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GYROSCOPES AND CHARGE CONTROL FOR THE RELATIVITY MISSION GRAVITY PROBE B

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ABSTRACT

The most demanding goal of the Gravity Probe B Relativity Mission (GP-B) is the measurement of the parametrized post-Newtonian parameter γ to one part in 10^5. This goal requires a total experimental accuracy of ≤ 0.044 marcsec/yr. Analysis of and results from 100,000 hours of gyroscope operation on the ground show that the residual Newtonian drift will be < 0.17 marcsec/yr for a supported gyroscope in 10^{-9} m/s^2, and < 0.020 marcsec/yr for an unsupported gyroscope in a fully inertial orbit. The expected error due to gyroscope drift is thus consistent with the measurement goal. The main gyroscope disturbance caused by cosmic radiation is charging of the rotor. A force modulation technique allows measurement of the charge of the gyroscope rotor to about 5 pC, while bipolar charge control to 10 pC is achieved using electrons generated by UV photoemission.

THE GP-B GYROSCOPES

Measuring γ to one part in 10^5 will extend the search for a possible scalar interaction in gravity by two orders of magnitude and allow a test of the critically damped version of the Damour-Nordtvedt "attractor mechanism" (Damour and Nordtvedt, 1993). We discuss the performance requirements and techniques used to build gyroscopes for GP-B compatible with this level of performance.

Four high precision, cryogenic, electrostatically suspended gyroscopes are used in GP-B to determine the inertial reference frame in the vicinity of Earth. Three are operated with the electrostatic suspension active, while the fourth will function as the drag-free proof-mass for the satellite. Residual torques are minimized by compensating for the drag of the satellite and by carefully controlling the sphericity of the gyroscope and its housing. The gyroscope rotors and their housings are fabricated of fused quartz. The density uniformity of the fused quartz for the rotors is measured by an interferometric technique using a cube of material immersed in an index matching fluid (DeFreitas, 1994). Fused quartz of the "Homosil" grade produced by Heraeus Amersil has a density uniformity of a few parts in 10^6 over the radius of the gyroscope; a factor of ten better than the required uniformity. Gyroscope rotors are polished using laps arranged in a tetrahedral configuration, and measured using a precision mechanical spindle with an LVDT transducer. A measurement over 17 large circles of each rotor ensures 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 better than 2%, or about 20 nm (Gill *et al.*, 1988). The superconducting film provides a conducting surface for the rotor and generates the London magnetic moment required by the read-out system. The very good spherical surface of the gyroscope rotors minimizes the torques caused by the electrostatic suspension.

The spherical cavity of the gyroscope housing is polished using a "tumble lapping" technique, whereby the two housing hemispheres are closed around a heavy lap in the shape of a spherical cap, and the whole assembly is randomly tumbled. A judicious combination of lap weight, tumbling speed, and polishing compound ensures that the lap remains within 40 degrees of the bottom of the cavity during the tumble lapping operation. The peak-to-valley sphericity of the 1.9 cm radius cavities thus produced is equal to or less than 150 nm. Titanium copper multi-layer coatings are then sputtered onto the electrode areas, providing the necessary electrical and thermal conductivity (Zhou *et al.*, 1995). Figure 1 shows a schematic view of an exploded gyroscope. Three pairs of mutually perpendicular electrodes are used to sense the position of the rotor relative to the housing, to apply the support voltage necessary for electrostatic suspension, and to apply the force modulation required to measure the potential of the rotor. The gap between the centered rotor and the electrodes is about 32 μm. Sputtered film support-lands placed around the electrodes and raised about 12 μm above them prevent the non-levitated rotor from touching the electrodes. In order to withstand launch loads the gyroscope rotors are caged against a set of caging-lands, of height similar to that of the support-lands, using a piston activated by bellows pressurized with liquid-helium. Accumulation of static charges in the vicinity of the housing is prevented by coating all surfaces on the interior of the housing with a conducting film that is grounded in common with the electrostatic suspension system.

