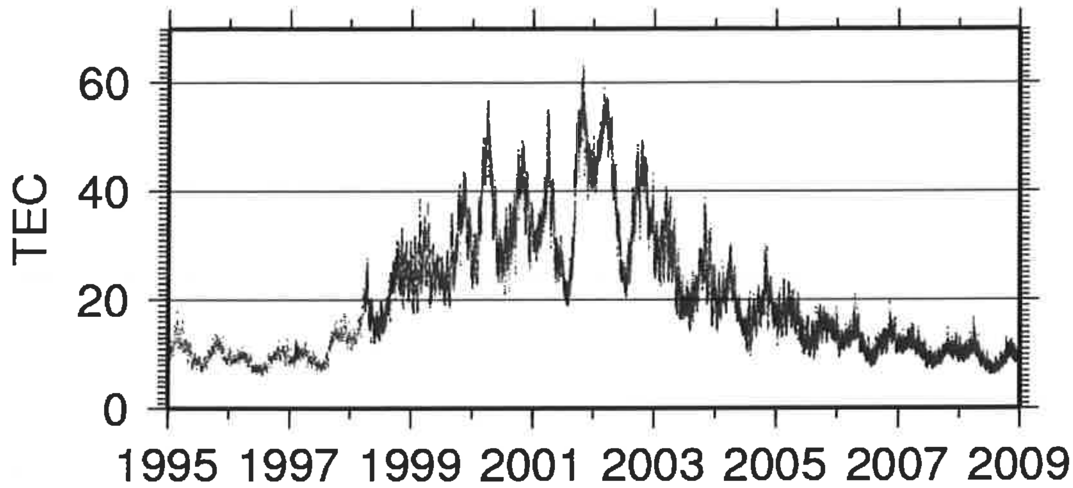

Figure 1. Mean Total Electron Content (in TECU) of the ionosphere showing rise and fall over the last solar cycle. Values obtained from ION files from the Centre for Orbit Determination in Europe (CODE). One TECU is 10^{16} electrons/m^2.

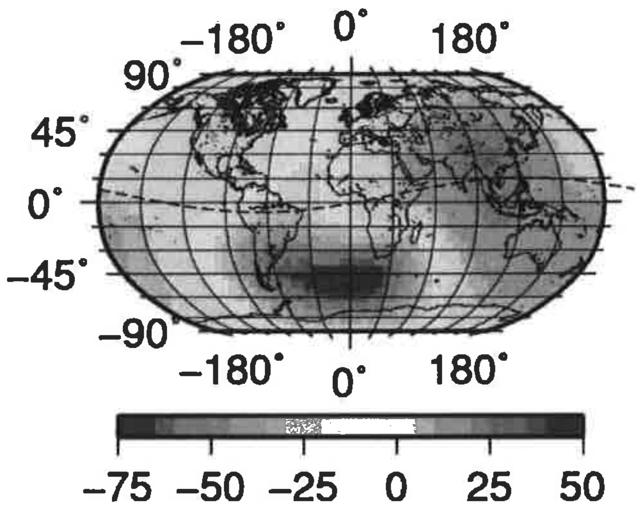

Figure 2. Percentage difference in magnetic field strength between the IGRF and a simple co-centric tilted dipole model, calculated as: (IGRF-dipole)/IGRF at decimal date 2003.83. The figure would be similar for other epochs during period of study.

