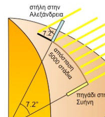

The impact of temporal geopotential variations on the GPS constellation

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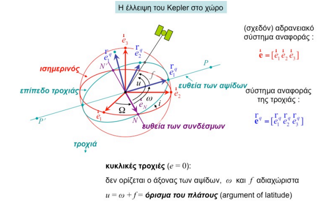

AGU Fall 2012 Meeting
San Francisco
Reference Frames, Technique Errors and Limiting Factors of Space Geodesy
(G53B-1140)

ABSTRACT

Lemoine et al. (2006) and Lemoine et al. (2010) showed that applying more detailed models of time-variable gravity (TVG) improved the quality of the altimeter satellite orbits (e.g. TOPEX/Poseidon, Jason-1, Jason-2). This modeling include application of atmospheric gravity derived from 6-hrly pressure fields obtained from the ECMWF and annual gravity variations to degree & order 20x20 in spherical harmonics derived from GRACE data. This approach allowed the development of a consistent geophysical model for application to altimeter satellite orbit determination from 1993 to 2011. In addition, we have also evaluated the impact of TVG modeling on the POD of Jason-1 and Jason-2 by application of a weekly degree & order four gravity coefficient time series developed using data from ten SLR & DORIS-tracked satellites from 1993 to 2011 (Lemoine et al., 2011).

In this study we first evaluate the impact of a more detailed TVG modeling to the GPS constellation orbits. Using the NASA GSFC GEODYN orbit determination software, we develop a series of simulated GPS constellation orbits by a least squares fitting approach to the coordinates of the IGS sp3 precise orbits in the period 2002-2004 and 2008-2012. We evaluated the inclusion of a gravity time series model with annual, and semi-annual terms with respect to the classical IERS 2010 standards. We quantify the impact of the new gravity field modeling to the GPS orbit constellation in a plane by slot approach. The impact is of the order of ~4 mm peak-to-peak at the Tx, Ty and ~1 mm peak-to-peak at the Tz centering of the orbits. Furthermore annual and semi-annual signatures on the orbits depend from the plane and slot of the orbit.

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Model strategy of the Time Variable geopotential solutions (Time Variable Gravity – TVG)

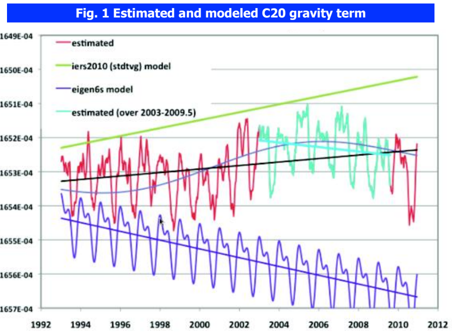
We use 4 TVG models to perform our study (***Table 1***). Those models are used in a least squares fitted Orbit Determination (OD) approach using, in lieu of tracking data, the IGS sp3 ephemerides. GPS satellite orbits are processed in 30-h long arcs and we fit the sp3 orbits with the different TVG models. For each arc we estimate the GPS satellite initial state, and one solar radiation coefficient per arc. For the purposes of our experiment, no empirical OPR acceleration parameters are estimated. As *a priori* to the SRP we only consider a 9-parameter ROCK4 model. Subsequently we generate a set of fitted orbits to the *a priori* data-set from IGS, were only the TVG forward modeling changes. For that we consider the terms of a mean gravity field (depending from the solution) up to degree and order 20. Then, we estimate a set of 7-Helmert transformation parameters by using the TVG standards solution that is closest to the current set of IGS standards as a reference to compare to our different test TVG solutions.

Table 1. Time Variable Gravity (TVG) Models (cf. G53B-1136 presentation)