The superconducting gyroscopes are spun to above 100 Hz, using 6 K helium gas flowing at 12 $cm^3 sec^{-1}$ STP 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 frequency $f(t)$ closely follows the exponential function $f(t)=f_a\cdot[1-\exp(-t/\tau)]$ during spin-up, with f_a about 100 Hz and τ about 2000 sec.

The spinning spheres generate a London magnetic dipole moment $\boldsymbol{M_L}$ aligned with the gyroscope instantaneous spin axis ω_S, with m and e the mass and charge of the electron, and c the speed of light:

$$\boldsymbol{M}_L = -\frac{mc}{e} r^3 \omega_S = -5.69\times10^{-8}\ r^3\omega_S\ (\mathrm{G\cdot cm^3}) \qquad (1)$$

The angular momentum is the conserved quantity that represents the orientation of the local frame of reference, while the instantaneous spin axis cones around it. For a force free gyroscope with a small fractional difference in the principal moments of inertia $\Delta I/I$, the coning angle and frequency are given by $\Delta I/I$ and the spin angular frequency ω_S respectively. The gyroscopes have $\Delta I/I \leq 5\times10^{-6}$ causing the coning angle to be ≤ 1 arcsec, and to average to the level of 1 marcsec in less than 5 seconds. Thus the London magnetic dipole represents the angular momentum direction, independent of polhoding. 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 system operating at 2.3 K. The telescope is pointing to the reference star with rms accuracy better than 20 marcsec. As a means of minimizing asymmetric torques on the gyroscopes the satellite rolls about the line of sight to the star at a fixed rate between 0.3 and 1 rpm. External star sensors and rate gyroscopes maintain the roll rate constant to 1 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 applying a 40 mV peak-to-peak excitation voltage to each pair of electrodes. 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.

Molecular drag creates a major disturbance torque for the gyroscopes. This torque is reduced by a factor of 5×10^{-6} by averaging through spacecraft roll around the spin axis, resulting in the requirement for the pressure P at the GP-B gyroscopes: $P \leq 10^{-9}$ Pa. In order to reduce the pressure, subsequent to the introduction of the helium gas used for spin-up, we utilize a low temperature bake-out technique. The temperature of the surfaces is raised to about 7.5 K, thus promoting helium desorption, while simultaneously the desorbed gas is pumped out from the probe. Subsequent to the cool-down to about 2.5 K, the remaining gas is adsorbed in a sub mono-layer on the surface (Turneaure *et al.*, 1988). Pumping to pressure P_1 at temperature T_1, will result in the pressure P_2, when changing the temperature to T_2, given by:

$$P_2 = P_1 \cdot (T_2/T_1)^{3/2} \cdot \exp[(E_B/k_B)(1/T_1 - 1/T_2)] \qquad (2)$$

E_B is the binding energy of helium on metals with $E_B/k_B \approx 150$ K. In a prototypical test system under the GP-B operational conditions, with $P_1 \leq 10^{-5}$ Pa, the low temperature bake-out procedure has demonstrated a gyroscope pressure at 2.5 K of 10^{-13} to 10^{-15} Pa, limited by the measurement capability of the residual gas analyzer.

Table 1 gives a summary of the largest gyroscope disturbance torques calculated for a spin frequency of 100 Hz and for a residual helium gas pressure in the gyroscopes of about 10^{-9} Pa. The expected gyroscope disturbance precession is less than 0.17 marcsec/yr for the supported gyroscopes and less than 0.020 marcsec/yr for the unsupported one. While the GP-B design is optimized for minimal angular drift, Keiser *et al.* (1998) have computed the expected performance of the gyroscopes as differential accelerometers. They find that in the frequency range of 2×10^{-3} to 2×10^{-2} Hz the expected overall accuracy is about 2×10^{-10} m/(sec$^2\sqrt{\mathrm{Hz}}$) for the electrostatically supported gyroscopes and about 2×10^{-12} m/(sec$^2\sqrt{\mathrm{Hz}}$) for the unsupported gyroscope functioning as the drag-free proof mass.