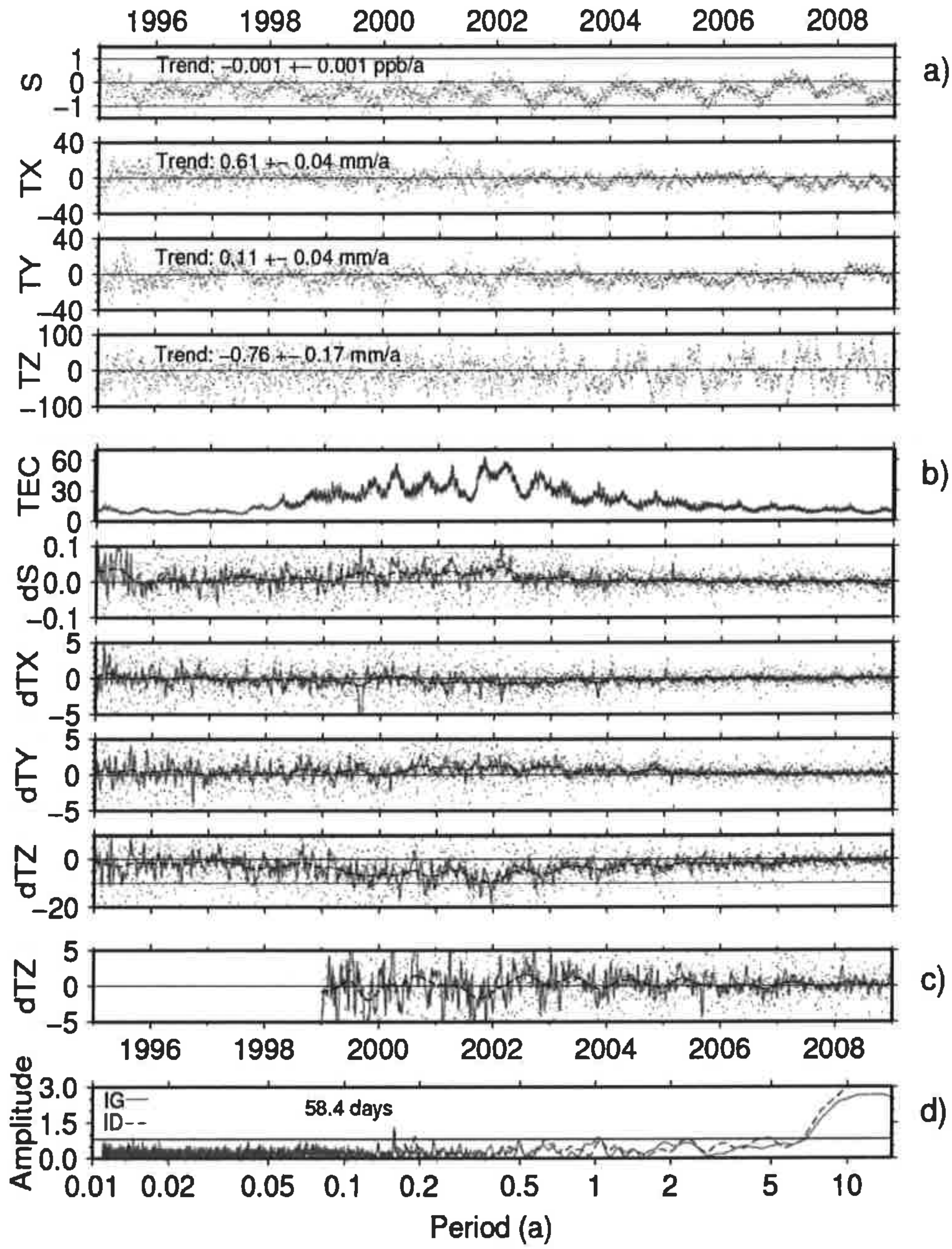

Figure 3. a) Estimated scale (S) and translation parameters (TX,TY,TZ) from solution IG to ITRF2005. b) Mean TEC (see Figure 1), scale (dS) and translation parameters (dTX,dTY,dTZ) from solution IG to N. c) Z translation parameter from ID to IG. d) Periodogram of Z translation of solution N to IG and ID frames, the 5% significance level is shown as a horizontal black line. All parameters shown in mm except S, dS in ppb and TEC in TECU. Blue data points in a), b), c) are from 24hr sessions, red and dashed black lines in b) and c) are 7 and 90 day Gaussian smoothing of the data points respectively.

