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Towards a follow-up of the MICROSCOPE mission

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The MICROSCOPE mission tested the Weak Equivalence Principle (WEP) with an unprecedented precision of order 10^{-15} , two orders of magnitude better than the previous best lab experiments. While the WEP, the cornerstone of General Relativity (GR), does not sway, the decade-long problems faced by fundamental physics stay still: how can we unify GR with the Standard Model, and how can we explain the acceleration of the cosmological expansion and dark matter? As most beyond-GR models predict a violation of the WEP, albeit at an unknown level, it remains critical to even better test the WEP. In this paper, we summarize the MICROSCOPE mission and build on its experimental limitations to show how we could improve them by a further two-order of magnitude in the precision of the test of the WEP.

1 Introduction

The universality of free-fall (UFF) has been recognized since Galileo rolled objects down inclined planes and found that, locally, they all undergo the same gravitational acceleration: all objects within the same gravitational field fall at the same rate, independently of their mass and composition. With Newton's second law, the UFF can be restated as the proportionality between the gravitational mass m_G and the inertial mass m_I , with the same proportionality constant for all bodies: this is the usual definition of the weak equivalence principle (WEP).

In the early 20th century, Einstein generalized the WEP, stating that in small enough regions of spacetime, the non-gravitational laws of physics reduce to those of special relativity. In particular, one cannot detect a gravitational field by means of local experiments. This is known as the Einstein equivalence principle (EEP). A subsequent version, the strong equivalence principle, generalizes the EEP to gravitation. That was the starting point to general relativity (GR).

GR describes gravitation as spacetime's curvature, while recovering Newton's description of gravitation as a classical inverse-square law force in weak gravitational fields and for velocities small compared to the speed of light. As a highly predictive theory, it has so far successfully passed all experimental tests¹. Standing next to GR, the Standard Model of Particle Physics (SM) was built from the realization that the microscopic world is intrinsically quantum.

Although both GR and the SM are very successful in their own domain of validity and seem unassailable in their respective regimes (low vs high energy phenomena, macroscopic vs microscopic worlds), difficulties have been lurking for decades. Firstly, the question of whether GR and the SM should and could be unified remains open. Major theoretical endeavors delivered models such as string theory, but still fail to provide a coherent, unified vision of the fundamental interactions and fields. Secondly, unexpected components turn out to make up most of the Universes mass-energy budget: dark matter and dark energy are undoubtedly the largest conundrums of modern fundamental physics.

This explains that new models beyond GR and the SM have recently flourished to explain these dark components and understand their relation with the SM fields. They make generic predictions such as deviations from GR in the Solar system or a violation of the WEP that can be revealed by either a violation of UFF or variations of some fundamental constants^{2,3,4}. It led to an intense activity to sharpen tests of GR in the Solar system. In particular, the power and complementarity of atomic clocks experiments and free-fall experiments such as MICROSCOPE, have been demonstrated.

Though no extensions of our current theories make sharp predictions about the level of WEP violation that one should expect, there exist some models, notably string-inspired models involving dilaton fields, where this level is naturally below the currently explored 10^{-15} level. The existence of such models show that a 10^{-17} -level test of the WEP is not only breaking new ground in testing one of the theoretical pillars of physics, but is also exploring a landscape of possible new gravitational phenomena.

The WEP has been tested for four centuries with increased precision¹. The concept of a test in space emerged in the 1970s⁵, motivated by the quiet environment that space can provide and by the benefit of test periods much longer than on-ground experiments. In 1999, ONERA (Office National d'Etudes et de Recherches Aéropatiales) and OCA (Observatoire de la Côte d'Azur) proposed the MICROSCOPE mission (MICRO-Satellite Compensation de traînée pour l'Observation du Principe d'Equivalence) to CNES. Selected within the framework of the MYRIADE micro-satellite line, MICROSCOPE operating at room temperature aimed to test the WEP with a more modest accuracy than the space cryogenic missions STEP⁶, QuickSTEP, MiniSTEP or GEOSTEP⁷, all of which have been canceled by now. MICROSCOPE was eventually launched in 2016. After two and a half years of operations, we published an unprecedented upper bound at the level of 10^{-15} on the validity of the WEP⁸ in 2022.

