On-orbit Performance of the Gravity Probe B Gyroscopes and Electrostatic Suspension System

W.J. Bencze, D.N. Hipkins, Y. Ohshima, T. Holmes, G.M. Keiser, B. Muhlfelder, S. Buchman, C.W.F Everitt

The Relativity Mission Gravity Probe B , Hansen Experimental Physics Laboratory
Stanford University, Stanford, CA 94305-4085 USA
bencze@relgyro.stanford.edu

Abstract: The NASA/Stanford University Relativity Mission Gravity Probe B (GP-B), launched in April 2004, experimentally tests key predictions of the theory of General Relativity - the geodetic and frame dragging effects - by observing the precession of four redundant mechanical gyroscopes in Earth orbit. Presented here is the on-orbit performance of the electrostatic suspension system for the science gyroscopes. During the checkout, calibration, and science data gathering phases of the mission, the operation of the adaptive LQE controller and analog backup systems were verified, drag-free orbit performance was established, and the initial spin axes of the gyroscopes were aligned using residual electrostatic torques from the suspension.

Keywords: Electrostatic suspension, gyroscope, LQE, adaptive control, drag-free orbit, hybrid system.

1. Introduction

The Relativity Mission Gravity Probe B(GP-B) is a NASA-sponsored experiment aboard a satellite in Earth orbit to, designed to test some of the predictions of Einstein's theory of General Relativity. During the course of the satellite's 16 month mission, this experiment measures both the geodetic and frame-dragging effects by observing the spin axis precessions of four ultra-precise mechanical gyroscopes with respect to an inertial reference given by a well characterized distant star located in the orbital plane.[1] The precessions, as predicted by General Relativity, are shown in Fig. 1. The spacecraft was launched on 20 April 2004 into a 642 km polar orbit aboard a Boeing Delta-II expendable booster from Vandenberg Air Force Base near Santa Barbara, California, USA, and has been collecting science data since 28 August 2004.

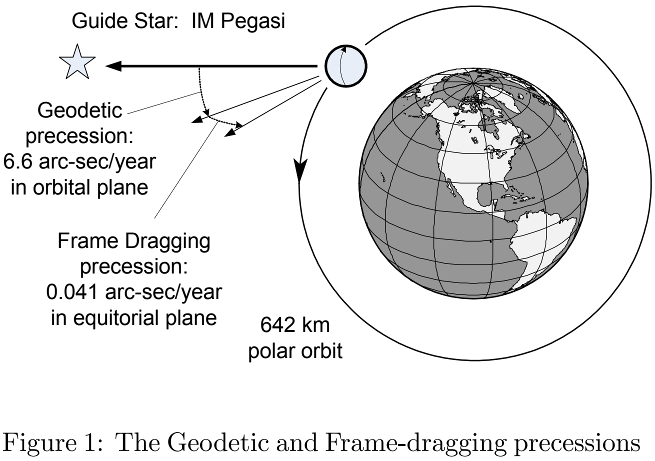

Figure 1: The Geodetic and Frame-dragging precessions predicted by General Relativity.

2. The GP-B Gyroscopes

At the heart of the experiment are the four redundant ultra-precise mechanical gyroscopes that are the reference for local inertial space in the gravitational field around Earth.[6] Each gyroscope will supply the measurement of both effects. The gyroscope rotors are 3.8 cm diameter precision machined fused quartz spheres (63.3 g) coated with a uniform layer of niobium metal. They are spherical to 10 nm and are mass-balanced to 10 nm. The rotors are housed in an evacuated, spherical quartz cavity with a nominal rotor-to-housing gap of 32 μm. The position of the rotor in the cavity is determined by measuring the differential capacitance between three pairs of electrodes on the housing wall and the rotor surface. These rotors are electrostatically suspended using the same electrodes. The rotor is spun-up by a helium gas jet flowing through a channel in the housing wall; see Fig. 2. The final spin rates of the four gyroscopes are in the range of 60 Hz to 80 Hz; spin-down rates average 2.7×10^{-10} Hz·s^{-1} (time constant τ = 10 000 yr).

