EÖTVÖS, a new concept for low disturbance measurements in space

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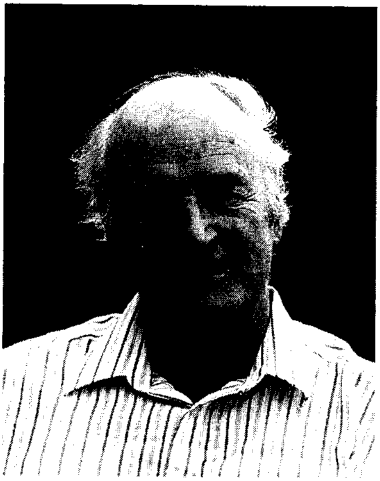

Summary

In space, for measurements like the test of the equivalence principle, a limiting source of error on differential accelerometers is the residual noise of the drag-free system. To allow a further increase in sensitivity, it is suggested to make a spin-stabilised instrument virtually drag-free by placing it free inside an outer spacecraft (s/c) which follows it by servoed thrusters. For cryogenic instruments cooling is done by gas conduction. The mechanical separation of the instrument from the outer s/c allows the use of cryo-coolers instead of liquid Helium. Two temperature levels of the instrument allow to dispose of electronics heat dissipation of the order of Watts. For a normal temperature instrument radiation cooling could remove tens of Watts.

1. Introduction

A number of fundamental measurements like testing the equivalence principle, the inverse-square law, a "fifth force", the gravitomagnetic force, as well as determining the gravitational constant G and gradiometry for geodesy, require the measurement of extremely small accelerations. Experiments on Earth use torsion balances to compensate gravity. One of the limitations is the acceleration noise due to microseism. Going to space allows to work in weightless state and to benefit from a quieter environment. For high sensitivity, however, even space is not free from disturbing accelerations, and these residual forces (air drag, radiation pressure and electromagnetic disturbances) must be compensated by a drag-free system.

Future missions like GP-B and STEP will use proportional Helium thrusters to compensate drag accelerations. However, though such servo systems can be made extremely sensitive at a given frequency, their residual noise increases away from this optimised frequency. As an example, in STEP, compensation is possible down to E-12 m/s^2/Sqrt(Hz) at 3E-4 Hz but rises by a factor 1000 towards the frequency of E-2 Hz, required for geodesy signals. Therefore, an ultimate factor limiting the precision is the coupling of residual drag noise through the differential accelerometer alignment errors.

2. Concept of EÖTVÖS

To overcome the limitations due to the residual drag, the only possibility is to have the instrument block (called the "instrument" in what follows) carrying the accelerometers freely floating and shielded from all outside disturbances by an outer spacecraft. Their relative position is measured optically and a servo system actuates thrusters in order to have the outer s/c follow the instrument. The latter acts as the reference proof mass and, in principle, follows an orbit determined uniquely by the Earth gravitational field. The main advantage of the concept is the possibility of using a conventional drag-free system correcting displacement to a few tenths of a millimeter, without having to compensate acceleration to a very high level.

The price to pay for these great advantages is twofold. First, the instrument must be supplied with power and signals exchanged without mechanical effects. Secondly, the instrument must be thermally controlled, which, in the case of a cryogenic instrument, is not trivial.

In what follows, the case of an experiment complement like that of STEP is discussed as an example. The basic detectors for testing the equivalence principle (EP) are differential accelerometers composed of two concentric cylinders. The instrument makes essential use of superconductivity for levitation, for position measurements by SQUIDs, as well as for shielding against magnetic fields. This requires temperatures below about 5K.

3. Mechanical design

It is suggested to have the instrument slowly rotating, with some 1000 s period. This frequency ω_s , added to the orbit frequency ω_o , determines the frequency of a possible EP violation signal $(\omega_s \pm \omega_o)$. It can be chosen arbitrarily and changed to eliminate errors correlating with the orbit revolution period or other disturbances.

The orientation of the accelerometers must be known and adjustable. Coarse sensing from the outer s/c can be done by star trackers. The three axis geodesy gradiometers give very sensitive orientation signals relative to the Earth field. The instrument behaving like a gyroscope, its orientation must be changed by applying torques, which make it precess. This can be done by the system of electrostatic electrodes shown in figure 1.

The rotation of the instrument itself could be adjusted by means of induction motors. The Helium gas will slow down this rotation in days or weeks if the outer s/c is in a fixed orientation. If on the other hand it is co-rotating, the rotation period will stay constant. This latter scheme is adopted here as it has further advantages as discussed below. It requires, however, that the center of mass of the outer s/c be adjustable to fall exactly on the axis of free rotation of the instrument.

4. Thermal design

A *cryogenic* instrument like STEP could be cooled by thermal conduction in dilute Helium gas at a pressure slightly above the molecular regime. It is clear that only an instrument having two temperature levels is possible (see figure 1). At the superconductivity level T_1 only very few milliwatts of dissipation can be tolerated. The main dissipation of the electronics which absolutely must be located on the instrument has to be removed at a higher temperature level T_2 , where the Carnot efficiency and gas conduction are much higher. Temperatures T_2 of 25 to 50 K are suggested, where most electronics would work. The critical point is the heat leaks between the two parts at T_1 and T_2. There are three: heat conduction through the support axle, heat flow through the gas (molecular regime) and the thermal conductivity of the wires connecting the electronics (these could possibly be HiTc superconductors). One should be able to keep the total leak to a few mW.

