GRAVITY PROBE B:
LAUNCH AND INITIALIZATION

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The scientific instrument and the major subsystems of the Gravity Probe B satellite are described. Following launch, the initial on-orbit operations were designed to check the operations of each of these major subsystems, provide an initial on-orbit calibration of the scientific instrument, set up the instrument in its operational mode, and spin up and align each of the four gyroscopes.

1. Introduction

The Gravity Probe B satellite was launched from Vandenburg Airforce Base at 9:57 am PDT on April 20, 2004. The Boeing Delta II 7920-10 expendable launch vehicle carried it south over the Pacific Ocean. Six of the nine 40 inch diameter solid rocket motors were ignited at lift-off to supplement the Rocketdyne RS 27-A main engine, and the remaining three solid rocket motors were ignited in flight. Four minutes after lift-off, the second stage ignited. The second stage cutoff occurred shortly after crossing the equator as the satellite traveled south. After passing over the South Pole, a brief second stage burn occurred to circularize the orbit at an altitude of 642 km. Cameras attached to the second stage verified that all four solar arrays deployed before the second stage separation, which occurred when the satellite was about to pass over the North Pole.

The Gravity Probe B satellite is designed to measure the precession of the spin axes of four electrostatically-supported, cryogenic, mechanical gyroscopes relative to the guide star, IM Pegasi or HR 8703. The proper motion of this guide star relative to extragalactic reference sources is independently being measured by a group at the Harvard-Smithsonian Center for Astrophysics and York University [1]. When these two measurements are combined, the drift rate of the gyroscope relative to the extragalactic reference sources will be known and may be compared to the values predicted by the general theory of relativity. In 1960, Schiff [2], [3] and Pugh [4] independently pointed out that a gyroscope will precess due to two general relativistic effects. The geodetic effect, due to the gravitational interaction between the gyroscope and its orbital motion, will cause its spin axis to precess about a direction normal to the orbit plane. The frame-dragging effect will cause the gyroscope to precess about the direction of the earths rotation axis. At an altitude of 640 km, the predicted magnitude of the geodetic effect is ~ 6.6 arc-sec/year (as/yr), and the predicted magnitude of the frame-dragging effect is ~ 42 milli-arc-sec/year (mas/yr). Accurate values for these effects as predicted by general relativity [5] will be calculated based on the orbital data.The precession rates due to expected classical torques on each gyroscopes are less than 0.14 mas/yr, and statistical and systematic error in the measurement of the gyroscope drift rate, based on prelaunch tests, are expected be less than 0.17 mas/yr. When combined with the uncertainty in the proper motion of the guide star, the overall error in the drift rate of each of the gyroscopes relative to the extragalactic reference sources is expected to be less than 0.23 mas/yr [6].

2. Gravity Probe B Payload and Satellite

The rotor of each of the four gyroscopes is a fused quartz sphere, 1.9 cm in radius, which has been polished to a sphericity of better than 25 nm and coated with a 1.25 μm thick coating of niobium. Electron backscattering measurements verified that the uniformity of the coating was better than 2%. The niobium coating not only provides a conducting surface for the electrostatic suspension system but also is the superconducting surface for the London moment readout described below. Six electrodes lying along three perpendicular axes are used to both measure the position of the rotor with a 34.1 KHz capacitance bridge and also provide the electric field necessary to maintain the rotor at a centered position 32 μm from each of the electrodes. The rotors are spun up to full spin speed with helium gas at 6 K, which flows through the channel cut into one side of the housing. A four-turn superconducting pickup loop lies on the parting plane between the two halves of the housing. A superconducting cable connects the pickup loop to a SQUID magnetometer. The interior surfaces of the housing have been coated with a conducting ground plane to minimize the effects of electrostatic charges on the interior surface of the housing. On orbit, the rotor potential is expected to increase at a rate of 0.15 mV per day due to ionizing radiation. This rotor potential may be reduced by using fiber optic cables to illuminate the surface of the rotor and the housing with ultraviolet light. The direction of flow of the emitted photoelectrons is controlled by a special (dedicated) electrode so that the rotor potential relative to the ground plane may either be increased or decreased. The rotor potential is measured by applying a sinusoidally varying voltages with opposite sign on opposite electrodes and measuring the control effort necessary to maintain the rotor at its centered position [7].

The superconducting coating of the spinning rotor produces a London magnetic dipole moment [8] aligned with the instantaneous spin axis of the rotor. The orientation of the spin axis is designed to lie nearly in the plane of the readout loop. As the satellite rolls on its axis about the direction to the guide star, the magnetic flux through this pickup loop is modulated at the satellite roll rate. The orientation of the gyroscope spin axis may be determined from the magnitude and phase of the change in the magnetic flux through the pickup loop as measured by the SQUID readout system.

Each of the four gyroscope housings are rigidly mounted within a fused quartz block which serves as a metrology reference frame. A Cassegrainian telescope, designed to operate at cryogenic temperatures, is bonded to the quartz block. On each of the two telescope axes, the light is focused on a roof prism which divides the light from the guide star. Silicon photodiodes measure the relative intensity of the light from each side of both roof prisms. When the telescope axis is aligned with the direction to the guide star, the light intensities on each side of the roof prism is equal. When the axis moves away, and the giude star stays within the linear range of the telescope, the pointing error is proportional to the difference between the photodiode currents for that axis.