The uncompensated drift rate of these gyroscopes is expected to be better than 1.6×10^{-11}deg·hr^{-1} (0.5 marc-sec·yr^{-1}), a factor of about 10^6 times better than the highest performance terrestrial navigation gyroscopes.[9] This very low drift rate is achieved by virtually eliminating Newtonian torques on the rotors by: 1) making the rotors extremely round and homogeneous, 2) minimizing the external forces on the rotors by placing them in a drag-free orbit, and 3) minimizing the magnitude of the suspension voltages that couple with asphericities to generate distrubance torques.

The gyroscopes operate at 2.5 K within a cryogenic vacuum probe inside a 2440 liter superfluid helium dewar (1.8 K). Temperatures below 9.25 K cause the nio-

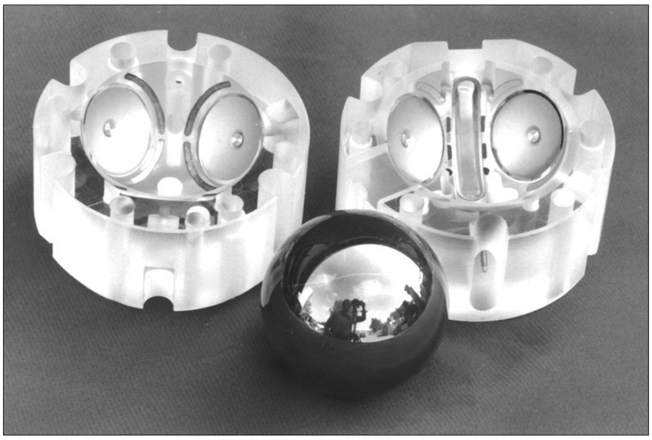

Figure 2: Photograph of gyroscope and housing. Electrodes (6) and spin-up channel (right housing) are clearly seen. The pickup loop is patterned on the parting plane on the left housing (not visible in photo).

bium coatings to transition to a superconducting state. The orientation of the rotor's spin axis is determined by measuring the dipolar magnetic moment, the London moment, generated by a spinning superconductor. The detection is performed with a highly sensitive SQUID magnetometer coupled to a superconducting pickup coil patterned on the parting plane of the gyroscope housing.[7)]

Spin axis measurement is accomplished at the roll rate of the space vehicle about the line of sight of the guide star. The time varying coupling between the dipole London moment and the pickup loop give both the magnitude of the angle between the spin axis and the roll axis as well as its roll phase when compared to the star field measured by a pair of star tracking cameras.

3. Suspension Requirements

The Gyroscope Suspension System (GSS) must satisfy a number of core requirements to perform its mission successfully:

- Operate over 8 orders of force magnitude; the same system must be able to suspend the gyroscopes on Earth in a 1 g field as well as generate minimal disturbances at the 10^{-8} g level during data collection.
- Suspend the gyroscopes reliably; the system must never let a spinning rotor touch the housing. There is sufficient mechanical energy in a rotor spinning at 60 Hz to effectively destroy the rotor and housing in such an event.
- Operate compatibly with the SQUID readout system. The SQUID magnetometers are very sensitive, thus the suspension system must not interfere with these sensors during ground and on-orbit operation.
- Minimize electrostatic torques during science data collection. The suspension system must meet centering requirements with minimal control effort and thus with minimal residual torques on the rotors.
- Apply controlled torques to the rotor for calibration and initial rotor spin axis alignment.
- Act as an accelerometer as part of the "drag-free" translation control system to further minimize classical torques on the rotors.

The position of each gyroscope rotor in its housing is sensed through and electrostatic centering forces are applied via six circular electrodes located on the gyroscope housing wall. This non-contact suspension eliminates gimbal and bearing torques evident in other mechanical gyroscopes; the residual electrostatic torques that do remain are proportional to 1) the rotor's spherical asymmetry, 2) the rotor's mass-imbalance, 3) spin axis misalignment from the vehicle roll axis, and 4) the magnitudes of the electrostatic suspension fields. Low-torque operation requires the control authority (bandwidth) of the controller to be minimized. The disturbance environment, however, is characterized by random micrometeoroid strikes that can apply impulsive disturbances as large as 10 000 times the nominal acceleration environment. A fixed control scheme that can handle these impulses produces gyroscope disturbance torques far in excess of mission requirements.

