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Gravity Probe B:
Status and Flight Plans

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Abstract

The Gravity Probe B Relativity Gyroscope Experiment will test two independent predictions of the General Theory of Relativity by measuring the precession rates of gyroscopes in a 650 km high polar orbit about the earth. The goal is to measure the geodetic effect to a precision to 2 parts in 10^5 and the frame-dragging effect to a precision of 3 parts in 10^3. This paper presents the status of the program and progress toward science mission launch.

1 Introduction

Gravity Probe B, also known as the Relativity Mission, is a space-based experiment being developed at Stanford University to test two predictions of Einstein's General Theory of Relativity. The goal of the experiment is to make very accurate measurements of the geodetic and frame-dragging effects by means of measuring changes in the spin direction of gyroscopes in polar orbit about the earth. It is an experiment that requires a dedicated satellite, which is scheduled to be launched in December 1999.

The relativistic precession, $\vec{\Omega}$ of a gyroscope in a circular orbit around the earth was calculated in 1960 by Schiff [1] and is given by:

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

where R is the position and v the orbital velocity of the gyroscope, and I, M, and ω_e are the moment of inertia, mass, and angular velocity of the earth, and G is the gravitational constant.

The first term describes the geodetic precession, which arises from the curvature of space-time due to the mass of the earth. General

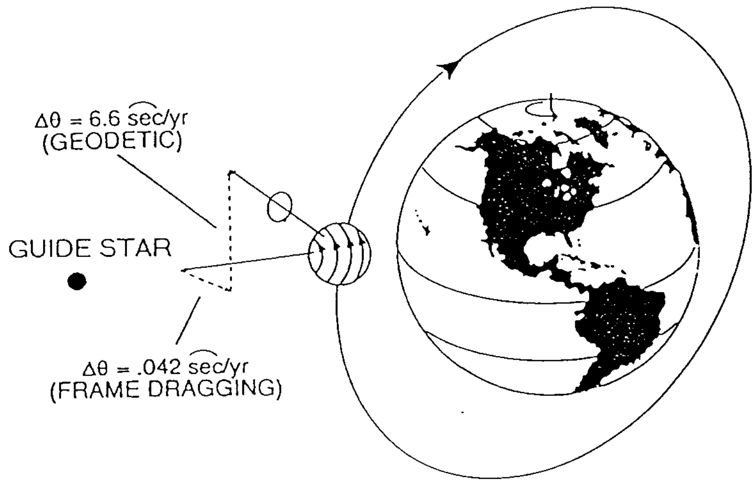

Figure 1: A gyroscope in orbit about the earth. Arrows indicate the directions of the relativistic precessions.

Relativity predicts that the direction of the gyroscope will change at the rate of 6.6 arcsec per year for a gyroscope in a 650 km high polar orbit. The experimental goal is to measure the geodetic effect to 2 parts in 10^5, making this the most precise non-null test of General Relativity. The second term represents the precession due to the dragging of the inertial frame by the rotation of the earth. General Relativity predicts the rate of precession of a Gravity Probe B gyroscope to be 0.042 arcsec per year (42 marcsec/yr). The experimental goal is to measure this effect to 3 parts in 10^3. This will be the first test of General Relativity to directly measure the dragging of inertial frames by the rotation of a massive body. A polar orbit is chosen so that the two precessions are orthogonal and can therefore be discerned independently. Alternative theories of gravitation have been proposed that predict different magnitudes for either or both of these effects [2, 3]. Gravity Probe B will measure the geodetic and frame-dragging effects with sufficient precision to be able to distinguish between several alternative theories and General Relativity.

2 Experiment System Overview

The small sizes of the relativity precessions require that the experiment system have extreme measurement precision and that all sources of error be controlled. In order to achieve this requirement the experiment exploits the advantages of a near zero-g orbit in space and a near zero temperature in the experiment probe [5, 6, 7, 8]. Figure 2

