High-accuracy orbit determination for the GOCE re-entry phase

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Introduction

When the Xenon ion propulsion of ESA's GOCE (Gravity field and steady-state Ocean Circulation Explorer) stopped operating after October 21, 2013, the satellite experienced a rapid decay of orbital altitude (see Fig. 1). Despite the increasing air drag conditions, GOCE accelerometers and GPS receivers delivered high-quality data until November 8 and November 10, respectively, before GOCE finally disintegrated on November 11, around 0:16 UTC near the Falkland islands (see Fig 2).

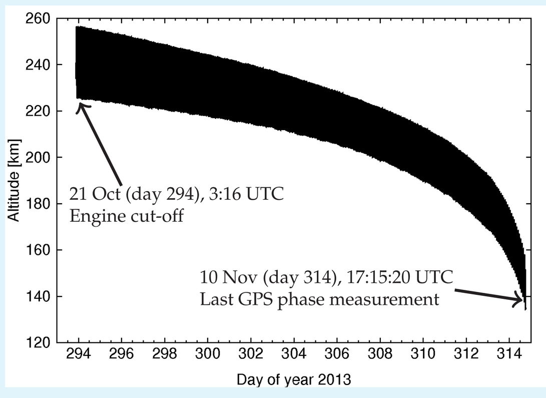

Figure 1: Altitude of GOCE above WGS-84 reference ellipsoid for the last three weeks (days 13/294-13/314).

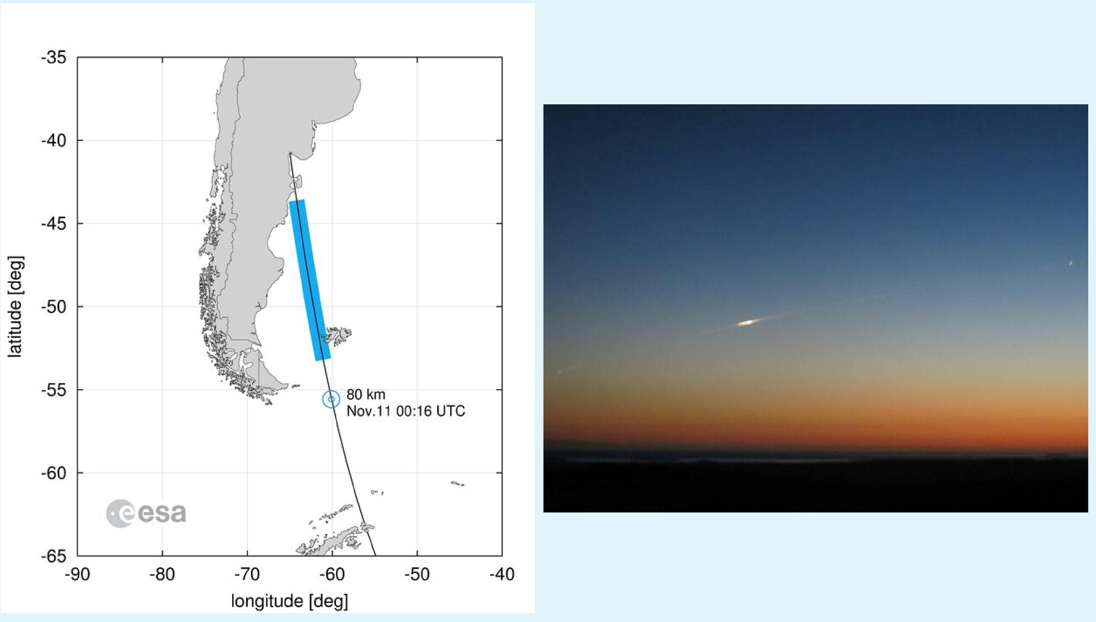

Figure 2: Left: 80 km GOCE re-entry point and re-entry swath. Right: GOCE burning up in the atmosphere over Falklands (photo by Bill Charter).

In the frame of the ESA study PREGO the data provided by GOCE during its re-entry phase shall be exploited to improve the capacities on re-entry prediction. The study is conducted by Deimos Space, Madrid as tenderer and the Astronomical Institute of the University of Bern (AIUB) as well as the Centre National d'Etudes Spatiales (CNES), Toulouse as subcontractors. The AIUB re-computes and provides the GPS-based precise GOCE orbits, which then serve as the reference truth for further re-entry analysis including Tracking and Imaging RADAR (TIRA) and Two-Line Elements (TLE) data.

