BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. 40, N. 3-4, pp. 303-307; SEP.-DEC. 1999

GOCE sensor combination and error analysis

H. OBERNDORFER[(1)], R. DOROBANTU[(1)], C. GERLACH[(1)], J. MÜLLER[(1)], R. RUMMEL[(1)], N. SNEEUW[(1)], R. KOOP[(2)], P. VISSER[(2)], P. HOYNG[(3)], A. SELIG[(3)] and M. SMIT[(3)]

[(1)] *Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Germany*

[(2)] *Delft Institute for Earth-Oriented Space Research, Delft University of Technology, The Netherlands*

[(3)] *Space Research Organization Netherlands, Utrecht, The Netherlands*

(Received October 4, 1998; accepted August 5, 1999)

Abstract. GOCE (Gravity field and steady-state Ocean Circulation Explorer mission) is one of the candidates of ESA's planned explorer programme. The aim of GOCE is to provide a global model of the Earth's gravity field with high spatial resolution and high accuracy. A combination of different sensors is used to determine the gravity field. The simulation of the gradiometer measurements and the propagation of error sources onto the end-products is performed by the SID consortium which consists of three organisations: The Istitut für Astronomische und Physikalische Geodäsie (IAPG), the Delft Institute for Earth-Oriented Space Research (DEOS) and the Space Research Organization Netherlands (SRON). The goal is to provide a reliable error budget for the GOCE system, identify its weaknesses and limitations and make a complete error analysis of the mission. By a spectral analysis of simulated time series of GPS and Gradiometer data, it is possible to estimate the accuracy and resolution (up to degree and order 250) of the gravity field to be determined by GOCE.

1. Introduction

The launch of the ESA mission GOCE, is envisaged for the year 2003 (ESA 1996). The project is one of four selected missions in ESA's Earth Explorer Programme (GOCE Phase A started in July 1998). A combination of different sensors is used to measure the spatial variations of the gravity field on board an Earth-orbiting spacecraft. On one hand, the satellite itself is the

---

Corresponding author: H. Oberndorfer; Institut für Astronomische und Physikalische Geodäsie (IAPG), Technische Universität München, Arcisstr. 21, D-80290 München, Germany; phone: + 49 89 289 23185; fax: +49 89 289 23178; e-mail: helmut@alpha.fesg.tu-muenchen.de

© *1999 Osservatorio Geofisico Sperimentale*

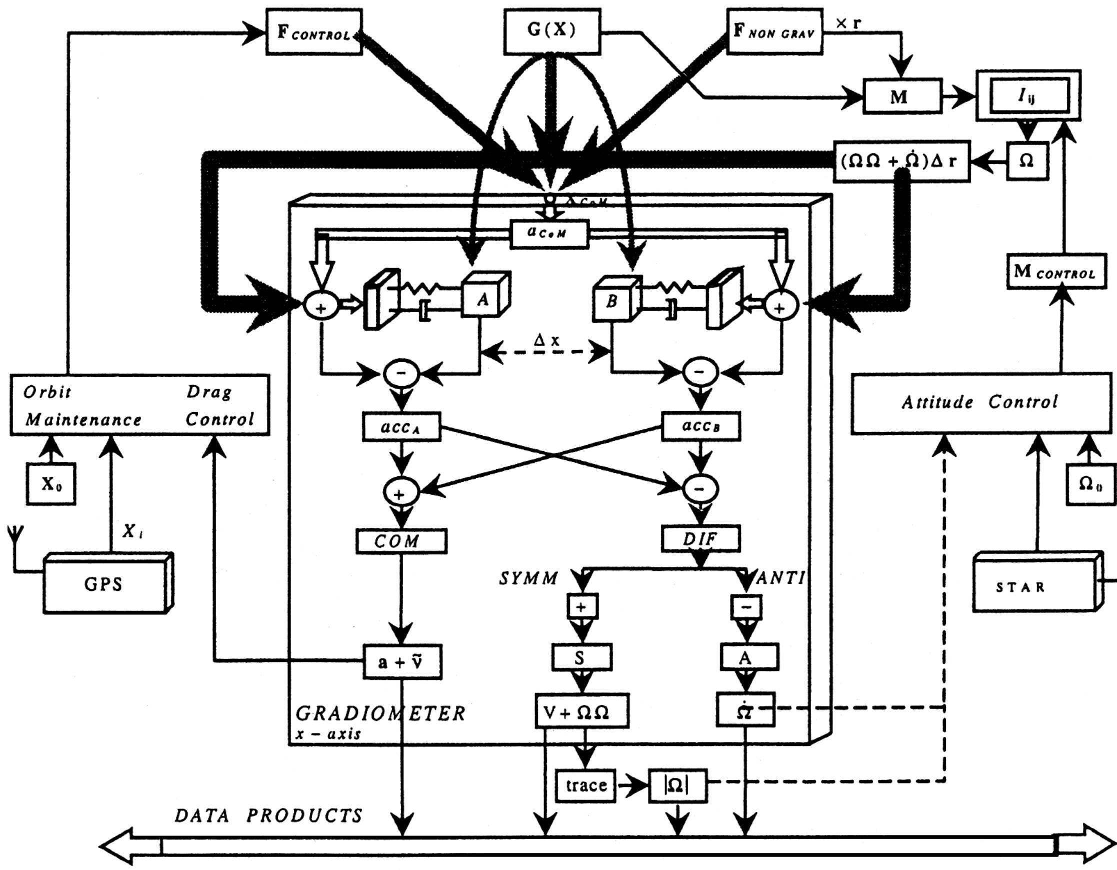

Fig. 1 - Interaction of forces, sensor and control loops of GOCE.

