

Experimental techniques for gyroscope performance enhancement for the Gravity Probe B relativity mission

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Abstract. The Gravity Probe B relativity mission experiment is designed to measure the frame dragging and geodetic relativistic precessions in a 650 km polar orbit. We describe some of the advanced experimental techniques used to achieve the required gyroscope accuracy of between 0.05 and 0.3 marcsec yr⁻¹. The subjects discussed are: (i) the development of high-precision gyroscopes with drift rates of less than 0.02 marcsec yr⁻¹, (ii) a low-temperature bake-out procedure resulting in a helium pressure of less than 3×10^{-12} Pa at 2.5 K, (iii) a read-out system using DC SQUID magnetometers with a noise figure of 5×10^{-29} J Hz⁻¹ at 5 mHz and (iv) AC and DC magnetic shielding techniques which produce an AC attenuation factor in excess of 10^{13} and a residual DC field of less than 10^{-7} G.

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1. Introduction

The most demanding goal of the Gravity Probe B relativity mission [1] (GP-B) is the measurement of the parametrized post-Newtonian parameter γ to one part in 10^5 ; with γ determined from the measurement of the geodetic effect in Earth orbit. The knowledge of 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 [2] ‘attractor mechanism’. This goal implies a measurement of the geodetic precession to 0.67×10^{-5} , and combined gyroscope drift and read-out noise of less than $50 \mu\text{marcsec yr}^{-1}$ (1.7×10^{-12} deg hr⁻¹).

We discuss the performance requirements and techniques used to build the gyroscopes for GP-B, as well as the methods used to ensure an experimental environment compatible with this level of performance. System testing of the GP-B flight back-up probe shows that the instrument meets all requirements, and is expected to achieve the stated goal. Results from 100 000 hours of gyroscope operation indicate that residual Newtonian drift is less than $0.14 \text{ marcsec yr}^{-1}$ for a supported gyroscope in 10^{-9} m s^{-2} , and less than $0.02 \text{ marcsec yr}^{-1}$ for a fully inertial orbit. Low-temperature bake-out is used in conjunction with a sintered titanium cryopump to achieve a vacuum level measured to be less than 3×10^{-12} Pa (2×10^{-14} Torr).

The London moment gyroscope readout system, based on DC SQUIDS, has demonstrated a noise performance of 5×10^{-29} J Hz⁻¹ at 5 mHz (the spacecraft roll frequency). This is equivalent to an angular resolution of 1 marcsec for an integration period of four hours, thus fully meeting GP-B requirements. Through the use of normal

and superconducting shields, the DC magnetic field of the science instrument is reduced to less than 10^{-7} G, with an attenuation of the AC field in excess of 10^{13} . Additional GP-B technology, pertaining to the management of the gyroscope charge using electrons generated by UV photoemission, is described in an accompanying paper by Jafry *et al* [3].

2. Gyroscopes

Four high-precision, cryogenic, electrostatically suspended gyroscopes are used in GP-B to determine the inertial reference frame in the vicinity of the Earth. Residual torques are reduced to a minimum by compensating for the drag of the satellite [4] and by carefully controlling the sphericity of the gyroscope and its housing. Two gyroscopes are fabricated of fused quartz and two of single-crystal silicon. The density uniformity of the quartz is measured by an interferometric technique using a cube of material immersed in index matching fluid [5]. Quartz of the ‘Homosil’ grade produced by Heraeus Amersil [6] has a density uniformity of about one part in 10^7 over the radius of the gyroscope; a factor of ten better than the required uniformity. Single-crystal silicon, with very light doping, has a density uniformity similar to that of the Homosil quartz. Figure 1 shows a schematic view of an exploded gyroscope.

