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Gradiometer calibration and performance verification: GOCE approach

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Abstract. The GOCE project aims at measuring the gravity gradient of the Earth with a noise spectral density of 1 to 5 mE/Hz$^{1/2}$, depending on the scenario, in a bandwidth going from 0.005 to 0.1Hz, and at an altitude of 250 km. An Electrostatic Gravity Gradiometer (EGG) is studied at ONERA, and requires (i) ultra-sensitive space accelerometers with a noise of around 4×10^{-13} m.s^{-2}/Hz$^{1/2}$, (ii) a very demanding calibration, and (iii) a very quiet environment inside the satellite (thermal and geometrical stability, fine drag compensation...). These performances cannot all be verified directly, on the ground, with the required level. The main reasons are the presence of 1g, and seismic noise. As a consequence, the EGG calibration, with its performance verification plan, demand a trade-off between the on-ground partial verifications, the in-flight ones, the pure calculations, and the combination of complementary approaches. This approach has been developed at ONERA, in parallel with experimental verifications, under ESA contract.

1. Introduction

Gravity Gradiometers have been studied in ONERA since 1987, first in the frame of the ARISTOTELES mission of ESA, cancelled in 1993, and now in the frame of the GOCE mission studied by ESA (see GOCE study team, 1996).

The present concept is to have six ultra-sensitive accelerometers mounted in a diamond configuration, composing a three axes gradiometer (see Fig. 1). The distance between two accelerometers of the same pair is of the order of 0.5m. Each accelerometer has two translation axes optimised for a noise of around 4×10^{-13} m.s^{-2}/Hz$^{1/2}$, and the third translation axis optimised to sustain one *g* on ground, thus allowing ground tests. The arrangement presented in Fig. 1 allows a certain redundancy (e.g. $1/2${Z3+Z4} can replace Z5), and the separate testing of each gradiometer axis on ground. It also allows the use of the gradiometer as an attitude sensor.

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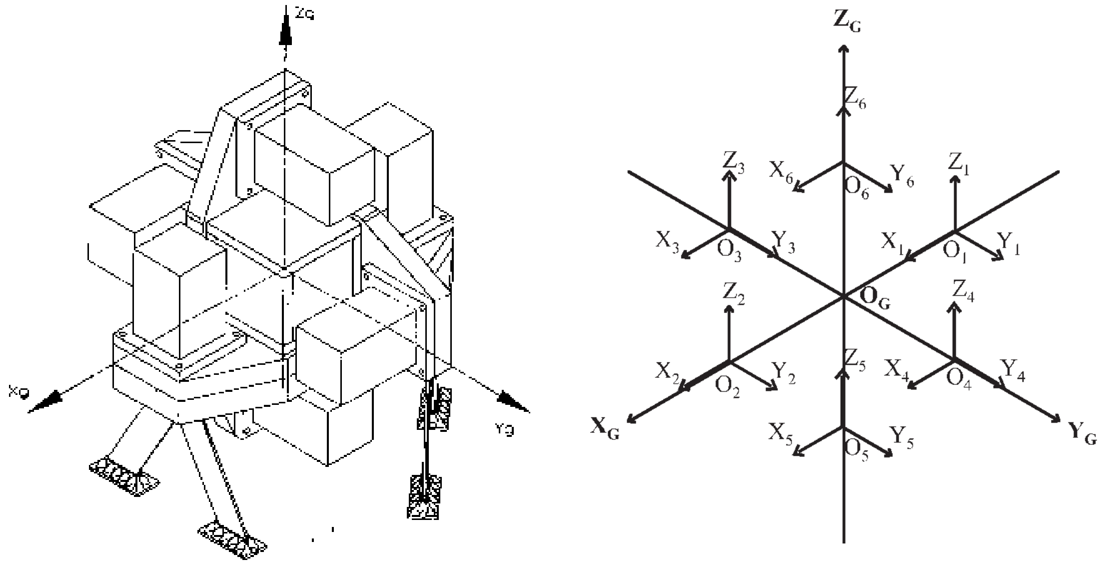

Fig. 1 - Diamond configuration of the EGG, composed of six accelerometers mounted on a C/C structure. Each accelerometer has two very sensitive axes (printed in bold) and a less sensitive one.

A Carbon/Carbon structure and a fine thermal control are studied by ALCATEL SPACE to support the accelerometers with the required geometrical stability.

2. The need for a calibration and verification plan

2.1. Accelerometer and gradiometer noise

Going into space is not only a way of having a global map of the Earth gravity field, it is also a way of having a very quiet environment in which accelerometers have very small accelerations to sustain. In GOCE, the total acceleration applied on each accelerometer should be of the order of 10^{-6} m.s^{-2}, mainly due to the gravity gradient and the angular acceleration (i.e. 4×10^{-6} s^{-2}) multiplied by the EGG half baseline of 0.25 m. This environment is not available on the ground, mainly because of one g. Present ONERA ground tests of space accelerometers reach a noise spectral density of around 3×10^{-9} m.s^{-2}/Hz$^{1/2}$, at about 0.1Hz, with a 1/sqrt(f) increase at lower frequencies. This ground test limit does not allow us to verify, directly, the performance of accelerometers for GOCE, nor the stability of the mounting structure. It is then necessary to establish a verification plan which aims at verifying, as far as possible, the stability of the structure and the noise sources in the accelerometers.

