GRAVITY PROBE B: Experiment and Mission

Paul Shestople[1], M.E. Adams, W.J. Bencze, K. Bower, R.W. Brumley, S. Buchman, B. Clarke, D. DeBra, M. Dolphin, C.W.F. Everitt, C. Gray, G. Green, M.I. Heifetz, D.N. Hipkins, T. Holmes, B.T. Jones, G.M. Keiser, T. Langenstein, M. Lemieux, J. Li, J. Lockhart*, P.M.C. McGown, H.D. Meriwether, J. Mester, B. Muhlfelder, D. Murray, J.R. Newquist, Y. Ohshima, B.D. Owens, B.W. Parkinson, S. Patterson, C.C. Perry, G.V. Picard, M. Salomon, D.I. Santiago, R.J. Sharbaugh, A.S. Silbergleit, V. Solomonik, J Spencer, K.A. Stahl, B.A. Stroozas, M.A. Taber, B. Tham, J.P. Turneaure, J. Wade, C.E. Westblom, S.M. Young

W.W. Hansen Experimental Physics Laboratories, Stanford University, Stanford, CA 94305-4085

**Also at Department of Physics and Astronomy, San Francisco State University, 1600 Holloway Ave, San Francisco, CA 94132-4163*

Abstract

The Gravity Probe B satellite was launched on April 20th, 2004, at 17:57:24 UTC. The science data collection phase of the mission began on August 28th, at 00:08:32. Prior to that, the satellite was in the Initialization and On-orbit Checkout (IOC) phase. During the nineteen weeks of IOC, all payload subsystems were thoroughly tested and calibrated, science gyroscopes were spun up and aligned towards the guide star. Many additional activities occurred. This paper will give background on the Gravity Probe B experiment, discuss payload subsystems, highlight IOC activities, and present the current mission status, as of January 6, 2005. The paper will conclude with an outline of future planned activities.

1 Introduction

Two years after the launch of Sputnik 1 by the Soviet Union, George Pugh[1] (1959) and Leonard Schiff[2,3] (1960) independently realized that an orbiting gyroscope could be used to test general relativity. Specifically, two effects could be observed by monitoring the drift of the spin axis of an orbiting gyroscope: The Frame Dragging effect and the Geodetic effect. Frame dragging, also called the Lense-Thirring effect, is the notion that a rotating mass will drag local inertial frame. This effect is also called gravitomagnetism, in analogy with classical electrodynamics. The Geodetic effect is a relativistic warping of local space time caused by a massive object. The Gravity Probe B (GP-B) experiment is designed to measure these effects to an accuracy of better than 0.5 mas/yr (milli-arc-sec/year).

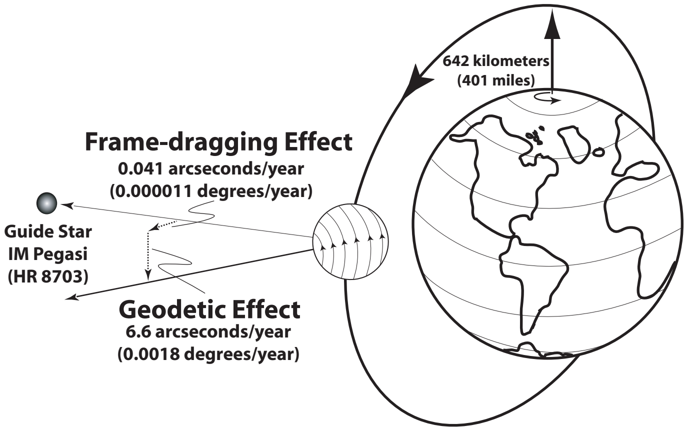

Figure 1: The Gravity Probe B orbit

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[1] E-mail: shestopl@relgyro.stanford.edu

