IN-ORBIT DATA VERIFICATION OF THE ACCELEROMETERS OF THE ESA GOCE MISSION

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Abstract. The ESA GOCE mission aims to map Earth gravity field in unprecedented detail. The Gradiometer is the instrument which makes possible the high resolution restitution of the gravity field to the science communities. The tri-axes Gradiometer of the GOCE Mission is conceived around six electrostatic accelerometers developed by ONERA. The satellite was launched on March 17th, 2009 and the gradiometer was switched on in Science mode on April 7th. Since, the accelerometers are continuously feeding the science channel with data, first during the commissioning and calibration phases, then during the first measurement phase started in September 2009. The paper will illustrate the in-flight behaviour of the six accelerometers as deduced from the analysis of their output signals.

Keywords: GOCE, gravity, gradiometry, accelerometer, noise

1 Introduction

The ESA GOCE mission aims to map Earth gravity field in unprecedented detail. The Gradiometer is the instrument which makes possible the high resolution restitution of the gravity field to the scientific communities to advance our understanding of global ocean circulation patterns and climate change.

The tri-axes Gradiometer of the GOCE Mission is conceived around six electrostatic accelerometers developed by ONERA. Servo-controlled electrostatic suspension provides the control of the sensing proof mass of each accelerometers in terms of linear and rotational motion. Three pairs of identical accelerometers, which form three gradiometer arms, are mounted on an ultra-stable structure. From the difference between accelerations measured by each pair of accelerometers, it is possible to derive the gravity gradient components as well as the perturbing angular accelerations. GOCE is the first mission to access directly to the of Gravity Gradient Tensor (GGT) components in orbit.

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2 GOCE accelerometer

The main functions of the accelerometric chains are to provide:

- The time-stamped voltages corresponding to the 3D linear accelerations at the position of each accelerometer sensor, delivered at 1 Hz, they are used to retrieve the final components of the GGT.
- The real time 3D linear accelerations of the satellite at the centre of the gradiometer, close to the spacecraft centre of gravity. They are delivered to the Drag Free and Attitude Control System (DFACS) at 10 Hz.

The schematic of the control loop for the ultra-sensitive Y and Z axes is shown on Fig. 1.

2×2 pairs of electrodes control 3 degrees of freedom (dof): the Y and Z translation and the ϕ rotation (roll angle). Going from the 4 electrode voltages at the position detector output to the three dof to be processed by the controller needs a digital combination matrix at the position detector output and a recombination matrix for the inverse operation at the controller output. Main functions inside the loop are provided by the proof-mass position sensor, the digital controller and the action which applies the needed control voltages back to electrodes.

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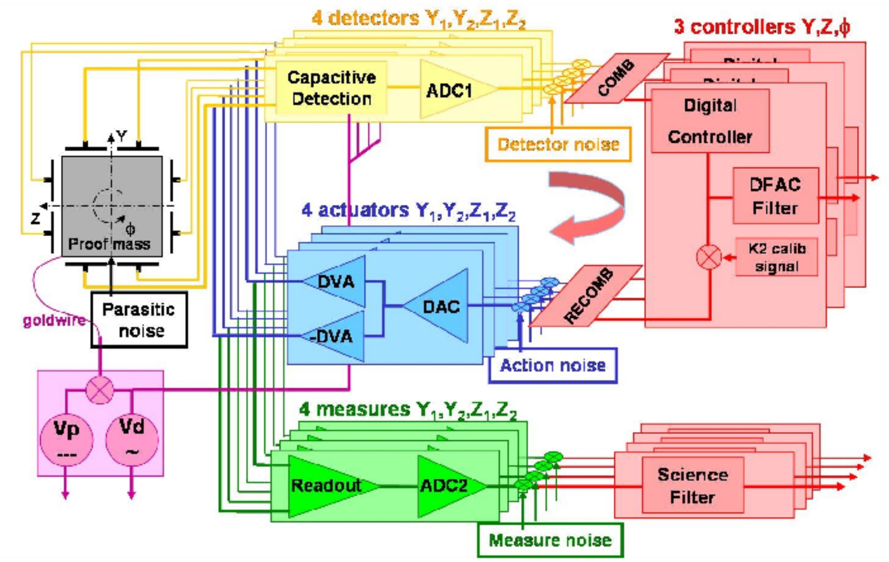

Fig. 1. Schematics of the Y/Z axes control loop

3 Drag-Free Performance

The performance drag free was evaluated for the first time during the commissioning phase in fine drag free mode. On Fig. 2 the red spectrum represents the spectral density of the residual satellite acceleration along the track, with a mean value of $10^{-9}\ m/s^2/\sqrt{Hz}$ below 100 mHz, to be compared with the specified value (the green line) of $2.5\ 10^{-8}\ m/s^2/\sqrt{Hz}$. The drag free control system of the satellite, in which the accelerometers are involved as the detectors, was found to be working perfectly providing an excellent rejection of the common mode acceleration. As the 6 accelerometers have a ultra-sensitive measurement axis along the X, in track, direction, the noise figure of the accelerometer DFACS channel can be computed from the combination of the 6 signals. The spectral density of the noise is shown on Fig. 2 by the blue spectrum.

