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SOFTWARE TOOLS FOR THE VALIDATION OF THE IN-FLIGHT CALIBRATION PERFORMANCE OF THE MICROSCOPE SPACE MISSION

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Abstract. The MICROSCOPE space mission aims at testing the Equivalence Principle (EP) with an accuracy of 10^{-15}. The instrument will be embarked on board a drag-free microsatellite orbiting the Earth, and consists in a differential electrostatic accelerometer composed of two cylindrical test masses submitted to the same gravitational field but made of different materials. The electrostatic accelerations applied to the masses to maintain them relatively motionless are measured; inequality would demonstrate a violation of the universality of free fall.

The accuracy of the measurement exploited for the EP test is limited by our *a priori* knowledge of the instrument physical parameters. An in-orbit calibration is needed to finely characterize them in order to correct the measurement. The calibration procedures have been determined and their analytical performances evaluated. The two stages of the measurement processing are numerically simulated: first the calibration sessions, then the measurement correction using the estimated parameters in order to validate the mission performance on the EP parameter determination.

Keywords: MICROSCOPE, test of the Equivalence Principle, in-orbit calibration, measurement processing

1 Introduction

The MICROSCOPE space mission aims at testing the Equivalence Principle (EP). This principle is at the basis of General Relativity and has for main consequence the Universality of Free Fall: the acceleration of an object in a gravitational field is independent of its mass and its internal composition. It leads to the equivalence between the inertial mass (which measures the resistance of an object to a modification of its motion) and the gravitational mass (coupled to the gravitational field). The Universality of Free Fall has been tested throughout the centuries with an improving accuracy. Recently, sophisticated torsion-balances or Lunar laser ranging experiments have been conducted, leading to a record accuracy of a few 10^{-13} (Gundlach et al. 2009). However, the accuracy of these on-ground experiments is limited by the terrestrial environment's numerous perturbations. Some unification theories, representing alternatives to General Relativity and aiming at merging gravitation with the three other fundamental interactions, expect a violation of the EP at a level never tested before (Damour et al. 2002). Being performed in space, the MICROSCOPE mission will be able to overcome the terrestrial perturbations in order to test the Equivalence Principle with an accuracy of 10^{-15} (Touboul et al. 2001).

MICROSCOPE is a microsatellite developed by CNES with a contribution of ESA. It will orbit around the Earth at low altitude for a two years' mission. The launch of the satellite is scheduled for 2016. The on-board payload is composed of two differential electrostatic accelerometers developed by ONERA, each one consisting in two concentric cylindrical test masses in electrostatic levitation. The position of the masses is detected using a capacitive measurement, and a control loop keeps them at the center of the accelerometer cage. Both masses are submitted to the same gravitational field. For one of the differential accelerometer, the two masses are made of different materials. A difference between the measured forces applied to maintain them on the same trajectory would therefore indicate a violation of the Universality of Free Fall, and thus of the Equivalence

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Principle. The second accelerometer includes two test masses of the same composition and enables us to test the measurement accuracy.

The accuracy of the measurement exploited for the EP test is limited by our *a priori* knowledge of the instrument physical parameters. It is necessary to finely characterize them in order to correct the measurement. An in-orbit calibration of the instrument is therefore needed. Appropriate calibration procedures have been determined and their analytical performances evaluated. These procedures have been implemented in a numerical simulator in order to validate them numerically (section 2). The estimation of the instrumental parameters is used to correct the scientific measurement and therefore to evaluate the EP violation parameter with the best accuracy. A mission simulator has been developed in order to simulate the measurement processing and thus to validate the mission performances (section 3).

2 In-orbit calibration of the instrument

2.1 Necessity and principle of the in-orbit calibration

The ideal measurement of the MICROSCOPE instrument corresponds to the electrostatic acceleration applied to the internal or the external test mass to keep it relatively motionless at the center of the accelerometer. The real measurement provided by the instrument differs from the ideal measurement because of instrumental parameters: scale factors, couplings, misalignments and quadratic parameters.

