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Geocenter Coordinates Estimated from a Combined Multi-GNSS Data Analysis

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Introduction

When estimating the orbits of artificial Earth satellites using observations from terrestrial sites, one may solve for the coordinates of the Earth´s center of mass–the geocenter.

The relation between the geocenter coordinates Δx, Δy, and Δz and the first-degree coefficients C_{10}, C_{11}, and S_{11} of the spherical harmonics of the geopotential is given by:

$$C_{10} = \frac{\Delta z}{a_E}, \quad C_{11} = \frac{\Delta x}{a_E}, \quad S_{11} = \frac{\Delta y}{a_E}$$

where a_E is the equatorial radius of the Earth.

One may directly determine the geocenter by solving for the geopotential coefficients. On the other hand one may also set the coefficients $C_{10} = C_{11} = S_{11} = 0$, i.e., use a truely geocentric coordinate system for orbits and stations and solve for a common translation of the entire system of reference stations. The two approaches give identical results. In our analysis we actually estimated the common offsets but follow common practice and speak of geocenter offsets.

All our experiments are based on observation data from a network of 92 globally distributed GPS/GLONASS-combined tracking stations (see Fig. 1). The data was continuously recorded for the years 2008 through 2011.

Special care was taken to keep the GPS and GLONASS solutions on a comparable level, in particular concerning the selection of the tracking sites. All stations for which a pronounced imbalance between the available GPS and GLONASS observations could be identified, were excluded from processing. Figure 2 (left) shows the number of available stations during the four years. After an almost linear increase from 35 to about 80 stations in 2008, a stable level was reached.

The number of GPS satellites ranges between 30 and 32. The numerous „drop-outs" of single satellites are caused by repositioning events. The number of GLONASS satellites increases from initially 14 in 2008 to 24 in 2011. In 2008, the GLONASS constellation was still very weak. Figure 2 (right) shows the development of the number of satellites.

We have computed high-quality GPS-only, GLONASS-only, and combined GPS/GLONASS solutions. Up-to-date models were used and the procesing closely followed the processing scheme used by CODE, the Center for Orbit Determination in Europe.

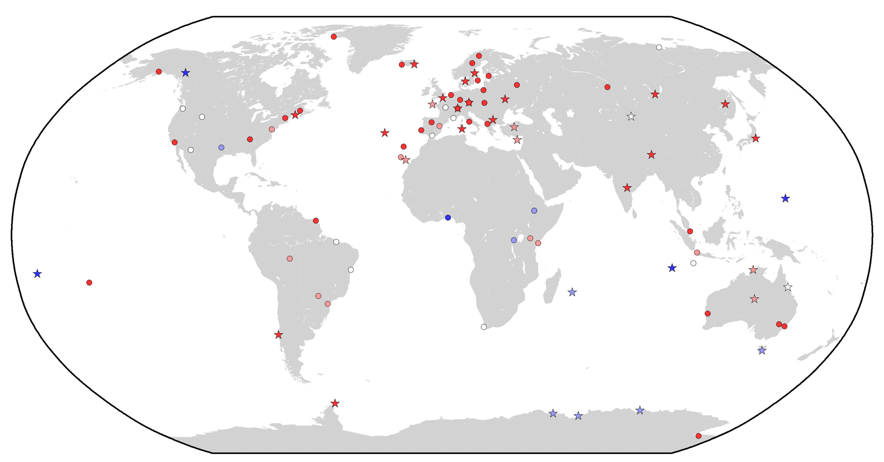

Figure 1: Tracking network of 92 globally distributed stations..