The experimental concept is deceptively simple. Merely observe the spin axis orientation of a spinning mechanical gyroscope in an inertial frame isolated from Newtonian torques. In practice, four gyros are mounted inside the Gravity Probe B satellite, which is in a low Earth, polar orbit, at an altitude of 642 km. An inertial frame is established by pointing the satellite towards a single guide star, IM Pegasi, in the constellation Pegasus. The two effects are orthogonal in a polar orbit (see figure 1). The predicted magnitude of the frame-dragging effect is 41 mas/yr at GP-B's altitude. The predicted magnitude of the Geodetic effect at GP-B's altitude is 6.6 as/yr (arc-sec/year). More precise values will be computed based on on-orbit data[4]. For a more rigorous background regarding the Gravity Probe B experiment, please see reference 5.

2 Payload Subsystems

GP-B is perhaps the most sophisticated satellite ever flown. The complexity arises from the motivation to minimize classical torques and noise sources. Those goals require the large number of payload subsystems, all of which must work in harmony to achieve the desired measurement. At the core of the experiment are the four gyroscopes, contained within the gyroscope housings. The housings are rigidly mounted inside a fused quartz block. The quartz block is mated to a Cassegrain telescope such that the spin axis of the gyroscope is precisely aligned with the boresight of the telescope. The quartz block, telescope and gyroscopes are referred to as the Science Instrument Assembly (SIA). The SIA is attached to a cryogenic probe, enclosed in a vacuum can, and then inserted into the flight Dewar while maintained at low temperature. The residual gas pressure inside the vacuum can is less than 10^{-11} torr. At the time of launch, the Dewar contains 2317 liters of superfluid liquid helium at 1.8 K, a quantity sufficient to keep the experiment at cryogenic temperatures for the duration of the mission. The satellite structure is built around the Dewar, and subsystem electronics boxes are fastened to the structure.

Significant integration testing was conducted prior to launch to verify proper functionality. In this section, the Gyroscope Suspension, Superconducting QUantum Interference Device (SQUID) Readout Electronics, Attitude and Translation Control, Telescope Readout Electronics, Experimental Control Unit, and Global Positioning System subsystems are discussed.

The Gyroscope Suspension System (GSS) has several essential functions. During launch the gyroscopes were not spinning, and were, in fact, resting inside their housings. Once on orbit, each gyroscope must be electrostatically levitated, and spun up to the desired spin speed using helium gas at 6 K, accomplished in a series of steps. Once levitated and spun up, each gyroscope must be aligned towards the guide star, as will be discussed further. Finally, the GSS must ensure that a spinning gyroscope never touches the housing; the rotational energy of a spinning gyroscope is sufficient to catastrophically damage the gyroscopes and the housing, effectively destroying that gyroscope. To accomplish these tasks the GSS has four controllers: a digital controller for normal operations, and three analog controllers used during auxiliary operations and as backups. While the digital controller offers the least amount of control authority, and therefore exerts the least amount of electrostatic torque on a gyroscope, it cannot provide sufficient stiffness to ensure gyroscope safety in the event of, say, a micrometeoroid strike. The analog controllers therefore take control if the gyroscope exceeds preset radius limits. The analog controllers exert considerably more electrostatic torque on the gyroscope, undesirable for normal operations, but required during the auxiliary operations of spin-up and spin axis orientation.

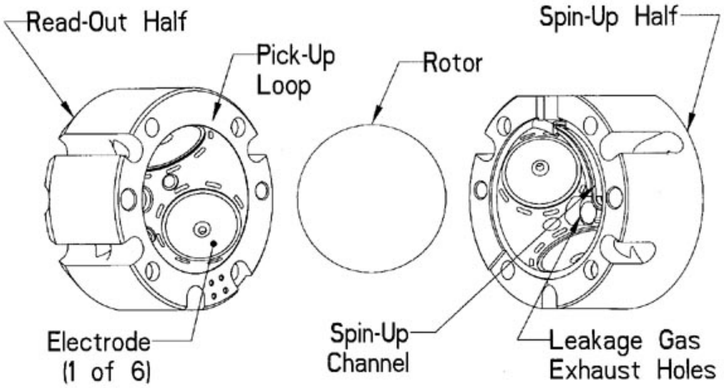

Figure 2: Gyroscope and Housing. Note the electrodes, gas spin-up channel and SQUID pickup loop position.

