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Has MICROSCOPE revealed a violation of the Equivalence Principle?

Manuel Rodrigues^{a*}, Joël Bergé^a, Gilles Métris^b

^a *Department of Physics, Instrumentation, Environment and Space, Office National d' Etudes et de Recherches Aérospatiales, Université Paris Saclay, F-92322 Châtillon, France, manuel.rodrigues@onera.fr*

^b *Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250 avenue Albert Einstein, F-06560 Valbonne, France*

* Corresponding Author

Abstract

The MICROSCOPE satellite completed its mission in October 2018. It aimed at testing the Equivalence Principle (EP), the funding hypothesis of General Relativity (GR) with unprecedented precision. A first publication in 2017 showed no evidence of a violation at 10^{-14} level. Since then, three years of analysis made it possible to improve the accuracy by one order of magnitude, placing this test as a reference for the test of GR.

This paper focuses on the most challenging topic of the data analysis: estimating errors and ensuring the best accurate test. The final result will be discussed and its impact on alternative theories to GR will be given.

Keywords: Accelerometer, General Relativity

Acronyms/Abbreviations

EP: Equivalence Principle

GR: General Relativity

MICROSCOPE: French acronym for “drag-free controlled microsatellite for the observation of the EP”

MLI: Multi-Layer Insulator

LLR: Lunar Laser Ranging

T-SAGE: Twin-Space Accelerometer for Gravitation Experiment

1. Introduction

In the early twentieth century, Einstein's theory of general relativity (GR) [1] revealed to be the breaking theory in Physics with non-intuitive predictions such as black holes and gravitational waves [2]. The latter now make the highlight of science news with impressive results. Although GR seems to pass all experimental tests with outstanding success, fundamental physics still fails to unify GR to the Standard Model. Physicists struggle to explain the accelerated expansion of the Universe [3], the missing mass at cosmological scale [4] or the unbalance of matter and antimatter.

By adding new fields to GR, scalar-tensor theories are among the model candidates giving some hope [5,6]. But, as a matter of fact, they propose new physics that breaks the equivalence principle.

The weak equivalence principle, that we abusively call equivalence principle hereafter, is the fact that all bodies shall fall in the same way in a gravitational field independently of their mass or composition: this is the universality of free-fall. This principle is the fundamental starting point from which Einstein built his theory.

Although observed since Galileo Galilei and Newton, there is no argument to state that “inertial mass” should be equivalent to “gravitational mass”. Tests confirming this statement and with increasing accuracy were led by the end of the nineteenth century by Eötvös, Pekár [7] and Fekete and improved by Bessel [8]. The EP is quantified as the relative difference in the ratio of gravitational mass and inertial mass of two bodies in free fall and is expressed by the so called Eötvös parameter:

$$\eta(2,1) = 2 \frac{a_2 - a_1}{a_2 + a_1} = \frac{2 \left(\frac{m_{g2}}{m_{i2}} - \frac{m_{g1}}{m_{i1}} \right)}{\left(\frac{m_{g2}}{m_{i2}} + \frac{m_{g1}}{m_{i1}} \right)}$$

where a_i are the acceleration undergone by the bodies. They showed that $|\eta| < 5 \times 10^{-9}$.

More recently the Eöt-Wash [9] group set an upper limit $|\eta| < \text{a few } 10^{-13}$. Lunar Laser Ranging helped to compare the motion of the Moon and the Earth in the Sun gravity field and found out a comparable upper limit [10].

Ground tests are disturbed by the impact of the environment on the stability of the local gravity field (local gradients, seismic noise, human activity, ...) and limited time of observation. LLR relies on the quality of the mirrors placed on the Moon, the atmosphere disturbances and on the laser source power. All of this makes it difficult to get significant improvements unless there is a technology breakthrough.

That's why since the 1970's [11], the interest of doing an experiment in space taking advantage of quiet environment and of long period of free-fall (as the satellite orbits around the Earth's) has increased with the availability of new technologies: high performance accelerometers, micro-newton thrusters and on-board performant computer for the satellite real time control.