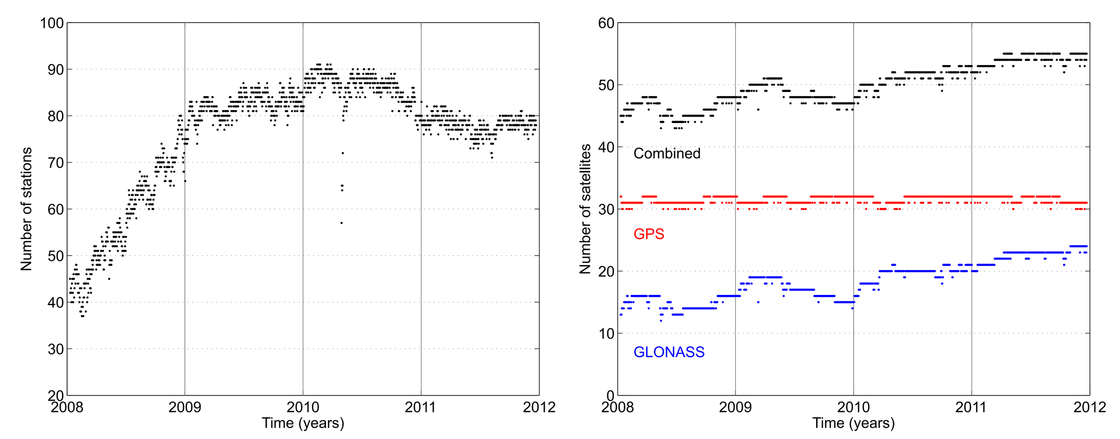

Figure 2: Number of available stations (left) and satellites (right) for the four years 2008–2011.

Geocenter Coordinates Estimated from GPS and GLONASS Data

Figure 3 shows the X-, Y-, and Z-components of the estimated geocenter coordinates (GCC) for the years 2008 through 2011. The top row shows the GPS-only (red), the GLONASS-only (blue), and the GPS/GLONASS results (black). The noise is significantly larger for the pure GLONASS than for the GPS solution—in particular in 2008, where the GLONASS observation geometry was rather weak due to the small number of satellites (see Fig. 2, right).

The X- and Y-coordinates of the geocenter estimated from GPS and GLONASS are highly correlated. Apart from the noise, the two solutions are comparable. The combined solution is very close to the GPS-only solution. The picture is completely different, however, for the Z-component (top right). The GLONASS-derived geocenter coordinates are much larger (peak-to-peak variations of about 30 cm) than those emerging from GPS. The GLONASS variations are spurious and cannot be explained by geophysical means. Note that the combined solution is close to the GPS solution, indicating that the GPS-derived geocenter coordinates are much stronger than the GLONASS-derived results. Nevertheless, the combined solution also contains traces of the GLONASS excursions—an effect which is not wanted.

The middle and bottom row of Fig. 3 give the GPS- and GLONASS-only results (blue) together with the elevation β_0 (green) of the Sun above the single orbital planes. There is an eye-catching correlation between the large GLONASS-derived excursions of the Z-component and the maximum values of β_0.

This is a strong indication that these extreme excursions are artifacts and caused by the correlation of the geocenter Z-coordinate and one or a linear combination of orbit parameters.

We cannot yet say whether the GPS-derived Z-coordinate of the geocenter contains artifacts as well. The X- and Y-coordinates do not show a dependence on the elevation angle of the Sun above the orbital planes—neither for GPS nor for GLONASS. For the time being, we do therefore not advocate correlations between the X- and Y-coordinates of the geocenter on the one hand and the parameters of the orbit models on the other hand.