Reproducing the GOCE HPF orbits

In the framework of the GOCE High-level Processing Facility (HPF) the AIUB was responsible for the generation of the official GOCE Precise Science Orbits (PSOs). Fig. 3 shows the work flow.

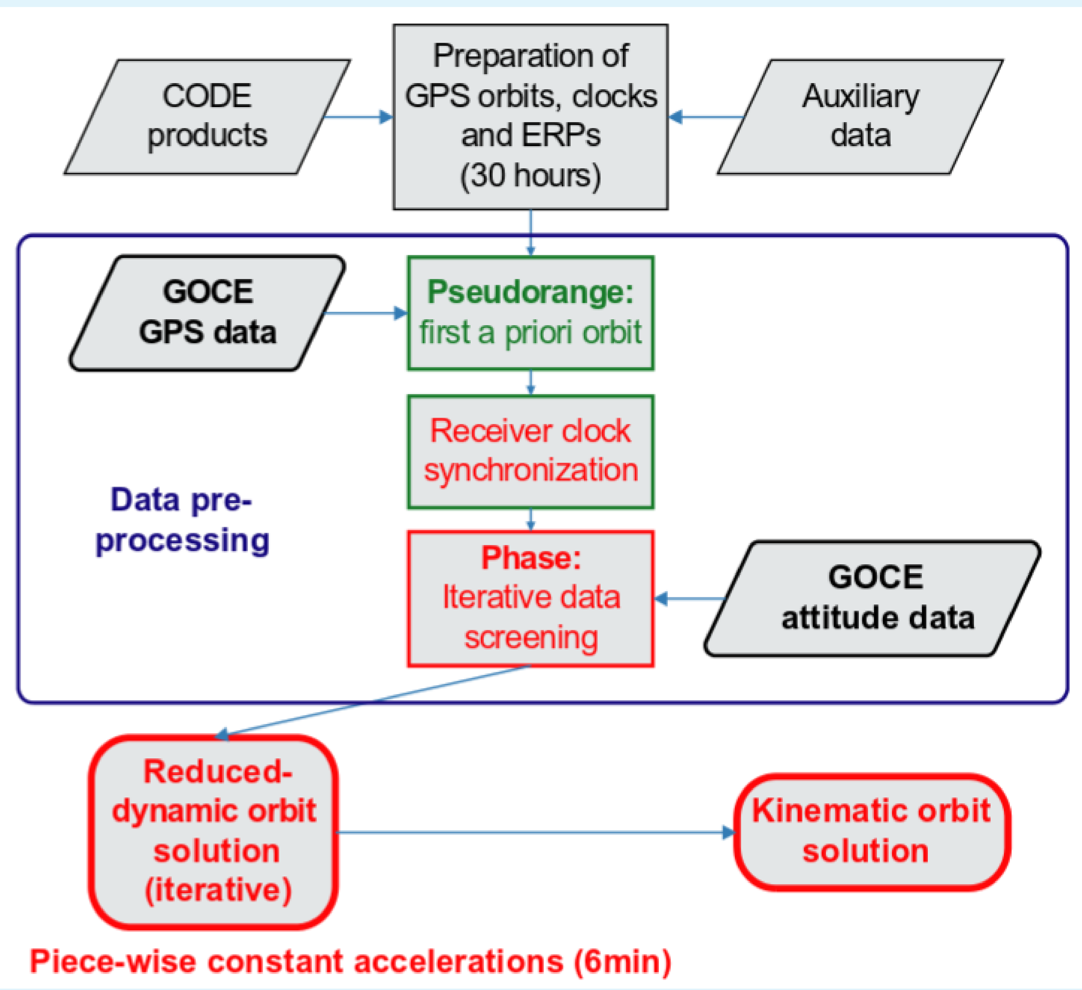

Figure 3: Flow diagram of GOCE PSO determination (from Bock et al., 2007). CODE: Center for Orbit Determination in Europe.

The PSOs were computed with a special version of the Bernese GNSS Software, which was frozen at the beginning of the GOCE activities. Non-gravitational accelerations were taken into account exclusively by estimating 6 minutes pseudo-stochastic piecewise-constant empirical accelerations. The orbits for this study are computed with the latest version of the Bernese GNSS Software. As a zero test, orbits have been computed with the new software and the old settings. They agree with the PSOs on a good level (see Fig. 4).