2. MICROSCOPE mission overview

2.1 The starting point

In 1999, the French space agency, CNES, made available a new microsatellite line called MYRIADE to incite French laboratories to do low-cost science missions in space. In this frame, ONERA and OCA proposed the MICROSCOPE mission [12] dedicated to test the EP at 10^{-15} level, 2 orders of magnitude better than all previous experiments. Then started an ambitious project tackling with the limits of the state of the art in several areas. OCA brought its experience in space dynamics, ESA brought the micro-propulsion thrusters developed for GAIA and LISAPathfinder [13], PTB¹ (Physikalisch-Technische Bundesanstalt – the German National Metrology Institute) brought its expertise in producing standards for the BIPM, ZARM¹ (microgravity laboratory) in Germany brought its know-how in testing bodies in free-fall and in fundamental physics missions.

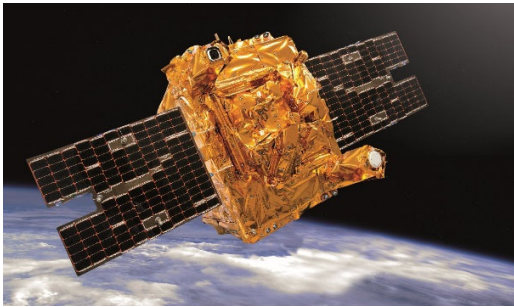


Fig. 1. Image of the MICROSCOPE satellite in orbit (CNES credits)

2.2 The experiment principle

In order to test the EP, two concentric bodies in a tight vacuum housing have been placed at 710km altitude in a circular sun-synchronous orbit (Fig. 2) [14]. The bodies are the test-masses of a double accelerometer and surrounded by electrodes that allow us to finely measure the position of the test-mass through capacitive sensing.

The scientific payload [15] is composed of two double accelerometers or sensors, each one comprising two test-masses. One pair of test-masses made of different material (PtRh and Ti) is used to test the EP by the sensor called SUEP. Another pair of test-masses made of the same material (PtRh) composes the sensor called SUREF. For this latter no violation is expected and its data analysis helps to check the in-flight procedures and ground data process.

In this experiment, the test-masses are not let entirely free. Their position measurements are used by a feedback

loop to maintain the two concentric test-masses motionless with respect to the surrounding electrodes by the application of electrostatic forces (Fig. 3). It is the principle of the space electrostatic accelerometers that have been developed in ONERA for different missions (CHAMP, GRACE, GOCE and GRACE-FO). The accelerometer in this configuration measured the applied acceleration on the satellite.

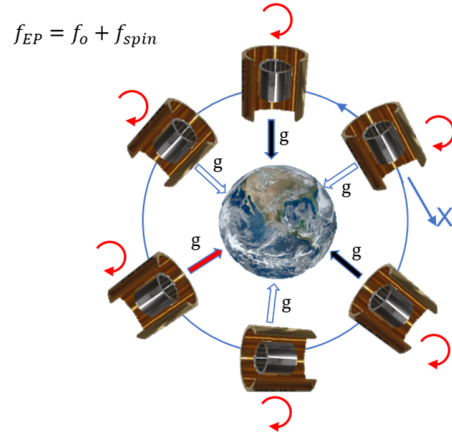


Fig. 2. Schema of the two concentric test-masses orbiting around the Earth: the satellite rotation Y-axis is orthogonal to the orbital plane; the measurement X-axis is defined by the cylinder axis and undergoes the projection of the gravity field at the frequency f_{EP}

If the EP is verified, both test-masses undergo the same applied electrostatic acceleration independently of their mass or composition. The measurement of applied voltages on electrodes allows us to calculate the applied electrostatic forces and thus to estimate the Eötvös parameter.