An adaptive Linear Quadratic Estimator (LQE) control algorithm has been developed to meet the high dynamic range requirements for the mission's electrostatic suspension.[2)] The controller architecture is novel because it uses estimates of the plant's state, rather than estimates of the plant's parameter, as inputs for adaptation. During operation, this allows the algorithm to dynamically increase its control authority and bandwidth to the level needed to respond to large impulsive disturbances while continuously minimizing control authority – and torques – during nominal operation. The net result of this scheme is that the control system performs like a high-bandwidth and high authority controller with respect to disturbances that move the rotor far from the commanded position, but performs like a low-bandwidth, low-authority control system with respect to gyroscope disturbance torques. Figure 3 shows the simulated response to variously sized micrometeoroids; this performance has been verified in orbit. This variable bandwidth control scheme, in part, allows the GP-B mission achieve its goal for the non-relativistic residual gyroscope precession rate of less than 1.6×10^{-11} deg·hr^{-1}. This algorithm is implemented in a radiation-hardened digital computer based on a PowerPC-derived British Aerospace RAD6000 processor running at 16.368 MHz within the suspension electronics package. To achieve maximum performance from the processor, a single-thread, non-preemptive real

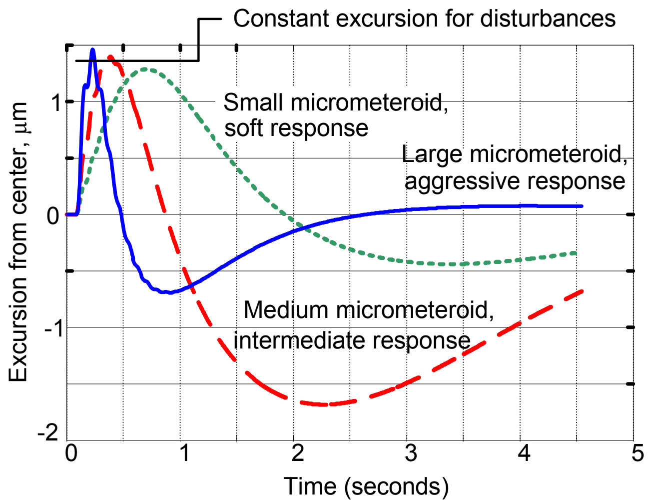

Figure 3: Simulated response of adaptive LQE controller showing constant excursion for varying disturbance magnitudes.

time operating system was written for this application. During peak demand periods during spin-up operations, the processor is loaded to 96% of its capacity; science operation requires approximately 65% of capacity The code for this application is small, however, only occupying 500 kbytes of memory.

The range of operation of the digital control algorithm is shown in Fig. 4. The digital controller is able to operate over 8 orders of magnitude of force disturbances while minimizing the torques on the gyroscope rotors. The primary science mode digital suspension operates over a specific force range from 10^{-7} m·s^{-2} to 10^{-2} m·s^{-2} and bandwidths of 1.5 Hz to 8 Hz, respectively, at a sample rate of 220 Hz. The spin-up controller bandwidth is not adaptive, has a 660 Hz sample rate, and has been designed to reject the disturbances from the spin-up gas flow (helium, 725 sccm at 6 K). During spin-up, electrostatic torques are not a concern, thus a computationally simpler, fixed control scheme is used. This system is also able to suspend a gyroscope in the laboratory in 1 g conditions, and can apply up to 2000 VDC to provide the required electric fields to suspend on the ground for performance testing.

Computer systems are notoriously unreliable in a space radiation environment. Three all-analog backup control systems are also provided to suspend the gyroscope in the event of a computer fault. The spin-up backup controller is used during gas flow operations, and the two science mode backups are active during the remainder of the mission. All the analog controllers are robust proportional/derivative (PD) designs with a force-to-voltage nonlinearity inversion circuit to allow good control over the range of motion of the rotor in the housing. The primary role of these controllers is to prevent the rotor from contacting the housing wall, thus a integral term in the controller is not needed, thus significantly simplifying the design of these compensators.