TVG	Description (atmosphere gravity is always forward modeled using ECMWF 6-hour pressure data)
stdtvg	Linear rates for C_{20}, C_{30}, C_{40}, C_{21}, S_{21}, (IERS 2010, 2003) based on 17 years of SLR data. Atmospheric gravity is not forward modeled.
eigen.gl04s1+ annual	Linear rates for C_{20}, C_{30}, C_{40}, C_{21}, S_{21}, (IERS 2010, 2003) based on 17 years of SLR data + 20x20 annual field derived from GRACE data. Atmospheric gravity is forward modeled.
tvg4x4	GSFC 4X4 7-day time series from 1993 re-estimated using SLR/DORIS tracking to 10 satellites; GGM03S is the background field. Plus 20x20 annual field derived from GRACE data from degree/order 5x5. Atmospheric gravity is forward modeled.
goco2s_fit	GSFC annual, semi-annual and linear terms estimated from the 19-year tvg4x4 time series are applied depending on the coefficient . Plus 20x20 annual field derived from GRACE data with tvg4x4 fit annual terms replacing the 20x20 original. GOCO2S 250x250 static field estimated using GRACE (7 years), GOCE (8-12 months), CHAMP (8 years), and SLR (5 years) data (Goiginer et al., 2011). Atmospheric gravity is forward modeled.
grgs20x20	GRGS RL02 20x20 10-day time series from the 50x50 time series estimated using GRACE+Lageos; GRGS RL02 mean is the reference field. Available from August 2002. Atmospheric gravity is forward modeled.
atgrav	Same as stdtvg where the atmospheric gravity is forward modeled.

We use TVG models that are consistent over the entire span of the GPS time series, available from 2002 to present. Current IGS processing (and repro1) standards follow TVG modeling , that is defined by the IERS conventions and includes secular rates for the low degree zonal harmonics (C20, C30, C40, C21 & S21). However this approach supplies a consistent model only for the time-span over which these linear terms are estimated. Lemoine et al. (2011) and Zelensky et al. (2011) show that the C20 term does not always follow a secular linear pattern (***Fig. 1***). The majority of the IGS Analysis centers follow this approach of applying a constant term (at epoch) together with a linear rate term for the lowest degrees of the gravity field. Instead we follow Lemoine et al. (2011) and Zelensky et al. (2011), where the lower degrees are represented as a time-series data set (tvg4x4, grgs20x20) or as an enhanced TVG model with annual, semi-annual and lower frequency terms (goco2s_fit). So in this paper we are dealing with the problem of how much exactly are the GPS constellation orbits sensitive to these new TVG modeling approaches.

Fig. 1 Estimated and modeled C20 gravity term



Acknowledgements: We acknowledge the NASA Physical Oceanography program and the MEaSURE's project, and the IDS program in Mean Sea Level for their support. We thank the International Laser Ranging Service (ILRS), the International DORIS Service (IDS), and the International GNSS Service for their continued support.

GPS Constellation sensitivity to the TVG

The six orbital planes of the GPS are evenly spaced by 60° (in the equatorial plane) and labeled by A, B, C, D, E, F. The planes A, C, and E and their normal are provided in Figure 2 taken from Meindl et al. (2012). The three planes are mutually orthogonal since they are separated by 120° in the equator with and inclination of ~ 55°. Consequently, the three planes B, D, and F are also orthogonal by the same definition. In every case the normal vector of one of the planes is the interception of the other two orbital planes. The two plane sets are the "building blocks".

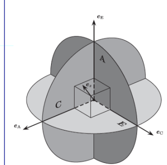


Fig. 2 : Orbital planes A, C and E and the corresponding normal vectors (from Meindl et al. 2012)

Fig.3 : Along, Cross and Radial RMS differences between orbit eigen.gl04sl (std iers2010) and the test orbit for PRN14 F-1

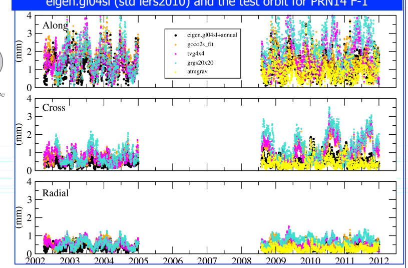


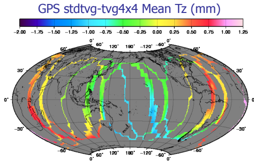
Table 2 : 3D total RMS orbit differences for PRN14 plane F slot 1 (in mm), doy 094 2002 – 366 2004 and doy 213 2008 – 001 2012

with stdtvg	Radial	Cross	Along
Eigen.gl04s1 +annual	0.38	0.51	1.23
goco2s_fit	0.50	0.88	1.48
tvg4x4	0.55	0.95	1.64
grgs20x20	0.64	1.17	2.04
atgrav	0.28	0.42	0.91

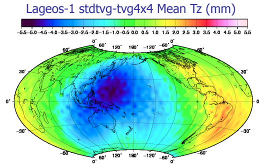
The computed orbits using goco2s_fit, tvg4x4 and grgs20x20 exhibit larger signal even when compared to the standard TVG modeling where an annual signal and atmospheric gravity signal have been added ***(Table 2)***. ***Figure 3*** also shows that the resonant terms of the new TVG models largely affect the cross and along components and only to a lesser extent the radial component.