Figure 2 shows the gyroscope and housing. Several features merit comment. The gyroscope, or gyro, is fabricated from quartz and coated with niobium. The gyros are perhaps the most spherical objects ever manufactured - if increased to the same diameter as the Earth, the largest deviation from perfect sphericity would be less than 3 meters. The niobium coating allows the gyros to be electrostatically manipulated by three orthogonal pairs of electrodes. Each gyro is spun up by flowing helium gas through the spin-up channel, tangential to the gyro. The leakage gas exhaust holes are used to evacuate the gyro housing during and after the spin-up operation, since the pressure in the housing directly effects the spin-down rate of the rotating gyroscope. Also shown in figure 2 is the location of a four turn, superconducting pick-up loop, used by the SQUID readout electronics (SRE) discussed in the next paragraph. Additional information about the GSS subsystem can be found in reference 6.

The instrument is designed such that the gyro spin axis is nearly in the plane of the niobium pick-up loop. Recall that niobium is a superconductor. A spinning superconductor generates a magnetic field aligned with its instantaneous spin axis, called the London magnetic dipole moment. The London moment can be detected by the pick-up loop, provided the loop is attached to a sufficiently sensitive detector. GP-B uses a SQUID as the detector, sensitive enough to resolve an angle of 1 mas (milli-arc-second) in 5 hours. The SRE also contains a precision oven controlled crystal oscillator, which oscillates at 16.368 MHz, from which all satellite time is derived.

A brief digression regarding GP-B's orbit. Since the guide star is, on average, in the orbital plane of the satellite, the Earth eclipses the guide star during roughly half of every orbit. GP-B has a telescope mounted such that the spin axis of the gyroscopes is precisely aligned with the boresight of the telescope. When the guide star is not eclipsed, GP-B's telescope is used to track the relative position of the optical center of the guide star. Because GP-B collects valid data only while the guide star is within the linear range of the telescope, it is important that the telescope begin tracking the guide star as quickly as possible after the end of every eclipse period.

The Telescope Readout Electronics subsystem (TRE) works with the Attitude and Translation Control subsystem (ATC) to ensure that the telescope is pointed to within 200 mas of the guide star's optical centroid when the guide star is in view. The ATC keeps the satellite pointed towards the known position of the guide star during the eclipse periods. The TRE's Cassegrain telescope contains roof prisms, located at the image of the star, which divide the focused image into separate beams, and four sets of redundant silicon photodiodes, two sets each for the telescope's X and Y axes. When the relative photocurrent of each set of photodiodes is equal (after calibration), the optical center of the guide star is in the center of the telescope's field of view. The ATC's sixteen micro-thrusters, which use boil-off gas from the liquid helium Dewar as a propellant, enable precision adjustment of the satellite's attitude to keep the guide star in the center of the field of view. The thrusters also enable drag-free operation, as will be discussed below. The ATC also has star sensors and rate gyroscopes which allow the ATC to point towards the last known position of the guide star during eclipse periods. The star sensors, rate gyroscopes and thrusters enable smooth rotation of the satellite about the telescope axis, averaging body-fixed torques towards zero.

GP-B is heavily instrumented with operational sensors, e.g. thermometers, whose data must be telemetered to the ground. The Experiment Control Unit (ECU) provides access to that data, and also provides other key functions. Primary among these functions is control of the Gas Management Assembly (GMA), used to spin up the gyros at the start of the mission. A Proton Detector, and a set of four three-axis Magnetometers are used to track the radiation and magnetic environment of the satellite, and are also controlled through the ECU. Ionizing radiation increases the gyro potential by about 0.1 mV per day; an ultraviolet lamp controlled through the ECU is used to discharge the accumulated charge.