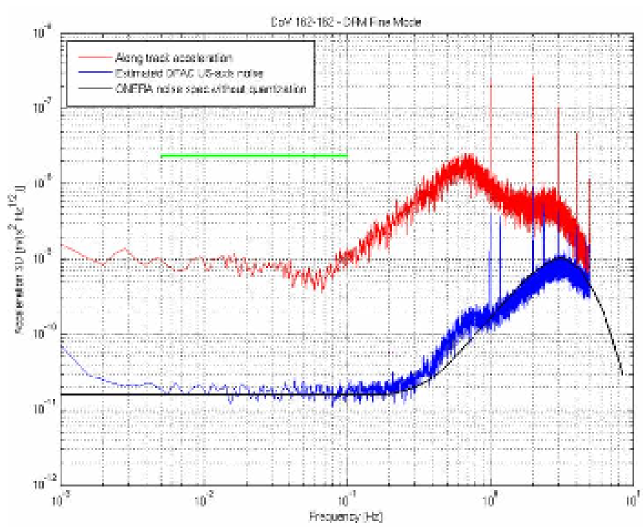

Fig. 2. Drag Free performance: residual satellite acceleration and accelerometer DFACS channel noise (Thales Alenia Space Italy)

The spectrum perfectly matches the predicted noise (black line), leading to the conclusion that the position detection noise and the actuation noise (DVA + DAC), which are the main contributors in the respective frequency bandwidth, have been correctly modeled and suffered no modification during the launch phase.

4 In-orbit verification

As the accelerometer is nominally the main contributor of the GOCE performance in the Upper Measurement Bandwidth (UMBW), several tests were performed for an in-flight evaluation of the accelerometer noise contributor, in the science channel. Some of these verifications are detailed hereafter.

4.1 Stiffness verification

Parasitic stiffness, preventing the proof-mass to move as freely as expected, can be present within the sensor cage. High cleanliness integration conditions and dedicated on ground test allowed to check the correct behaviour of the proof-mass under levitation. However, as parasitic stiffness can occur in space after launch, it is checked in flight with a still better accuracy than on ground test. Such a test is performed by moving the proof-mass inside the cage and recording the corresponding variation of the accelerometer bias. The measured value shall be compared to the value of the nominal stiffness including the negative electrostatic stiffness about $-510^{-2} m/s^2/m$ and the gold wire contribution at a level of $10^{-4} m/s^2/m$.

The stiffness was estimated along the in-line axis of each arm. The results for the 6 accelerometers are in agreement with the expected values, within the accuracy of the estimation of the accelerometer bias. Fig. 3 presents the results of such verification for the three gradiometer arm.

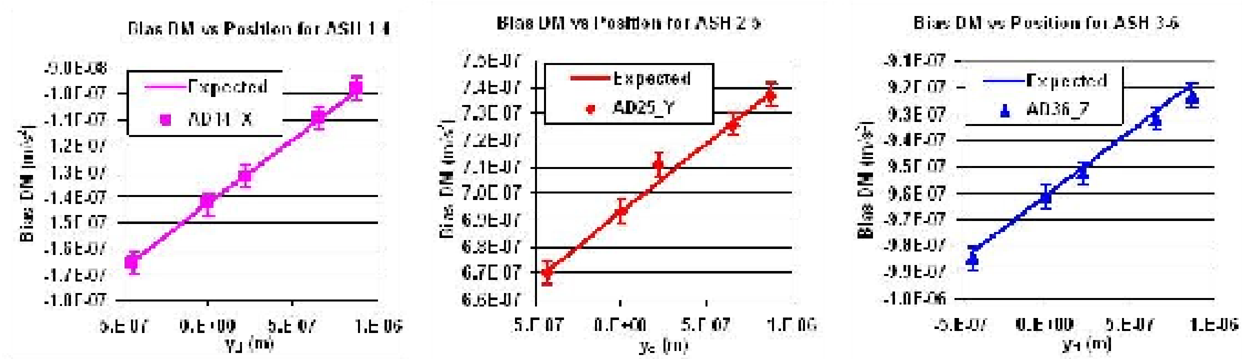

Fig. 3. Verification of the theoretical stiffness of the first (left) the second (center) and the third (right) one-axis gradiometer.

