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Development of a differential accelerometer to test the equivalence principle in the microscope mission

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Abstract

A violation of the Equivalence Principle (EP), which hypothesizes the equality of inertial mass and gravitational mass, is indicated by current theories in modern physics. The MICROSCOPE mission seeks to extend the accuracy of previous EP tests to 10^{-15}, by avoiding the disturbances inherent to every Earth based test facility. The test will involve the measurement of the electrostatic forces required to maintain two concentric masses on the same orbit. The satellite, to be launched in 2008, will carry two differential accelerometers, one with masses of platinum and titanium, and a second with two platinum masses for baseline measurements. Each accelerometer will contain two coaxial cylindrical proof masses, each encompassed by a silica cage, all in a vacuum housing. The capacitance between electrodes etched into the silica, and the surface of the gold-coated proof masses provides a measurement of the proof mass position, which is then controlled by adjusting the voltages applied to the electrodes. Because an EP violation will appear as a difference between the forces required to keep each mass centred, the quality and stability of the silica cages is essential to achieve the desired test accuracy. This paper presents the overall design of the accelerometer, focusing on areas critical to the instrument core design, integration, and final performance requirements. The models and experimental investigations designed to overcome these issues are also discussed.

1. Introduction

In 1911, Einstein proposed his Principle of Equivalence, postulating the equality of gravitational mass and inertial mass. In the years since, this theory has been tested using numerous methods, but the noise and vibrations inherent in any Earth-bound test environment have restricted the test accuracy to less than 10^{-13}. Recent efforts to obtain a unification theory of fundamental forces have renewed interest in disproving the Equivalence Principle (EP), and present day satellite technology provides an opportunity to perform EP tests with unprecedented accuracy.

The MICROSCOPE mission (a French acronym for MICROSatellite à traînée Compensée pour I'Observation du Principe d'Equivalence) intends to verify the EP to 10^{-15} by placing two test masses of different materials on the same orbit to within

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10^{-11} m. They will be maintained on the same orbit by means of electrostatic forces and a difference in the required forces will indicate an EP violation.

The mission is approved and funded under the CNES MYRIADE microsatellite programme, which places restrictions on the payload size and power consumption. This constrains the experiment design, allowing only two science instruments and prohibiting the use of cryogenics. One will contain proof masses of two different materials for the EP test, while the other will have two masses of the same material to provide a science baseline.

Performing this test in space greatly reduces the experiment noise. In addition to having none of the seismic vibrations of an earth bound lab, remaining vibration sources are further reduced by a drag compensating satellite control system. The space environment also allows a long measurement duration. By integrating over many orbits the signal to noise ratio can be significantly improved. Performing this test in space offers another advantage besides low noise levels: the frequency at which an EP violation may appear is well known, being the sum of the orbit frequency and the frequency of any spin of the measurement axis in the orbit plane. The experiment will therefore be performed in both inertial mode, with the satellite attitude fixed in inertial space, and spin mode, with a controlled, constant rate of spin applied to the satellite, in order to increase the frequency of the EP violation signal.

The two SAGE (Space Accelerometer for Gravitation Experimentation) accelerometers for MICROSCOPE are based on a successful heritage of high sensitivity electrostatic accelerometers developed by ONERA, including STAR, used on the CHAMP mission [1], and SuperSTAR, for the GRACE mission [2]. The differential accelerometer, however, is a step away from previous instruments due to the necessity of positioning two proof masses with a common centre of mass. This paper provides a detailed description of the SAGE instrument followed by a discussion of various design details critical to reach the targeted 10^{-15} accuracy. Finally, Section 4 provides an overview of the various models and tests used in the development process.

2. The differential electrostatic accelerometer

An electrostatic accelerometer consists, fundamentally, of a proof mass suspended in a highly stable electrode cage. The principle of operation is to measure the electrostatic forces required to maintain the position of the proof mass with respect to the electrodes. Because the suspended proof mass is, in the nominal operation of a perfect instrument, susceptible only to the field forces of gravity and the electrostatic forces applied by the electrodes, the latter is proportional to the difference between the total acceleration of the cage and the gravitational acceleration of the proof mass. In the differential model, the two electrode cages experience the same acceleration, so that in the differential measurement the cage accelerations cancel to leave only the difference between the gravitational acceleration of the two masses.

There are three components to each SAGE instrument. The sensor unit (SU) contains the two inertial sensors carefully aligned in a vacuum tight housing. This is electrically connected to the front end electronics unit (FEEU), which contains the low noise analogue electronics required for proof mass levitation, including the ADCs, DACs, and position sensors, which require more thermal stability than the digital electronics of the interface control unit (ICU). This latter unit contains the remaining electronics for SU operation, specifically the proof mass position control loop, as well as the systems for general experiment control and the satellite interface.

2.1. Sensor unit

The objective of the MICROSCOPE mission is to compare the effect of gravity on two masses of different material, which requires subjecting them to the same gravitational field simultaneously. To achieve this in the variable field of Earth's gravity two restrictions are placed on the accelerometer design: the masses must be concentric to share a common centre of gravity, and the shape of the masses must be chosen so that the gravity gradient effects are analogous on the two masses. Optimally, the masses would be gravity monopoles [3], such as spherical shells, but as a more practical choice the SAGE instrument uses concentric cylinders. This enables access to the inner mass, and dimensions which produce equal