In this paper, we describe the MICROSCOPE mission in Sect. 2 and its results in Sect. 3. Finally, Sect. 4 draws ways of improvements to design a future advanced MICROSCOPE mission. More details about MICROSCOPE can be found in Bergé (2023)⁹ and references therein.

2 MICROSCOPE mission overview

2.1 WEP test experiment principle

The validity of the WEP is described by the Eötvös parameter, defined through the difference of acceleration undergone by two free-falling bodies:

$$\delta(2, 1) = 2 \frac{a_2 - a_1}{a_2 + a_1}. \quad (1)$$

MICROSCOPE's measurement relies on comparing the accelerations of two concentric cylinders in orbit around the Earth. As shown in Fig. 1, it is performed along the cylinders' main axis (X). In an inertial pointing configuration, it is pointing in the same direction of the Earth's gravity field vector once per orbit. Thus, if a WEP violation exists, it can be detected as a signal with a well-known frequency (the orbital frequency f_{orb} in the case of Fig. 1) in the differential acceleration measured by the accelerometer.

The measurement precision can be improved by rotating the satellite about the axis normal to the orbital plane, thus moving the modulation frequency of the Earth's gravity vector projected onto the X-axis closer to the minimum of the instrumental noise. The WEP-violation frequency becomes $f_{\text{EP}} = f_{\text{orb}} + f_{\text{spin}}$, with f_{spin} the rotation frequency of the satellite.

In MICROSCOPE, the test-masses are part of a double concentric accelerometer. The test-masses are finely controlled by electrostatic forces to be motionless with respect to the surrounding electrodes as illustrated in the right panel of Fig. 1. The forces applied by the set of electrodes are determined by the voltage applied on the test-mass and on each electrodes. The combination of these voltages with the geometry of the instrument defines the electrostatic

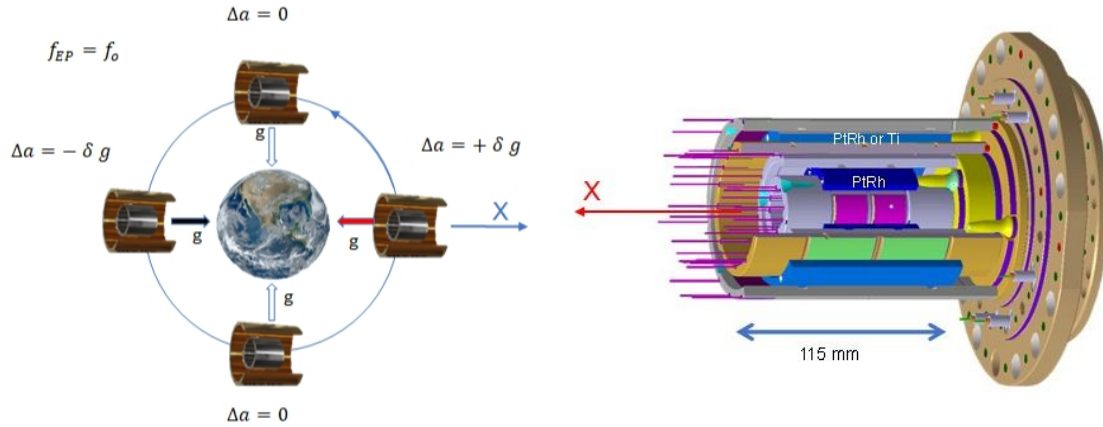


Figure 1 – Experimental principle (left) and accelerometer core (right).

forces and torques applied to each test-mass in order to counteract all the other effects that prevent the test-mass to stay motionless with respect to the satellite.