The measurements provided for the internal and the external test masses are combined in a common mode (the half sum of both measurements) and a differential mode (the half difference of both measurements). The common mode acceleration is used as a command for the satellite Attitude and Orbit Control System (AOCS). This system compensates for the external non-gravitationnal perturbations, such as the residual drag or the Earth and Sun radiation pressure. The differential mode is used for the EP test.

This differential acceleration includes the potential violation signal due to a non-null EP violation parameter $\delta_{EP} = \frac{m_{g2}}{m_{I2}} - \frac{m_{g1}}{m_{I1}}$, where m_g is the gravitational mass and m_I is the inertial mass respectively of the internal test mass (index 1) and external test mass (index 2). A second order model of the differential measurement has been defined (Hardy et al. 2011). The form of the acceleration measurement along the $\vec{X}$ axis (which is the axis of the test masses cylinders as well as the most sensible axis) is:

$$\Gamma_{mes,dx} = \frac{1}{2}(\Gamma_{mes,1x} - \Gamma_{mes,2x}) = \frac{1}{2} \cdot g_x \cdot \delta_{EP} + \Gamma_{inst,x} \tag{2.1}$$

with:

- g_x the component of the gravitational acceleration along the $\vec{X}$ axis of the instrument;
- Γ_{inst} the perturbative acceleration reducing the accuracy of the EP parameter determination. This acceleration is composed of a stochastic part (noise of the instrument and of the drag-free system) that can be reduced by integrating the measurement over a large duration, and an harmonic part that is due to instrumental parameters (scale factors, off-centering between the two test masses that introduces effect of the Earth gravity gradient and the inertia gradient, misalignements and couplings between the axes of the two sensors or between the axes of the differential accelerometer and the axes of the instrument, quadratical parameters that introduces non linear terms).

The instrumental parameters reduce the accuracy of the estimation of δ_{EP}. The best performances possible for the instrument construction and integration in the satellite lead to a contribution of these terms incompatible with the mission's accuracy objective. It is therefore necessary to correct the measurement. An accurate estimation of the instrumental parameters is not possible on-ground, where the instrument is saturated. That is why in-orbit calibration sessions are needed.

The in-orbit calibration of the MICROSCOPE instrument consists in amplifying the effect of the parameter to be estimated so that the corresponding term is predominant in the measurement, and thus easily measurable. For this purpose, a strong signal at a known frequency is used: either a naturally strong signal is used (the Earth gravity gradient), or a strong signal is created by oscillating the satellite (through the AOCS system) or the test masses (through their control loop) at a chosen frequency and along or around a chosen axis.

A specific calibration procedure has been determined for each instrumental parameter. Each calibration session will last 10 orbits in order to reduce the noise to an acceptable level, and the complete calibration will be run at least twice during the mission, so as to take into account a potential drift of the parameters value with time.

The performances of the calibration procedures have been evaluated analytically (Levy et al. 2010). The results are compatible with the specification. However, this analysis cannot take into account all the effects that impact the calibration result, in particular the dynamics of the systems. In order to validate their performances numerically, the calibration procedures have been implemented in a simulator.

2.2 *The calibration simulator*

The calibration simulator has been developed in Simulink (figure 1). It simulates the instrument, the satellite AOCS loop and the external environment.