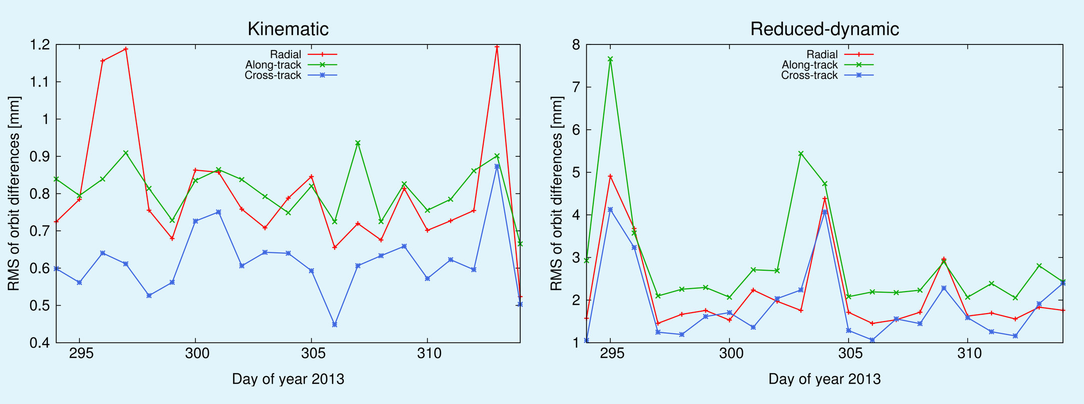

Figure 4: Differences between GOCE orbits as computed with the latest version of the Bernese GNSS Software (w/o air drag modeling) and the PSOs.

Air drag modeling

Air drag modeling has been implemented into the Bernese GNSS Software. GOCE is represented by a collection of flat plates, each characterized by an area A and a normal vector $\vec{n}$, contributing to the total drag and lift acceleration as follows:

$$\vec{a}_D = -\frac{\rho A_{\text{ref}}}{2m} C_D v^2 \vec{e}_D\,, \quad \vec{a}_L = -\frac{\rho A_{\text{ref}}}{2m} C_L v^2 \vec{e}_L\,, \tag{1}$$

where ρ is the atmospheric density, m the satellite mass, A_{ref} a reference area, $v = |\vec{v}|$ the magnitude of the velocity w.r.t. the atmosphere, $\vec{e}_D = -\vec{v}/v$, and $\vec{e}_L = \vec{e}_D \times (\vec{e}_D \times \vec{n})$. For each plate the drag and lift coefficient C_D and C_L is computed according to Sentman's theory (Moe and Moe, 2005), which assumes that the atmospheric molecules are in a free molecular flow (for GOCE true only above ~150 km), have a Maxwellian velocity distribution and are diffusely reflected. A central quantity of the theory is the energy accommodation coefficient α, characterizing the degree to which the incident molecules reach thermal equilibrium before re-emission. For this study it is computed as

$$\alpha = \frac{3.6\mu}{(1+\mu)^2}\,, \tag{2}$$

where $\mu = \bar{m}/16$ is the ratio of the mean molecular mass $\bar{m}$ of the atmosphere w.r.t. the molecular mass of atomic oxygen, which is assumed to fully coat the satellite surface.
The following types of GOCE macro models were tested:

- 6-plate box model with surfaces of 0.70 m^2 (x), 10.77 m^2 (y), 5.90 m^2 (z),
- 44-plate macro model of Thales Alenia Space,
- 36-plate variant of the 44-plate model without radiator (self-shadowing).