Finally, GP-B is outfitted with a redundant pair of Global Positioning System (GPS) receivers. The GPS subsystem provides relatively coarse orbit position and velocity data. Ground processing uses that data to calculate precise satellite ephemeris, augmented by laser ranging position solutions. The GPS subsystem is retrofit with electronics which output a pulse per second (PPS), on the GPS second. That pulse is fed into the SRE, and allows reconciliation of satellite time with Coordinated Universal Time (UTC).

Before moving on to IOC activities, it is worth noting that every effort has been made to remove single-point failures from the GP-B mission. For example, only one science gyroscopes are needed, yet four are flown. Similarly, most of the electronics subsystems described above have built-in redundancy, and many of the electronic subsystems have a fully functional backup on-board. In this way, the satellite has, in effect, two quasi-independent sides, both of which are capable of achieving mission goals. While the mission is designed to operate on side A, catastrophic failure of any subsystem results in an automatic switch to side B.

3 Initialization and On-orbit Checkout activities

The spin-up of gyroscopes is but one of literally thousands of activities which occurred during the IOC phase of the mission. Stanford maintains a complete listing of the activities, which fills several large filing cabinets. The activities can be categorized into three areas: 1) Verification and optimization of satellite performance, 2) verification and optimization of payload performance, and 3) verification and optimization of the science mission setup. What follows is a highlight of activities broken down by week, and is meant only to provide the flavor of IOC operations, as well as additional details regarding the complexity of the mission.

On the first day of the mission the satellite was vaulted into space atop a Boeing Delta II 7920-10 expendable launch satellite. Because the GP-B target orbit is highly constrained, significant pre-launch effort had been dedicated towards correcting any possible initial orbital error. Happily, none was needed, as Boeing placed the satellite into an orbit which can only be described as a bull's eye. Shortly thereafter, and for the next several days, the various subsystems were turned on and self tested to verify on-orbit functionality. Towards the end of the first week one of the sixteen ATC micro-thrusters was turned off, as it had developed a leak.

The gyroscopes were successfully suspended in digital mode for the first time during the second week of the mission. Two radiation induced multi-bit memory upsets occurred within one second in the main flight computer, automatically switching the satellite to the B side. Only one such multi-bit error (MBE) is predicted during the course of the mission; it was quite surprising that two MBEs should occur during week two. While the single bit error (SBE) rate agrees with pre-launch predictions, GP-B has shown a higher than anticipated susceptibility to MBEs. The increased susceptibility is under investigation. While the mission could have continued to operate on the B side, the decision was made to return to the A side. The return to the A side was a significant and complicated effort which took the rest of the week, but went very well.

During the third week, mission operators practiced a low temperature bake-out. The low temperature bake-out reduces the residual gas pressure in the gyro housing, thereby reducing the spin down rate of the gyroscope. The operation did result in the partial spin-up of the gyroscopes to about 5 mHz. As will become clear, typical operational mode for the IOC phase is to first practice high risk operations in a low risk scenario, in some cases several times. This is done because the complexity of the GP-B satellite leaves little margin for error.

To best reduce classical torques on the gyroscopes, the satellite is flown drag-free about one of the gyroscopes, meaning that one gyroscope is essentially in free fall, with the satellite flying around it. During week 4 a position based method for flying drag-free was achieved for the first time. ATC star sensors were used to roughly align the science telescope with the guide star, and a series of small maneuvers were started to locate the guide star.