The actual dissipation of the low temperature electronics is therefore the crucial element and determines the cooling schemes which could be considered. Three variants are:

- Completely mechanical cooling by Stirling cycle cryo-coolers down to T_2 and by combined Stirling/Joule-Thompson units down to T_1. Typical cooling powers of existing, partly already space-qualified units are 2 W and 10 mW, respectively. Any Helium tides are eliminated.

- Stirling cryo-cooler down to T_2 and a Helium Dewar for the low temperature part. Several schemes involving superfluid as well as supercritical Helium are conceivable.

The detailed problems of gravitational disturbances by Helium tides must be taken into account, though quite small quantities of Helium should suffice.

- A fully Helium-based cooling is only pratical for dissipations below the Watt level and for short mission duration. It would require rather large Helium quantities and the tide problems remain.

The second scheme seems particularly attractive.

For *non-cryogenic* accelerometers (e.g. using electrostatic sensors) the single instrument block could be in vacuum and radiation cooled, a few tens of Watts being removable at temperatures of 250-300K.

5. Position measurement, power and signal transmission

The position of the rotating instrument relative to the outer s/c must be measured continuously in all six degrees of freedom. Modern micro-optoelectronic techniques should permit measurements to a few microns, this being especially easy in the case of co-rotation.

Power of a few Watts must be supplied to the instrument without any mechanical disturbance and with no significant heat input. This could be achieved by a microwave link, quite easily in the case of co-rotation. Superconducting devices are, however, very sensitive to microwaves so a high shielding factor is necessary.

Both command and measuring signals must be transmitted wireless between the instrument and the outer s/c. The low data rates needed should be easy to transmit by digital IR links.

6. Orbit

The choice depends on the actual goals of a mission. Cryo-coolers need a few hundred Watts of power, so sufficiently illuminated solar panels are required. Eclipses and unfavourable panel orientation can be critical. In the case of an equivalence principle test, a sun-synchronous orbit and a mission of less than six months is suitable. The orbit precession would then require periodic or continuous readjustments of the rotation axis of the instrument. For a geodetic mission, an exactly polar orbit of longer duration would be best, raising the problems of panel illumination mentionend above.

7. Disturbances and error budget

The instrument rotating rather fast will give rise to inertial forces: centrifugal accelerations and the effects of a possible nutation. However, most gravity and acceleration errrors are modulated at frequencies other than the EP signal frequency $(\omega_s \pm \omega_o)$. In particular, the centre of mass matching requirement, arising from coupling to the Earth gravity gradient, is reduced by two orders of magnitude from the non-spinning case. This in turn relaxes the charge control requirement.

The instrument being the reference proof mass, its centre of mass will be inertial. Therefore, the accelerometers located at a distance from this point will experience tidal forces due to the gradients of the Earth gravity field. If these forces have to be rejected to E-18 g (g=9.81m/s^2), the sensitve axes of the accelerometers must be aligned to 5E-6 rad. The uneven mass distribution in the outer s/c and its relative movements due to the drag-free operation will exert gravitational forces on the instrument. These will, on one hand, lead to a self-acceleration of the whole, which cannot be exactly known. On the other, it will give rise to time-varying gradients disturbing the geodesy gradiometry. These gravitational forces will also exert small torques on the instrument and make it precess. This small effect is absent in the case of co-rotation.

In the case of a three-axis gradiometer, the two axes oriented perpendicular to the spin axis will experience a large centrifugal acceleration in addition to a fully modulated Earth gradient. The co-rotation will stabilize the spin frequency and keep the centrifugal accelaration constant. A time-varying part of this acceleration can be removed to the first order by using the gradiometers themselves as attitude sensors and imposing the tracelesness condition for the gravity gradient tensor.

The full modulation of the Earth gravity requires a dynamic range of 2E7 for gradient sensitivity of E-4 E (1 Eötvös=E-9 s^{-2}). The SQUID electronics can provide such a dynamic range at the low frequencies involved, but it poses a great challenge to A/D converters and scale factor linearity. These problems can of course be alleviated if one sticks to a single axis configuration, as baselined for STEP.

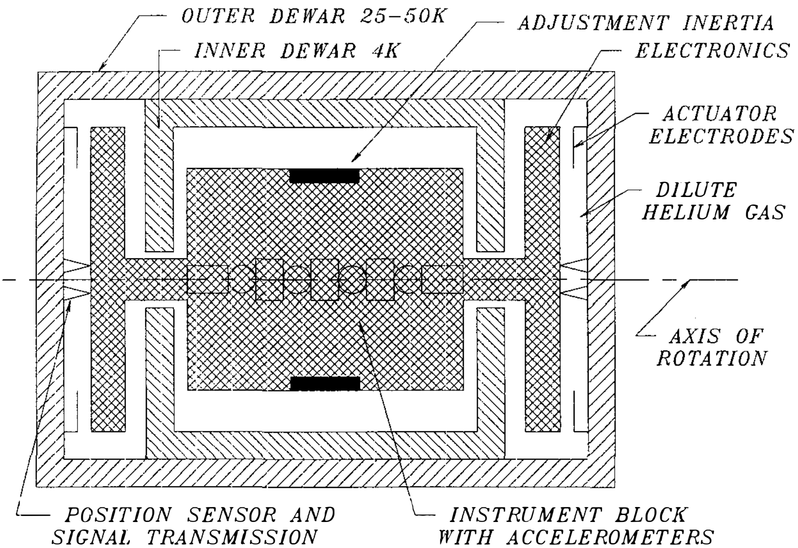

Figure 1: Schematic structure of a cryogenic spacecraft with fully inertial instrument