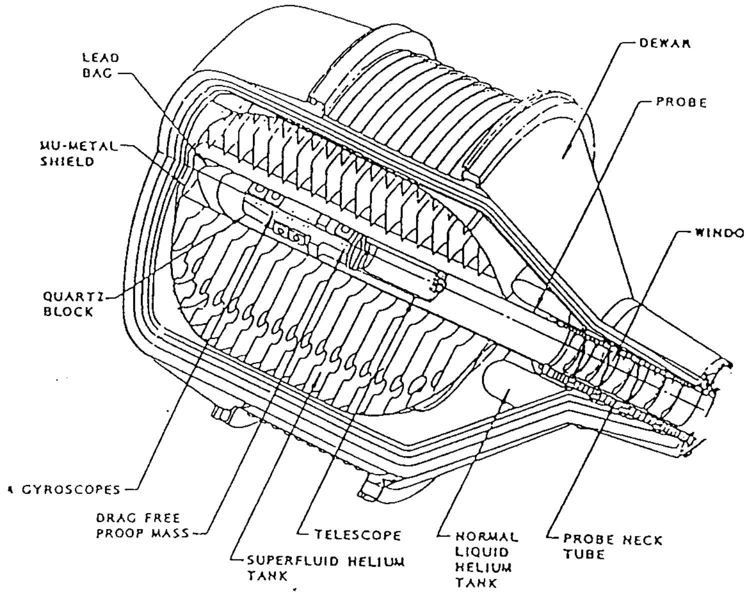

Figure 2: Gravity Probe B experiment module.

shows the experiment module consisting of a helium dewar, which holds 2300 liters of superfluid helium, surrounding the experiment probe consisting of 4 gyroscopes, a quartz block, and a star tracking telescope. The dewar is designed to have an on-orbit helium lifetime of greater than 16.5 months. The helium is maintained at a temperature of 1.8 K by means of a porous plug venting system and the boil-off gas is used to power proportional thrusters used in drag-free control. The thrusters keep the spacecraft centered around a gyroscope in free fall to produce residual accelerations at this gyroscope of less than 10^{-9}g ($g=9.8\ m/s^2$). Three other gyroscopes and a redundant drag-free proof mass are mounted within a rigid quartz block assembly. The quartz block provides precise positioning of the gyroscopes and the telescope, with cryogenic temperatures increasing mechanical stability. A series of windows provide an open line of sight out of the dewar. The star tracking telescope is used to point the spacecraft towards a guide star, providing a distant inertial reference with which to compare the gyro spin direction.

The spacecraft rolls about the line of sight to the guide star with a period of 3 minutes. This averages off-axis accelerations (which contribute to Newtonian torques at the gyroscopes) to 10^{-12}g and allows the gyroscope spin direction to be measured at roll frequency, greatly reducing the effects of DC bias and drift.

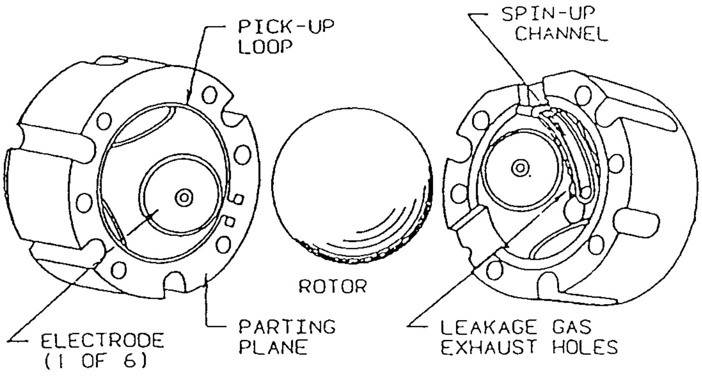

Figure 3: Exploded view of GPB gyroscope.

3 Gyroscopes and Gyroscope Readout

The heart of the Gravity Probe B mission are the gyroscopes. The experiment accuracy dictates that the fundamental requirement for the Gravity Probe B mission is to orbit gyroscopes whose absolute Newtonian drift rates are of order or less than 0.1 marcsec/yr and whose total inertial drift can be verified to an accuracy of 0.1 marcsec/yr. Figure 3 gives a schematic, exploded view of a gyroscope. The gyroscope is comprised of a rotor approximately 39 mm in diameter, which spins freely within the spherical cavity of a quartz housing. Newtonian torques on the gyroscope are minimized by the drag-free control system and by manufacturing rotors of high sphericity and density homogeneity.

Rotors are fabricated from fused quartz and single crystal silicon with density inhomogeneity of less than 2 parts per million and are polished to achieve peak-to-valley asphericity of less than 25 nm. The rotors are coated with a thin, uniform layer of niobium, which has a superconducting transition temperature of 9.2 K. The niobium coating enables the rotor to be electrostically suspended within the housing and provides a means for sensing the gyroscope spin direction, discussed below. The housing for the rotor, shown in two halves split by a parting plane, has 3 orthogonal pairs of electrodes used to sense the rotor position and electrostatically suspend it. Once suspended, the rotor is spun up by sending helium gas through the spin-up channel. A final spin speed of about 130 Hz is chosen to increase the readout signal without excessively distorting the rotor shape due to centrifugal loads. The helium gas is then pumped away to high vacuum to eliminate residual gas damping of the rotor.