Because determination of gyro spin axis orientation is based upon the London moment, the experiment requires a very low background magnetic field. The magnetic properties of each component were carefully measured prior to assembly, but without a clever exploitation of superconducting properties the Earth's magnetic field would have dominated the magnetic field within the Dewar. A lead bag was cooled below its superconducting transition temperature, then expanded, leaving a significantly lower field within. By using a series of lead bags during the Dewar preparation process, GP-B was able to achieve a background magnetic level of 10^{-7} gauss, prior to insertion of the Science Instrument Assembly. Additional magnetic fields, however, are generated and trapped in the gyro rotors by the launch environment, and in week five a magnetic flux reduction procedure was completed, reducing the trapped flux to acceptable limits.

A second micro-thruster was turned off during week five. Although the loss of the second thruster does not adversely affected the satellite's ability to fly drag-free, the additional loss of any one of several key micro-thrusters would have. For that reason, it was decided to develop a new thruster control algorithm. As will be seen, the development would take several weeks.

During week six, mission specialists performed a low flow spin-up procedure, flowing just 2 sccm (standard cubic centimeters per minute) past the gyros for 90 seconds, to practice the process of spinning up the gyroscopes and verify functionality of all subsystems required for the full spin-up. The practice spin-up resulted in a gyro spin speed of approximately 0.3 Hz. Note that the helium gas used for gyro spin-up comes from a reservoir of gas within the GMA, not from boil-off of the liquid helium used to cool the experiment.

The guide star was acquired with the science telescope during week seven. The satellite was then maneuvered so as to point the science telescope towards a series of adjacent stars.

A brief digression concerning the guide star is in order. HR 8703 is a variable star in a binary system in the Pegasus constellation. The star's position relative to extragalactic reference sources was first measured by the Very Long Base Interferometer (VLBI) in December of 1991, and has been measured at least 29 times since 1991[7]. The star's position relative to extragalactic reference sources is perhaps the best known in the catalogue. The periodicity of the variable star is also well documented, allowing additional calibration of the science telescope. Such detailed understanding is essential for the mission, as was the maneuver towards the two adjacent stars to confirm that the guide star being used was indeed IM Pegasi.

A series of practice calibration tests involving the application of asymmetric science gyro suspension voltages were started during week seven and continued through week ten. The tests were designed to exert a well understood torque on the gyroscopes. The actual tests will be run on the fully spinning gyroscope at the end of the mission, during the post-science calibration phase.

Also during weeks seven and eight, mission operators successfully demonstrated the ability to discharge the science gyroscopes to specification (< 15 mV) and successfully tested a control-effort based method of flying drag-free for one orbit. The control-effort drag-free mode minimizes the GSS control efforts on the gyroscope, while the position drag-free mode applies no control effort to the gyroscope. Both modes are sufficient to meet mission requirements, but the control-effort drag-free mode turned out to be more robust, and was therefore chosen as the mission baseline drag-free mode.

During weeks nine and ten the roll rate of the satellite was increased from 0.1 rpm to 0.9 rpm for several reasons. The mass of the satellite must be properly balanced to allow the satellite to roll precisely about the telescope boresight. Gravity Probe B has five mass balance mechanisms, each essentially a weight on an motorized, threaded rod, which allow sub-millimeter adjustments to the center of mass and cross products of moments of inertia. Additionally, increasing the satellite's roll rate increases the likelihood of wrapping the gaseous helium bubble about the well of the Dewar (which houses the cryogenic probe and SIA). Furthermore, a higher roll rate places the science signal in a more quiet region of the SQUID noise spectrum, and decreases thermally induced bias errors. The desire for a higher roll rate is balanced against the ATC and GPS subsystems decreasing performance at a higher roll rate.

Also during week ten, the GSS team applied 120 percent of the expected gyro spin-up voltages as a stress/health test in preparation for gyro spin-up; all gyroscopes worked perfectly. Mission programmers completed the reworked ATC control algorithm in week ten; the new code was uploaded in week eleven. Implementing the new code required rebooting the flight computer. As planned, during the four minute reboot process the satellite was completely out of contact with the ground. The procedure was perfectly executed.