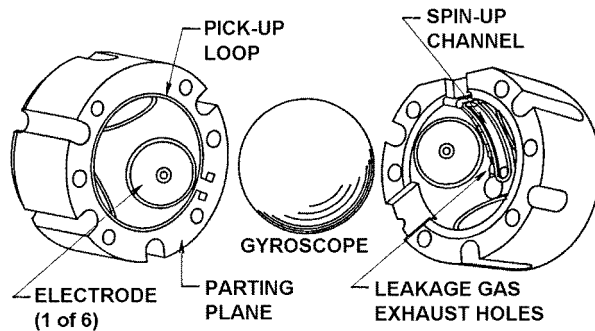


Figure 1. Schematic view of the gyroscope.

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 great 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 $1.25 \mu\text{m}$ thick is sputtered onto the rotors in 32 symmetric patches, achieving a peak-to-valley uniformity of better than 2%, or about 20 nm [7]. The very good spherical surface of the gyroscope rotors ensures the minimization of 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° of the bottom of the cavity during the tumble lapping operation. The peak-to-valley sphericity of the approximately 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 [8].

Table 1 summarizes the disturbance precessions for supported and unsupported gyroscopes [9]. The unsupported gyroscope, which is also used as the drag-free sensor, does not need electrostatic support, thus eliminating the largest disturbance precession. Ground testing of the gyroscopes has demonstrated a performance consistent with the relativity mission requirements. The performance of the unsupported gyroscope will allow the measurement of γ to one part in 10^5 .

Table 1. Gyroscope disturbance precessions.

Disturbance type	Supported (marcsec yr ⁻¹)	Unsupported (marcsec yr ⁻¹)
Mass imbalance (25 nm)	< 0.014	< 0.002
Electrostatic suspension	< 0.140	< 0.010
Residual He gas (10 ⁻¹¹ Torr)		
differential damping	< 0.006	< 0.006
Brownian motion	< 0.001	< 0.001
Rotor charge (10 pC)	< 0.010	< 0.010
Gravity gradient	< 0.001	< 0.001
Cosmic radiation	< 0.001	< 0.001
Magnetic	< 0.001	< 0.001
Photon gas	< 0.001	< 0.001
Root sum square	< 0.140	< 0.016

3. Low-temperature bake-out

Molecular drag represents a major disturbance torque for the gyroscope. Note, however, that gyroscope housing symmetry and spacecraft roll reduce the precession torque caused by the residual gas by more than 5×10^{-6} . The pressure requirement for the GP-B gyroscope precession measurement requires $P \leq 10^{-9}$ 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. Similar to standard bake-out, the temperature of the surfaces is raised, thus promoting helium desorption, while simultaneously the desorbed gas is pumped out from the probe. In addition, exploiting the large binding energy of helium on metals, the remaining gas is adsorbed, subsequent to the cool-down, in a surface submonolayer. The binding energy is typically $E_B/k_B \gg 150$ K [10]. Pumping out a volume V to the pressure P_1 at the bake-out temperature T_1 , will result (in the ideal case) in the pressure P_2 at temperature T_2 being

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{3/2} \exp\left[\frac{E_B}{k_B} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]. \quad (1)$$

Equation (1) is valid for the case of small volume to area ratio V/A :

$$V/A \ll \lambda \exp(E_B/k_B T) \quad \lambda \equiv (h^2/2\pi m_{\text{He}} k_B T)^{1/2} \quad (2)$$

where λ is the de Broglie thermal wavelength, all helium atoms are assumed to reside on the surface at T_2 , and the surface density σ is related to the volume density n by

$$\sigma = n\lambda \exp(E_B/k_B T). \quad (3)$$

For the GP-B operational conditions, $T_1 = 7.5$ K, $T_2 = 2.5$ K ($P_1 \leq 10^{-5}$ Pa), the expected pressure reduction factor is $P_2/P_1 \leq 5 \times 10^{-17}$. In practice this factor is not fully achievable

due to the open-cell geometry, the gas desorption from the higher temperature regions, and the non-complete bake-out of all surfaces. Using the low-temperature bake-out and an additional large-area adsorption pump, we expect to achieve a gyroscope pressure at 2.5 K of 10^{-13} – 10^{-15} Pa. A prototypical test system has demonstrated helium pressures of less than 3×10^{-12} Pa (2×10^{-14} Torr) limited only by the measurement capability of the residual gas analyser. Figure 2 shows the results of a bake-out test using the following procedure: (i) pumping at 2.5 K; (ii) turn heaters on for a temperature of about 6 K and continue pumping; (iii) turn heaters off and continue pumping at 2.5 K. The results for a system without a cryopump are also indicated in figure 2.

