Determination of Non-Conservative Accelerations from Orbit Analysis

Jose van den IJssel[1], Pieter Visser[1], and Roger Haagmans[2]

[1] Delft Institute for Earth-Oriented Space Research, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands, *jose@deos.tudelft.nl*
[2] ESA/ESTEC, Keplerlaan 1, 2200 AG, Noordwijk, The Netherlands

Summary. It is shown by means of an extensive simulation study as well as an experiment using real CHAMP data that it is feasible to accurately estimate non-conservative accelerations from precise GPS-based orbit perturbations. Assuming the availability of high-precision gravity field models, such as anticipated for GRACE and GOCE, an accuracy of better than 50 nm/s^2 seems possible for 30-seconds averaged accelerations. The remaining dominant error sources seem to be GPS receiver carrier-phase noise and GPS ephemeris errors.

Key words: CHAMP, GPS, precise orbit determination, non-conservative acceleration, accelerometer

1 Introduction

One of the key science instruments aboard CHAMP is the STAR accelerometer, which measures the non-conservative accelerations acting on the spacecraft in order to separate these from the gravitational ones when determining the gravity field from orbit perturbations. However, when a highly accurate gravity model and very precise GPS-based orbit determination are available, it is also possible to extract the non-conservative accelerations from the total accelerations. For satellites equipped with an accelerometer this could provide a good validation check for e.g. the obtained accelerometer calibration parameters and gravity models. For satellites without an accelerometer this could be used for e.g. atmospheric density modeling.

An extensive simulation study has been carried out in order to investigate the feasibility of determining non-conservative accelerations from orbit analysis. The CHAMP mission is used as the basis for this assessment study, which has the advantage that real accelerometer data are available. After a short description of the simulation scenario, the results of the simulation study are presented. Next, the results of experiments using real CHAMP data are shown and the paper concludes with a short summary of the results.

2 Simulation scenario

The non-conservative acceleration recovery experiments are largely based on our regular CHAMP precise orbit determination (POD) infrastructure [1].

The core of this infrastructure is the well-known GEODYN software package [5]. The orbit determination strategy is based on a reduced-dynamic approach and uses ionospheric-free triple differenced GPS phase measurements along with precise GPS orbits computed by the International GPS Service. For the assessment study 1 day was selected with a high level of atmospheric perturbations, 25 September 2001. For this day, triple differenced GPS phase measurements have been simulated between the CHAMP satellite, the existing GPS constellation and a network of 50 ground stations, with a data rate of 0.1 Hz. The CHAMP orbit has been simulated using real accelerometer observations for the non-conservative accelerations and state-of-the-art models for the conservative accelerations. This means that all non-conservative force models (drag, solar radiation and albedo) were switched off and replaced by CHAMP accelerometer observations, properly corrected for the advertised biases and scale factors. Full use was made of the observed along-track and cross-track accelerations, but the radial accelerations were put to zero because of the well-known electrode problems causing large biases and drifts in this direction [3]. Although the radial accelerations were put to zero in the simulation of GPS observations, in the recovery process constant empirical accelerations are estimated in all 3 directions, in order to have a realistic set of unknown parameters and the proper correlations.

3 Results

3.1 Simulations in an error-free environment

In order to assess the model error several recovery experiments are conducted based on error-free observations. The model error is caused by the fact that the simulated orbit is based on 10 seconds CHAMP accelerometer observations, whereas the empirical accelerations are accelerations averaged over their estimation time interval, which is in general larger than 10 seconds. Therefore it is expected that the model error will increase with longer estimation intervals for the empirical accelerations. Furthermore it is known that model errors usually increase with longer orbit arcs. The results shown in table 1 are in agreement with these expectations. The rms of the recovery error clearly decreases with smaller orbit arc and smaller estimation intervals. It can be concluded that for short arcs and estimation intervals the model error is very small, in the order of a few nm/s^2 (10^{-9} m/s^2), and can be ignored.