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As stated earlier, one of the gyroscopes is used as a drag-free sensor. No electrostatic suspension voltages are required for this gyro, which is kept centered in the housing by the positioning of the spacecraft around it. Suspension voltages are required for the other gyroscopes to overcome small accelerations ($< 10^{-7}$g) produced by the earth's gravity gradient. Suspension system forces produce the leading disturbance torques on the gyroscopes. Modeling of the gyroscope performance based on over 70,000 hours of ground testing indicates that the residual torques yield drift rates of 0.1 marcsec/yr for the suspended gyroscopes and about an order of magnitude less for the unsuspended gyroscope.

The gyroscope readout system must be capable of resolving changes in the rotor spin direction of 0.1 marcsec without producing interaction torques that could disturb that spin direction. The experiment probe's low operating temperature allows the properties of superconductivity to be exploited, both as the physical basis of the readout signal and for the signal's detection. The readout signal is based on the magnetic field produced by the London moment of a rotating superconductor [6]. As the niobium coated rotor is spun up, it develops a London magnetic moment aligned with the instantaneous spin axis. The London moment produces an equivalent magnetic field just outside the rotor of magnitude:

$$B_{\mathrm{L}} = 1.14 \times 10^{-7} \omega_{\mathrm{s}} \text{ Gauss} ,$$

where ω_{s} is the spin angular velocity.

The London field is measured using a dc SQUID (superconducting quantum interference device) magnetometer, as shown in figure 4. On the parting plane between the two housing halves there is a four turn superconducting pickup loop which couples the London moment flux to the SQUID. The gyro spin axis is aligned close to the spacecraft roll axis, so the London moment produces a signal modulated at roll frequency. At our design spin speed (130 Hz), the London field is just below 1×10^{-4} Gauss. Therefore, to resolve 0.1 marcsec changes in spin direction a field sensitivity of 5×10^{-14} Gauss is required. The measured noise performance of the Gravity Probe B SQUIDs establish that 1 marsec resolution is achieved in less than 10 hours of integration time, consistent with mission requirements.

Such low field levels also dictate the need for extensive magnetic shielding. Ultralow dc fields of less than 10^{-7} Gauss, required to minimize flux trapping in the rotor, are produced using the expanded superconducting lead bag shielding technique [6]. This lead shield coupled with additional internal superconducting shielding and an external cryoperm shield yield ac (roll frequency) field attenuation at the gyroscopes of greater than 1×10^{12}.

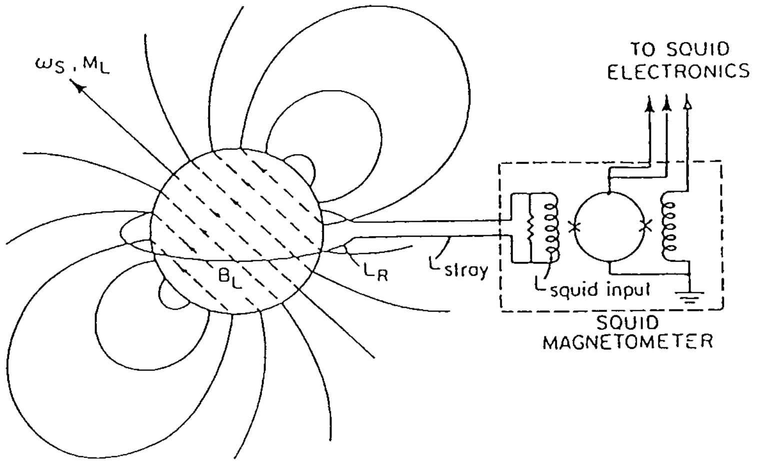

Figure 4: London moment readout system.

4 Telescope and Guide Star Selection

It is necessary to measure the spin direction of the gyroscopes relative to a distant reference frame, one not affected by the mass or spin of the earth. Therefore, a telescope is incorporated into the experiment module to track the position of a guide star.