An analog arbiter monitors computer health and rotor position and will autonomously switch into the appropriate backup controller in the event of a computer fault or a large position excursion of the rotor.

This architecture permits the controller to operate over the required 8 orders of force magnitude, providing reliable suspension of the rotors (via prime and backup systems), and minimize electrostatic torques on the rotor via the variable bandwidth adaptive control law.

4. Suspension Performance

The suspension systems for all of the four gyroscopes have been performing well on orbit. The position bridge exhibits a 0.1 nm·Hz$^{-1/2}$ position sensing noise which results in demonstrated rotor positioning performance of 0.5 nm$_{\mathrm{RMS}}$ positioning in the 1.5 Hz science control bandwidth. This represents a capacitive sensitivity of 2.2×10^{-16} F, or 3 ppm of the nominal 72 pF rotor/electrode capacitance. Performance of the position sensor is limited in this system by the requirement to minimize the EMI interference to the SQUID magnetometer and to limit electrostatic torques on the rotor due to sense voltages. The bridge drive has been set to 20 mV at 34.1 kHz to limit SQUID interference.

Each GSS unit consists of two separate assemblies on the spacecraft: aft-mounted and forward-mounted subsystems. The aft-mounted unit comprises the low noise and high voltage power supplies, clock generation logic, and the RAD6000 computer board; it draws 11.2 W from the 28 V spacecraft power bus, and weighs 16.7 kg. The forward-mounted analog electronics subsystem contains the suspension drive amplifiers, position sensing bridge, analog backup controllers, arbiter logic, and the analog-to-digital conversion electronics; this unit draws 16.8 W and weighs 15.6 kg. This forward unit, as well as the other sensitive science instruments, has been carefully designed to exhibit a low temperature coefficient by component choice and circuit topology. Further, they are passively thermally controlled to 5 mK at the space vehicle roll rate (77.5 s) and to 15 mK at the orbit rate (97.6 min) to minimize thermally induced drifts in the measurement. Over the course of

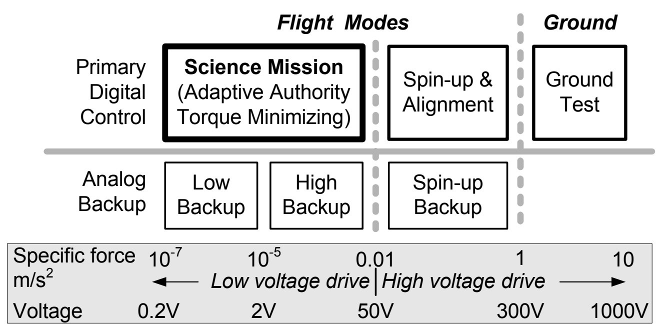

Figure 4: Gyro suspension controller suite and the associated ranges acceleration/voltage ranges for each.

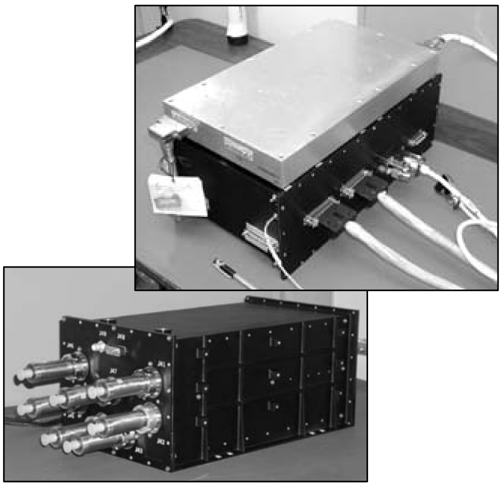

Figure 5: Photograph of GSS units - Aft processor and power supply (top), forward quiet analog electronics (bottom). One pair is required for each gyroscope.

the mission, the temperature of the aft assembly ranges between 300 K and 320 K; the forward assembly range is 265 K to 300 K.