2.2 Payload

The payload is composed of two identical differential accelerometers also called sensor units (SUs) except for the test-mass material. Each SU has two concentric hollow cylindrical test-masses surrounded by electrodes engraved on gold-coated silica parts. Each SU is connected to a front-end electronics unit (FEEU) which delivers the voltages to the test-masses and electrodes and transmits the data to the interface control unit (ICU). Each ICU connected to the FEEU contains all the digital electronics and software to operate the test-mass control servo-loops and data conditioning for the satellite and then the ground telemetry. The SU and the FEEU are integrated in a thermal cocoon placed at the core of the satellite which offers a micro-Kelvin stability around the measurement frequencies.

The first SU, called SUREF (reference instrument, expected to give a null signal at f_{EP}), comprises two test-masses of the same material (platinum-rhodium alloy). The second SU, called SUEP (dedicated to the WEP test), comprises two test-masses of different material: the same platinum-rhodium alloy for the inner test-mass and a titanium alloy for the outer test-mass.

2.3 Drag-free satellite

One of the challenges of the mission objectives is to make the satellite environment as quiet as possible for the payload to prevent any corruption of acceleration measurements.

The MICROSCOPE mission has been developed on the basis of scientific missions exploiting the CNES MYRIADE microsatellite product line whose architecture comprises a platform with generic functional chains (energy, communication, computer, structure, no moving-part, etc.), though adaptations and modifications were necessary to cope with the unusual performance requirements.

The satellite thermal design was optimised to offer the payload a tight temperature stability. The thermal control on the satellite purely relied on passive methods: the dissipation of the electronic units was ensured by satellite external radiators. The payload was also shielded from the Earth's and satellite's magnetic fields. In addition, the mechanical or electronic micro disturbances were minimized by a careful design and analysis to ensure an optimal environment (e.g. choice of multi-layer insulation (MLI) to minimize cracking, minimisation of current loops, study of thermoelastic deformations to estimate internal gravitational effects).

To counteract non-gravitational forces and torques, an active control of accelerations and attitude of the satellite was implemented through the drag-free and attitude control system (DFACS), which used the scientific instrument itself as main sensor for delivering the linear as well as the angular accelerations hybridized with the star tracker measurements. The control laws for acceleration and attitude estimated the total forces and torques to be applied on the satellite which were transformed into eight micro-thrust commands sent to the cold gas propulsion system placed on two opposite walls of the satellite.

3 MICROSCOPE results

3.1 An unprecedented upper bound on the validity of the WEP

The final MICROSCOPE's constraint on the validity of the WEP is⁸

$$\delta(\text{Ti, Pt}) = [-1.5 \pm 2.3 \text{ (stat)} \pm 1.5 \text{ (syst)}] \times 10^{-15}, \quad (2)$$

where the statistical error is given at 1σ .

The reference instrument provided a null result, $\delta(\text{Pt, Pt}) = [0.0 \pm 1.1 \text{ (stat)} \pm 2.3 \text{ (syst)}] \times 10^{-15}$, showing no sign of unaccounted systematic errors in Eq. (2). As expected from its higher sensitivity, SUREF's result has a smaller statistical error than SUEP's. Its higher systematic error is dominated by thermal effects.

3.2 Beyond the WEP

MICROSCOPE was the first space-based laboratory dedicated to testing the WEP. Beside reaching its main goal, it allowed for state-of-the-art bounds on alternative models. Indeed, most gravitation theories beyond GR predict a violation of the WEP, albeit at an unknown level. As demonstrated by MICROSCOPE, several of them can be strongly constrained with the same data as those used for the test of the WEP. For instance, the parameter spaces of dilaton-like fields¹⁰, dark photon¹¹, Ultra-Light Dark Matter¹² and Axion-Like Particles¹³ were significantly constrained with MICROSCOPE. MICROSCOPE also allowed for unprecedented constraints on the Local Lorentz Invariance coefficients of the Standard Model Extension¹⁴.