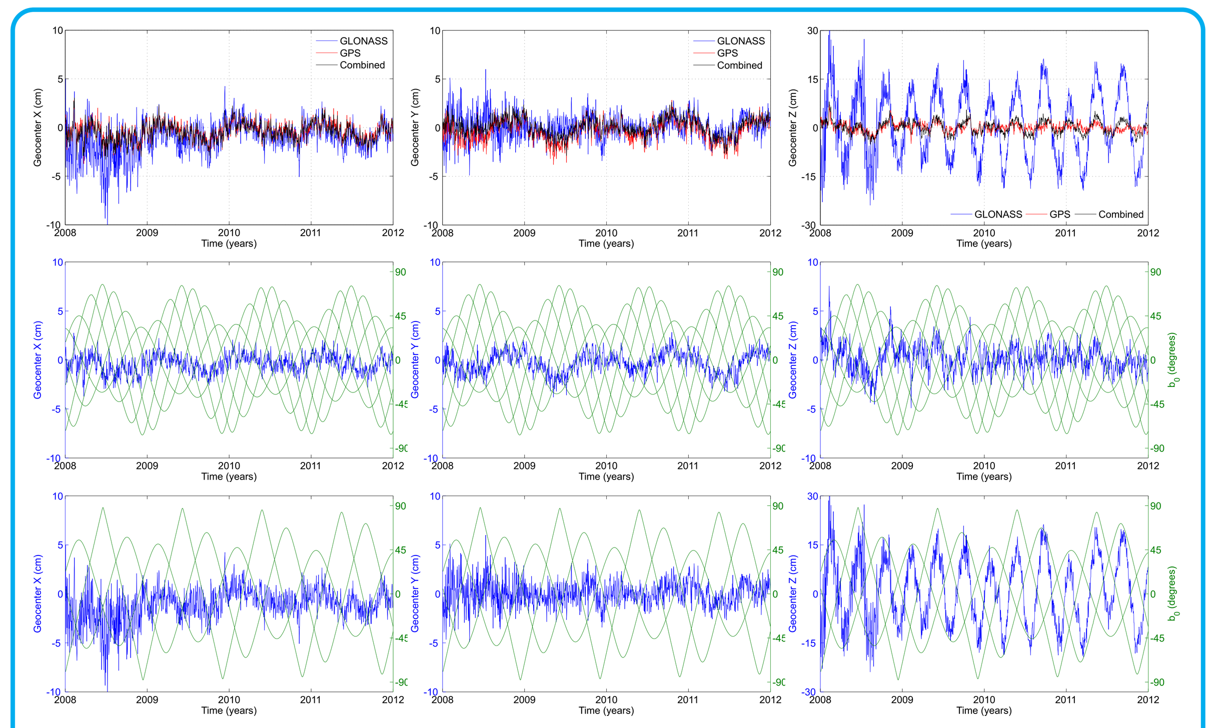

Figure 3: Geocenter X- (left), Y- (middle), and Z-coordinates (right).
Top Comparison of GPS-only (red), GLONASS-only (blue), and combination (black).
Middle GPS-only geocenter coordinates and elevation β_0 of the Sun above orbital planes.
Bottom GLONASS-only geocenter coordinates and elevation β_0 of the Sun above orbital planes.

Geocenter Variations Viewed by Perturbation Theory

In our analysis each orbit is parameterized with six osculating orbital elements (semi-major axis *a*, eccentricity *e*, inclination *i* of the orbital plane w.r.t. the inertial equatorial plane, right ascension of the ascending node Ω, argument of perigee ω, and perigee passage time T_0). In addition, three constant forces in the $\boldsymbol{e}_D$-, $\boldsymbol{e}_Y$-, and $\boldsymbol{e}_X$-direction are set up together with two once-per-revolution parameters in the $\boldsymbol{e}_X$-direction. These parameters are estimated for each orbital arc. The unit vector $\boldsymbol{e}_D$ points from the satellite to the Sun, $\boldsymbol{e}_Y$ coincides with the solar panel axis, and $\boldsymbol{e}_X = \boldsymbol{e}_D \times \boldsymbol{e}_Y$.

When interested in the correlations between geocenter Z-offset and orbit parameters, one has to study only the impact of a force perpendicular to the orbital plane (W-direction). Other components cannot affect the orbital plane (i.e., the elements *i*, Ω, and ω). In order to further simplify the problem we assume circular orbits, which is why ω may be replaced by the argument of latitude *u*.

The perturbation equations give the effect of a force in W-direction as

$$\Delta i = \frac{W}{n^2 a} \sin u, \quad \Delta\Omega = \frac{W}{n^2 a \sin i}(\cos u - 1), \quad \Delta u = \frac{W}{n^2 a \tan i} \cos u$$

This relationship implies that the pole of the perturbed orbit moves with uniform angular velocity on a circle with radius $\delta i = \frac{W}{n^2 a}$ around the unperturbed pole. The motion is synchronous to the motion of the satellite, implying that the envelope of all perturbed orbits is a circle parallel to the unperturbed orbit shifted by $\delta z = \frac{W}{n^2}$. Figure 4 illustrates this parallel shift of the orbit.