During week twelve all four science gyroscopes were successfully spun up to approximately 3 Hz. The spin-up process required the maximum flow rate of 700 sccm for 90 seconds. Calibration testing of the gyros took the remainder of the week. Additionally, the satellite roll rate was reduced to 0.5 rpm. During week thirteen gyro 4 was successfully spun up to 106 Hz. The full spin-up used the maximum flow rate for several hours. Gyroscopes 2, 3, and 1 were spun up during week fourteen. As anticipated, because all four gyroscopes are in the same vacuum probe, the spin-up of one gyro causes spin down of the other gyros. The final spin speed for the four gyros was 79.4, 61.8, 82.1, and 64.9 Hz.

Weeks fifteen through nineteen were devoted primarily to spin axis alignment, a process of applying torques to the gyros in order to align the spin axis with the guide star. Alignment rates were significantly lower than predicted, suggesting that gyro sphericity is much better than required, and electrostatic interaction between the gyroscopes and the GSS is also lower than anticipated. Since electrostatic torques are the largest torques on the gyroscopes, the lower than predicted alignment rates were very welcome news, although it did require the spin axis alignment process to take longer than anticipated. The final alignment of the gyroscope spin axis was completed for gyros 1, 2 and 3 on August 28, and on September 14 for gyro 4. The satellite's roll rate was set to 0.77419 rpm (a 77.5 second period) for the science mission, a good balance between science and engineering needs.

4 Current Status

As of January 6, 2005, day 261 of the mission, the Gravity Probe B satellite and all subsystems are performing nominally.

The gyroscopes continue to operate as required. As previously mentioned, the sphericity of the gyroscopes is better than pre-launch estimations: The distance between the geometric center of each gyroscope and center of mass has been calculated to be on the order of five nanometers for all four gyros. The gyroscopes are experiencing a polhode motion[8], as predicted prior to launch. Not predicted was that the period of the polhode motion would change, decreasing towards an asymptotic value.

Current spin speeds and spin down rates of the gyroscopes are given in table 1. For a gyroscope spinning at 60 Hz, a spin down rate of 0.50 μHz/Hr corresponds to an exponential spin down time constant of almost 14,000 years.

Table 1: Spin Speeds and Spin Down Rates as of January 6, 2005

Gyroscope	Spin Speed (Hz)	Spin Down Rate (μHz/Hr)
1	79.3879	0.61
2	61.8181	0.51
3	82.0930	1.35
4	64.8506	0.32

Guide star acquisitions by the ATC occur typically one minute after the guide star comes within view; the guide star remains within the linear range of telescope better than ninety percent of the approximately fifty minute guide star valid period.