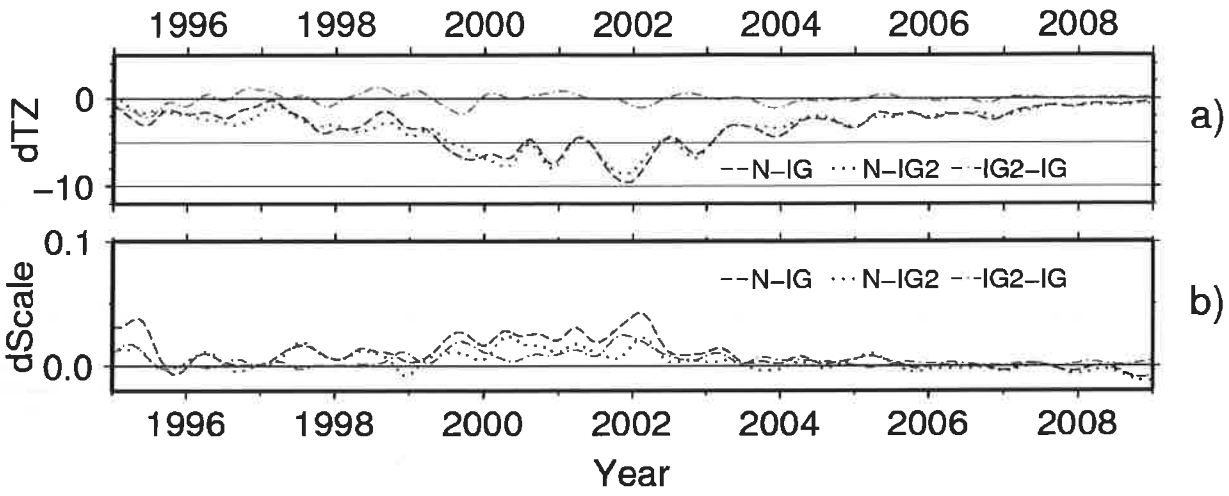

Figure 4. a) Effect on the Z-translations between solutions when modeling the third order term (mm). b) Effect on the scale of modeling the third order term (ppb). For both a) and b) three comparisons are shown: N-IG, the effect of modeling 2^{nd} & 3^{rd} order terms (black dashed line). N-IG2, the effect of modeling the 2^{nd} order term only (blue dotted line). IG2-IG, the effect of modeling the 3^{rd} order term (magenta dot-dashed line). All data are shown with 90 day Gaussian smoothing.

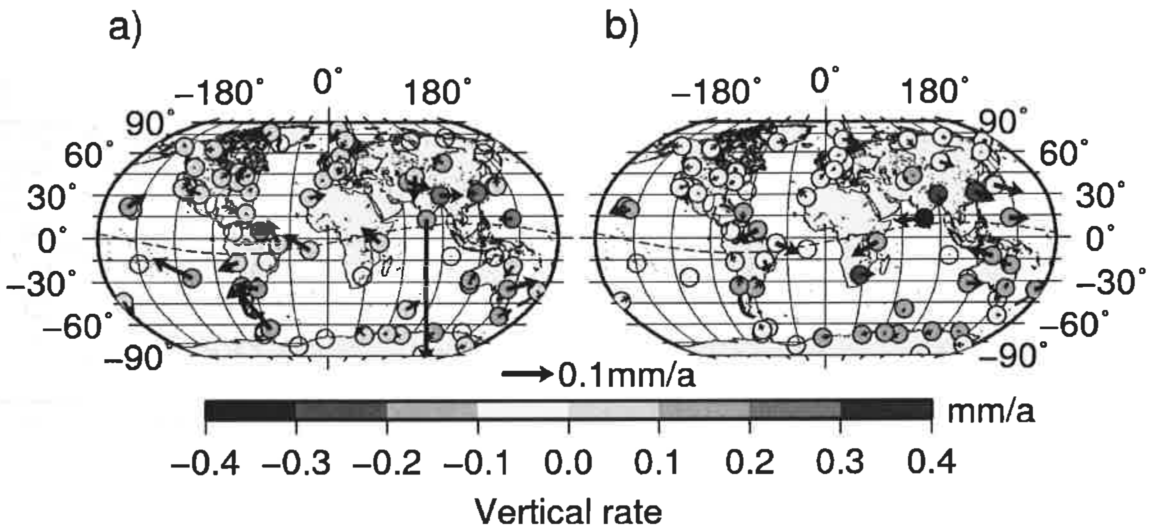

Figure 5. a) Velocity differences over the period 1996-2000 (N-IG). b) Velocity differences over the period 2001-2005 (N-IG). Arrows represent motion in plan. Geomagnetic equator shown as dashed line. Sites shown have data spanning at least 4.5 years of the 5 year period, with a minimum of 2.5 years of data. Empty circles show sites processed which did not meet these criteria.