The most important part of the empirical orbit model causing a force in W-direction is the perturbing force along the unit vector $\boldsymbol{e}_D$. This force is dominated by the direct radiation pressure w.r.t. the solar panels.

The force in W-direction caused by the direct radiation pressure is given by $W = D_0 \sin\beta$. Projecting the parallel orbit shift δz on the Z-direction of the geocenter, the Z-coordinate is correlated with the direct radiation pressure by $\delta Z = \frac{D_0 \sin\beta}{n^2 \cos i}$.

The theoretical correlation of the geocenter Z-coordinate and the direct solar radiation pressure parameter for all $k = 1, \ldots, n_p$ orbital planes is then given by

$$\delta Z = \frac{1}{n^2 \cos i} \cdot \sum_{k=1}^{n_p} D_k \sin\beta_k$$

where D_k and β_k are mean values over all satellites of the particular orbital plane *k* (assuming identical satellites).

No problem arises as long as only the D-component of the empirical force model, but no geocenter coordinates are estimated in the GNSS analysis. A problem shows up, however, as soon as geocenter coordinates are estimated in addition to constant radiation pressure parameters for all satellites of the constellation. The estimate of the Z-component of the geocenter might just compensate the shift of the orbital plane caused by an additional D-component, introduced by the simultaneous estimation of the geocenter and the D-components.

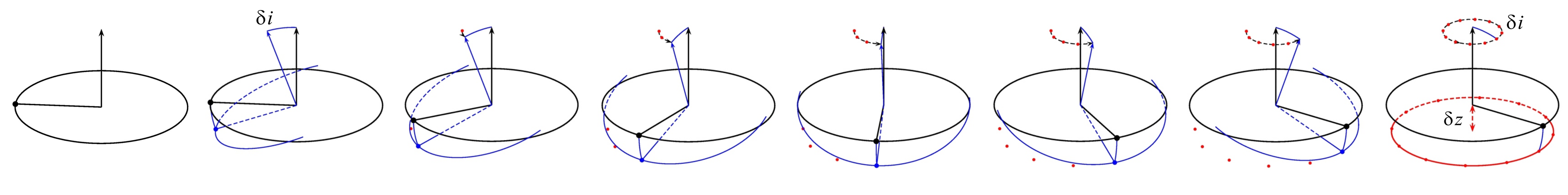

Figure 4: The W-component of a (perpendicular) perturbing force causes a tilting of the orbital plane (blue). The „tilted pole" moves in synchronization to the satellite on a circle around the undisturbed pole. The satellite seems to travel on a parallel orbit (red).

Reconstructed Geocenter Coordinates

To prove our assumption that geocenter Z-coordinate annihilate the orbit shift caused by an additional D-component of the radiation pressure model, we use the direct radiation pressure estimates from two independent analyses: one with estimated geocenter coordinates and one without. Figure 5 (top row) shows the two types of estimates for three GLONASS satellites (representing the three orbital planes). The bottom row shows the difference together with the β_0-angles.

The geocenter coordinate reconstructed from the radiation pressure differences should correspond to the estimated Z-coordinate. Figure 6 shows the estimated (blue) and the reconstructed (red) Z-coordinate of the geocenter: The curves coincide to a very high degree for GPS, as well as for GLONASS, amply justifying our assumption.