In the recovery use is made of a weighted Bayesian least-squares estimator. The recovery tests showed that attention had to be paid to the effect of observation weighting in relation to constraining the range of the empirical accelerations. Figure 1 shows this sensitivity for the last case of table 1. In each case the a priori σ of the estimated accelerations is kept fixed at a value of 10^{-6} m/s^2, which is close to the expected value of the parameters, and the observation data σ varies. It needs to be stressed that the optimal value of the observation data σ depends on the arc length and the estimation interval.

25 September 2001 Case	rms (nm/s^2) radial	along	cross	correlation along	cross	3D orbit error (cm)
24 hr arc + 20 min interval	84.23	13.92	18.10	0.9975	0.9893	3.03
24 hr arc + 10 min interval	37.71	17.47	12.13	0.9966	0.9882	1.57
24 hr arc + 5 min interval	34.96	13.93	12.40	0.9981	0.9844	1.28
5 hr arc + 5 min interval	18.94	11.35	6.06	0.9987	0.9979	0.71
5 hr arc + 2 min interval	6.71	4.59	2.32	0.9998	0.9996	0.12
5 hr arc + 1 min interval	5.20	3.29	1.38	0.9999	0.9999	0.05
5 hr arc + 30 sec interval	5.28	2.37	1.15	0.9999	0.9999	0.05

Table 1. Error-free simulation recovery results obtained with different orbit arcs and estimation intervals.

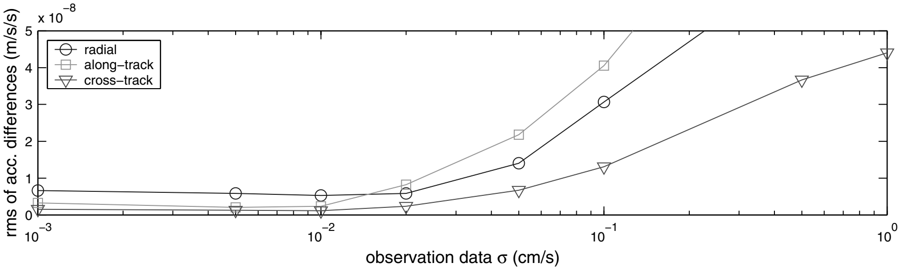

Fig. 1. Recovery errors in 3 directions for the error-free simulation using a 5-hour arc and a 30-seconds estimation interval.

The upper part of figure 2 shows for the last case of table 1 the estimated along-track accelerations as a function of time. The orbit arc is taken at the last 5 hours of the day, when a severe geomagnetic storm occurred. In the figure several distinctive peaks are visible, which occur when the satellite flies over the magnetic poles of the Earth. At these polar regions the geomagnetic storm causes sharp atmospheric density fluctuations. For comparison, the true accelerations averaged over the empirical acceleration estimation interval are also shown. Clearly there is a strong agreement between the true and the estimated accelerations. The differences between the true and the estimated accelerations are also shown, and from these differences it is clear that the recovery error is slightly larger during the sharp peaks caused by the storm. The recovery error also shows a small edge effect at the beginning and end of the orbit arc. This is caused by the fact that the orbit is less well constrained at the edge of the arc in the reduced-dynamic orbit determination. To avoid this effect in this study the first and last 40 minutes of each arc are eliminated.

3.2 Simulations using realistic error sources

Table 2 shows the effect of several realistic error sources on the recovery accuracy. It is clear that the largest recovery error is caused by the current gravity model error. The CHAMP clone has an accuracy that is expected of current available gravity models that include CHAMP data. When a GRACE clone is used, with an accuracy that is predicted for the GRACE mission [6],