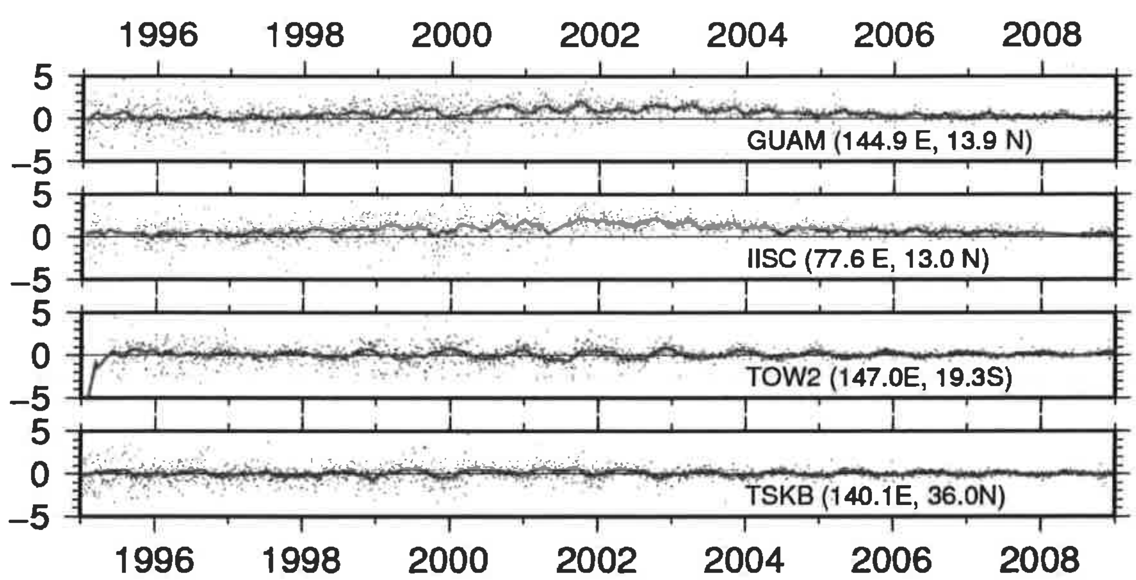

Figure 6. Examples of differenced site time series (IG-N) showing ionospheric effects in the north coordinate component (mm). Blue data points are from 24hr sessions and red lines are 30 day Gaussian smoothing of the data points.

