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Gravity Probe B - Testing Einstein at the Limits of Engineering

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The Gravity Probe B experiment was developed to test two predictions of General Relativity; the Geodetic and the frame-dragging precessions of a mechanical gyroscope due to the gravitational field of the Earth. This space-based, cryogenic experiment was carried into orbit on 20 April 2004 atop a Boeing Delta II rocket. On-orbit operations consisted of 4.3 months of experiment setup, 11.6 months of science data collection, and 1.4 months of post-science calibrations. Analysis of the science data is now in progress, scheduled to complete in 2007.

1. Introduction

Gravity Probe B is a space-based physics experiment designed to test two predictions of General Relativity. In 1959, G. Pugh [1] predicted that a gyroscope placed in orbit about the Earth would exhibit two precessions due to general relativistic effects, and in 1960, L. Schiff [2,3] showed that the effects were given by:

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

where $\vec{R}$ is the position of the gyroscope relative to the center of the Earth and $\vec{\nu}$ its orbital velocity. I, M, and $\vec{\omega}$ are the moment of inertia, mass, and angular velocity of the Earth, and G is the gravitational constant. γ and α_1 are PPN parameters; in general relativity $\gamma = 1$ and $\alpha_1 = 0$.

The first term in this equation quantifies the geodetic precession. This precession, due to the orbital motion of the gyroscope through the curved space surrounding the Earth, is in the orbit plane.

The second term gives the frame-dragging precession. This precession results from the rotation of the Earth and causes the gyroscope's spin axis to precess in the Earth's equatorial plane. For a polar orbit these two effects are at right angles to one another. Figure 1 shows the experimental configuration. For an orbital altitude of 642 km, general relativity predicts a geodetic precession of 6.6 arc-sec/yr and a frame dragging precession of 0.041 arc-sec/yr.

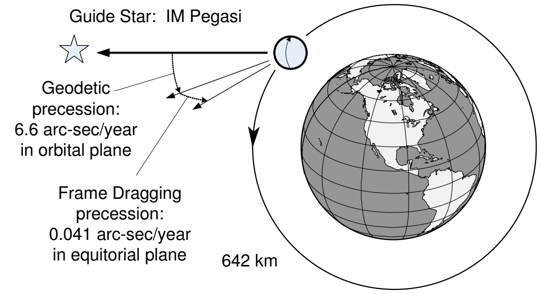

Figure 1. GP-B Experiment Configuration.

The required apparatus to perform this measurement is simple in concept. The long term drift of the spin axis orientation of a gyroscope is measured relative to inertial space. This inertial reference frame is realized on the spacecraft by use of a tracking telescope to lock on to a nearly fixed "guide" star. Correction for the residual

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proper motion of the star is achieved by precision guide star position tracking using measurements from ground-based very long baseline interferometry (VLBI). Spacecraft control is also needed for the rotational degree of freedom of the vehicle about the line-of-sight to the star. Optical sensors on the side of the spacecraft sight stars with known locations to allow the rotation of the vehicle to be controlled. This rotation or roll control allows the north-south gyroscope drift (geodetic) to be separated from the east-west gyroscope drift (frame dragging).

Although the true position of the guide star is nearly fixed in inertial space, the tracking telescope does not sense this true position. Instead, the telescope detects the star light aberrated by the spacecraft's transverse velocity, v_t, relative to the line of sight to the star. This transverse velocity causes a v_t/c angular shift in the observed and tracked star location relative to the true position. The aberration induced pitching of the vehicle causes a modulation of the orientation of the gyroscope relative to the apparent star location. The aberration signatures at orbital and annual frequencies serve as important checks on the validity of the experiment results. Furthermore, an on-board GPS receiver provides accurate vehicle position and velocity information to allow high accuracy determination of the aberration time signature. This time signature provides a high accuracy calibration of the angular scale of the gyroscope orientation data.

2. Gravity Probe B Hardware

There are 5 significant contributors to the total experiment error in the GP-B experiment:

1. Newtonian drift of the gyroscope spin axis caused by classical torques,
2. Mis-pointing of the space vehicle,
3. Measurement error arising from imperfect determination of a) the gyroscope's spin axis orientation, b) the location of the guide star, and c) the spacecraft orientation,
4. Uncertainty in the proper motion measurement of the guide star,
5. Uncertainty in the predicted precession rates due to imperfect knowledge of the parameters in Eq. 1.

