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Italian Spring Accelerometer (ISA): A fundamental support to BepiColombo Radio Science Experiments

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ABSTRACT

The Radio Science Experiments of the BepiColombo mission will enable substantial improvement of the knowledge of Mercury's orbit and rotation, and the relativistic dynamics in the solar system. A fundamental support to the spacecraft tracking data will be given by the Italian Spring Accelerometer (ISA). This is a three-axis accelerometer devoted to the measurement of the non-gravitational perturbations acting on the Mercury Planetary Orbiter (MPO), whose knowledge is important in order to fully exploit the quality of the tracking data. The intrinsic noise level of the instrument that will be onboard MPO, $10^{-9}\ \mathrm{m/s^2/\sqrt{Hz}}$ in the 3×10^{-5} to 10^{-1} Hz frequency range, guarantees the fulfilment of the RSE requirements. The main scientific and technological features of the instrument are discussed, together with its current error budget, experimental activities and foreseen calibration strategies.

1. Introduction—scientific objectives

Among the main scientific objectives of the BepiColombo mission to planet Mercury, an important set is formed by the so-called *Radio Science Experiments* (*RSE*). These aim to perform precise measurements of

- gravitational field of Mercury;
- rotation of Mercury;
- general relativistic effects, in particular Mercury perihelion precession

by state-of-the-art radiometric tracking of Mercury Planetary Orbiter (MPO) spacecraft. The overall procedure is fairly complex and is fully described in Iess (2009) (see also Milani et al., 2001, 2002). From the point of view of orbit determination, the tracking data—which in our case are range and range-rate—need to be fitted with a dynamical model as complete as possible and a model for the measurement types. In particular the dynamical model is based on general relativity (at the relevant post-Newtonian level) for the motion of bodies in the solar system and on a spherical harmonics expansion of the Hermean gravitational field, in order to determine accurately the MPO motion around Mercury. The models will depend in general on a set of parameters which will be adjusted in the orbit determination procedure; among them, the quantities of interest, like the PPN parameters and the spherical harmonics coefficients C_{lm} and S_{lm} of Mercury gravity field.

A distinctive feature of BepiColombo with respect to other deep-space missions is its relative proximity to the Sun. This has two fundamental consequences. Firstly, general relativistic effects are enhanced (motion near a massive body): this is the main reason to perform such an experiment. Secondly, the harsh environment the spacecraft will move in: non-gravitational effects due to surface forces, mainly the solar radiation pressure, perturb the motion of the spacecraft and mix with the gravitational effects. These forces are very difficult to model, since they depend in a complex way on incoming radiation and spacecraft surface optical properties and spacecraft attitude (Lucchesi and Iafolla, 2006). Analytical models do indeed exist, but they are effective only in particular cases, the simplest of which is a spherically symmetric spacecraft (for a general review of this issue see Milani et al., 1987). This is a serious problem, since it limits the accuracy with which the relativistic and geophysical parameters could be recovered. In order to overcome it, an accelerometer onboard the MPO—the *Italian Spring Accelerometer* (*ISA*)—will directly measure the non-gravitational perturbations so as to precisely take them into account in the orbit determination procedure and make the MPO an *a posteriori* drag-free satellite.

The use of high-performance accelerometers instead of analytical or numerical models, in order to improve the quality of orbit determination and especially of related parameter

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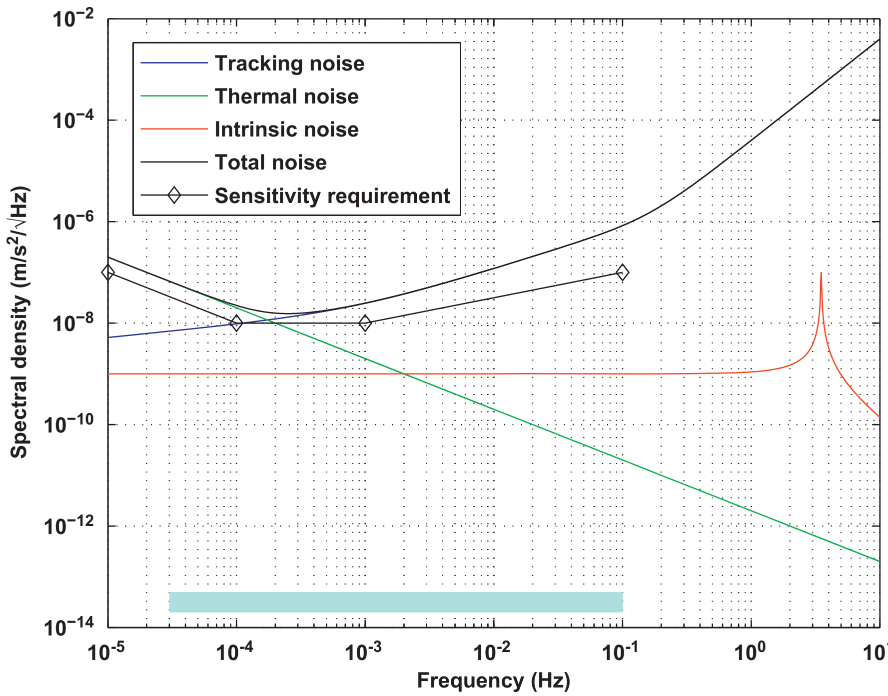