During science data collection, the primary disturbance operating on the rotors is the gravity gradient acceleration, which ranges from 4.4×10^{-7} m·s^{-2} to 8.0×10^{-7} m·s^{-2} peak amplitude (depending on the gyroscope), varies at twice-orbital frequency, and is directed in the plane of the orbit. This disturbance is further reduced by the drag-free control system described in the following section. From this regular, natural disturbance, the performance of the gyroscopes as accelerometers can be measured and calibrated. To reject this disturbance and other smaller disturbances, such as transverse forces from vehicle pointing, solar wind, small micrometeoroid strikes, etc., the peak suspension voltages required are 200 mV on each electrode. The 10^{-2} m·s^{-2} specific force limit for the science mission control modes corresponds to electrode voltage of 50 V, and is set by a requirement to be able to maintain suspension after a micrometeoroid strike with momentum 1 kg·m·s^{-1}. This is well within the derated voltage range of typical space-qualified power transistors.

To perform gyroscope spin-up, however, much higher suspension voltages are required, and this made necessary a high voltage amplifier and power supply system. During gyroscope spin-up, the helium gas pressure on the rotor peaks at a specific force of 0.5 m·s^{-2}. Approximately 140 V_{DC} is required on the suspension electrodes to hold the rotor in position when spin-up gas is flowing. The spin-up and alignment controllers, Fig. 4, were used during this phase. The high voltage amplifier used here was a custom designed 5 kHz bandwidth, 2000 V_{DC} MOSFET ladder with an optocoupler isolation stage between the low voltage input chain and the output stage. To meet the spaceflight derating requirements, eight 550 V n-channel and eight 500 V p-channel devices were required. The high voltage system is isolated from the low voltage science drive by six 3 kV vacuum relays, one per electrode. When high voltage drive is required, the rotor is first centered and held motionless, the high and low voltage drives are set to zero, the relays are switched, and then high voltage drive is enabled. This process takes 1 ms to complete, wherein the rotor is essentially in non-suspended free-float. This 1 ms duration is small compared to the 2 s nominally required to travel the 32 μm rotor/housing gap at a residual vehicle acceleration of 10^{-5} m·s^{-2}, thus the rotor is at very little risk of collision during this uncontrolled period.

5. Drag-free Orbital Performance

To further eliminate suspension-induced torques, the GP-B satellite uses one of the science gyroscopes as an accelerometer and the spacecraft is flown to minimize the acceleration measured by this gyroscope. Known as "drag free" operation, this mode eliminates most all effects of solar wind, radiation pressure, and atmospheric drag to permit the spacecraft to follow a purely gravitational orbit. By doing this, a large fraction of the disturbance forces from the environment can be eliminated. The largest disturbance on the gyroscopes, not shielded by the physical structure of the dewar and vacuum probe, is the gravity gradient acceleration. The center of mass of the space vehicle is approximately 23 cm away from the location of the first gyroscope; each subsequent gyroscope is 8.8 cm further from the vehicle mass center along the vehicle roll axis. The gravity gradient acceleration is on the order of 4×10^{-8} m·s^{-2} on the rotor closest to the vehicle mass center and increased linearly to the other gyroscopes. Drag free operation in effect moves the vehicle center of mass to the location of the drag free gyroscope; this reduces the gravity gradient acceleration on the other gyroscopes as well.

Representative drag-free performance is shown in Fig. 6. The top curve shows the spectrum of the space vehicle translation control effort showing the twice-orbit gravity gradient signature at 3.4×10^{-4} Hz, the peak at 1.7×10^{-4} Hz is the suspension system measuring the 10 nm rotor asphericity as modulated by rotor's polhode motion. The residual acceleration on the rotor is 5×10^{-11} m·s^{-2} from DC to 1 mHz in inertial space.

When viewed as an accelerometer, the gyroscope noise floor is 1.2×10^{-9} m·s^{-2}·Hz$^{-1/2}$ in inertial space. Performance of the gyroscopes as accelerometers is limited by noise introduced through coupling from the spacecraft's pointing system and the low signal to noise ratio on position sense bridge, as required for compatibility with the SQUID readout system.[8)]

A GPS receiver on board the spacecraft measures the position of the vehicle in orbit and is used, together with ground-based laser ranging data, to confirm that the resulting vehicle orbit is indeed drag free. This orbit data has been used to identify force biases in both the ATC and GSS systems.