Figure 2. GP-B Gyroscope; clearly seen are the suspension electrodes and spin-up channel.

These five sources of experiment error are listed in order from largest to smallest. Prior to launch the overall experiment error including contributions from these and all other known sources was calculated to be less than 0.0005 arc-sec/yr

The GP-B science instrument houses four gyroscopes of the same design. Since, in principle, only one gyroscope is needed to measure the two relativity effects, the four gyroscopes provide redundancy and agreement of the measurements will add credibility to the result. Each gyroscope rotor is a fused quartz sphere, 38 mm in diameter, and uniformly coated with 1250 nm of niobium. The rotor is encased within a two-piece clamshell housing as shown in Figure 2. It is actively suspended within the housing cavity using electrostatic fields (non-contact suspension) applied through a set of six electrodes arranged on orthogonal axes.

The rotor is spun by flowing helium gas through a channel located on the inner spherical surface of the housing. The resulting flow of the helium gas over the rotor surface causes the rotor to reach spin frequencies of up to 80 Hz (4800 RPM). The gas is vented to space and the spinning rotor is operated in ultra high vacuum for the relativity measurements. The rotor's location within the housing is inferred by measuring the capacitance between the rotor and the three pairs of suspension. A controls electronics package applies small voltages (200 mV) to the electrodes to center the rotor in the housing cavity.

Management of the static electric charge on the rotor is needed to limit electrostatic forces and torques. The housing's electrodes allow for a measurement of the rotor's DC potential from which the rotor charge can be estimated. Control of the rotor charge is achieved by applying UV light to the rotor to generate photoelectrons. Electric charge on the inner spherical surface of the housing may also cause electrostatic forces and torques on the rotor. These charges are minimized by use of a grounded conductive housing coating.

A unique translation control system dramatically reduces spacecraft and gyroscope acceleration that would otherwise result from external forces acting on the exterior of the spacecraft. If left uncorrected, the induced acceleration due to solar radiation and atmospheric drag would cause excessive gyroscope torques. To minimize this acceleration, a drag-free system has been implemented on one of the gyroscopes. This system forces the center of mass of the otherwise accelerated spacecraft to follow the protected and unaccelerated center of mass of one of the gyroscopes. The three non-drag-free gyroscopes do experience small residual gravity gradient accelerations; however the net effect of the drag-free system is to dramatically reduce the science impact of support forces acting on the gyroscopes.

Measurement of the spin axis orientation of the gyroscope relies upon the unique properties of superconducting materials. The spinning superconducting niobium surface of the rotor generates a London magnetic moment that is co-aligned with the rotor's instantaneous spin axis. A superconducting pickup loop, located on the housing parting plane, couples the London moment to a SQUID magnetometer. The plane of the pickup loop is aligned with the telescope boresight, making the treaded signal is proportional to the sine of , the angle formed by the gyroscope spin axis direction and the telescope axis. This measurement system provides a signal that is proportional to the angle between the rotor spin axis orientation and the telescope axis. The telescope is pointed along the line of sight to guide star, and therefore, the rotor spin axis orientation can measured relative to the direction to this star.

The telescope serves as the key input to the spacecraft's attitude control system to track the guide star. This telescope is bonded to a quartz block that houses the four gyroscopes at the operating temperature of $\sim$ 3K. The mechanical stability of the quartz block at this low temperature ensures the telescope and gyroscopes share a common reference frame. An image divider within the telescope splits the star light for simultaneous two-axis orientation measurements. The light is split by a pair of orthogonal roof prisms to allow a differential measurement for each axis using photodiodes operating at $\sim$ 72K. The spacecraft attitude control system keeps the telescope pointed at the star by maintaining balanced light intensities on the two sides of each roof prism.

