Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 47 (2011) 1020–1028
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

GPS-only gravity field recovery with GOCE, CHAMP, and GRACE

A. Jäggi *, H. Bock, L. Prange, U. Meyer, G. Beutler

Astronomical Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

Received 23 August 2010; received in revised form 5 November 2010; accepted 8 November 2010
Available online 13 November 2010

Abstract

Gravity missions such as the Gravity field and steady-state Ocean Circulation Explorer (GOCE) are equipped with onboard Global Positioning System (GPS) receivers for precise orbit determination (POD), instrument time-tagging, and the extraction of the long wavelength part of the Earth's gravity field. The very low orbital altitude of the GOCE satellite and the availability of dense 1 s GPS tracking data are ideal characteristics to exploit the contribution of GPS high-low Satellite-to-Satellite Tracking (hl-SST) to gravity field determination. We present gravity field solutions based on about 8 months of GOCE GPS hl-SST data from 2009 and compare the results with those obtained from the CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery And Climate Experiment (GRACE) missions. The very low orbital altitude of GOCE significantly improves gravity field recovery from GPS hl-SST data above degree 20, but not for the degrees below 20, where the quality of the spherical harmonic coefficients remains essentially unchanged. Despite the limited time span of GOCE data used, the gravity field of the Earth can be resolved up to about degree 115 using GPS data only. Empirically determined phase center variations (PCVs) of the GOCE onboard GPS helix antenna are, however, mandatory to achieve this performance.

Keywords: GOCE; Kinematic positions; Gravity field recovery; Polar gap; Phase center variations (PCVs); GPS

1. Introduction

In the last decade observations from the Global Positioning System (GPS) have been established as an important pillar for gravity missions. Since the launch of the CHAllenging Minisatellite Payload mission (CHAMP, Reigber et al., 1998) GPS sensors are not only used as a key tracking system for precise orbit determination (POD) but also for extracting the long wavelength part of the Earth's static gravity field (Reigber et al., 2003). Although current gravity missions such as the Gravity Recovery And Climate Experiment (GRACE, Tapley et al., 2004) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE, Drinkwater et al., 2006) are equipped with other core instruments, they still make use of the GPS high-low Satellite-to-Satellite Tracking (hl-SST) to support the determination of the low degree spherical harmonic (SH) coefficients of the Earth's gravity field. In the case of GOCE these coefficients are even exclusively determined from GPS data as the measurements of the core instrument, the three-axis gravity gradiometer, are band-limited (Pail et al., 2006).

GOCE was launched on 17 March, 2009 into a sun-synchronous, dusk-dawn orbit with an initial mean altitude of 287.91 km (mean distance from the geocenter minus the equatorial Earth radius). After a descent phase of about half a year the first measurement and operational phase (MOP-1) has started on 29 September, 2009 at a mean altitude of 259.56 km, which corresponds to a repeat cycle of 979 revolutions in 61 days. The very low Earth orbit (LEO) of the GOCE satellite is perfectly suited to exploit the contribution of GPS hl-SST to gravity field recovery and to compare the GOCE results with those obtained from CHAMP and GRACE, which have been providing GPS hl-SST data for more than 8 years.

Section 2 shortly reviews the methods of kinematic orbit determination and subsequent gravity field determination

* Corresponding author.
E-mail address: adrian.jaeggi@aiub.unibe.ch (A. Jäggi).

0273-1177/$36.00
doi:10.1016/j.asr.2010.11.008

underlying this article. Section 3 compares gravity field solutions obtained from GOCE, CHAMP, and GRACE, and discusses the impact of a high data sampling rate and the limitation due to the polar gap in the case of the sun-synchronous GOCE orbit. Section 4 has the focus on the phase center modeling of the GOCE GPS antenna and compares the results with the experience gained from the analysis of GRACE data. Section 5 compares the results with those obtained in the frame of the GOCE High-level Processing Facility (HPF, Koop et al., 2006).

2. Method used for GPS-only gravity field recovery

A three-step procedure is applied to gravity field recovery from GOCE, CHAMP, and GRACE GPS data according to the Celestial Mechanics Approach (Beutler et al., 2010). In a first step GPS observations are processed to derive kinematic LEO positions at the measurement epochs together with the associated covariance information (see Section 2.1). In a second step the kinematic LEO positions are weighted according to the covariance information and serve as pseudo-observations to set up normal equations on a daily basis for the unknown gravity field coefficients in a generalized orbit determination problem (see Section 2.2). In a third step the daily normal equations may be modified and are accumulated into monthly, annual, and multi-annual systems (see Section 2.3).

