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Cryogenic gyroscopes for the Relativity Mission

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Abstract

The Relativity Mission, also known as Gravity Probe B (GP-B), uses high precision electrostatically suspended cryogenic gyroscopes for measuring the relativistic precessions of the frame of reference in a 650 km polar orbit. A 2 K environment is used to ensure the thermal stability and to implement the readout technique based on the magnetic dipole moment generated by a rotating superconductor. Analysis and results from more than 100,000 hours of gyroscope operation show that the residual Newtonian drift is less than 0.17 marcsec/yr for a supported gyroscope in 10^{-9} m/s^2, and less than 0.020 marcsec/yr for a gyroscope in a fully inertial orbit.

Keywords: Cryogenic gyroscope; inertial sensor; London moment; experimental relativity

GP-B is designed to measure two rotational relativistic effects [1]. The geodetic effect causes a 6.6 arcsec/yr precession in the plane of the orbit to be measured to about one part in 10^5, thus providing the most precise test to date of any of the non-zero predictions of General Relativity. Frame dragging results in a precession perpendicular to the plane of the orbit of 0.042 arcsec/yr to be determined with an accuracy of about three parts in 10^3. These effects are measured by comparing the local frame of reference, determined by the gyroscopes, to the reference frame of the distant stars, determined by a telescope pointed to the star HR8703. The main experimental requirement for the gyroscopes is an accuracy of better than 0.3 marcsec/yr. The 650 km orbit exposes the gyroscopes to cosmic radiation, making it necessary to implement charge measurement and control systems [2]. Ground testing capability results in a requirement for functionality in the range 10^{-8} g to 1 g, while non-functional survivability of loads of about 8 g is required for launch capability. Three of the four gyroscopes are operated with their electrostatic suspension active, while the fourth functions as the drag-free proof-mass for the satellite.

The gyroscope rotors and their housings are fabricated of fused quartz. Gyroscope rotors are polished using laps arranged in a tetrahedral configuration, and measured using a precision mechanical spindle. A measurement over 17 large circles of each rotor insures good mapping of the spherical surface. The peak-to-valley deviation of the rotor surface from the best fit sphere is about 10^{-6} with respect to the 1.9 cm gyroscope radius, or about 20 nm. A film of niobium 1.25 μm thick is sputtered onto the rotors in two layers of 32 symmetric patches, achieving a peak-to-valley uniformity of

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better than 2%, or about 20 nm [3]. The very good spherical surface of the gyroscope rotors is needed to minimize the torques caused by the electrostatic suspension. The superconducting film provides a conducting surface for the rotor and generates the London magnetic moment measured by the read-out system and representing the orientation of the local frame of reference.

The 1.9 cm radius cavity of the gyroscope housing is polished using a "tumble lapping" technique, achieving a peak-to-valley sphericity of equal to or less than 150 nm. Three pairs of mutually perpendicular electrodes are used to sense the position of the rotor relative to the housing and to apply the electrostatic suspension support voltages and the force modulation required to measure the potential of the rotor. The gap between the centered rotor and the electrodes is 32 μm. In order to withstand the launch loads the gyroscope rotors are caged using a piston activated by bellows pressurized with liquid-helium.

The superconducting gyroscopes are spun to above 100 Hz, using 6 K helium gas flowing at 12 cm^{3}sec^{-1} through the central orifice of the spin-up channel in the gyroscope housing. About 95% of the gas is flowing along the channel and is exhausted by pumping through the orifice close to the parting plane. The remainder of the gas flows above a metal film channel land raised 12 μm above the electrodes, and is evacuated from the gyroscope housing by separate pumping through special openings. The spin speed $f(t)$ closely follows the exponential function $f(t) = f_a[1 - \exp(-t/\tau)]$ during spin-up, with f_a about 100 Hz and τ about 1500 sec.

A superconducting four-turn read-out loop coated on the parting plane of the quartz housing couples the variations of the London magnetic moment to a dc SQUID magnetometer. The four gyroscopes are rigidly mounted in a quartz block that is bonded to the telescope, with the entire system operating at about 2 K. The telescope is pointing to the reference star with rms accuracy of better than 20 marcsec. In order to minimize asymmetric torques on the gyroscopes the satellite rolls about the line of sight to the star at a fixed rate of about 0.3 rpm, while star sensors and rate gyroscopes maintain the roll rate constant to one part in 10^5.

The spin axis of the gyroscopes is aligned to the roll axis to better than 1 arcsec. Rotor position is sensed with a 35 kHz capacitance bridge using a 40 mV peak-to-peak excitation voltage. The demodulated position signal is sensed at 220 Hz and used to control the satellite thrusters for the drag free sensor or the electrostatic suspension system for the other three gyroscopes. For a spin speed of 100 Hz the calculated gyroscope disturbance precession is less than 0.17 marcsec/yr for the supported gyroscopes and less than 0.02 marcsec/yr for the drag-free sensor. More than 100,000 hours of ground testing indicate that the gyroscope performance meets all GP-B requirements.

Keiser *et al.* [4] have computed the expected performance of the gyroscopes as differential accelerometers. In the frequency range of 2×10^{-3} to 2×10^{-2} Hz the expected accuracy is about 2×10^{-10}m/(sec^{2}Hz$^{1/2}$) for the electrostatically supported gyroscopes and about 2×10^{-12}m/(sec^{2}Hz$^{1/2}$) for the gyroscope functioning as the drag-free proof mass.

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