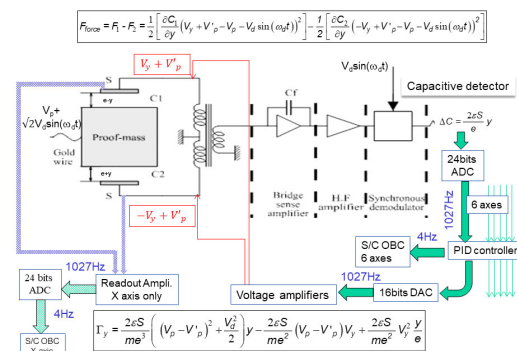


Fig. 3. Schema of servo-loop principle of the electrostatic accelerometer.

Because of the particular chosen pointing law of the instrument in the orbit (Fig. 2), inertial or slowly rotating about the normal to the orbital plane, the cylinder axis of the test-masses (X-axis) will be aligned to g , the gravity

field vector, at the particular frequency $f_{EP} = f_o + f_{spin}$, where f_o is the orbital frequency and f_{spin} the satellite rotation frequency. A potential violation of the EP should then occur at this particular frequency f_{EP} as the difference of acceleration should be collinear to the gravity field vector.

the equation of measurements is described in details In Ref. [14] and can be simplified as follows:

$$\Delta a = \eta g + \Delta a_c + K_d a_m + C_a + n + Q + B_0 \quad (1)$$

where:

- Δa is the measured differential acceleration.
- Δa_c is the component of the applied acceleration induced by the residual off-centring of the test-masses coupled to the Earth's gravity gradients or to the Inertia gradients. Thanks to in-orbit calibration of the off-centrings, this part of the acceleration can be corrected.
- $K_d a_m$ represents the part of the common mode acceleration which is projected on the differential mode because of instrument defects like difference of scale factors, mis-alignments. These parameters are also calibrated in orbit in order to correct this term. The common mode acceleration is obtained from the accelerometer output and is largely reduced by the drag-free and attitude control system of the MICROSCOPE satellite.
- C_a represents the disturbing couplings of angular motions to linear accelerations
- n represents the noise of measurement
- Q represents the quadratic term that leads to inject at f_{EP} part the common acceleration at other frequencies than f_{EP} .
- B_0 represents the measurement offset or systematic error in the measurement output.

3. Data processing

During the operational phase from April 2016 to October 2018, most of the data processing consisted of monitoring the good behaviour of all the system. The science mission centre (CMSM), based in ONERA and developed in cooperation with OCA, was in close contact with the Drag-Free Expertise Centre (CECT) in charge of producing the data coming from the control centre (CC). Both CC and CECT were based in CNES Toulouse. The role of the CMSM was:

- to verify every day the good realisation of the science operation on board,
- to proceed to a preliminary data analysis to check the performance,
- to update the mission scenario each week,
- to cumulate data for deep analysis and to produce science calibrated data.

The promising analyses in 2016 led the team to publish the first result in Ref [16-17] based on 8 days of cumulated data (120 orbits). This result was already an outstanding improving by one order of magnitude the current limit on the EP.

Since then, 2768 orbits of calibrated and science cleaned data have been selected over the total 13193 orbits that the mission lasted. In addition, more than 600 orbits were dedicated to thermal in-orbit tests to help the error analysis.

The data process was performed in two steps: error analysis and science data process. Two types of errors have been considered: statistical and systematic errors.

3.1 Statistical error

The statistical error comes from the instrumental stochastic noise and is estimated by the iterative weighted least square fit used to estimate the Eötvös parameter in equation (1). The least square fit is performed in the frequency domain by applying a Discrete Fourier Transform (DFT) to the data. Although conferring to the covariance matrix an optimal weighting with the PSD of the noise, this method is not robust to missing data. Very few data are missing due to mission operations or telemetry but as it is described in the following paragraph, it was necessary to eliminate data affected by glitches and to replace them by "clean" data (see §3.2). This process was very successful and helped to use the DFT. The least square fit gave an error of estimation dominated by the instrument random noise. When cumulating data, this error contribution reduces with the inverse square of the data time duration.

At the end, a certain number of sessions distributed over 2.5 years of the mission were analysed individually and their result combined with an ad-hoc method to give the final number.