The star tracking telescope is of the folded Schmidt-Cassegrainian type with a 140 mm diameter mirror and 3.81 m focal length. It is constructed out of fused quartz and has an overall physical length of 350 mm. Two focused images are formed on the edges of roof prisms by splitting the incoming star light with a beam splitter. The edges of the roof prisms are perpendicular, providing two axes of readout. Each prism divides the star image into two partial images whose intensities are determined using cryogenic silicon photo detectors and cryogenic preamplifiers. The relative intensities of the prism-split images determine the direction of the line of sight to the guide star. Using this signal, the spacecraft attitude is controlled to point in the direction of the guide star.

Cryogenic telescope tests have been performed using a ground-based light source to act as a guide star. These tests have determined that the leading noise sources, photon counting noise and telescope readout electronics noise, are well below system requirements ($<$10 marcsec/$\sqrt{\text{Hz}}$) for stars brighter than magnitude 6.

An important factor in reaching measurement accuracy is the selection of the guide star to act as an inertial reference. The two main science issues concerning guide star selection are the proper motion of the guide star, or change of the guide star position with respect to very distant "fixed" stars, and the effect of declination on the magnitude of frame-dragging. For a polar orbit, Equation 1 indicates that the frame-dragging term is proportional to the cosine of the declination, thus favoring selection of a star near the equatorial plane. Uncertainties in the proper motion of the guide star contribute to experimental error and therefore the guide star proper motion needs to be known to high accuracy. Fortunately, several candidate stars brighter than the magnitude 6 threshold are also radio sources, allowing their proper motion to be determined using Very Long Baseline Interferometry (VLBI). Leading guide star candidates, HR5110, HR1099, and HR8703, now have sub or near marcsec/yr proper motion uncertainties and VLBI observations are continuing to further reduce these uncertainties [7].

5 Ground Testing and Error Analysis

All individual experimental components are continuing to undergo intensive ground testing to provide data for error estimates. In addition, Gravity Probe B is involved in a series of rigorous integrated systems tests. We are presently proceeding with a ground test of a full scale experiment probe, with a full complement of 4 gyroscopes and a telescope, housed within an engineering dewar. This probe will serve as a backup for the science mission. The present test is investigating the interaction of all the experimental systems and is due to be completed in 1995. The science mission flight dewar is now in construction. We have scheduled an integrated test of the full scale experiment probe and the science mission flight dewar in 1997. In parallel, construction is beginning on the science mission flight experiment probe; a series of tests with the flight probe and the flight dewar (science mission payload verification) is scheduled for late 1997. The spacecraft will be completed by the end of 1998 to prepare for science mission launch.

Ground tests of the gyroscopes, telescope, and integrated systems have enabled us to determine our expected experimental error. Estimates of all individual error sources are combined to yield overall expected geodetic and frame-dragging error as a function of the mission duration. The covariant error analyses are checked against the results of Monte Carlo simulations of measurement error that include gyroscope readout system noise, telescope noise, and error in the scale factor relating the telescope and gyroscope readout directions. The most recent results predict most probable standard errors of 0.20 marcsec/yr and 0.18 marcsec/yr for the geodetic and frame-dragging measurements, respectively, for each gyroscope taken singly. For combined measurements of all four gyroscopes these errors are 0.11 marcsec/yr and 0.10 marcsec/yr, which will allow the determination of the geodetic effect to a precision of 1.7 parts in 10^5 and of the frame-dragging effect to 2.3

parts in 10^3. We anticipate mission launch from Vandenberg Air Force Base in December, 1999.

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References

[1] L. I. Schiff, *Proc. Nat. Acad. Sci.* 46 871 (1960).

[2] T. Damour and K. Nordtvedt, *Phys. Rev. Lett.* 70 2217 (1993).

[3] C. Will, *Theory and Experiment in Gravitational Physics* Rev. ed. Cambridge [England] ; Cambridge University Press, (1993).

[4] D. Bardas, et al., *Proc. of SPIE* 619 29 (1986).

[5] C. W. F. Everitt, D. Davidson, and R. Van Patten, *Proc. of SPIE* 619 89 (1986).

[6] J. Lockhart, *Proc. of SPIE* 619 148 (1986).

[7] C. W. F. Everitt and S. Buchman. *XXIXth Rencontre de Moriond, Particle Astrophysics, Atomic Physics and Gravitation* Ed. by J. Tran Thanh Van, G. Fontaine, E. Hinds Editions Frontieres (1994).

[8] B. Muhlfelder, et al., in *Proc. of the Seventh Marcel Grossmann Meeting on General Relativity* World Scientific, Singapore, (1995).