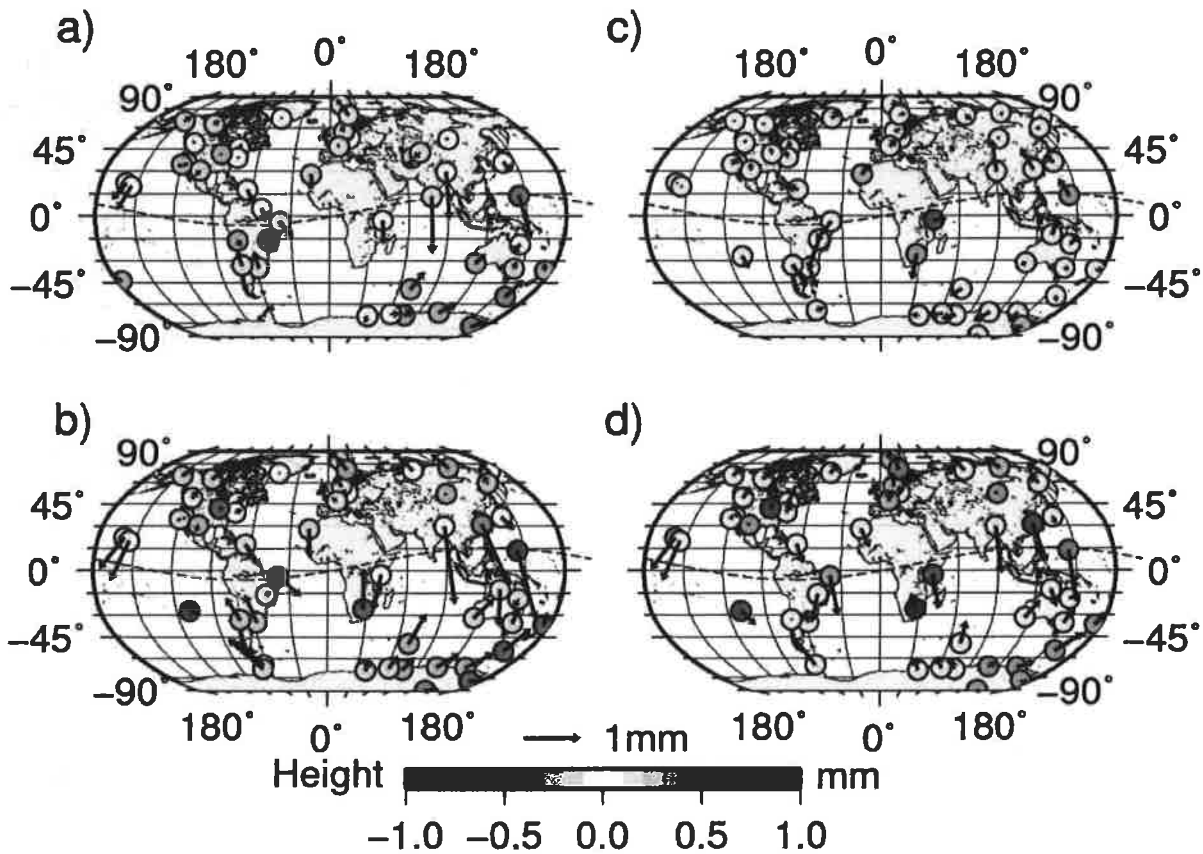

Figure 7. Mean coordinate differences: a) IG-N for 1995-2007 (sites with > 10 years of data). b) IG-N for 2001-2003 (sites with > 2.5 years of data). c) ID-IG for 2001-2003 (sites with > 2.5 years of data). d) ID-N for 2001-2003 (sites with > 2.5 years of data). Arrows represent shifts in plan. Geomagnetic equator shown as dashed line.

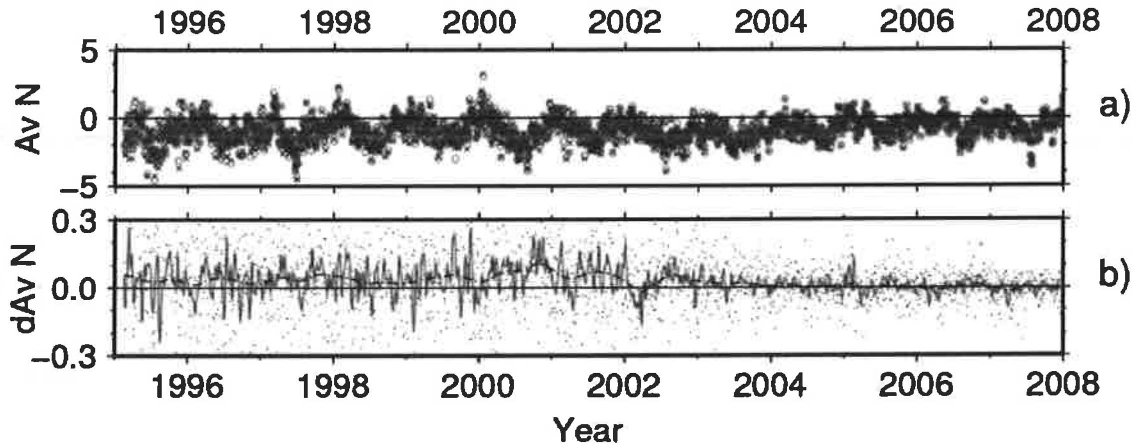

Figure 8. a) North mean residual coordinate time series after transforming to ITRF for runs N (blue crosses) and IG (red circles). b) Difference of North mean residual coordinate time series for runs N and IG. All parameters shown in mm. Data points in a) and b) are from 24hr sessions, red and dashed black lines in b) are 7 and 90 day Gaussian smoothing of the data points respectively.