Empirical accelerations

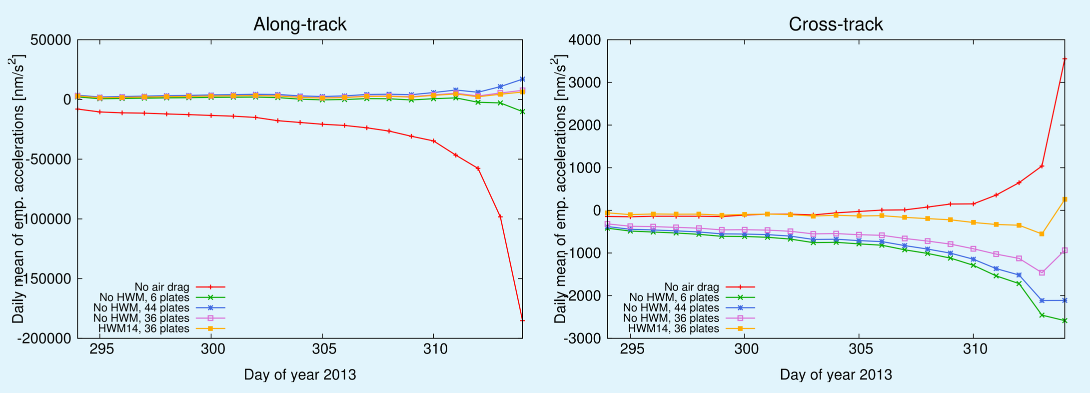

Figure 5: Daily mean of estimated empirical accelerations in along-track and cross-track direction when applying no air drag modeling (red) and different macro models. DTM2013 is used for the atmospheric densities, no drag scaling factor is estimated. The piecewise-constant accelerations are constrained towards zero with an a priori standard deviation of $1 \cdot 10^{-6}$ m/s^2. HWM: horizontal wind model.

Figure 5 shows that the air drag modeling substantially reduces the estimated along-track and cross-track empirical accelerations in a reduced-dynamic orbit determination for the last three weeks of GOCE. Note that the use of the horizontal wind model HWM14 reduces the negative offset in the cross-track empirical accelerations.

For the atmospheric (partial) densities and temperatures the three models DTM2013, MSISE-00, and JB2008 are tested. JB2008 does not yield partial densities and, when using it, for the the computation of α in Eq. (2) a mean molecular mass of $\bar{m} = 21.2$ g/mol is assumed, which corresponds to the average of the masses provided by MSISE-00 and DTM2013 over days 13/294-13/314 along the GOCE orbit.

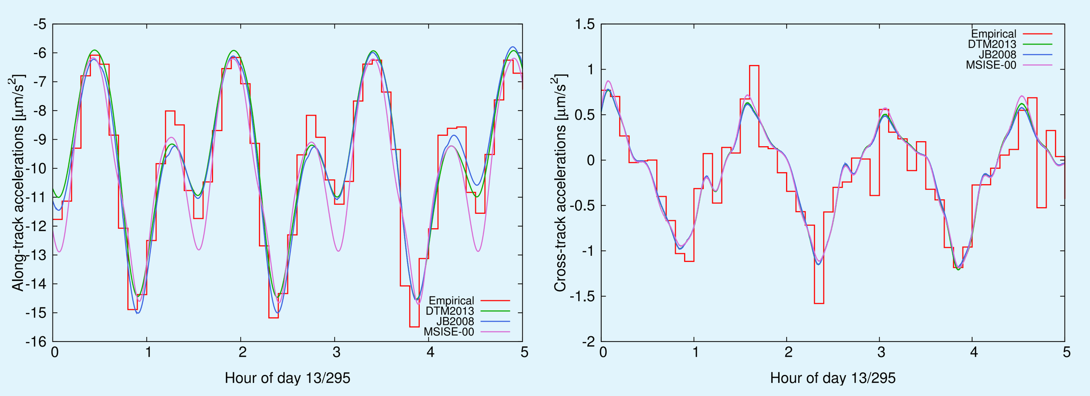

Figure 6: 6 minutes piecewise-constant empirical and modeled along-track and cross-track accelerations for the first five hours of day 13/295. For the air drag modeling the 36-plate macro model, HWM14, and the indicated atmospheric density models is used.

Orbits with more dynamical stiffness

With GOCE in the drag-free mode, the constraint of the piecewise-constant accelerations of the PSOs was $2 \cdot 10^{-8}$ m/s^2. Due to lack of air drag modeling, for the generation of the PSOs of the last days, it had to be released (up to $5 \cdot 10^{-6}$ m/s^2), resulting in less dynamical orbits (Jäggi et al., 2014). Figure 7 shows that, including now explicit air drag modeling, the constraints can be tighten again.