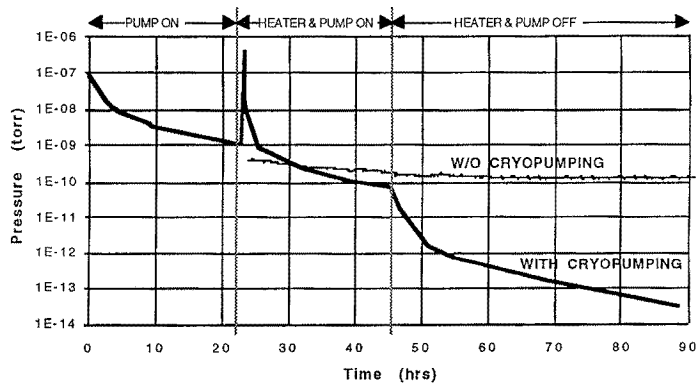


Figure 2. Results of a low-temperature bake-out test.

4. Read-out system

The London moment is the effect by which a rotating superconductor produces a magnetic field B_L throughout its volume aligned with the instantaneous spin axis ω_s . For a sphere of radius r , B_L results in a magnetic dipole moment M_L of magnitude

$$M_L = \frac{r^3 B_L}{2} = -\frac{mc}{e} r^3 \omega_s = -5.69 \times 10^{-8} r^3 \omega_s \text{ (G cm}^3\text{)} \quad (4)$$

where m and e are the mass and the charge of the electron, respectively, and c is the speed of light. The angular momentum is the conserved quantity which 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 speed ω_s , respectively [11]. The GP-B gyroscopes have $\Delta I/I \leq 5 \times 10^{-6}$, causing the coning angle to be smaller than 1 arcsec, and to average to the level of 1 marcsec in less than 5 s. Thus the London magnetic dipole represents the angular momentum direction, independent of polhoding. Figure 3 is a schematic of the London moment read-out concept. Experiments conducted at GP-B [12] have demonstrated that the London moment is the ground state of a superconducting rotating sphere. The same magnetic dipole is achieved independently of the thermal history of the process, that is cooling through the superconducting transition followed by spinning, or cooling after spinning. Note also that for films of above about 100 Å the London moment magnitude does not depend on the thickness. The low-noise DC SQUID magnetometer is coupled into a four-turn pick-up loop deposited onto the equatorial

parting surface of the gyroscope housing. Figure 4 shows the noise properties of the flux-locked DC SQUID system. At the 5 mHz detection frequency, the noise performance of the read-out in a fully prototypical experimental system is about $5 \times 10^{-29} \text{ J Hz}^{-1}$. This is equivalent to a resolution of 1 marcsec for an integration time of four hours, or about 20% better than the GP-B requirements.

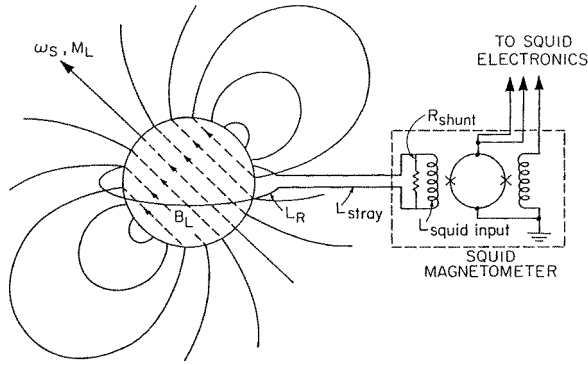


Figure 3. Schematic of the London moment read-out sensing system.