2.2. Accelerometer and gradiometer calibration

Several parameters need to be calibrated before the gravity gradient measurement is possible

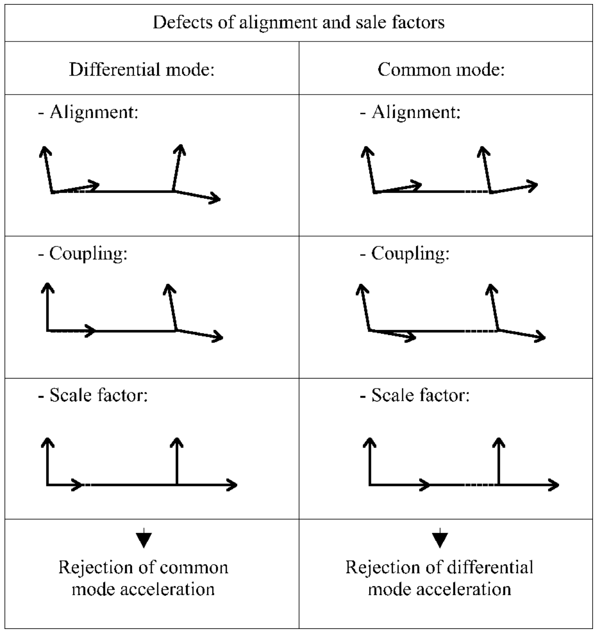

Fig. 2 - Scale factors, alignments and couplings, must be calibrated to reject unwanted accelerations of the spacecraft.

(see Fig. 2). The scale factors of two accelerometers of the same pair, must be matched with a relative error smaller than 10^{-5}, and the misalignments and couplings between axes must be known with an error smaller than 10^{-5} rad, in order to reject the residual accelerations due to the spacecraft acceleration (~ a few 10^{-8} m.s^{-2}/Hz$^{1/2}$) and attitude motion (~ a few 10^{-8} rad.s^{-2}/Hz$^{1/2}$). This value of 10^{-5} cannot be obtained directly through its manufacturing, and demands a fine calibration procedure.

3. The calibration and verification approach

3.1. Sharing of responsibilities

The performances to be verified during the development of the mission have been divided into four categories, which are presented below, with some examples of their contents. Each category presents sub-categories, among which the operation (does it work ?), the noise performance, and the calibration performance.

1. At the accelerometer level: the accelerometer operation, the intrinsic acceleration noise (effect of a discharging gold wire, effect of potential contact differences, etc.), the calibration of the absolute scale factor and the non-linearity, the bias, etc.;
2. at the gradiometer pair level: the operation, the differential acceleration noise, the calibration of misalignments and the scale factor difference of the two accelerometers, the stability of misalignments and scale factors, etc.;