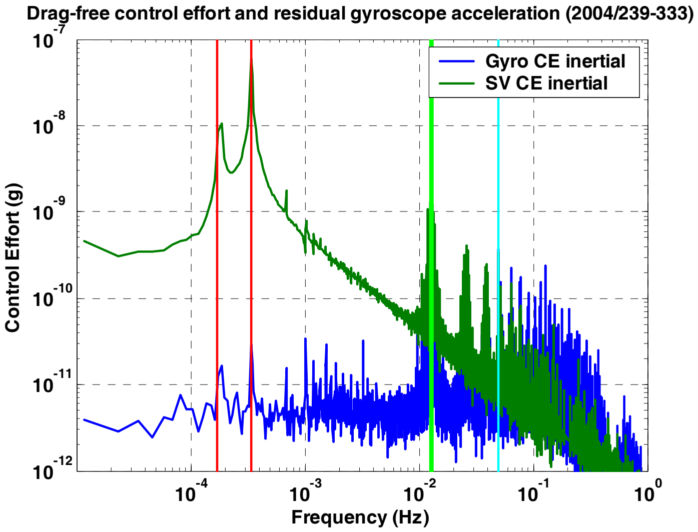

Figure 6: Representative drag-free performance: Vehicle and gyro control efforts, in g, show $5{\times}10^{-11}$m·s^{-2} residual acceleration on the drag-free gyroscope.

6. Rotor Spin Axis Alignment

In contrast to the suspension system's primary function of minimizing suspension-induced disturbance torques on the gyroscope, this system can also harness and control these disturbances torques to perform a post spin-up alignment of the gyroscope spin axes. For maximum accuracy in the spin axis orientation measurement, and in order to minimize a class of electrostatic torques on the rotor, it is desirable to align the spin axes of the rotors following the gas spin-up operation, to within $4.6{\times}10^{-5}$ rad (10 arc-sec) of the line of sight to the guide star.

This is accomplished by a coordinated application of electrode voltages in the forcing null space of the position control system that interact with the centrifugal bulge and natural shape of the rotor to produce predictable and controllable torques. These electrostatic torques are strong functions of the electric field intensity between the rotor and electrodes. During science data gathering, these fields are reduced to the levels needed to meet the gyroscope centering and safety requirements which results in approximately 200 mV on the electrodes. During alignment, however, the electric fields are increased by a factor 300 over the science levels and explicit imbalances are introduced to increase the torques on the rotor by a factor of approximately 10^8 over the nominal science levels. The suspension system bandwidth has been set so that the positioning servo will not respond to signals at the rotor's spin speed, thus the rotor shape seen by the suspension system is a spin-averaged body of revolution about the rotor spin

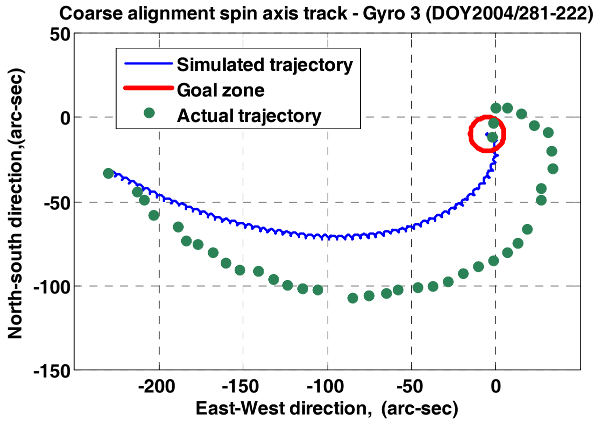

Figure 7: Telescope boresight plot of a typical spin axis alignment trajectory toward the goal orientation.

axis. In this case, the torques generated by the suspension voltage on a pair of electrodes tend to cause the rotor to precess about that electrode axis.[3)]

Making one electrode pair dominant by increasing the common mode voltage, or "preload" on its electrodes, the spin axis can be forced to preferentially precess about this dominant axis. If the preferential axis is switched synchronously with the vehicle roll phase, this precession can be rectified and the gyroscope orientation can be driven to a desired orientation in inertial space.