The telescope, quartz block, and gyroscopes, referred to collectively as the science instrument assembly (SIA), are assembled into a vacuum probe that is in turn assembled into the dry well of a 2400 liter superfluid liquid helium dewar. The probe provides a 16.5 cm diameter unobstructed optical path for the telescope to sight the star. The heat leak into the 1.8 K liquid helium is limited to 170 mW resulting in an on-orbit liquid helium lifetime of 17.3 months. This very low heat leak has been accomplished by controlling the conduction and radiation of heat into the liquid helium from outside the spacecraft. Four windows in the optical path intercept most of the radiated heat flowing into the probe through the telescope viewing port. The outermost window acts as a vacuum seal for the probe, and an indium-tin oxide film on this window reduces RF interference leaking into the SIA.

Magnetic shielding is required to isolate the London magnetic moment readout system from the Earth's magnetic field. The shielding is also required to limit magnetically induced gyroscope torques. This primary shielding is implemented with the use of an expanded superconducting lead bag and a ferromagnetic shield located within the dewar well. Together, these components give a static magnetic field of less than $\sim 10^{-7}$ gauss, and, when combined with a cylindrical niobium shield around each gyroscope and gyroscope selfshielding, provide an AC magnetic attenuation of more than 220 dB.

The dewar and probe are held within a custom spacecraft bus. Gyroscope and telescope support electronics are mounted in a thermally controlled enclosure at the top of the probe. Additional electronics are located toward the aft end of the spacecraft. These electronics include the six computers on the spacecraft, a solid state recorder to store the science data, and the telemetry system to transmit data to the ground.

3. On-Orbit Operations

The GP-B spacecraft was launched from Vandenberg Air Force Base, California, on 20 April 2004 on a Boeing Delta II two stage rocket. The resulting orbit injection placed the vehicle within 100 meters of its target near the Earth's poles. This near perfect orbit injection eliminated the need for a 1-month orbit trim procedure.

During the first 4.3 months on-orbit the spacecraft was configured for science data collection. The guide star, HR 8703 (IM Pegasi), was acquired approximately 40 days after launch. Prior to spinning the gyroscopes, a magnetic flux reduction procedure was successfully performed to reduce the magnetic flux trapped in each rotor to less than $5 \cdot 10^{-6}$ gauss. Operationally, this procedure was accomplished by raising the temperature of the superconducting rotors above their transition temperatures and then slowly lowering the temperature back down through that temperature. The gyroscope charge measurement and control system was used to reduce the gyroscope electric charge to less than 10^{-10} coulomb (1 mV). The telescope and attitude control system were adjusted to optimize the spacecraft's pointing performance. The spacecraft drag-free system was adjusted to reduce external accelerations to less than $5 \cdot 10^{-11} m/s^2$. Following the spin up of the gyroscopes, the temperature of the SIA was raised to 6-7 K to remove helium gas adsorbed on cold SIA surfaces. The spin down time constant of the four gyroscopes following this procedure ranged from 7000 yr to 25,000 yr. These spin down time constants imply a probe gas pressure of less than 10^{-11} torr. Additional analysis suggests a probe pressure of approximately 10^{-13} torr. The final operation prior to the start of science data collection was to adjust the spin axis orientation of each of the gyroscopes to point to within 10 arc-sec of the guide star to reduce torques and meet readout requirements.

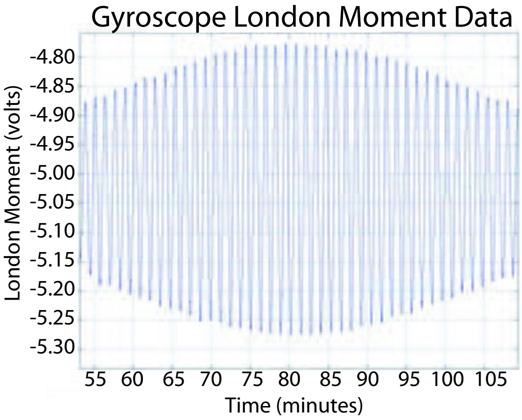

Figure 3. Gyroscope orientation data.

The science data collection phase started in late August 2004 and concluded on 15 August 2005. During this time, the primary science activity was to record the London moment spin axis data for each of the four gyroscopes. This raw data was transmitted to the ground daily where it was stored for later analysis. A plot of the data as a function of time has two obvious and expected deviations from the sloped line of a slowly precessing gyroscope. Representative data for approximately one half of an orbit are shown in Figure 3.