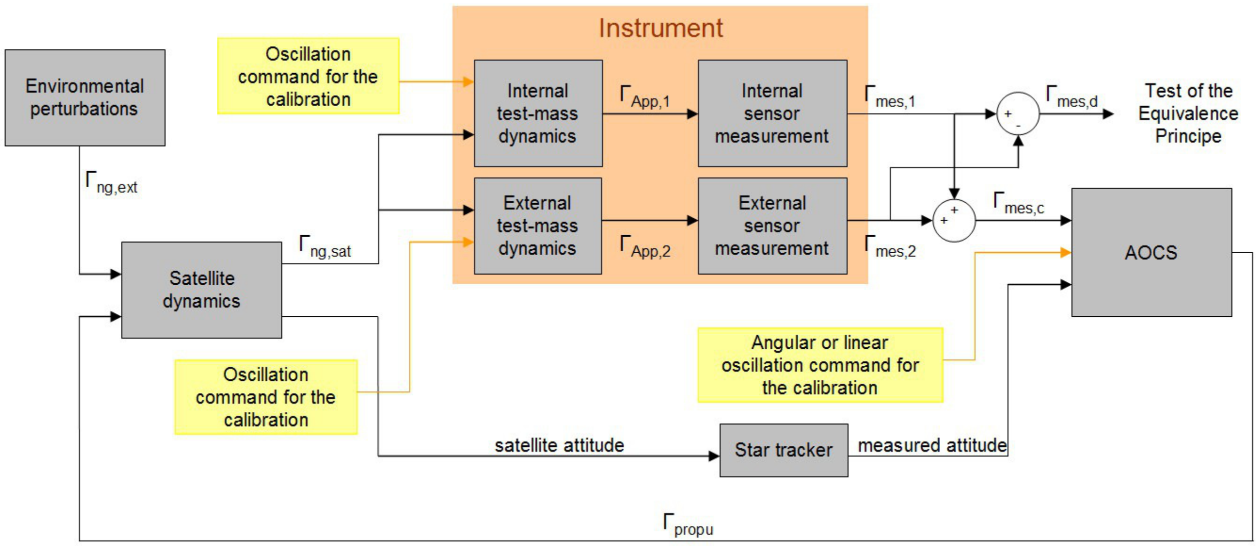

Fig. 1. The calibration simulator: the yellow blocks correspond to secondary inputs designed to oscillate the satellite or the test masses for the calibration.

The simulated differential measurement is processed to estimate the parameter to be calibrated: a pass-band filter is applied around the calibration frequency and a least squares inversion is used. A statistical study based on 100 simulations with a random initialization of the parameters to be calibrated has been conducted. The resulting accuracy on the instrumental parameters estimations is compatible with the specifications (Hardy et al. 2013). The performances of the foreseen calibration procedures are thus numerically validated.

3 Measurement correction

The in-orbit calibration provides an estimation of the instrumental parameters. These estimated values are used to correct the EP test measurement. In order to validate the complete mission scenario, including the in-orbit calibration, the EP test session, the correction and the processing of the scientific measurement, a mission simulator has been developed in FORTRAN starting from a simulator of the OCA initially dedicated to the EP test sessions. The mission simulator enables us to simulate calibration sessions as well as EP test sessions, and the data processing for the estimation of the parameters (including the estimation of the instrumental parameters for the calibration, the correction of the scientific measurement using the estimated values of the instrumental parameters and the estimation of the EP violation parameter).

In contrary to the calibration simulator, the mission simulator takes into account the orbital motion of the satellite. Therefore, an input of the simulator is an ephemerid file. This file provides the speed and acceleration of the satellite along its orbit. For each point of the orbit, the gravity acceleration and the Earth gravity gradient are computed from a model of the Earth gravity potential. Concurrently, the attitude of the satellite is computed. Three attitude laws are possible: inertial pointing of the satellite, spinning pointing, or oscillation of the satellite around one axis chosen for the calibration. These data are used to simulate the measurement

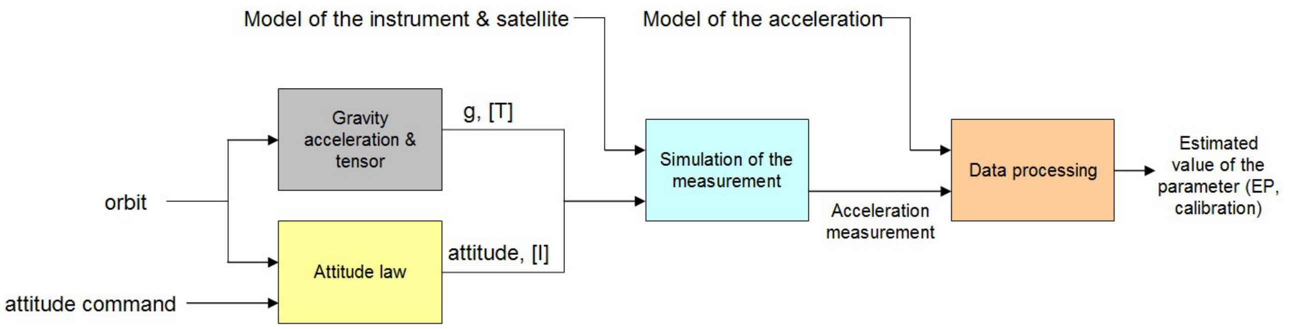

Fig. 2. The mission simulator.

