THE RELATIVITY MISSION GYROSCOPES

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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. The expected upper limit for residual gyroscope drift is 0.14 marcsec/yr (~5×10^{-12} deg/hr) for a supported gyroscope in 10^{-7} *g*, and 0.016 marcsec/yr (~5×10^{-13} deg/hr) for a free floating gyroscope. We present examples of test results from the more than 70,000 hours of gyroscope operation at both room and low temperature.

Overview

The primary goals of the Relativity Mission[1] are to measure the frame dragging effect to better than 3×10^{-3} and the geodetic effect to better than 2×10^{-5} (the PPN parameter γ will therefore be measured to better than 3×10^{-5}). For the planned 650 km polar orbit, this translates into a total error per gyroscope, including drift and read-out errors, of 0.3 marcsec/yr (~10^{-11} deg/hr). Allocating equal error budgets to the raw gyroscope drift and the read-out error, we get the requirement that the gyroscope drift be less than or equal to 0.2 marcsec/yr. In addition the experiment as a whole imposes a number of system requirements on the gyroscope. The space environment means that the gyroscopes should function in orbit and withstand the cosmic radiation effects. System compatibility with the London moment SQUID read-out and with the telescope inertial frame read-out requires gyroscopes which produce magnetic fields of less than 10^{-6} G and whose read-out loops are mechanically stable to better than 0.05 marcsec/yr. The lifetime of the system must exceed four years; two years of ground pre-testing and two years of actual space operation. Finally, the gyroscopes must function in Earth gravity, in order to allow for thorough performance testing, and should withstand (while not operating) vibration launch loads of approximately 10 *g*.

GP-B uses three main solutions to the problem of gyroscope drift reduction. First, and most important, the Newtonian torque is reduced by more than ten orders of magnitude by going to space in a drag-free satellite.[2] Figure 1 shows the typical performance level for various gyroscope types, underlining the necessity for a space experiment. Secondly the torques are minimized by machining the GP-B gyroscopes to the best achievable sphericity and mass unbalance; less than 25 nm asphericity and less than 50 nm mass unbalance for the 4 cm spheres. Thirdly the remaining torques are averaged by more than four orders of magnitude by rolling the spacecraft (and thus the gyroscope housing) around the gyroscope spin axis. Some disturbances (e.g. gas drag) are averaged by rolling but not reduced in orbit, and therefore the low gravity and rolling improvements are not additive.

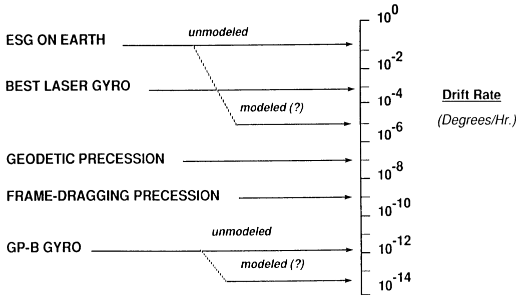

Figure 1. Typical gyroscope performances.

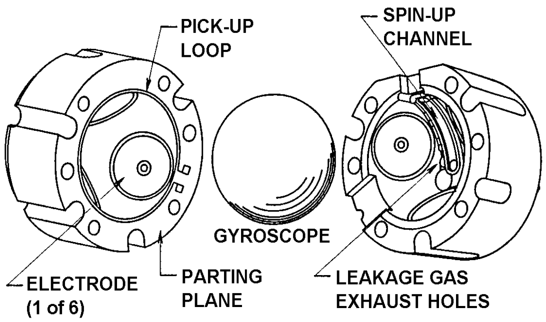

Figure 2. Schematic view of the gyroscope.

The Relativity Mission uses the London moment[3] of the spinning gyroscopes as its principal read-out. To implement this method, and also to insure the instrument's thermal and mechanical stability, the gyroscopes are cooled to 2 K by superfluid liquid helium. A low temperature bake-out technique is used to reduce the residual gas pressure in the gyroscopes to less than 10^{-11}torr. Caging of the gyroscopes using a piston actuated with pressurized ^{3}He protects them from damage during launch. Finally, GP-B will have four gyroscopes thus providing for multiple redundancy, extensive cross checks for systematic errors, and increased overall experimental accuracy.