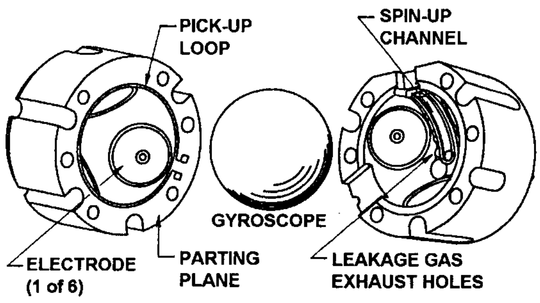

Fig. 1. Schematic view of an exploded gyroscope.

Table 1. Gyroscope disturbance precessions

DISTURBANCE TYPE	**Supported** (marcsec/yr)	**Unsupported** (marcsec/yr)
Control Voltages	< 0.17	0
Position Sensing Voltages	< 0.015	< 0.015
Gravity Gradient	< 0.011	< 0.011
Magnetic Torques	< 0.005	< 0.005
Differential Damping	< 0.004	< 0.004
Rotor Charge (10pC)	< 0.002	< 0.002
Cosmic Radiation	< 0.002	< 0.002
Brownian Motion	< 0.001	< 0.001
Root Sum Square	**< 0.17**	**< 0.020**

CHARGE MEASUREMENT AND CONTROL

In the 650 km polar orbit used by GP-B the main contributions to the radiation environment are due to charged particles trapped in the Earth's magnetic field (Vette, 1991) and to charged particles generated by solar flares (Feynman, 1993). Figure 2 shows the daily orbit-averaged integral flux of protons and electrons for the GP-B orbit. Proton trapping is the main cause of gyroscope charging, with the effect that the net charge is positive. The shielding provided by the spacecraft stops most primary electrons, while secondary emission of electrons has a yield of less than unity for the GP-B environment. During experiment-initialization stages two additional mechanisms can cause gyroscope charging: the separation of dissimilar metals during gyroscope levitation off the housing, and charge deposition by ionized helium during the spin-up of the gyroscopes. The polarity of the charging due to gyroscope levitation and spin-up are difficult to predict, making it necessary for the charge control technique to have bipolar capability.

In order to reduce heating and charging during solar flares, a radiation shield of 10 $g \cdot cm^{-2}$ was added, resulting in a total shielding for the gyroscopes of 20 $g \cdot cm^{-2}$ aluminum equivalent. Standard space technology is used to mitigate the effects of cosmic radiation on the electronics. However, the gyroscope rotors are mechanically isolated systems spinning in ultrahigh vacuum, thus making it necessary to use non-contact methods for charge control and to rely on thermal radiation for cooling.

Gyroscope requirements, due to torque and acceleration considerations, limit the rotor charge to 10 pC, or equivalently to a 10 mV potential (for the 1 nF rotor capacitance). The total charge accumulation over the 1.5 year mission is about 600 pC making it necessary to monitor the gyroscope potential and use active charge control.

The rotor charge is measured using a force modulation method, in which excitation voltages are applied 180° out-of-phase to two opposite electrodes (Buchman *et al.*, 1995). Two variations of this technique are used for GP-B. For the electrostatically suspended gyroscopes the modulation frequency is chosen at 0.05 Hz, or about 1% of the suspension system feedback bandwidth, insuring that no actual motion of the gyroscope takes place. In this case the charge of the gyroscope is proportional to the modulation of the control effort in the suspension feedback loop. In contrast, the charge measurement force modulation for the drag free sensor is applied at 4 Hz, about ten times the frequency of the feedback loop for the attitude and translation control thrusters of the space vehicle. The charge of the drag free sensor is then proportional to its motion with respect to the position-sensing electrodes. The advantages of this second variant of the force modulation method are that no actual motion of the space vehicle takes place, and that consequently, the positions of the three electrostatically suspended gyroscopes are not modulated by the drag free sensor excitation.