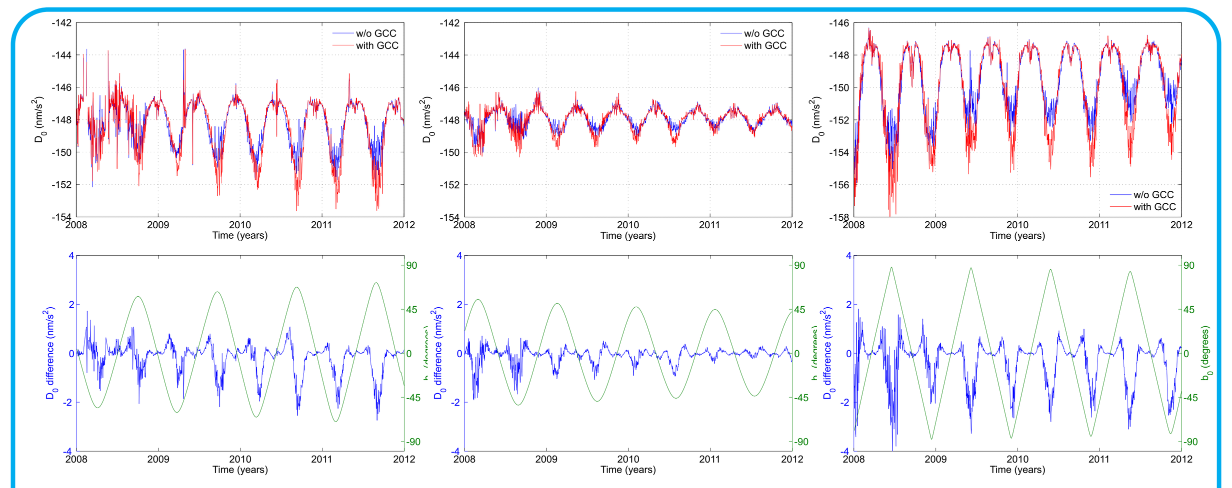

Figure 5: Constant radiaion pressure D_0 for 3 GLONASS satellites (representing the 3 orbital planes).
Top Resulting D_0 values if geocenter coordinates are solved for (red) or not (blue).
Middle Difference of estimated D_0 values and elevation β_0 of Sun above orbital planes.

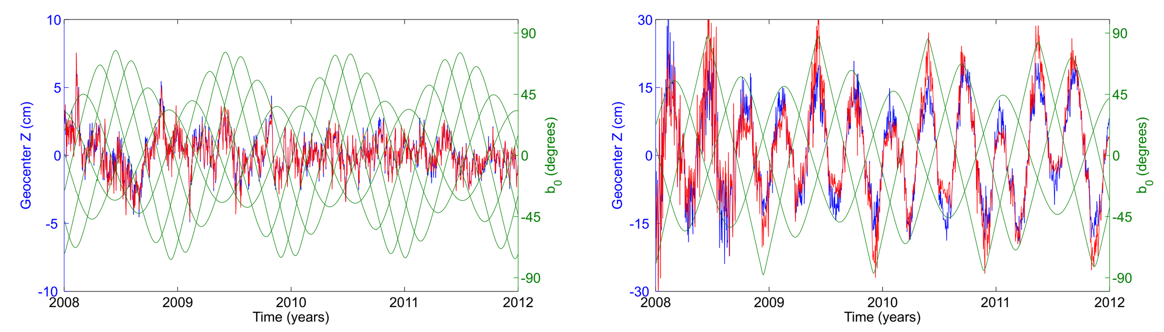

Figure 6: Estimated (blue) and reconstructed (red) geocenter Z-coordinate for GPS (left) and GLONASS (right).

Conclusion

The Z-component of the geocenter estimated from a GLONASS data analysis shows very large variations (30 cm peak-to-peak).

These variations could be explained by perturbation theory: The geocenter Z-coordinate and the constant direct radiation pressure D-component of the orbit model are highly correlated.

The geocenter Z-coordinate thus compensates a shift of the orbital planes caused by an additional D-component, introduced by the simultaneous estimation of the geocenter and radiation pressure parameters. The geocenter Z-coordinate can be reconstructed to a very high degree from the difference of the D-components estimated with and without solving for geocenter coordinates. This is true for both, GPS as well as GLONASS.

The geocenter Z-coordinates derived from GPS and GLONASS do not have much in common. Moreover, the geocenter Z-coordinates derived solely from GLONASS observations are purely artifactual in nature. They should not be interpreted geophysically.

Literature

The presented results are based on and extend the PhD thesis:
Meindl M., *Combined Analysis of Observations from Different Global Navigation Satellite Systems*, Vol. 83 of Geodätisch-geophysikalische Arbeiten in der Schweiz, SGK, Zürich, Switzerland, 2011, ISBN: 978-3-908440-27-7, available at http://www.sgc.ethz.ch

The theoretical background on perturbation theory can be found in
Beutler G., *Methods of celestial mechanics*, Vol. I/II, Springer-Verlag, Berlin, Germany, 2005.

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