PROSPECTS FOR MEASURING γ TO A PART IN 10^5 IN THE GRAVITY PROBE B EXPERIMENT

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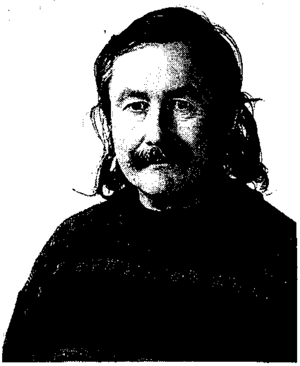

ABSTRACT

Gravity Probe B is a space based test of gravitational theory, making use of gyroscopes in a 650 km polar orbit to measure the precessions due to the geodetic and frame dragging effects. The present requirement for experimental accuracy is 0.3 marcsec/yr. We discuss improvements in the areas of gyroscope performance, gyroscope readout, and star tracking which will increase the measurement accuracy to about 0.07 marcsec for the 1.5 years experiment duration. This translates in a measurement of the parametrized post-Newtonian (PPN) parameter γ (mass produced curvature of three dimensional space) to one part in 10^5, extending the search for a possible scalar in gravity by two orders of magnitude, and allowing a test of the critically damped version of the Damour-Nordtvedt "attractor mechanism".

I. INTRODUCTION

Gravity Probe B (GP-B)[1], also known as the Relativity Gyroscope experiment, is designed to measure very precisely the frame dragging and geodetic effects predicted by Einstein's General Relativity theory. Leonard Schiff[2] has calculated the relativistic precession $\vec{\Omega}$ of a gyroscope in a circular Earth orbit to be:

$$\vec{\Omega} = \frac{3GM}{2c^2R^3}\left(\vec{R}\times\vec{v}\right)+\frac{GI}{c^2R^3}\left[\frac{3\vec{R}}{R^2}\cdot\left(\vec{\omega}_e\cdot\vec{R}\right)-\vec{\omega}_e\right] \tag{1}$$

where $\vec{R}$ and $\vec{v}$ are the location and the orbital velocity of the gyroscope, and I, M, and $\vec{\omega}_e$ are the moment of inertia, the mass, and the angular velocity of the Earth.

The first term represents the geodetic effect, which produces a precession with a rate of 6.6 arcsec/yr for a 650 km polar orbit, and is due to the motion of the gyroscope through the curved space-time around the Earth. This effect will be measured to about one part in 10^5, providing the most precise test to date of any of the positive predictions of General Relativity. The second term represents the effect is due to the dragging of the inertial frame by the rotation of the Earth, and its rate is 0.042 arcsec/yr. GP-B will measure the frame dragging effect for the first time and with a precision of about three parts in 10^3.

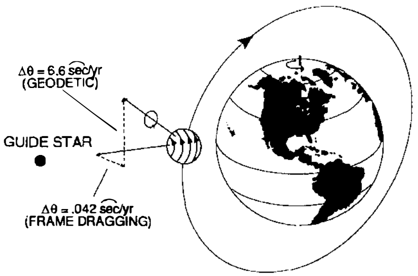

Figure 1. Geodetic and frame dragging precessions predicted by General Relativity for a 650 km polar orbit

The two precessions are measured by referring the local frame, determined by the gyroscopes, to the universal inertial frame, determined by a telescope pointed to a remote star, namely HR5110. Note that the proper motion of the star must be determined in a separate experiment. The experiment will be placed in a drag free satellite[3]. As shown schematically in Figure 1, the polar orbit will result in orthogonal geodetic and frame dragging precessions, thus significantly simplifying the data analysis.

Recent work by Damour and Nordtvedt[4] shows that tensor-scalar theories of gravity can result in deviations from zero of the PPN parameter γ of up to $\gamma - 1 \leq 4\times10^{-5}$. These theories contain a mechanism which drives the world towards pure General Relativity, with the above deviation a result of the finite time elapsed since the end of the radiation-dominated era. This provides additional incentive to increase the measurement accuracy in order to add the test of this prediction to the GP-B tests[5]. Expressed in terms of the PPN parameters, the relativistic precessions are:

$$\vec{\Omega} = \left(\gamma + \frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\vec{R}\times\vec{v}\right) + \left(\gamma + 1 + \frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\vec{R}}{R^2}\cdot\left(\vec{\omega}_e\cdot\vec{R}\right) - \vec{\omega}_e\right] \tag{2}$$

The following sections of this paper describe progress recently made at GP-B, in the areas of gyroscope performance and readout, and of guide star tracking, which resulted in the increase of the measurement accuracy from 0.3 marcsec/yr to about 0.07 marcsec for 1.5 years, thus offering the means of measuring γ to one part in 10^5.

II. GYROSCOPE PERFORMANCE

Four high precision, cryogenic, electrostatically suspended gyroscopes determine the reference frame in the vicinity of Earth. Residual torques are reduced to a minimum by using a drag free satellite and by carefully controlling the sphericity of the gyroscope and its housing. The ratio of the surface non-uniformity, with respect to the 1.9 cm spherical radius, is about 10^{-6} for the gyroscope and 10^{-5} for its housing. The drag free technique uses the thrust of helium, boiloff from the experiment's dewar, to maintain the spacecraft centered around a drag free sensor which floats in vacuum near the center of mass of the satellite. This assures a residual acceleration level of about $10^{-9}\,g$ ($g = 9.81\ \text{m/s}^2$) at the drag free sensor, which is averaged by the satellite roll to better than $10^{-12}\,g$ transverse acceleration. Due to their location away from this sensor, the individual gyroscopes will experience a residual acceleration of about $10^{-8}\,g$ caused by the Earth's gravity gradient. The main residual torques on the gyroscopes are caused by the interaction of the electrostatic suspension system (needed to compensate for the gravity gradient acceleration) with the imperfections of the gyroscope surface.