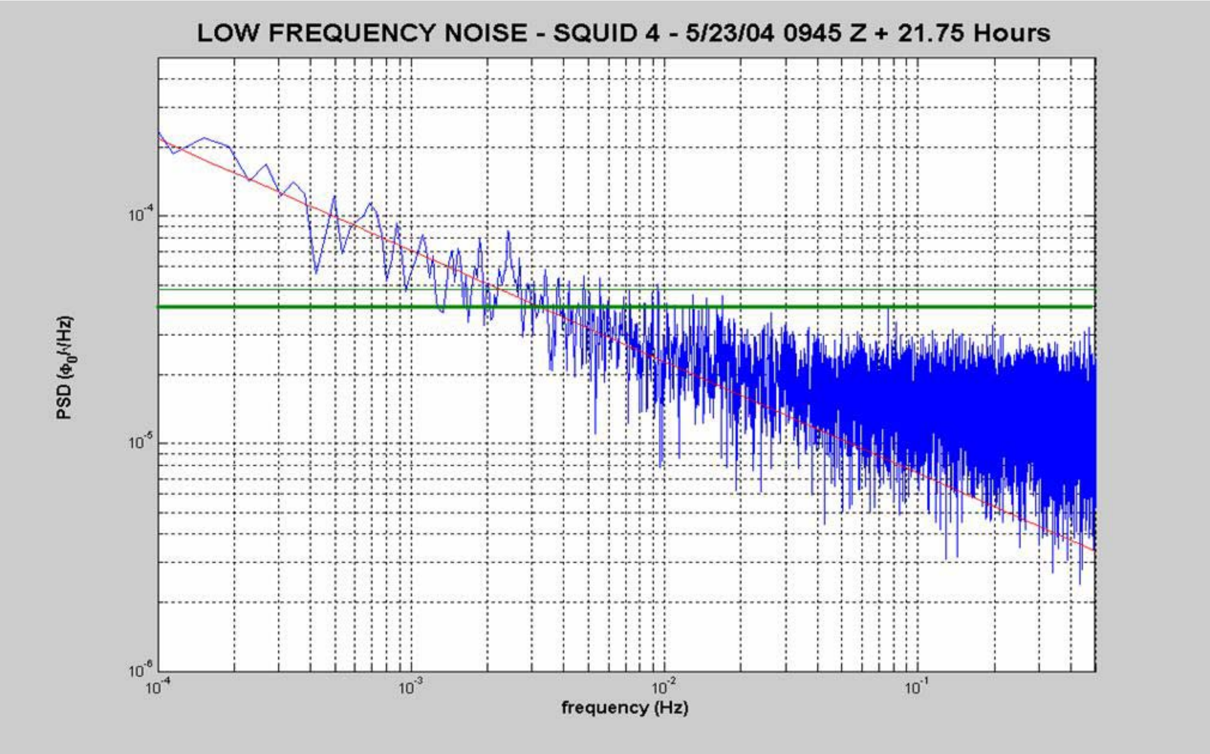

Figure 3: SQUID Readout Electronics Noise. The heavy line is the noise requirement. The science signal occurs at the roll frequency of 12.9 mHz.

The SRE is performing very well; the SQUID noise is lower than specifications, as seen in figure 3.

The GPS subsystem is performing extremely well. The subsystem maintains a lock with the GPS constellation better than 98 percent of the time at the current roll rate of 0.77419 rpm.

Orbit Determination is performing exceptionally. GP-B uses a commercial software package to calculate post-processed orbits. Based on overlapping post fit residuals between consecutive datasets, on-orbit cross-track position accuracy is less than 10 meters, while cross-track velocity accuracy is less than 8 mm/s.