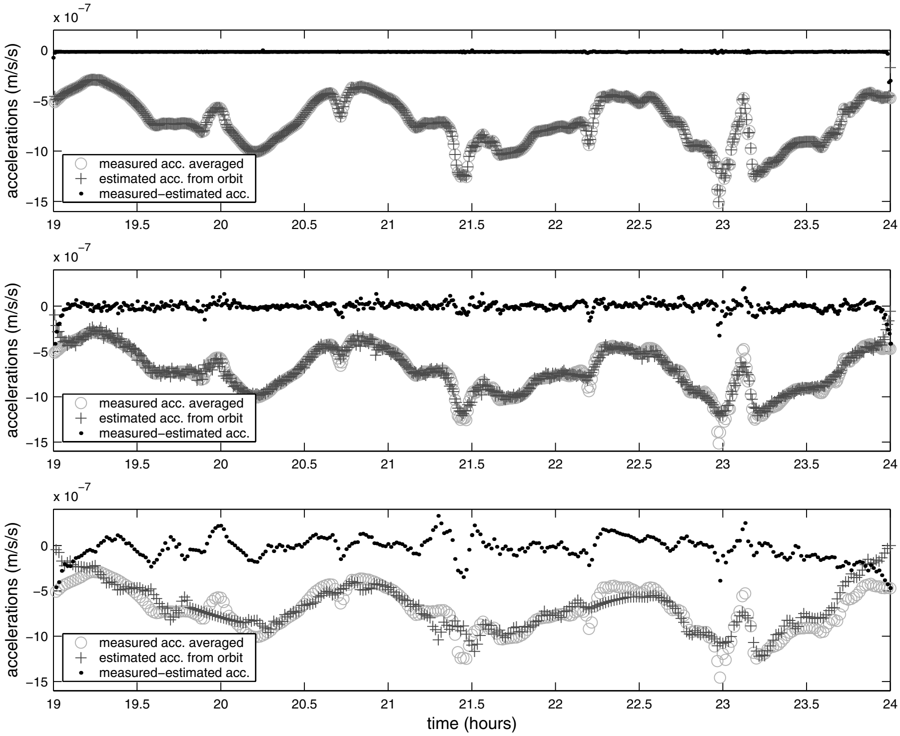

Fig. 2. Estimated along-track accelerations as a function of time. The accelerations in the upper and middle figure are obtained in respectively an error-free simulation and a simulation taking all error sources combined into account. In both simulations a 30-seconds estimation interval is used. The lower figure shows accelerations obtained with real CHAMP GPS data and a 1-minute estimation interval.

the recovery error reduces significantly. In that case the largest remaining recovery errors are due to observation noise and GPS ephemeris errors. The last lines of table 2 show that a recovery error of less than 50 nm/s^2 seems possible when all error sources combined are taken into account, assuming a precise post-mission GRACE model is available. The middle part of figure 2 shows the estimated along-track accelerations for the last case of table 2. Compared to the error-free case the recovery error has become larger, with the largest errors again during the sharp peaks. Most of the peaks are quite well determined, however, the sharpest peaks are no longer properly estimated.

3.3 Real CHAMP data processing

In addition to the simulation study, several recovery experiments have been conducted using real CHAMP observation data with a 30-seconds time interval. Table 3 shows the results of these tests. The results for the radial direction are very poor, which is due to the well-known accelerometer prob-

25 September 2001 Case	rms (nm/s^2) radial	along	cross	correlation along	cross	3D orbit error (cm)
error-free	5.20	3.29	1.38	0.9999	0.9999	0.05
noise (0.6 mm iono-free)	34.84	42.94	22.17	0.9868	0.9658	1.45
gravity (GRACE clone)	5.27	3.29	1.46	0.9999	0.9998	0.05
gravity (CHAMP clone)	141.83	102.19	157.40	0.9139	0.3964	0.06
tides	6.53	5.45	4.07	0.9997	0.9991	0.05
troposphere	11.55	7.80	5.80	0.9994	0.9976	0.18
GPS ephem. (5 cm 1-cpr)	45.12	29.28	22.37	0.9923	0.9657	1.93
station (1 cm)	7.40	4.17	2.62	0.9998	0.9996	0.21
reference frame	12.97	6.50	6.94	0.9996	0.9980	0.42
total (GRACE clone)	41.60	42.90	30.10	0.9852	0.9453	1.84
total (GRACE clone)*	44.75	47.91	37.26	0.9800	0.9154	1.84

Table 2. Recovery results for different simulated error sources using a 5-hour arc and a 1-minute estimation interval. The * indicates a 30-seconds interval is used.