2.1. Step I: kinematic orbit determination

The geometric strength and the high density of GPS observations allows for a purely geometrical approach to determine kinematic LEO positions at the observation epochs by precise point positioning (Švehla and Rothacher, 2004). The kinematic positions are determined in a standard least-squares adjustment process of GPS observations together with all other relevant parameters without using any information on LEO dynamics. A band-limited part of the full covariance matrix of kinematic positions may be efficiently derived in the course of kinematic orbit determination.

The high-rate satellite clock corrections (Bock et al., 2009) and the final GPS orbits from the Center for Orbit Determination in Europe (CODE, Dach et al., 2009) are used together with attitude data from the star trackers to process the undifferenced Level 1b GPS carrier phase tracking data of the CHAMP, GRACE, and GOCE mission for kinematic orbit determination.

GRACE 30 s kinematic positions were computed at the Astronomical Institute of the University of Bern (AIUB) for various studies on LEO POD (e.g., Jäggi et al., 2009b) and for gravity field recovery with inter-satellite K-band data (Jäggi et al., in press), whereas CHAMP 10 s kinematic positions were used to exploit GPS-based gravity field recovery (Prange et al., 2010). GOCE 1 s kinematic positions are computed at AIUB in the frame of the GOCE HPF as part of the GOCE precise science orbit product (Bock et al., 2007). They are provided to the user community together with a band-limited part of the covariance matrix covering four off-diagonal blocks (EGG-C, 2008).

Kinematic positions are particularly sensitive to a correct modeling of the antenna phase center location as no constraints are imposed by dynamic models on the epoch-wise estimated positions. Special care has to be taken to empirically correct for phase center variations (PCVs) of the LEO GPS antennas in order not to deteriorate the kinematic positions and the subsequent gravity field recovery (Jäggi et al., 2009b). If not stated differently, empirical PCVs are used for kinematic orbit determination in this article.

2.2. Step II: generalized orbit determination

The equation of motion of a LEO satellite including all perturbations reads in the inertial frame as

$$\ddot{\boldsymbol{r}} = -GM\frac{\boldsymbol{r}}{r^3} + \boldsymbol{f}_1(t, \boldsymbol{r}, \dot{\boldsymbol{r}}, q_1, \ldots, q_d), \qquad (1)$$

where GM denotes the gravity parameter of the Earth, $\boldsymbol{r}$ and $\dot{\boldsymbol{r}}$ represent the satellite position and velocity, and $\boldsymbol{f}_1$ denotes the perturbing acceleration. The initial conditions $\boldsymbol{r}(t_0) = \boldsymbol{r}(a, e, i, \Omega, \omega, T_0; t_0)$ and $\dot{\boldsymbol{r}}(t_0) = \dot{\boldsymbol{r}}(a, e, i, \Omega, \omega, T_0; t_0)$ at epoch t_0 are defined by six Keplerian osculating elements, e.g., $a, e, i, \Omega, \omega, T_0$. The parameters $q_1, \ldots, q_d$ in Eq. (1) denote d additional parameters considered as unknowns, e.g., arc-specific orbit parameters and general parameters such as gravity field coefficients.

In a first step a priori orbits for gravity field determination are computed on a daily basis. Based on a selected a priori force model (defined by an a priori gravity field model, ocean tide model, etc.) the kinematic positions, weighted according to the covariance information from Section 2.1, are fitted by numerically integrating the equation of motion (1) and by adjusting arc-specific orbit parameters. Efficient numerical integration techniques are applied to solve the variational equations (Beutler, 2005) in order to obtain the required partial derivatives. As accelerometer data need not necessarily be taken into account to derive GPS-only gravity field solutions of high quality (Prange et al., 2009), arc-specific empirical parameters are set up in addition to the six Keplerian osculating elements. Constant and once-per-revolution empirical accelerations acting over the entire daily arcs are set up in the radial, along-track, and cross-track directions to compensate for the main part of the unmodeled non-gravitational perturbations. In analogy to Jäggi et al. (2009a), remaining deficiencies are captured by setting up low-degree polynomials (degree 3) for the along-track accelerations and, in particular, by estimating additional pseudo-stochastic pulses (instantaneous velocity changes) at predefined epochs for the radial, along-track, and cross-track directions. Pseudo-stochastic pulses do not affect the LEO trajectory in-between the pulse epochs and are thus well suited for gravity field recovery. A