Gyroscope Design and Performance

Figure 2 is an exploded schematic view of the gyroscope and its housing. The gyroscopes are made of either fused quartz or single crystal silicon in order to insure the density uniformity $\Delta\rho/\rho \leq 10^{-6}$ over the 4 cm diameter. A film of niobium 1.3 μm thick, with a non-uniformity of less than 1%, is deposited on the gyroscopes thus making them superconducting at the nominal 2 K operation temperature. The gyroscope housing is also made of fused quartz, and its cavity has a sphericity of better than 200 nm. The electrostatic suspension is implemented using three orthogonal pairs of thin film electrodes sputtered on the housing and spaced 32 μm from the centered gyroscope. A race track shaped channel allows spin-up to above 100 Hz using ^{4}He gas. Two concentric multi-turn pick-up loops, located on the equatorial plane separating the two housing halves, couple the London moment generated by the spinning gyroscope to the read-out system. Additional coatings on the housing cavity prevent the accumulation of static charges on the quartz, insure the correct positioning of the gyroscope prior to levitation, and limit the amount of leakage gas over the perimeter of the spin-up channel.

Table I summarizes the principal disturbance precessions for the gyroscopes. One of the gyroscopes will also serve as the drag free sensor and therefore will not require active suspension. The remaining three gyroscopes will be electrostatically supported, with an acceleration level of about $10^{-7}\,g$. Relativity Mission flight prototype gyroscopes have undergone more than 70,000 hours of testing at various spin frequencies at both room and low temperature (2 K-10 K). Figure 3 shows an example of a low temperature helium spin-up experiment followed by a period of free spin and then by spin-down effected using reverse helium gas flow. Figure 4 compares the spin-down rates (normalized to unity) of

Table I. Summary of gyroscope disturbances.

DISTURBANCE TYPE	GYRO SUPPORT	
	YES marcs/y	NO marcs/y
Electrostatic Susp.	< 0.140	< 0.010
Mass Unbalance <25nm	< 0.014	< 0.002
Rotor Charge <10pC	< 0.010	< 0.010
Residual He <10^{-11} torr		
Diff. Damping	< 0.006	< 0.006
Brownian Motion	< 0.001	< 0.001
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**

two gyroscopes operating in the same room temperature vacuum enclosure. The actual spin rates are 3.5 Hz and 1.6 Hz for the two gyroscopes respectively. This arrangement makes possible the subtraction of the drag effect due to the residual gas, and thus permits the setting of an upper limit to possible dissipative drag mechanisms. Taking into consideration the averaging effect of the housing roll around the spin axis, this limit corresponds to a precession rate of less than 0.05 marcsec/yr, well below the requirements.

Conclusions

Prototype gyroscopes for the Relativity Mission have been tested for over 70,000 hours under various conditions and have met all experiment requirements. The expected disturbance precession for the unsupported gyroscope is less than 0.016 marcsec/yr, while the precession for each of the three supported gyroscopes is less than 0.14 marcsec/yr. An experimental upper limit of 0.05 marcsec/yr has been set for any unmodeled dissipative torques. In conclusion, the precession of the gyroscopes is expected to make only a minor contribution to the total experimental error.

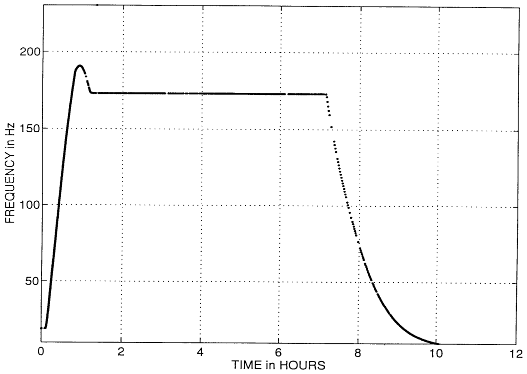

Figure 3. Low temperature nominal spin test.

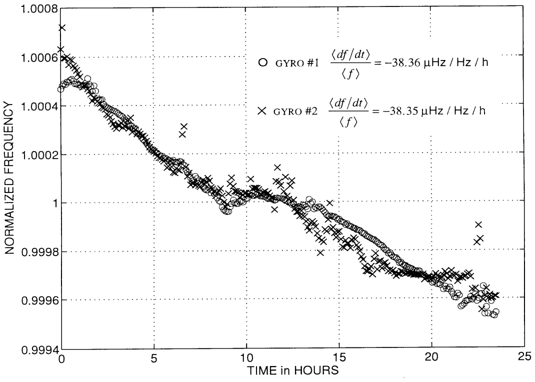

Figure 4. Room temperature test of two gyros.

References

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2. Staff of Space Dept. Johns Hopkins Univ. and Staff of Guidance and Control Lab. Stanford Univ., Journal of Spacecraft **11**, 637 (1974).
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