test mass which is tracked by GPS (high-low Satellite-to-Satellite Tracking SST), on the other, the accelerometers are combined into a gradiometer (Satellite Gravity Gradiometer SGG) to measure gravity gradients. To meet the mission requirements, it is necessary to observe the dynamics of the satellite disturbed by non-gravitational forces, and to control these effects by thrusters or correct them in post-processing. Therefore, GPS star trackers and the gradiometer are employed for orbit control, precise positioning, orientation and gravity field measurements. The SID consortium's objective is to provide a reliable error budget for the GOCE system, identify its weaknesses and limitations and make a complete error analysis of the mission. The consortium is aided by the space division of Alenia Aerospazio, Torino, which is also the prime contractor of the GOCE Phase A Study. A complete simulator of the gradiometer has been developed within SID that describes the test mass motion as a mass-spring system. The outputs are gravity gradients *(V_{ij}^{out})* and measured, as if they were based on input gravity accelerations, S/C position, orientation and disturbing forces. The difference between input and output gradients caused by instrumental and measurement errors, results in errors in Power Spectral Densities (PSD's) which serve as input for further error analysis of the end-products (spherical harmonic coefficients, geoid heights, gravity anomalies). For this line of simulation the name *end-to-end* is used.

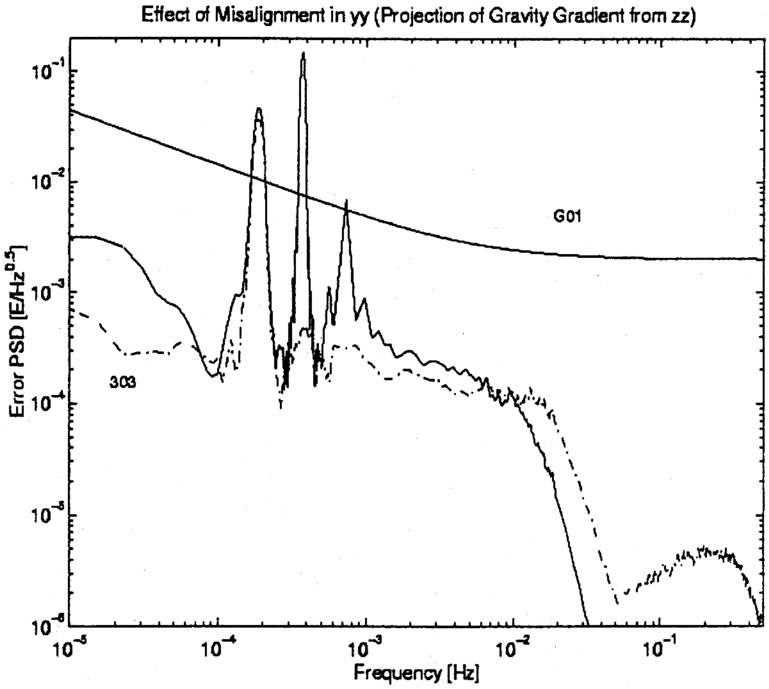

Fig. 2 - Effect of common misalingnment on V_{yy} (Projection of gravity gradient *zz*).

Besides error analyses, the coefficients themselves are recovered, which is one of the tasks of DEOS.

In particular, the effects of misalignment, instrument errors, calibration strategy, non-perfect drag-free control, etc. can be investigated. Moreover, the control loops for attitude and orbit determination (AOCS) and the drag-free control (DFC) are incorporated. A realistic simulation has to consider all possible mission scenarios: if, for example, the star sensors observe an unwanted attitude motion, the thrusters have to control this motion, or, if the accelerometers sense non-gravitational orbit perturbations, the orbit has to be reconstituted within the prescribed margins. These control processes, on the other hand, affect the orbit, the observations, and finally the end-products. Thus, the simulator has to take care of the control loops, that is the simulation has to take place in a *closed-loop.*

2. Interaction of forces, sensors and control loops

In the flow chart (Fig. 1) the interaction of forces, sensors and control loops is described. It is the basis for the closed-loop simulation. The central block is the satellite platform with the gradiometer instrument mounted on it. All linear forces acting on the platform/accelerometer frame, are focussed on the center of mass. Forces are listed in the first line, torques on the right upper block, angular effects in the third line. The left block shows orbit maintenance and the control of the linear accelerations, the right block the attitude control. The flow chart is based on the pre-phase-A report by Alenia. Linear acceleration control is divided into orbit maintenance and drag control in an extended measurement bandwidth. Angular control is shown in the right block. Kalman filtering should be used for intelligent sensor data processing to estimate for example angular velocities.