Using the SQUID output as a measure of the gyroscope's orientation, a bang-bang control scheme is used to switch the dominant preload between two electrode axes that are oriented at a 45°angle from the vehicle roll axis. Proper phasing of this signal allows the spin axis orientation to be moved from the post spin-up orientation – up to 500 arc-sec from the vehicle roll axis – to a final, specified, orientation within 10 arc-sec of the roll axis[5)].

Figure 7 shows the trajectory of a gyro spin axis during the final alignment process; the goal is the origin. With this system, alignment rates on the order of 3 arc-sec·hr^{-1} can be generated when driven by the high voltage amplifier using 50 V common mode on the electrode axes, while rates of 0.1 arc-sec·hr^{-1} with a 8 V drive from the low voltage amplifiers. The spiral shape of the predicted trajectory is expected because a convenient, though sub-optimal, switching surface was used in the bang-bang controller: the pickup loop on the gyroscope parting plane.

The spiral is exaggerated in the actual data because of an additonal phase shift introduced by the on-orbit algorithm. To ensure reliable orientation estimates and to fit conveniently into real-time contact periods with the spacecraft, the spin axis orientation measurement is interleaved with the torque application operations. During torque generation periods, which can last up to 3

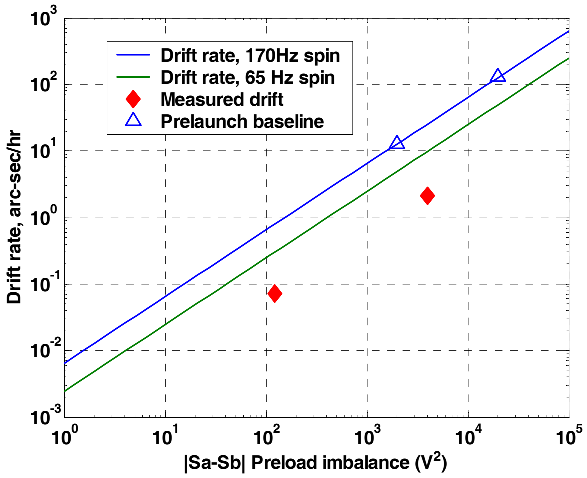

Figure 8: Measured spin axis alignment rates for coarse and fine alignment modes (solid diamonds) along with pre-launch predictions.

hours at a stretch, the spin axis of the gyroscope moves, but the switching surface that is used to generate the torques does not. This introduces an increasing phase error over time during the torque application, and thus exaggerates the spiral trajectory.

Figure 8 shows the predicted drift rates for a gyro with spin rates of 170 Hz and 65 Hz, as well as the actual alignment rates. It was found that the precession rate, though proportional to the square of the common-mode preload voltage as expected, was 20% of the prelaunch estimate. This implies that the rotors are effectively rounder than estimated on the ground prior to launch. This observed spin axis alignment rate is a very valuable calibration measurement, as it allows sensitivity bounds to set on the disturbance torques that operate on the gyroscope during the science data gathering phase of the mission.

Higher preload voltages, in principle, can be used to align the spin axes more rapidly, however, the experimentalists decided to be conservative with the voltage imbalance ratios to ensure that the alignment process did not cause any stability problems with the suspension control loops. Roughly 1 week in coarse alignment and 1 week in fine alignment mode was required to move the spin axes from their initial 200 arc-sec offset to better than the 10 arc-sec, the requirement for start of the science mission data collection period.

7. Summary

GP-B has completed its in-orbit checkout phase on 28 August 2004 when science data collection began, and will collect data until approximately August, 2005, when the liquid helium cryogen is depleted. The Gyroscope Suspension Systems have been performing very well during the mission and have met their requirements. They have been shown to be reliable, protecting the spinning gyroscope from damage while keeping the electrostatic torques to a minimum. They generate no significant interference with the SQUID readout system, perform the acceleration measurement for the drag free control loop, and have successfully aligned the gyroscope spin axes as needed to set up the experiment.

Following the depletion of the liquid helium, data analysis and cross-checking will continue through mid-2006, when it is anticipated that the results of the experiment will be announced. This work was supported by NASA under contract NAS8-39225. Additional technical and programmatic information about the Relativity Mission Gravity Probe B can be found at `http://einstein.stanford.edu.`

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