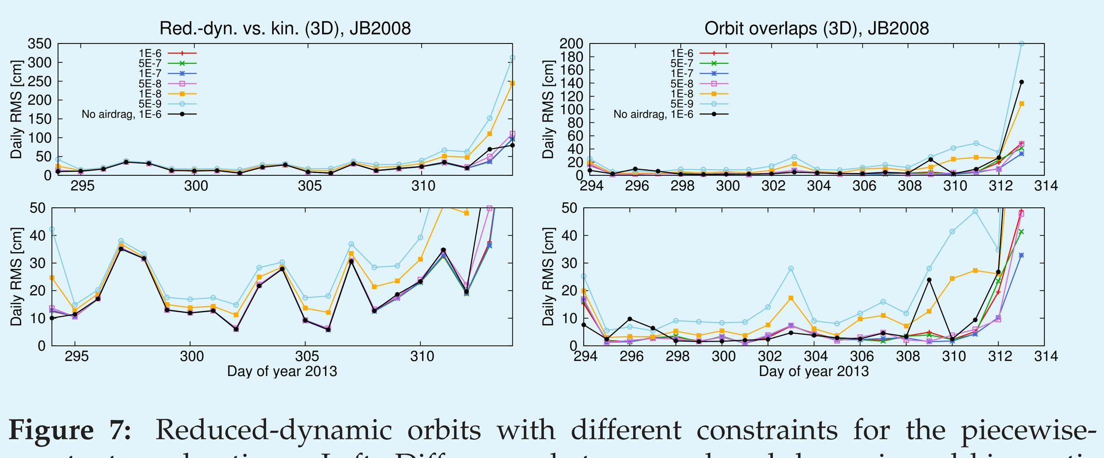

Figure 7: Reduced-dynamic orbits with different constraints for the piecewise-constant accelerations. Left: Differences between reduced-dynamic and kinematic orbits. Right: 6 hour orbit overlaps of subsequent 30 hour arcs. JB2008 and the 36-plate macro model are used. Lower figures are zooms of upper ones. The constraint can be tightened to roughly $5 \cdot 10^{-6}$ m/s^2 without degrading the orbits.

During the last three weeks, GOCE was tracked by Satellite Laser Ranging (SLR) on days 13/297 (Zimmerwald, 32 normal points), 13/298 (Monument Peak, 9 normal points), and 13/306 (Yaragadee, 8 normal points). Figure 8 shows the SLR residuals for the above reduced-dynamic orbits.

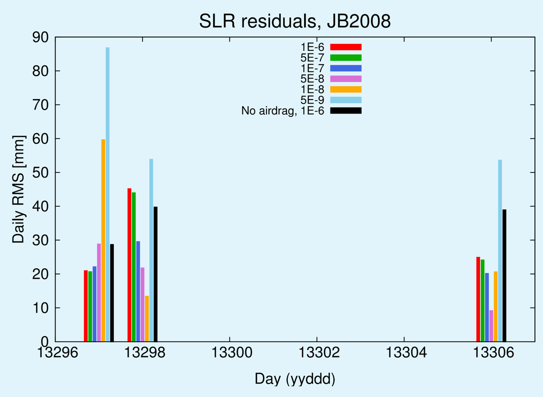

Figure 8: SLR residuals (differences between ranges as measured by SLR and as computed from the orbits) for reduced-dynamic orbits with different constraints for the piecewise-constant accelerations. It should be kept in mind that the number of SLR normal points is very low, reducing the significance of the statistics.

In order to use accelerometer measurements for the derivation of atmospheric densities along the GOCE orbit, the kinematic orbit positions computed with the Bernese GNSS Software were fit using the software package GINS of CNES. Figure 9 shows the impact of using different atmospheric models and orbit parametrizations.

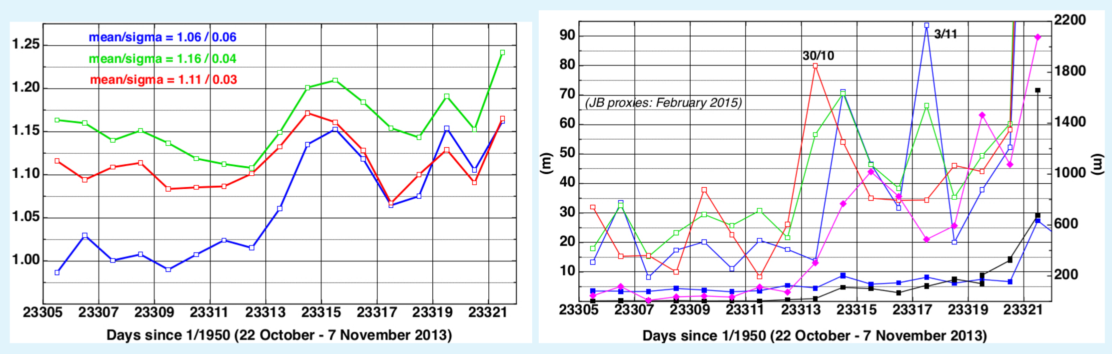

Figure 9: Fitting the kinematic GOCE positions with the GINS software of CNES. Left: Estimated drag scaling factors (1/day) when using the 6-plate macro model and DTM2013 (blue), MSISE-00 (green), and JB2008 (red). Right: RMS of fit when using the non-gravitational accelerations as provided by the accelerometers (black) or the 6-plate macro model. Blue solid: DTM2013 with 3 drag scale factors and 1 along-track 1/rev empirical acceleration per day. Blue open: DTM2013 with 1 drag scale factor per day. Green: MSISE-00 with 1 drag scale factor per day. Red: JB2008 with 1 drag scale factor per day. Pink, right y-axis: DTM2013 without drag scale factor.