In parallel, the data coming from all these sessions were gathered and analysed as a single set of data. The comparison of the two methods is consistent and gives a total statistical error on the Eötvös parameter **of 2.3×10^{-15} on the SUEP and of 1.1×10^{-15} on the SUREF.**

3.2 Systematic error

Whereas statistical error can be reduced by cumulating data, it is not possible in the case of systematics.

In particular, because of the accelerometer's sensitivity to temperature, variations of temperature at f_{EP} can mimic a signal at the same frequency of the expected potential violation signal and thus bias the final result. This is what we call systematic errors. Temperature systematic was the main contributor to the error in the Ref [16-17] because at that time, it was not possible to estimate the real temperature, but only an

upper limit at $15\mu\text{K}$. Thanks to dedicated temperature sessions and the sensitivity analysis of both instruments (SUREF and SUEP), it was possible to reduce this upper limit to $0.1\mu\text{K}$ at the mechanical core level [18]. Temperature variations at electronics level still remain and lead to finally reduce the thermal systematic error to a few 10^{-15} in the Eötvös parameter.

The second major systematic error comes from the satellite cracking [19]. The MLI covering the satellite to optimise its thermal behaviour is submitted to the Earth's albedo apparent variation due to the satellite rotation. Then small temperature variations occur at satellite surface inducing the cracking of the MLI at f_{EP} and thus small local vibrations seen as accelerations by the accelerometers. This phenomenon was well known prior to the launch and expected to be rejected by the matching of scale factors which reduces the impact of the common mode accelerations. However, a non-linear process, which is still not well established, led to still have disturbing measured accelerations due to cracking in the differential mode even with calibrated scale factors. The science team developed then a new strategy for the data process:

- firstly, the impact of the cracking in the measured time span is detected by a sigma clipping method and the corresponding data eliminated (5 sec before the detected event and 15 sec after in order to clean the short effect which is seen through the accelerometer transfer function);
- secondly, the missing data is replaced with a reconstruction method based on the maximisation of the likelihood. It assumes a linear model for the signal and a stationary Gaussian distribution of the noise. The algorithm called M-ECM (Modified Expectation Conditional Maximization) allowed us to fill in the gaps in order to use the DFT. The validation of the algorithm was performed by injecting in the real data a fake violation signal with two sets of amplitude in all sessions. Then the process was applied to all sessions with the extraction of the final Eötvös parameter which demonstrates an estimation accuracy better than a few percent with respect to the injected fake signal.

The total systematic error on the Eötvös parameter was finally estimated to **1.5×10^{-15} on the SUEP and to 2.3×10^{-15} on the SUREF.**

4. Results and conclusions

The MICROSCOPE satellite has flown during more than 2.5 years, providing useful data to scientists. The performance of the Drag-Free and Attitude Control System is unprecedented in a low Earth orbit and made

the linear acceleration environment limited to about 10^{-13}ms/s^2 and the angular acceleration environment to less than 10^{-12}rad/s^2 . The satellite was built as a space laboratory with the payload inside a thermal cocoon. The temperature variations of the sensor core at the frequency of interest was reduced to less than $0.1\mu\text{K}$.

The outstanding performance of the satellite system combined to the performance of the accelerometers led the science team to test the Equivalence Principle with a resolution near 10^{-15} . The value of the Eötvös parameter, which could indicate a violation of the EP, is to be published in a special edition [20] and will be presented at the IAC 2022.

This is actually the most accurate test of the EP with an improvement of one order of magnitude with respect to the current state of the art. The implication on alternative models GR is a stronger constraint on the model parameters. Any new model should pass the experimental MICROSCOPE result in order not to be ruled out as potential new theory in Physics.

Other missions are envisaged with different materials and better performance in the next decade. MICROSCOPE demonstrated that experimenting fundamental physics in space is possible but needs high performance instruments at the limit of the state of the art. ONERA is involved in such developments and studies a follow-up mission called MICROSCOPE 2 with 3 concentric test-masses for a better rejection of systematics.

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