25 September 2001 Case	rms (nm/s^2) radial	along	cross	correlation radial	along	cross
1 min interval	827.80	105.18	73.75	0.6071	0.8934	0.6371
5 min interval	827.53	83.85	70.37	0.6169	0.9297	0.6648
10 min interval	827.94	51.44	64.69	0.6346	0.9712	0.7046
20 min interval	824.85	31.38	45.00	0.7264	0.9863	0.8103

Table 3. Recovery results obtained with real CHAMP data using a 5-hour arc and different estimation intervals.

lems in this direction. The results for the along-track and cross-track direction are much better. However, for small estimation intervals the recovery error is still quite large. In the simulation study it was already shown that for small estimation intervals the recovery error due to the current gravity model error is expected to be large. To assess the effect of the current gravity model error on the recovery accuracy, a covariance analysis has been conducted using the EIGEN-1S gravity model [4], which is the nominal model in the recovery experiments. The covariance analysis is based on the diagonals of this model only, but tests with the EGM96 model [2] have shown that using diagonals instead of the full matrix gives results that are of the same order of magnitude. The results of table 3 and table 4 show a reasonable agreement. Finally, the lower part of figure 2 shows the along-track accelerations for the first case of table 3. The agreement between the estimated and true accelerations is quite reasonable, although there are some significant differences, especially during the sharp peaks. However, several peaks are still well observed.

4 Conclusions and outlook

The concept of estimating non-conservative accelerations from precise GPS-based total accelerations has been evaluated by an extensive simulation study and an experiment using real CHAMP data. Both studies have shown the feasibility of the concept. It is shown that even high-frequency density pertur-

Covariance model	averaging interval	rms (nm/s^2)		
		radial	along	cross
EIGEN-1S diagonal	1 min	523	390	339
EIGEN-1S diagonal	5 min	199	74	182
EIGEN-1S diagonal	10 min	137	37	130
EIGEN-1S diagonal	20 min	96	19	93
GRACE clone diagonal	1 min	0.16	0.07	0.14

Table 4. Predicted gravity field induced satellite acceleration errors.

bations, as e.g. caused by magnetic storms, can be observed indirectly from orbit perturbations. The simulation study indicates that the current gravity model error is probably the dominant error source and that the impact of anticipated gravity model improvements will be significant: an accuracy level of 50 nm/s^2 seems feasible for 30-seconds averaged non-conservative accelerations after completion of the GRACE mission. The remaining dominant error sources are expected to be GPS carrier-phase noise and GPS ephemeris errors. The assessment study also showed that the non-conservative acceleration estimation is a complicated optimization problem. It requires optimization with respect to arc length and observation weighting in conjunction with the estimation interval of the accelerations and their constraint level. Finally, it is expected that the estimation problem can be further improved by properly taking into account the correlations between triple differenced observation errors, which are so far neglected.

Acknowledgement. The GeoForschungsZentrum is acknowledged for providing the CHAMP observations and the EIGEN-1S gravity model. The Goddard Space Flight Center kindly provided the GEODYN software. Part of the study was supported by ESA funding in the framework of the SWARM end-to-end simulator study.

References

1. IJssel J van den, Visser P, Patiño Rodriguez E (2003) CHAMP precise orbit determination using GPS data. Adv Space Res *31(8)*: 1889–1895.
2. Lemoine F, Kenyon S, Factor J, et al. (1998) The development of the joint NASA GSFC and National Imagery and Mapping Agency (NIMA) geopotential model EGM96. NASA/TP-1998-206861.
3. Perosanz F, Biancale R, Loyer S, et al. (2003) On board evaluation of the STAR accelerometer. In: Reigber Ch, Luhr H and Schwintzer P (eds) First CHAMP Mission Results for Gravity, Magnetic & Atmospheric Studies, Springer: 11-18.
4. Reigber Ch, Balmino G, Schwintzer P, et al. (2002) A high quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S). Geophys Res Lett *29(14)*: 10.1029/2002GL015064.
5. Rowlands D, Marshall JA, McCarthy J, et al. (1995) GEODYN II system description. *1-5*, Contractor Report, Hughes STX Corp., Greenbelt, MD.
6. Visser P, Rummel R, Balmino G, et al. (2002) The European Earth Explorer Mission GOCE: Impact for the Geosciences. Ice Sheets, Sea Level and the Dynamic Earth, Geodynamics Series *29*, American Geophysical Union, edited by Mitrovica J and Vermeersen L: 95-107.