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ScienceDirect
Advances in Space Research 45 (2010) 200–207
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Simulation of ASTROD I test mass charging due to solar energetic particles and interplanetary electrons

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Received 1 November 2006; received in revised form 10 September 2009; accepted 11 September 2009

Abstract

As ASTROD I travels through space, its test mass will accrue charge due to exposure of the spacecraft to high-energy particles. This test mass charge will result in Coulomb forces between the test mass and the surrounding electrodes. In earlier work, we have used the GEANT 4 toolkit to simulate charging of the ASTROD test mass due to cosmic-ray protons of energies between 0.1 and 1000 GeV at solar maximum and at solar minimum. Here we use GEANT 4 to simulate the charging process due to solar energetic particle events and interplanetary electrons. We then estimate the test mass acceleration noise due to these fluxes. The predicted charging rates range from 2247 e^+/s to 47,055 e^+/s, at peak intensity, for the four largest SEP events in September and October 1989. Although the noise due to charging exceeds the ASTROD I budget for the two larger events, it can be suppressed through continuous discharging. The acceleration noise during the two small events is well below the design target. The charging rate of the ASTROD I test mass due to interplanetary electrons in this simulation is about −11% of the cosmic-ray protons at solar minimum, and over −37% at solar maximum. In addition to the Monte Carlo uncertainty, an error of ±30% in the net charging rates should be added to account for uncertainties in the spectra, physics models and geometry implementations.

Keywords: ASTROD I; Solar energetic particles; Interplanetary electrons; Charging simulation; Drag-free; Disturbances

1. Introduction

The ASTROD I mission concept is based around a single, drag-free spacecraft and laser interferometric ranging and pulse ranging with ground stations. It is the first step towards realizing the ASTROD mission (the Astrodynamical Space Test of Relativity using Optical Devices) (Ni, 2008; Ni et al., 2004, 2006a,b). The scientific goals of ASTROD I include measuring relativistic parameters with better accuracy, improving the sensitivity achieved in using the optical Doppler tracking method for detecting gravitational waves, and measuring many solar system parameters more precisely. Key to realizing these goals is ensuring that all forces, other than gravity, acting on the test mass (TM), are reduced to negligible levels. Table 1 gives a summary of the scientific objectives of ASTROD I in testing relativistic gravity together with the present achieved accuracy from various experiments in the solar system.

Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) can penetrate the shielding provided by the spacecraft (SC) and deposit electrical charge on the test mass. This charge will interact with the surrounding electrodes, resulting in spurious Coulomb forces on the TM. Our previous work predicted the charging rates and disturbances for the ASTROD I test mass from GCRs at solar minimum and at solar maximum, first using a simplified geometry (Bao et al., 2007a) and subsequently using a more

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doi:10.1016/j.asr.2009.09.009

Table 1
Summary of the scientific objectives of the ASTROD I mission in testing relativistic gravity.

Effect/quantity	Present accuracy (Ni, 2005)	Projected accuracy
PPN parameter β	2×10^{-4}	1×10^{-7}
PPN parameter γ (Eddington parameter)	4.4×10^{-5}	1×10^{-7}
$(dG/dt)/G$	$10^{-12}\ \mathrm{yr}^{-1}$	$1 \times 10^{-13}\ \mathrm{yr}^{-1}$
Anomalous Pioneer acceleration A_a	$(8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$	$2.2 \times 10^{-16}\ \mathrm{m/s^2}$
Determination of solar quadrupole moment parameter J_2	$1–3 \times 10^{-7}$	3.8×10^{-9}

realistic geometry (Bao et al., 2007b, 2008). In this paper, we present a preliminary estimate of ASTROD I test mass charging due to protons generated by SEP events and interplanetary electrons and heavy nuclei. We compare this with charging due to primary protons at solar minimum and solar maximum. Using these results, we estimate and discuss the magnitude of the associated disturbances. We also estimate the impact of discharging on these disturbances.