Additionally, the mission demonstrated technological advances (e.g. 6-degrees-of-freedom drag-free and attitude control) and provided an experience on the limits of the experiment.

4 The future: STEIN (Satellite Test of Einstein's gravitation theory)

The European Space Agency issued a call for mission opportunity in March 2025. Using MICROSCOPE as a benchmark for improved space tests of the WEP, we answered to this call and proposed the STEIN (Satellite Test of Einstein's gravitation theory) mission. STEIN aims to improve MICROSCOPE's measurement by two orders of magnitude, to reach a 10^{-17} precision on the Eötvös parameter. Advanced technological choices, based on the MICROSCOPE's experience and most of them readily available, will allow for this significant jump in precision.

4.1 Science objectives of the STEIN mission

The primary objective of the STEIN mission is to test the WEP with a precision improved by two orders of magnitude with respect to MICROSCOPE. Thus, the mission profile, the payload and the platform will be dedicated and optimized to this aim. STEIN will also enrich the MICROSCOPE results by using more materials than MICROSCOPE. Therefore, while MICROSCOPE could measure the Eötvös parameters relating Titanium and Platinum, we plan to add a third proof mass made of a different material to be determined based on phenomenological aspects. Having three Eötvös parameters is particularly important in case of the detection of a WEP

violation. Indeed, any correlation of the Eötvös parameter with the pair of materials could hint towards specific models beyond GR and rule out others¹⁵.

With a two-order of magnitude improvement in precision, STEIN will also automatically constrain beyond-Einstein models with no increased cost nor instrumental tradeoff.

It must be underlined that STEIN will be developed, like MICROSCOPE, as a physics laboratory in space. It means that the system will be designed in order to allow for some flexibility in flight operations for doing physics experiments beyond the main objective without descopeing it. Beside fundamental physics, STEIN could provide geodesy results, for instance if equipped with retroreflectors allowing for laser tracking. It could also provide results on material degradation in space through radiation experiments.

4.2 Payload

The instrumental statistical noise can be significantly decreased with technologies derived from those of LISA Pathfinder¹⁶.

The thermal dissipation of the gold wires used to control MICROSCOPE's proof masses' charge was the cause of a $f^{-1/2}$ -frequency-dependence noise. It was the dominant low-frequency noise contributor. Since STEIN cannot reach its science requirements if such a wire is used, a contactless charge management system (CMS) will be used. LISA Pathfinder showed that illuminating proof masses with UV light allows one to control their charge. STEIN will embark a contactless CMS based on electron guns, which presents the advantage to charge the proof masses either negatively or positively, depending on the energy of the electrons.

With a low noise contribution from the CMS replacing the MICROSCOPE gold wire contribution, the effect of patch fields and contact potentials differences may come to impact the performance. Thus, increasing the gaps between the test-masses and the surrounding electrodes will play a major role. The drawback is a poorer capacitive sensing and acceleration noise at frequency about 0.01 Hz where the measurement frequency is expected to be selected. To cope with it, we can take advantage of the LISA Pathfinder heritage to complete MICROSCOPE's capacitive position sensing with a LISA-like interferometer position sensing. Additionally to the noise improvement, it also provides the possibility to perform a direct optical differential measurement between two test-masses (instead of MICROSCOPE's indirect" measurement – whereby the difference of measured accelerations was considered).

MICROSCOPE's two differential accelerometers (SUEP and SUREF sensor units) were placed side by side. Thus, although *stricto-sensu* a reference instrument, the SUREF instrument could not be used to estimate systematic errors simultaneously to SUEP's measurements. Nevertheless, it proved to be essential to identify systematics that could be corrected for *a posteriori* in SUEP's data (for instance, the fact that glitches mimicked a WEP violation signal was noticed with SUREF). Gathering all test-masses in a same instrument where simultaneously testing the WEP and monitoring the systematics can help cope with this drawback.