The force modulation technique is insensitive to gyroscope miscentering, is independent of the ambient acceleration, and achieves an accuracy of better than 5 mV for an integration time of 100 s, making it suitable for use for the GP-B mission. GP-B uses two levels of charge measurement excitation. a) A 10 mV level for continuous monitoring that achieves the 5 mV accuracy in 100 s. b) A 100 mV level for measurements during active control using the UV system, which achieves the 5 mV accuracy in about 1 s, thus making the control loop much simpler to implement.

UV photoemission is the method used by GP-B to generate the electrons used for charge control (Buchman *et al.*, 1995). Rotor and biasing electrode are illuminated with UV light, and the electrons generated by photoemission from both these surfaces are added or removed from the rotor using a dedicated biasing electrode. The direction of the charge flow is controlled by biasing of the charge control electrode to ±3 V with respect to the gyroscope surface.

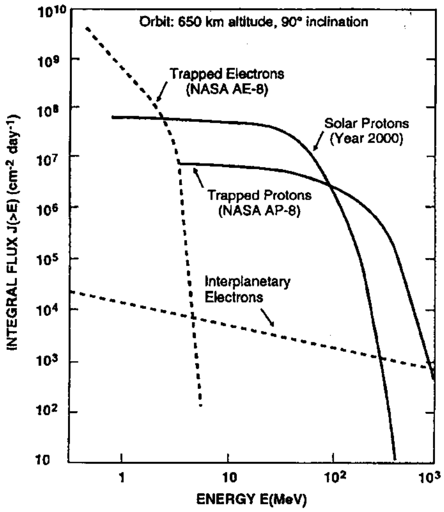

Fig. 2. Cosmic radiation background for the GP-B satellite

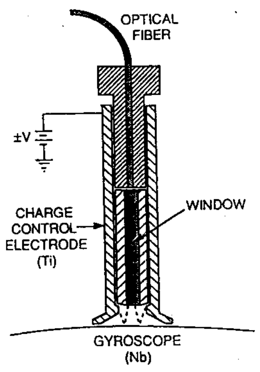

Fig. 3. Schematic view of UV charge control fixture

The gyroscope surface is a sputtered thin film of niobium, while the charge control electrode surface is electroplated gold. Experimental considerations pose additional constraints on the hardware near the gyroscope: low remnant magnetization, very high standards of cleanliness, a superconducting transition temperature below 1.5 K, and compatibility with the 2 K GP-B experimental temperature. Figure 3 is a schematic representation of the fixture mounted in the gyroscope housing which directs the UV light onto its inner surface and onto the gyroscope, while also fulfilling the function of the charge control bias electrode.

The UV source is a rf-discharge mercury lamp. About 10 μW of 254 nm mercury light is coupled from the lamp into each of twelve 300 μm UV fibers. For redundancy GP-B will fly two lamps, with two fibers from each lamp capable of illuminating the two UV fixtures on each gyroscope. Each of the eight fibers going to the four gyroscopes has a UV compatible switch developed by GP-B, thus allowing the choice of one of the two lamps for illumination. The photoemission efficiency is strongly dependent on the exact surface conditions of the transmitting and reflecting system elements, and varies between 20 and 200 fA/μW for the gyroscope and between 50 and 500 fA/μW for the UV fixtures. Ground testing of the charge control system is performed with the gyroscope not levitated, and the photoemission current measured directly through the connection to the ground-plane of the housing on which the gyroscope is resting.

More than 100,000 hours of gyroscope testing indicate that the gyroscope drift meets GP-B requirements and that charge management, using measurement by force modulation and electrons generated by ultraviolet photoemission, are the solutions for the GP-B gyroscope-charging problem.

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