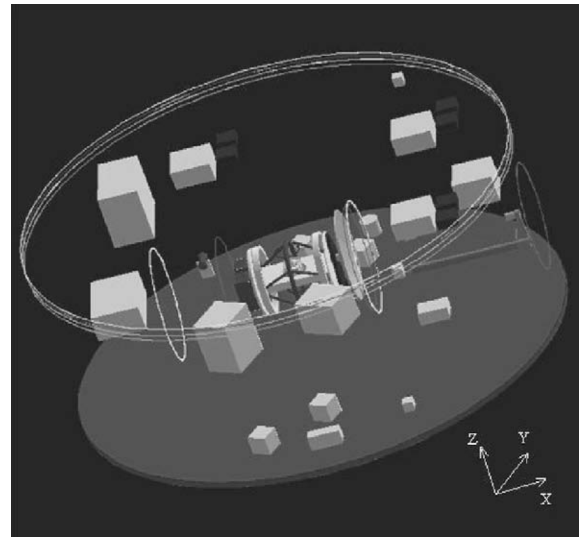

Fig. 1. The ASTROD I geometry model used in the GEANT 4 simulation. The basic structure is a cylinder of 2.5 m diameter, 2 m height and 10 mm thickness. The rectangular parallelepiped test mass is at the center of the spacecraft, surrounded by electrodes on all six sides. The X axis points toward the ground laser station and the Z axis is perpendicular to the orbital plane.

2. Modeling the charging process

In this section, we describe the charging simulation. We used the GEANT 4 toolkit (Agostinelli et al., 2003) for the simulation of the passage of particles through matter. It is a toolkit developed by an international collaboration, mainly from high-energy physics community, including CERN and KEK. GEANT 4 employs Monte Carlo particle ray-tracing techniques to follow all primary and secondary particles. The simulation program consists of three parts: (i) the source model for incoming particles; (ii) the geometry model of spacecraft and (iii) the model of the physical processes for interaction of the incoming particle and spacecraft materials. For the physical processes to be included, we follow previous work on LISA (Araújo et al., 2005) and ASTROD I (Bao et al., 2008). In the following subsections, we describe the geometry model and incident particle flux models used.

2.1. Geometry model

The ASTROD I geometry model we use for this work differ slightly from our previous GEANT 4 work (Bao et al., 2008). Since the computer code of our previous geometry model is lost, we have to re-write the geometry model. We follow the two-dimensional projection of the previous model as closely as we can. The two models differ only slightly. Fig. 1 shows a sketch of this model. The masses of the spacecraft and payload are 333 kg and 108 kg in this study (compared to 341 kg and 109 kg in our previous geometry model). The basic spacecraft structure is a cylinder of 2.5 m diameter, 2 m height and 10 mm thickness. All surfaces of spacecraft are covered with a thermal shield, consisting of five layers of materials, which serves as a sunlight shield and reduces temperature perturbations. The top and bottom of the spacecraft are covered by the upper deck and lower deck and the side surface by solar panels. In orbit, the cylindrical axis of spacecraft will be perpendicular to the orbital plane (Z axis direction in Fig. 1), with the telescope pointing toward the ground laser station (X axis direction in Fig. 1). The edges of upper deck and thermal shield are shown as large ellipses in Fig. 1. The inner lower deck is shown as the dark grey disc in Fig. 1. The payload structure is used to shield the optical bench, the inertial sensor and the telescope. The telescope, which collects the incoming light, is a 500 mm diameter f/1 Cassegrain telescope. Some 30 boxes represent the components above ~ 0.1 kg mass. A typical orbit of the ASTROD I spacecraft in the X–Y plane of the heliocentric ecliptic coordinate system is shown in Fig. 2 (Xia et al., 2005).

A $50 \times 50 \times 35\ \mathrm{mm}^3$ rectangular parallelepiped test mass made from Au–Pt alloy of low magnetic susceptibility ($<5 \times 10^{-5}$) is at the center of the spacecraft. The test mass is surrounded on all six sides by electrodes which are used for sensing and actuation. The test mass and electrodes are enclosed in a molybdenum housing. Together, the housing, electrodes and test mass form an inertial sensor (IS). The sensor is located on the optical bench, which is mounted behind the telescope. The test mass and all facing surfaces are plated with a 0.3 μm gold layer. The assembly is placed inside a titanium vacuum (<10 μPa) enclosure. The gap between test mass and electrodes along X axis and Y axis is 4 mm, and along Z axis is 2 mm (Bao et al., 2007). The characteristics of the inertial sensor are listed in Table 2. The GEANT 4 model for the IS is shown in Fig. 3.