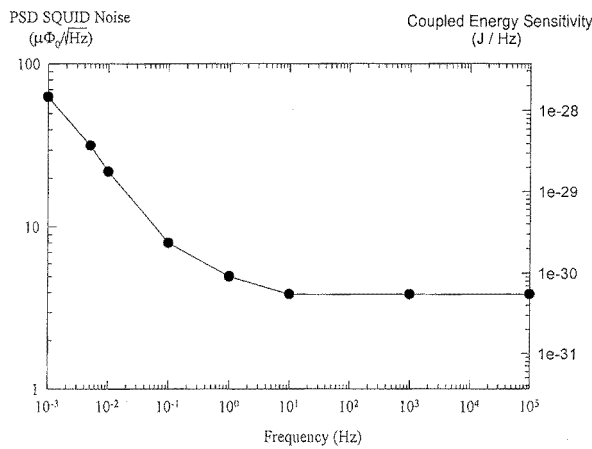


Figure 4. Noise properties of the flux-locked DC SQUID system.

5. Magnetic shielding

The London-moment-based read-out requires shielding from external AC magnetic fields by 13 orders of magnitude, and a DC field of less than 10^{-7} G is needed to ensure low trapped flux in the gyroscopes. This level of shielding is achieved by using a system of superconducting magnetic shields, in conjunction with controlling the magnetic properties of the probe materials. A ferromagnetic shield provides a 10 mG magnetic field region within which the main field reduction is achieved by the expansions of superconducting lead foil cylinders. The foil cylinder, folded to minimize the cross sectional area, is cooled through its superconducting transition temperature. Cooling rates are controlled in order to minimize

the currents induced by thermal gradients. Once the lead cylinder is superconducting, it is mechanically unfolded to its maximum diameter. This operation reduces the magnetic flux in the cylinder by roughly the ratio of the folded to the expanded cross sectional areas, a factor of about 20 in practice. Figure 5 represents the expansion process schematically. This process is repeated with additional lead cylinders being expanded one at a time inside the reduced field produced by the previous expansions. The lowest magnetic field values achieved are about 5×10^{-8} G; with further reduction prevented by thermoelectric effects in the lead foil [13]. The ferromagnetic shield and lead foil superconducting cylinder provide an AC shielding factor of about 10^9 , while a superconducting cylinder surrounding the gyroscope increases the shielding factor to 10^{12} . Finally, the superconducting gyroscope shields the readout loop from external fields by an additional factor of 10. The AC attenuation of this shielding scheme has been verified to be in excess of the 10^{13} level, the limitation being the noise performance of the RF SQUID detectors used. The DC residual field has been measured to be less than or equal to 10^{-7} G.

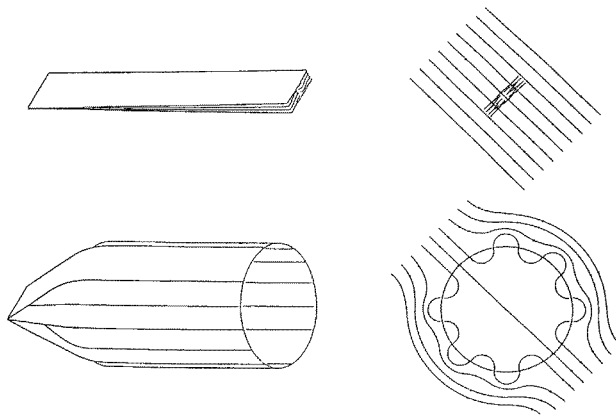


Figure 5. Lead cylinder expansion.

6. Conclusions

Advanced technologies developed for GP-B have made it possible to reach the experimental goals in the ground testing of prototypical experimental probes, and will ensure the achievement of the final accuracy required to measure γ to one part in 10^5 in the science mission flight. In addition, these same technologies can be applied to future high-precision experiments, both on Earth and in space. Among the space-based experiments which will use various GP-B developed technologies are the space test of the equivalence principle (STEP) and the gravity-wave detector using interferometry between drag-free satellites (LISA).

Acknowledgments

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