Considering the requirement to have three proof masses of different compositions, a more robust reference test can be performed by adding a fourth proof mass of the same material as another. For instance, the two innermost proof masses can be of the same composition and have similar masses (they then act as a reference), with the two outermost made of other two different materials. The related technological constraints of having four embedded accelerometers are still to be explored.

Furthermore, MICROSCOPE data were contaminated by periodic glitches, most likely linked to crackles of the satellite's coating, which created a signal at the frequency of the WEP test¹⁷. Their impact could be minimized at the data analysis level¹⁸. Nevertheless, using a stiffer platform's structure like that of the GOCE satellite is an option to prevent crackles.

Finally, MICROSCOPE showed that increasing the spinning rate of the satellite (to perform the measurement at a higher frequency), improves the temperature stability. A fast rotation then helps to reduce temperature-induced systematics.

4.3 Platform

As for MICROSCOPE, the test of the WEP by STEIN is expected to be performed in a drag-free satellite. The spacecraft should provide the lowest and most symmetrical gravitational field, and make coincide as much as possible the dry mass center of gravity, the propellant center of gravity and the accelerometer. Furthermore, the satellite should be as rigid as possible to minimize the impact of vibrations and glitches due to mechanical constraints, which could contaminate the science measurements. A platform similar to those of MICROSCOPE or LISA Pathfinder could be envisaged.

4.4 Mission profile and constraints

Like MICROSCOPE, STEIN will test the WEP in Earth orbit. MICROSCOPE's orbital parameters (Sun-synchronous, almost circular orbit) were found to be pertinent, and a similar orbit should be planned for STEIN. However, given MICROSCOPE's 710-km-altitude orbit, eclipses prevented science measurements (because of sudden temperature variations when the satellite passed through the Earth umbra) for about three months per year. Consequently, STEIN's orbit's altitude will be increased to avoid eclipses and allow for more science-dedicated time. At higher altitude, the impacts on the system are more constraining and should be assessed (radiation level, in orbit life-time, deorbitation...).

Operational constraints on the spacecraft limited MICROSCOPE's science sessions to 120 orbits, potentially impacting the experimental conditions, such as temperature, which varies as electronics are turned on and off. An advanced mission should rely on longer sessions to increase the integration time while allowing for more stable experimental conditions. Another operational limitation came from monthly Moon glares on the satellite's star sensor, forcing to depoint the satellite, which induced temperature changes incompatible with the science requirements. Since MICROSCOPE, technologies have improved and solutions currently exist to allow for continuous operations independently to Moon glares.

The MICROSCOPE mission lasted two and a half years. STEIN may have a nominal mission lasting three to four years (by choosing an orbit with no eclipse, this length of the mission can allow for twice as much data as MICROSCOPE). Allowing for three to four additional years will provide more data and may be beneficial to some secondary objectives (for instance, testing the Local Lorentz Invariance). Depending on the planned duration of the mission, a specific deorbitation system will have to be designed.

5 Conclusion

The MICROSCOPE mission allowed for an unprecedented precision of about 10^{-15} on the test of the WEP.

With the lessons learned from the MICROSCOPE mission, we identified key parts of the instrument, satellite and operations that can be improved to beat MICROSCOPE's precision on the test of the WEP by two orders of magnitude. A space mission, as similar as possible to MICROSCOPE could be designed with only almost off-the-shelf technology. Indeed, most improvements have already been shown to work in space, while others, more demanding, are not compulsory for the success of such as mission. We could thus expect a follow-up mission to MICROSCOPE to fly in the next few decades, on a low enough budget, but with high science outcomes about GR's validity and about beyond-Einstein theories. In that perspective, the STEIN (Satellite Test of Einstein's gravitation theory) has recently been proposed to ESA.

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