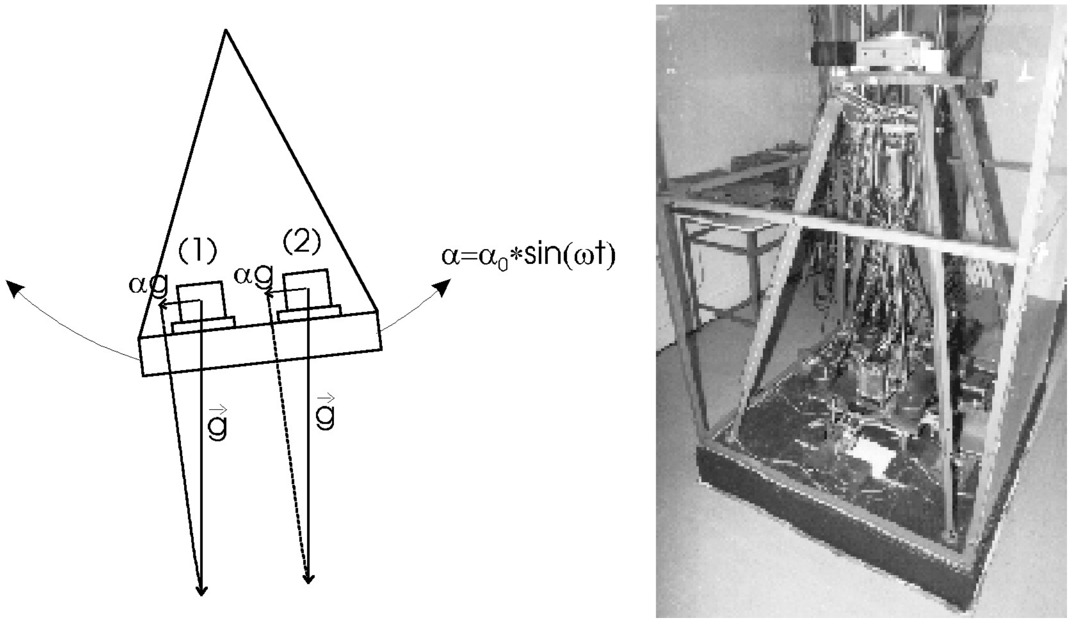

Fig. 3 - Scale-factor matching of two accelerometers by shaking the test bench with a sine wave. The matching is achieved when the sine wave projection of g disappears from the differential mode.

3. at the gradiometer level: coefficient of the Thermal Expansion of the structure, thermal control operation and performance, misalignments among the three gradiometer axes, etc.;
4. at the satellite level: drag-free operation and performance, differential acceleration due to mass motion in the satellite, misalignment of the EGG with the satellite, and its stability, etc.

3.2. Examples

Some items can be verified on the ground, others in flight. Some can be verified directly, others indirectly. Some can be totally verified, others only partially. Three very different examples are given below.

EXAMPLE 1. - The accelerometer operation can be totally verified on the ground thanks to drop-tower tests, as performed since 1996 for several flight models produced at ONERA. An example is given in Touboul (1996).

EXAMPLE 2. - The effect of a discharging wire can be totally verified, indirectly, on the ground. Such a discharging wire is sometimes used, between the proof-mass and the cage of the accelerometer, in order to avoid the charging of the proof-mass because of charged particles encountered in orbit. This gold wire, 5 microns in diameter, has a damping which brings acceleration thermal noise on the proof-mass (fluctuation-dissipation theorem, see McCombie, 1953). This damping and its thermal noise has been measured thanks to a torsion pendulum and extrapolated to space accelerometers (see Willemenot, 1997).

EXAMPLE 3. - The scale factor matching of two accelerometers can be verified directly, partial-

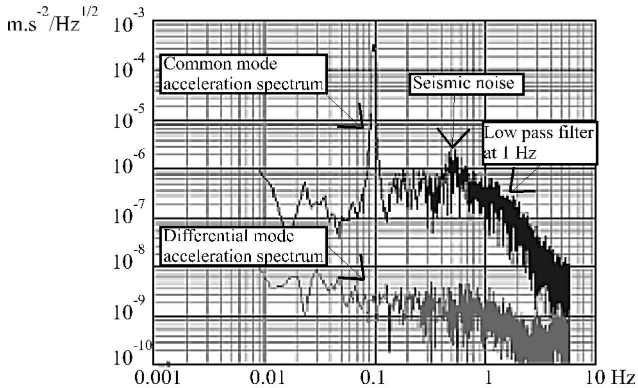

Fig. 4 - Experimental result of scale factor matching of two accelerometers.

ly on the ground (relative error of ~10^{-4}), and directly, totally, in flight (relative error ~10^{-5}). The flight verification is done by shaking the satellite and measuring the differential signal, that must be null when the matching is achieved. The on-ground partial verification is done by shaking a dedicated test bench (see Fig. 3) on which the two accelerometers are mounted. With the accelerometer flight configuration, a maximum excitation sine wave of amplitude 3×10^{-6} m.s^{-2} can be measured in common mode. Given a differential mode noise of 3×10^{-9} m.s^{-2}/Hz$^{1/2}$ due to ground test limits, the signal to noise ratio becomes 10^5 after 11 hours of integration. This integration time can be lower, down to around 10 minutes, by switching to an "acquisition mode" that can sustain 3×10^{-5} m.s^{-2} in order to facilitate both the ground tests and the drag-free system acquisition in flight.

The feasibility of such a scale factor matching, with a resolution better than 10^{-5}, has been recently demonstrated, with two accelerometer lab models, on the ONERA test bench, with an excitation signal of ~3×10^{-5} m.s^{-2} and 10 minutes of integration. Fig. 4 shows this result, with a peak at 0.1Hz in the common mode acceleration spectrum, and a differential signal smaller than 10^{-5} times the common signal at this frequency, showing the scale factor matching with a resolution better than 10^{-5}. It has been shown that this matching is stable over at least one week, and a campaign is being held to demonstrate a much better stability.

4. Conclusion

The verification approach of the Electrostatic Gravity Gradiometer is briefly described above. The ONERA experiments, on going for years, and the most recent ones presented above, show the interest and the maturity of the EGG concept.

In addition, the GOCE mission benefits from the experience of ONERA in producing accelerometer flight models (see Touboul, 1996; 1998), together with the experience of ALCATEL SPACE in stable structures for space instruments (Bailly, 1997).

The results obtained in this study are also very interesting to analyse the performance possibilities of a future ground gravity gradiometer.

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