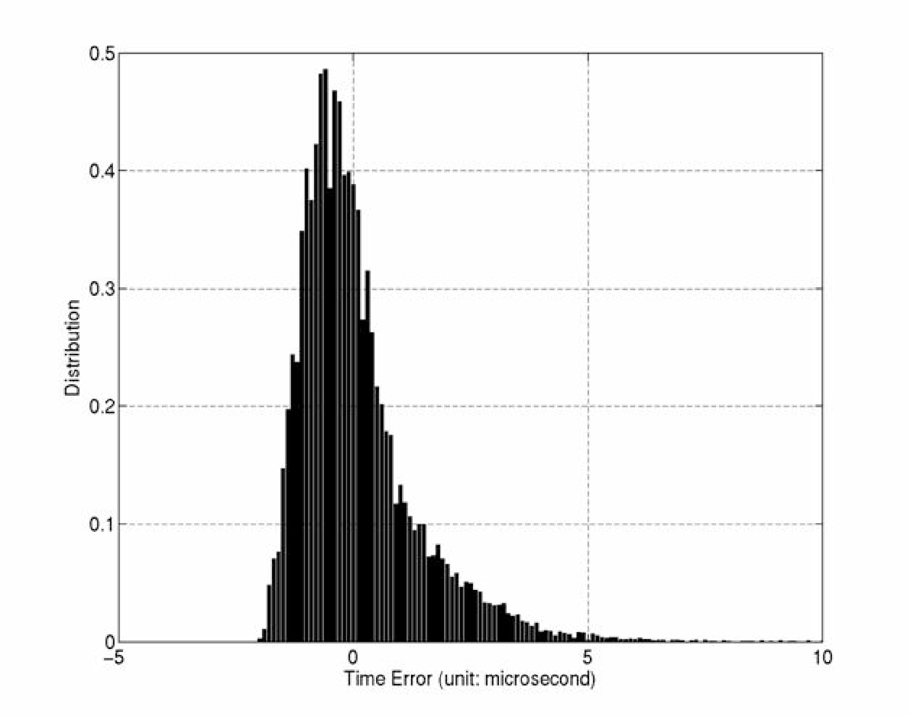

Figure 4: Time Transfer.

Time transfer has also been successful. Daily analysis includes calculating the time difference of Pulse Per Second (PPS) to integer GPS second. Differences are typically less than 2 microseconds, as shown in figure 4. The difference arises because the PPS circuitry within the GPS receiver only calculates a time, position, and velocity solution every 1.7 seconds, whereas the PPS signal is output every second. The receiver determines the time of the GPS second between consecutive solutions based on an internal 1.023 MHz oscillator.

5 Future Work

During the IOC phase of the mission a variety of calibrations were completed to characterize GP-B performance, primarily torques. These calibrations included measurements of the telescope and SQUID noise (see figure 3), measurements of thermal sensitivity of payload electronics, and of telescope and gyro readout scale factors. Post science phase calibrations will be started several weeks prior to running out of liquid helium. In addition to redoing many of the IOC phase calibrations in order to understand how the calibrations vary with time, new calibrations are planned which will place tight constraints on potential systematic errors.

For example, a number of calibrations involve applying enhanced torques to the science gyroscopes are planned. These calibrations were practiced from week seven through ten of IOC, when the gyroscopes were spinning at just 3 Hz. The satellite will also be maneuvered towards the adjacent stars, as was done during week seven of IOC. This maneuver will further calibrate the telescope, since the photocurrent can be compared to the earlier values. Dark currents can be measured by closing the telescope shutter. Other potential calibrations include applying a fixed acceleration to the satellite to understand how induced torques affect the gyros.

6 Conclusion

The Gravity Probe B satellite has completed the Initialization and On-orbit Checkout Phase and as of this writing has been collecting science data for eighteen weeks. All satellite and science subsystems required for completion of the mission are nominal. The Dewar liquid helium depletion rate is small enough to provide adequate time to complete the science phase and post-science calibrations.

With almost half of the science phase behind us, and post science phase calibrations before us, there are no known reasons why Gravity Probe B will not out perform its science mission requirement of 0.5 mas/yr.

7 Acknowledgements

Over the past forty years, many people have made significant contributions to the Gravity Probe B mission, without which the satellite would simply not be on-orbit today. A complete list of the contributors and their contributions would require an entire volume, but the authors would like to acknowledge the following partial list: J. Aguinaldo, N. Bennett, R. Demars, P. Dulgov, K. Burns, T. Cahoon, R.A. Campo, O. Chan, R. Farley, R. Fontecha, T. Gill, R. Miller, B. Jacobsen, M. Johnston, J. Kirshenbaum, S.E. Larsen, J. Lay, T. Mcginnis, F, Mendoza, R. Miller, P. Rittmuller, S. Shehata, R. Schultz, M. Simon, and D.M. Spencer of Lockheed Martin Missile and Space Corporation, and E. Ingraham, K. Galal, J. Goebel, J. Kolodziejczak, M.A. Smith, and K. Nevitt of NASA. Additional thanks to J. Bower, J. Conklin, H. Matthews, J. Qui, S. Wang and P. Worden of Stanford University. The authors would also like to thank both NASA and Lockheed Martin Missiles and Space for technical support and facilities.

Gravity Probe B has been accomplished under NASA funding, Contract No. NAS8-39225. Additional support for this paper was accomplished under funding from the 14th Workshop for General Relativity and Gravitation, YITP-W-04-13.

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