Orbit extrapolations

For the orbit extrapolation a certain part of an arc of a precise orbit is fit using a given set of parameters (e.g., constant and 1/rev empirical accelerations, pseudo-stochastic pulses, not yet scaling factors for drag acceleration). Based on the state vector at the end of the arc and the adjusted parameters the orbit is extrapolated and compared to the data-based orbit of the subsequent day.

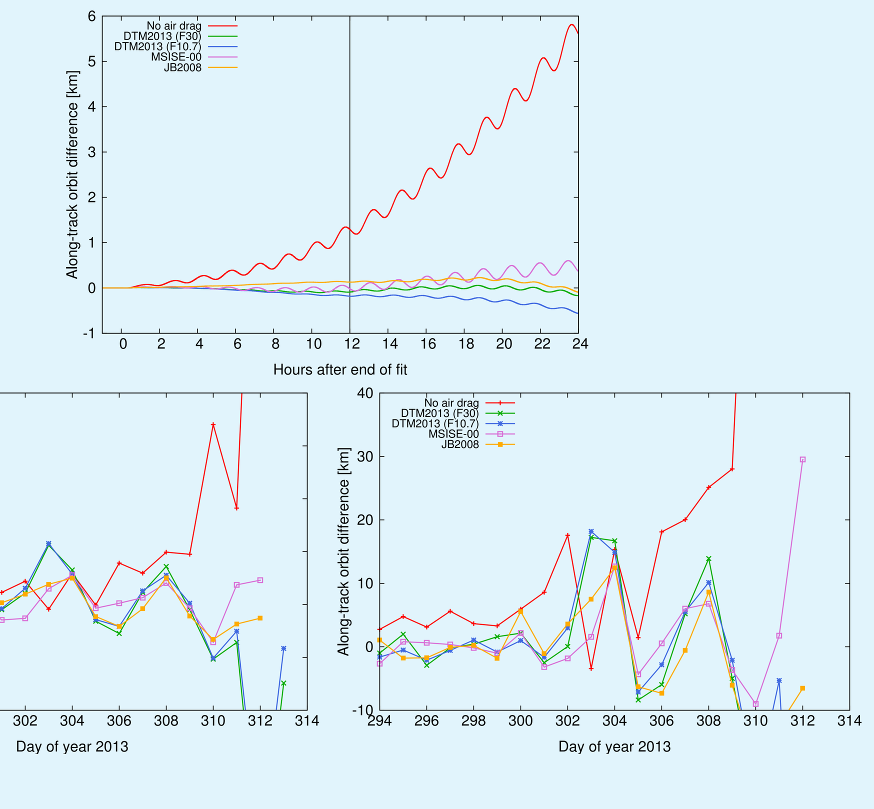

Figure 10: Top: Along-track (= main) extrapolation error for the orbit fit on day 13/297. Bottom: Along-track extrapolation error after 12 hours (left) and after 24 hours (right). For the air drag modeling the 36-plate macro model is used. A reduced-dynamic orbit is fit from 18:00 to 03:00, using constant empirical accelerations and 9 minutes pseudo-stochastic pulses in radial, along-track and cross-track direction. DTM2013 is used once with F10.7 (blue) and once with F30 (green) as proxy.

Conclusions and outlook

- The ESA study PREGO attempts to exploit the unique data set delivered by GOCE during its last days to improve re-entry prediction models. For this purpose high-accuracy GPS-based orbits are computed using the latest version of the Bernese GNSS Software.
- Air drag modeling has been implemented in the Bernese GNSS Software. This allows to substantially reduce the estimated empirical accelerations, to tighten the constraints of the piecewise-constant accelerations (resulting in orbits with more dynamical stiffness) and to reduce the error in the orbit extrapolation. Further improvements are expected once air drag scale factors are estimated.
- The on-board GPS receiver of GOCE produced a meter-accuracy navigation solution. While the last GPS phase measurement is at 17:15:20 UTC, the last position of this data set is at 22:46:10 UTC, and its appropriate inclusion can thus substantially improve the orbit extrapolation. Data problems (e.g., identical position at two or more different epochs) and the clarification of the related reference frame need to be addressed first.

References

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