Table 1. Gyroscope disturbance precessions

DISTURBANCE TYPE	**GYROSCOPE SUPPORT**	
	Supported (marcsec/yr)	**Unsupported (marcsec/yr)**
Mass Unbalance (25nm)	< 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 (10pC)	< 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**

One of the fourfold redundant gyroscopes can be used as the drag free sensor, thus removing the suspension, and therefore the main contributions to the torques. The drift rate is reduced from 0.14 marcsec/yr, for the supported gyroscopes, to 0.016 marcsec/yr for the unsupported gyroscope. Table 1 summarizes the disturbance precessions for supported and unsupported gyroscopes, assuming 130 Hz spin speed, $10^{-12}\,g$ average transverse acceleration, and 10 arcsec misalignment of the roll and spin axes. The disturbance precession increases with time, and is 0.024 marcsec for 1.5 years for the unsupported gyroscope, and 0.12 marcsec for the combined three supported gyroscopes.

III. GYROSCOPE READOUT

The gyroscope readout is based on the detection of the London dipole moment, created by a spinning superconductor. Precession of the angular momentum is mirrored by the precession of the magnetic dipole, and induces variations of the flux threading a loop concentric to the gyroscope, which are then measured by a SQUID magnetometer. Rolling of the satellite around the line of sight to the guide star, (also the gyroscope spin axis), allows readout at roll rate, thus avoiding zero frequency measurements.

The noise in the readout system is dominated by 1/f noise, making it desirable to increase the roll rate. This however has a number of drawbacks, the main one being the centrifugal force on the gyroscopes caused by misalignment of their centers of mass to the roll axis. Improvements in the experimental probe have recently allowed the increase of the roll rate from 1.7 mHz to 5.5 mHz thus significantly reducing the expected readout noise. Coupled with reductions in the noise level of the dc SQUID system, this has reduced the expected error in the readout system to the level of about 0.11 marcsec/yr. Figure 2 shows the results of a Monte Carlo simulation (0.09 marcsec/yr) and of the calculated readout error for a one year experiment. Each gyroscope has a dual readout, consisting of two parallel SQUID systems, thus allowing for a reduction of the error to 0.78 marcsec/yr. Furthermore, the readout error decreases with the square root of time, resulting in an error of 0.064 marcsec for 1.5 years, (9.9 arcsec geodetic precession).

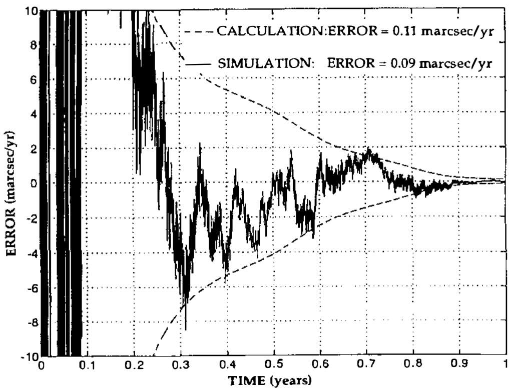

Figure 2. Monte Carlo simulation solid line) and theoretical calculation (dashed lines) of readout error for one year experiment.

IV. GUIDE STAR REFERENCE

The third and last major component of the experiment is the optical telescope which gives the reference to the guide star. Originally the guide star was Rigel with a declination of DECL = -8°13' and luminosity m_V = -0.1. This choice was dictated by the sensitivity of the optical detection system: photo multipliers, choppers, fiber optics, and optical windows. A new detection system using cryogenic photo detectors and JFET preamplifiers now allows the telescope readout to utilize stars down to magnitude $m_V \sim 6$. Consequently, guide star candidates now include stars with radio emission, making it possible to use VLBI to provide accurate measurements of the proper motion of these stars. Two promising candidates are the close in binary systems (< 1.6 marcsec) HR1099: DECL = 0°36', m_V = 5.7, and HR5110 DECL = 37°10', m_V = 5.0, with HR5110 being the present choice. The present accuracy of the measurement of the proper motion of HR5110 is 0.1 marcsec, and is expected to be improved to 0.025 marcsec in the next 3 years.

V. CONCLUSIONS

The errors in the three major areas of the GP-B experiment have been reduced to 0.064 marcsec, 0.025 marcsec, and 0.024 marcsec for the readout, star tracking, and gyroscope respectively, resulting in a total expected error of 0.073 marcsec for 1.5 years, and a measurement of γ to 1.1 parts in 10^5. Future possible improvements are: 1) lower gyroscope charge and position measurement voltages, and higher vacuum resulting in an unsupported gyroscope error of 0.012 marcsec, 2) reduction in the SQUID noise, and increased roll and spin rates, reducing the readout error to 0.040 marcsec, 3) determination of the proper motion of the guide star to the 0.01 marcsec level, and 4) modeling of the disturbance torques of the supported gyroscopes to the 10% level, reducing the error of their ensemble to 0.012 marcsec. If realized, the first three improvements will reduce the total error of 0.045 marcsec, and allow a measurement of γ to seven parts in 10^6, while torque modeling will further reduce the error to 0.032 marcsec, and result in a measurement of γ to five parts in 10^6.

ACKNOWLEDGMENTS

This work was supported by NASA contract No. NAS8-36125. The authors wish to thank John Turneaure, Mac Keiser, and Jeremy Kasdin, of the Stanford University GP-B group, for their help with the preparation of some of the data in this paper.

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