The main part is the gradiometer. It consists of 6 accelerometers in a so-called diamond configuration. In the flow chart, only two of them are shown. It describes the observation procedure of GOCE. Observables in gradiometry are differences of accelerations over short baselines, which can be interpreted as gradients of the gravitational field. On each axis of an assumed coordinate triad, two accelerometers are mounted, one on the positive, the other on the negative side.

Since the observations are performed on a rotating platform, inertial forces (centrifugal and Euler) are sensed. The observed gradient signal reads (Rummel, 1986):

$$\Gamma_{ik} = V_{ik} + \Omega_{ij}\Omega_{jk} + \dot{\Omega}_{ik}.$$

The first two tensors on the right hand side are symmetric, $\dot{\Omega}_{ik}$ is anti-symmetric. The gravitational signal is contained in V_{ik}, the rotational part in the Ω-terms. Naturally, apart from the above equation, the observations Γ_{ik} contain numerous error sources, as described in the previous section.

From the read-out of two accelerometers A and B in the same direction, both the difference and the means are derived. The former is denoted *differential mode*, the latter *common mode* acceleration. The differential mode, divided by the baseline, yields the gradient signal, one specific component Γ_{ik}. It is input for further processing of gravitational products and rotational quantities. The common mode acceleration contains all effects that lead to a linear disturbance of the satellite motion, drag forces, imperfections in the thrusters, and so on. Together with GPS observations, the common-mode acceleration is used for orbit restitution and DFC. On the other hand, the measurement with GPS and common-mode acceleration is the basis for high-low SST. Ideally, the tensor Γ can be split into a symmetric and an anti-symmetric part, leading to a separation of gravitational and rotational contributions. Subsequently, the angular velocities Ω are employed as indicators for the attitude control. The AOCS is aided by star sensors.

One problem to be considered, by the simulator, is the imperfection of any sensor or actuator. Obviously they operate only to a certain level of accuracy. Moreover, the geometry (position and direction) of the various instruments with respect to each other, can also only be realised to a certain accuracy. All these aspects affect the measurements, and consequently, the end-products. Tuhs they have to be considered in a realistic simulation.

3. Gradiometer errors

There are different types of error sources for gradiometer measurements: noise like Brownian noise or amplifier noise, relative or common misalignment and scale factor mismatching that cause, drag, angular acceleration and angular velocity as well as other gravity gradients to couple into the measurement. Fig. 2 shows, as an example, the error PSD of the V_{yy} component under the influence of relative misalignment of two accelerometers. Curve GO1 represents the mission requirement of 5 mEötvös/sqrt (Hz) withe noise and 1/f-behaviour below 1 mHz. The solid line shows the result of the simulator, and the dashed line the result estimated by the linear control theory.

Similarly, other error sources are investigated. This procedure allows the determination of a full error budget in the spectral domain, based on all types of realistic error sources, that have been and are identified during the whole project. During the mission all error sources have to be either measured with the same accuracy, compensated numerically or controlled.

4. Summary

The simulation of the GOCE mission is performed within a consortium so as to use everyone's specific knowledge. With the aid of the simulator, one can realistically compute the propagation of various error soruces onto the scientific end-products (*end-to-end*). It is possible to perform a complete spectral error analysis and to identify weaknesses and limitation of the mission. The simulation procedure is in a *closed-loop* in order to incorporate the interactions between the several system components (sensors, control loop, actuators).

Our investigations show that the intendend accuracy level ($\approx 10^{-3}$ E/sqrt(Hz)) can be achieved by GOCE. Therefore, the retrieval of the EArth's gravity field, up to degree and order 250, seems possible.

References

Aguirre-Martinez M.; 1997: *GOCE Error Analysis* JP/97-9-1571, Estec, Noordwijk.

Anselmi A.; 1996: *Gravity Field And Ocean Circulation Mission and System Disign Report.* GEM-RP-QI-0002, Alenia Spazio S.p.A.

Esa; 1996: *Gravity Field and Steady-State Ocean Circulation Mission.* Reports for Assessment: The Nine Candidate Earth Explorer Missions, ESA SP-1196 (1), ESA Publications Division, ESTEC, Noordwijk.

Hoyng R.; 1997: *High tides for GOCE*. SRON Document I.G. 0015R/97.

Rummel R.; 1986: *Satellite Gradiometry*. In: Sünkel H. (ed), Mathematical and Numerical Techniques in Physical Geodesy. Lecture Notes in Earth Sciences, vol. 7, Springer, Verlag, Berlin.

Sneeuw N., Koop R. and Schrama E.; 1996: *Global Gravity Field Analysis for the STEP Geodesy Co-Experiment Using GPS and Gradient Observations*. Proceedings of the STEP Symposium; 6-8 April 1993, Pisa, Italy, ESA WPP-115.