Fig. 1. Noise contributions from the accelerometer and the tracking system as used in the simulations that have been performed to prove the reliability of the RSE. The total noise level is mainly due to the thermal effects on the accelerometer at low frequencies and to the tracking noise at high frequencies. The light blue bar represents the ISA bandwidth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

determination, has been given increasing attention in recent years. Indeed, the performance of the tracking systems has been steadily improving, whereas this cannot be said about modelization. From near-Earth geodetic missions like the LAGEOS satellites to deep-space probes exploring the outer solar system, cases can be found where physical processes of non-gravitational origin could at least in principle play an important role (think to the so-called Pioneer anomaly, see Anderson et al., 1998, 2002). Examples of the accelerometers effectiveness are given by the CHAMP and GRACE geodetic missions, where the precise GPS position measurements are combined with accelerometric measurements (see van den Ijssel and Visser, 2007). The use of acceleration data improves the geophysical parameters estimation and is far better than the use of empirical acceleration terms in the modelization; these empirical accelerations could in fact improve the quality of the fit (post-fit RMS reduction), but at the cost of a predictivity lack (no or small correlation with physically relevant parameters).

The accelerometer characteristics requirements follow from the RSE requirements (see also Iafolla and Nozzoli, 2001). As discussed in van Casteren et al. (2009), the MPO spacecraft will be three-axis stabilized, Nadir pointing, characterized by a 400×1500 km polar orbit around Mercury. This orbit configuration is suitable for the recovery, with a signal-to-noise ratio larger than 10, of Mercury's gravity field up to degree $l = 25$, corresponding to a spatial resolution of about 300 km (Milani et al., 2001, 2002; Iess, 2009). In order to reach the goals of the RSE, the orbit must be known with an accuracy of at least 1 m in the along-track direction over one orbital revolution of the MPO around Mercury, i.e., over 8355 s. This corresponds to an along-track acceleration accuracy of about 10^{-8} m/s^2. Therefore, this number has been considered equivalent to the acceleration measurement error over the typical arc length during one observation session from Earth's ground antenna(s).

However, it is not necessary to retain a spectral density of 10^{-8} m/s$^2/\sqrt{\text{Hz}}$ through all the accelerometer's bandwidth.

Table 1
RSE related features and performances.

Parameter	Value
Measurement frequency range	3×10^{-5} to 10^{-1} Hz
Maximum expected signal	3×10^{-6} m/s^2
Measurement total noise	10^{-8} m/s$^2/\sqrt{\text{Hz}}$
Instrument intrinsic noise	10^{-9} m/s$^2/\sqrt{\text{Hz}}$
Required measurement accuracy	10^{-8} m/s^2
Read-out interval	1 s

Indeed, as shown in Fig. 1, which describes the noise contributions due to the accelerometer and to the tracking system, at low frequency the noise is dominated by the thermal disturbing effects at the interface between spacecraft and accelerometer while at higher frequencies the noise is dominated by the tracking errors. The red line represents ISA intrinsic noise; the green line represents the filtered thermal noise effects due to a possible white noise at a level of $4\,^{\circ}\text{C}/\sqrt{\text{Hz}}$, which may be present at the mechanical interface between the spacecraft structure and ISA; the blue line represents the equivalent acceleration associated with the Doppler noise; finally, the black line represents the total noise (quadratic sum of the previous noise sources). The various noise sources—ISA intrinsic noise, thermal noise, tracking noise—constrain the ISA sensitivity requirement. This requirement has been used in the error budget analysis described in Section 4 (sensitivity requirement, diamond line). The need to fully exploit the accelerometer performances only in a narrower bandwidth, between 10^{-4} and 10^{-3} Hz, is clear. We stress that these results have been obtained in the case of a passive thermal control. Currently, an active thermal control is foreseen as baseline; the thermal effects will be further attenuated by a factor 700. In Table 1 the main RSE-derived requirements are summarized.