of the electrostatic acceleration provided by the instrument. The simulated measurement is then processed by confronting it with a model of the measurement. The form of the model is:

$$\Gamma_{mes,dx} = \sum_k a_k \cdot p_k \tag{3.1}$$

with:

- p_k one of the parameters (instrumental parameters or EP violation parameter);
- a_k its partial derivate.

The measurement is corrected using the best estimation $\hat{p_k}$ of the parameter p_k available for the analysis:

$$\Gamma_{mes,dx,corr} = \sum_k a_k \cdot (p_k - \hat{p_k}) \tag{3.2}$$

In practice, the estimated value of the instrumental parameters, known from a previous calibration, will be used. After correction, the measurement is processed with a least squares method. The form of the measurement model is:

$$Y = A \cdot X \tag{3.3}$$

with:

- Y the observation vector (the measurement);
- X the vector of the parameter(s) to be estimated;
- A the partial derivates matrix.

The least squares solution is:

$$\hat{X} = (A^T \cdot W \cdot A)^{-1} \cdot A^T \cdot W \cdot Y \tag{3.4}$$

with W a symmetrical weight matrix. The variance of the estimator $\hat{X}$ is minimal if W is chosen so that $W^T \cdot W$ is the inverse of the measurement noise's variance-covariance matrix. This solution is optimal, but induces some difficulties. The variance-covariance matrix is not known: a model of the noise is therefore necessary. Moreover, this matrix has a high dimension (equal to the number of observations), therefore the inversion is difficult. The solution chosen for this study consists in applying a Fourier transform on both sides of the equation before the inversion. In the spectral domain, only the frequencies around the calibration frequency or the EP test frequency are selected. Thus, the number of observations is significantly reduced. Moreover, the noise spectral density can be considered flat on these narrow frequency bands.

The mission simulator has been used to simulate the in-orbit calibration sessions followed by an EP test session, with a simulated EP violation parameter equal to 10^{-15}. The EP test measurement has been corrected using the estimated values of the instrumental parameters, and the EP violation parameter has been estimated. The results of this estimation are gathered in table 1. Thanks to the calibration, the estimation accuracy after the measurement correction is better than 10^{-15}, and thus compatible with the MICROSCOPE accuracy objective.

	Estimation of δ_{EP}	Estimation error
Before calibration	$15.8 \cdot 10^{-15}$	$14.8 \cdot 10^{-15}$
After calibration	$1.25 \cdot 10^{-15}$	$0.25 \cdot 10^{-15}$

Table 1. Results of the mission simulator for an inertial session of 120 orbits, with $\delta_{EP} = 10^{-15}$.

4 Conclusions

The budget of the measurement equation before calibration does not comply with the objective of the EP test accuracy. Several in-flight calibration sessions are therefore necessary during the space experiment in order to estimate the instrumental parameters that limit the measurement accuracy, so as to correct the measurement. Parameters to be calibrated have been identified and appropriate methods of calibration have been proposed. In order to validate the calibration process, a simulation software including models of the instrument and of the satellite drag-free system has been developed and the calibration methods have been implemented in the simulator. The results are compatible with the specifications.

For the data processing validation, a second software has been developed, enabling us to test the entire mission scenario, including the correction of the measurement with the parameters estimated during the calibration process. The simulated estimation of the EP parameter is compatible with the mission accuracy objective and validates the mission performances.

The simulators can also be used to study other effects that have not been taken into account in this paper. For example, missing data can occur because of teletransmission errors. The missing data can be simulated with the mission simulator in order to define its impact on the EP parameter estimation and to test appropriate measurement processing for the reduction of this impact.

This study prepares for the Scientific Mission Center (CMS) which is currently under development at ONERA and whose mission will be to validate the operational data and process the scientific data of the MICROSCOPE mission.

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