The 77.5 second sinusoidal oscillation seen in this data are generated by the gyroscope misalignment and the intentional roll of the spacecraft about the telescope axis. This operation causes the orientation of the gyroscope to appear in the data at the roll frequency of the spacecraft. The purpose of this operation is to dramatically improve the drift rate determination. This improvement arises from two factors: reduced Newtonian-induced gyroscope drift and reduced London moment measurement noise. Newtonian-induced drift is reduced because the torque arm acting on each gyroscope is now roll-averaged. Measurement noise is reduced because the slowly changing gyroscope orientation signal is transformed by the rotation of the spacecraft into a time-varying signal.

The rotation operation, described above, causes the London moment measurement to appear in a rotating reference frame. To determine the gyroscope drift vector relative to inertial coordinates, the data is transformed into the stellar inertial reference frame with the use of the continuously measured spacecraft rotation angle. A separate concern, gyroscope centrifugal acceleration arises from space vehicle rotation. This acceleration is limited by placing the center of mass of each gyroscope very close to the rotation axis of the spacecraft.

The curved envelope in the Fig. 3 data reveals the aberration-induced vehicle pitch motion. The spacecraft's orbital velocity transverse to the line-of-sight to the star and the resulting orbital aberration are close to zero at the beginning and end of the data set. This occurs when the spacecraft is nearly above the Earth's poles (see Fig. 1). As the spacecraft velocity vector become perpendicular to the line of sight to the star near the middle of the data set, the effect of aberration reaches a maximum, in this case increasing the signal amplitude. Fitting the London moment data to the accurately known aberration time signature allows us to convert the data from the measured voltage to an inferred angle. Note that the data in Fig. 3 are acquired when the telescope is tracking the guide star. During approximately half of each orbit the Earth occults the guide star and the gyroscope London moment data are not used to determine the gyroscope precession rates.

The vehicle completed approximately 6000 orbits during the one year of science data collection. The data for each orbit may be analyzed to give an in-plane and out-of-plane gyroscope orientation. Tracking the gyroscope orientations over the course of the year gives the two components of the gyroscope drift rate. The one year experiment duration also allows the annual aberration due to the Earth's orbital motion to serve as an additional experiment cross-check. In practice, several factors contribute to the need to enhance the data analysis approach. An orbit-by-orbit analysis does not make full use of the information contained in the data. We are interested in the two relativistic precession rates. The optimal mathematical methodology to provide these rates considers all of the data as a single measurement. Ideally, all of the data are fit to a single set of parameters including the precession rates. A second related issue is the optimal methodology to combine the precession rate information of the four gyroscopes. The precession rates of the four gyroscopes must be combined so that each measurement is given the correct statistical weight.

The physical model underlying the data analysis may be enhanced to include additional known effects. These effects include gyroscope misalignment torques, gyroscope scale factor modulation, spacecraft pointing error, and spacecraft rotation phase error. The purpose of the 1.4 month post-science calibration phase was to study some of these error sources. This unique calibration data is now being analyzed. The results from this work will be incorporated the science data analysis model. Although it is too early to discuss final results, it is instructive to describe an example of this more sophisticated data analysis methodology.

After the performance of the telescope and attitude control systems were optimized, the inertial spacecraft pointing error was reduced to approximately 0.025 arc-sec. This pointing error, if left uncorrected, would significantly degrade the experiment error. The impact of this pointing error on the experiment error has been dramatically reduced by use of the following technique. During the experiment, the spacecraft pointing was intentionally modulated about the direction to the star. This modulation resulted in a signal in both the telescope and gyroscope measurement systems. Modeling these signals allows the telescope data to be scaled to the gyroscope data. Armed with this scaling, a large fraction of the vehicle pointing error can be subtracted from the gyroscope data resulting in reduced experiment error.

The data analysis is expected to continue until late 2006. After the analysis is completed, the separately measured proper motion of the guide star will be subtracted from the gyroscope precession rate estimates to give the final experiment result. Up to that point, the analysis will not know the exact number for the proper motion, reducing any unconscious bias in the results. The final results are planned to be announced in 2007.

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`http://einstein.stanford.edu`

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