4.2 Action and Science noise

Thanks to the digital control loop, it is possible to check the science noise by opening the control loop (PM no more in levitation) and by recording the science output. In this approach, the science noise is added to the action noise.

- Case 1: $V_{in} = 0$: A first verification is done with a null input at DAC level. In that case, the output noise is the sum of the action and science channel noise. Fig. 4a presents the results for the in-line axis of the OAGX arm. The measured noise is perfectly in agreement with the expected one from on-ground measurement. The same results are found for the 2 other arms.

- Case 2: $V_{in} \neq 0$: Due to the non-null input, there is an additional noise contribution due to the reference voltage stability of the ADC2. This test allows verifying this major contributor to the differential scale factor noise. Fig. 4b presents the results for the in-line axis of the OAGX arm. The measured noise is perfectly in agreement with the expected one as deduced from on-ground measurement. The same results are found for the 2 other arms.

5 Overall performance

The mission overall performance is evaluated by the amplitude spectral density (ASD) of the Gravity Gradient Trace, $(U_{XX} + U_{YY} + U_{ZZ})$. It is determined after the full calibration of the Gradiometer for the coupling and misalignments of the instrument axes, for the Scale factor and the quadratic factor of the accelerometers.

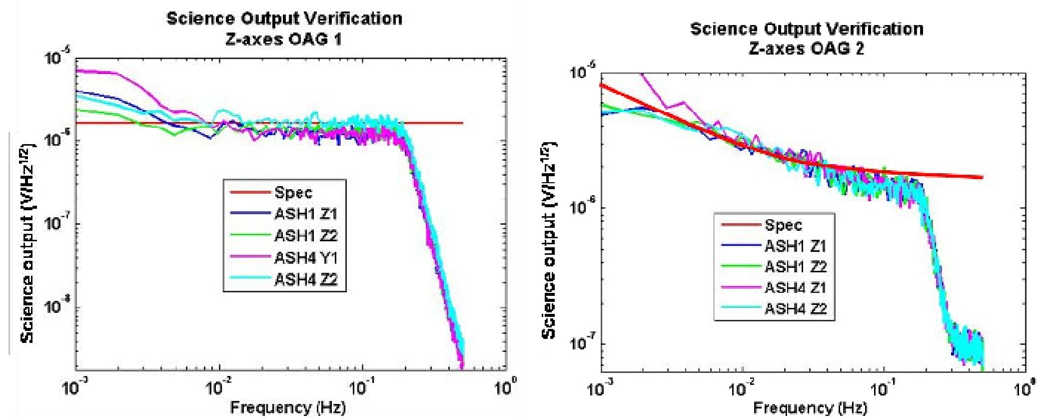

Fig. 4. In-flight verification of the action-science chain noise for in-line electrode of OAGX, (a)with null DAC input (left), (b) with non null DAC input (right)

The result deduced by Thalès Alenia Space Italy from the in-flight measurements shows that the in-flight trace value is 24 $mE/\sqrt{Hz}$ in the Upper MBW [40-100 mHz] (Floberghagen et al. 2010).

Although it is larger than expected, the performance of the gradiometer is very high and a gravity field model with high resolution and accuracy has already been obtained. The first GOCE Geoid, based on 2 months data, was presented in June 2010 by ESA at the ESA Living Planet Symposium in Bergen (Norway) (ESA 2010). Significant improvements were already observed in high resolution areas of the geoid and the gravity field model will be constantly improved with the continuous arrival of datas.

The origin of the performance deviation has not been yet elucidated. The in-flight tests of accelerometers, as described above, did not allow putting into evidence any unexpected behaviour of the accelerometers. A direct in flight evaluation of the accelerometer performance is not possible. Assuming a worst case estimation from the overall performance, the accelerometer noise performance would be within the range 3.1 10^{-12} $m/s^2/\sqrt{Hz}$ to 6.7 10^{-12} $m/s^2/\sqrt{Hz}$ (Marque et al. 2010).

This is the best performance never achieved in orbit by an accelerometer, 15 to 30 times better than the SuperSTAR accelerometer of the GRACE mission.

6 Conclusions

The 6 accelerometers are fully operational in orbit since 18 months as Drag-Free Sensors and as Science Instruments. From an operational point of view the return of experience after more than one year in orbit is a full success.

The verification of the in-flight electronic noise and accelerometer stiffness confirms the on-ground predictions. An identical behaviour is observed for the 6 accelerometers.

The level of 3 10^{-12} $m/s^2/\sqrt{Hz}$ verified in orbit, 15 to 30 times better than GRACE accelerometers, is the target performance required for the future generation of gravity mission. It is best performance never achieved in orbit by an accelerometer. The GOCE type accelerometers are today the best candidate for these future missions, with a high level of technological maturity.

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