This is specially true since under the influence of the time-variable C_{20} (the most significant term of the TVG model) the semi-major axis, the eccentricity and inclination do not change. **The computed orbits using goco2s_fit, tvg4x4 (and grgs50x050) begin to progressively diverge from the stdtvg orbit in the second period.** The remaining signals exhibit an annual and semi annual signature in all three components. In the following picture we represent the mean geographical values of the Tz component as those are mapped on the delta 7p orbit differences from spacecraft of each GPS orbital plane in the period 2002-2012. This result is compared to the Lageos-1 stdtvg-tvg4x4 Mean Tz for the period (1992-2012).

GPS stdtvg-tvg4x4 Mean Tz (mm)



Lageos-1 stdtvg-tvg4x4 Mean Tz (mm)



CONCLUSION

- The study has demonstrated that the GPS orbits are sensitive to the new TVG modeling,
- The new TVG model introduces annual and semi-annual perturbations to the orbits,
- The RMS differences diverge from the stdtvg solution during the second period (2008-2012),
- The origin of the GPS orbits exhibits annual, semi-annual and trends which are plane and slot dependent,
- The second part of this study will focus on the impact on the GPS stations

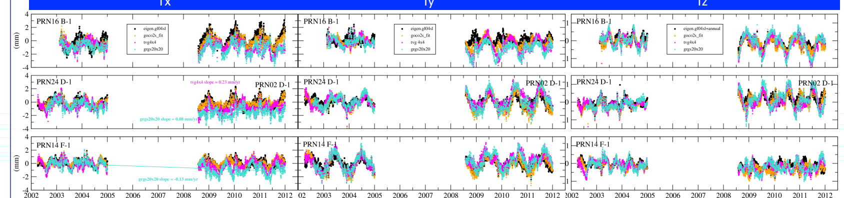
GPS Constellation centering sensitivity to the TVG

Our group has previously proven (Lemoine et al. 2011 and Zelensky et al. 2011) that **current methods of gravity field modeling used for LEO POD are inadequate for representing the physical reality**. As a first step, we answer to the question "how much of an impact are we to expect from an advanced TVG modeling in the GPS orbits OD process"? For the time being we're only focusing on the centering of a series of spacecraft orbits per building block.

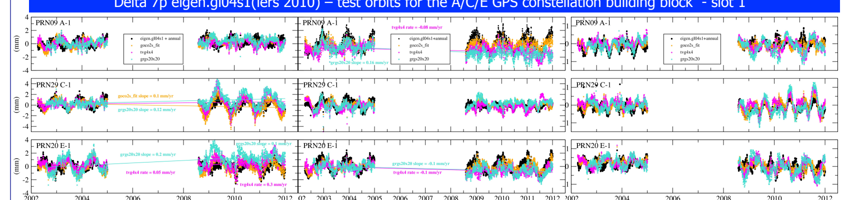
The 12 plots below illustrate that GPS orbit solutions are sensitive to the TVG modeling and especially so when the model grows less adequate as with stdtvg following 2008-2012. This is most evident in the X, Y components of the GPS orbits. The X and Y components are the ones that are the most affected from the new TVG modeling. The Z component exhibits the lowest signatures. Depending from the satellite plane and slot the slope may vary between 0.1 mm/yr to 0.3mm/yr.

Delta 7p eigen.gl04s1(iers 2010) – test orbits for the B/D/F GPS constellation building block - slot 1

Tx Ty Tz

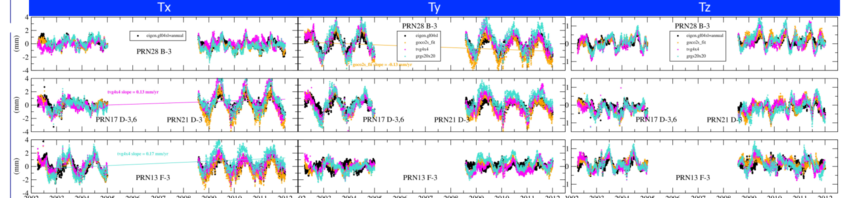


Delta 7p eigen.gl04s1(iers 2010) – test orbits for the A/C/E GPS constellation building block - slot 1



Delta 7p eigen.gl04s1(iers 2010) – test orbits for the B/D/F GPS constellation building block - slot 3

Tx Ty Tz



Delta 7p eigen.gl04s1(iers 2010) – test orbits for the A/C/E GPS constellation building block - slot 3