The four gyroscopes, the quartz block, and the telescope comprise the Science Instrument Assembly which is attached to the cryogenic probe. A vacuum can encloses the entire assembly. A sintered titanium vacuum cryopump within the vacuum probe provides the necessary surface area to adsorb the residual helium within the probe. After the gas spin up the residual gas within the probe is vented to space, and the cryogenic region of the vacuum probe and the cryopump are heated from a temperature of 2 K to 6 K. This temperature increase drives most of the adsorbed helium off the interior surfaces of the probe. With the exhaust valves open to vent the probe to space, the pressure on the interior of the probe is $\sim 10^{-7}$ torr. When the valves are closed and the temperature of the interior surfaces are reduced to 2 K, most of the residual gas is adsorbed onto the interior surfaces. Ground based tests of this low temperature bakeout in the flight probe showed that the residual pressures was less than 2×10^{-10} torr.

The vacuum probe is inserted into the well of the liquid helium dewar, which also contains a superconducting magnetic shield. The residual magnetic field within this shield has been measured to be less than 3 μgauss, and the attenuation of the external magnetic field has been demonstrated to be better than 2×10^{-12}. Four magnetometers are mounted near the open end of the cylindrical shield to measure the magnetic field. At launch, the dewar holds 2317 liters of superfluid helium at 1.8 K, which is designed to hold the science instrument assembly at cryogenic temperatures for more than 16 months. A sunshade is attached to the warm end of the probe to prevent sunlight from entering the probe and interfering with the measurement of the light from the guide star.

This entire assembly is inserted into the spacecraft framework. A Forward Equipment Enclosure provides a passive thermal shield for the sensitive electronics, which are mounted near the cable connectors at the top of the probe. Global Positioning System antennas receive the signals which are used to determine the position and velocity of the spacecraft. In addition, a retroreflector array, mounted on the aft end of the spacecraft, allows laser range measurements to be made. Two proton monitor telescopes are used to monitor protons incident from the side and the aft of the spacecraft. Two sets of rate gyroscopes and star trackers are used to determine the orientation of the spacecraft when the guide star is not in the field of view of the cryogenic telescope. In addition, these instruments measure the roll phase of the spacecraft. Proportional helium thrusters, which use the boiloff gas from the liquid helium dewar, control the attitude and translation of the spacecraft. At launch the four gallium arsenide solar arrays are folded to fit within the shroud of the Delta II rocket.

3. Initial On–Orbit Operations

The initial phase of the on-orbit operations of the satellite began immediately after launch and continued through the end of August, 2004. These operations included the initial checkout of the major subsystems of the satellite, the acquisition and verification of the guide star, adjustments of the attitude and translation control system, the initial on-orbit calibration of science instrument, gyroscope operations, and the low temperature bakeout of the vacuum probe.

Prior to launch, plans had been made to make the final adjustments to the orbit using the spacecraft thrusters to nudge the satellite into its final orbit. This orbit had been carefully selected to minimize the forces and torques acting on the gyroscopes due to the gradient in the Earths gravitational field. However, these plans for adjusting the final orbit were found to be unnecessary because of the very high accuracy of the initial orbit provided by the Delta II rocket. At the North and South Poles, this orbit differed by less than 100 meters from the planned orbit.

The guide star, HR 8703, was acquired using the satellites star trackers and rate gyroscopes. Although the current from the photodiodes agreed well with prelaunch estimates, the identity of the guide star was confirmed by commanding the spacecraft to point toward two nearby stars, HR Pegasi and HD 216636. The second star is also used as a comparison star for ground-based photometry measurements by G. Henry at Tennessee State University. Both the brightness and location of these nearby stars confirmed that HR 8703 was correctly identified. Subsequent measurements by G. Henry [9] of the variation with time in the brightness of HR 8703 agreed well with the brightness as measured by the Gravity Probe B telescope.

The satellites attitude and translation control system has the demanding requirement to keep the telescope pointed to within 200 mas of the centroid of the star image while the guide star is within the field of view. Because of Gravity Probe Bs polar orbit, the guide star is eclipsed by the Earth for roughly 40% of each orbit. During this time, the attitude control system relies on the rate gyroscope and star trackers. Then, the attitude control system must reacquire the guide star and orient the spacecraft so that the telescope is pointed within its linear range. Ionizing radiation, particularly during passage through the South Atlantic Anomaly in the Earths magnetic field, decreased. by a small amount, the fraction of time that the telescope output can be used as a sensor for the attitude control system. Adjustments to the attitude control system and software to limit the impact of particle hits in the telescope photodiodes allowed the attitude control system to acquire the guide star within a few minutes and to use the telescope as a sensor during a significant portion of the passage through the South Atlantic Anomaly. In addition, the attitude control uses the rate gyroscopes and star trackers to maintain the satellite roll rate at 0.7742 rpm.

Initial on-orbit calibrations included measurement of the SQUID and telescope noise, verification of the telescope and gyroscope readout scale factors, measurements of the temperature sensitivity of various electronics boards, and verification of the magnetic shielding provided by the Cryoperm and superconducting magnetic shields. In addition, while the gyroscopes were spinning slowly, rehearsals were performed for calibrations that are planned for the end of the mission when the gyroscopes will be spinning at full speed. These calibrations are designed to deliberately enhance the classical torques on the gyroscope to place tight limits on potential systematic experimental errors.

The initial levitation of the gyroscopes with the electrostatic suspension system [10] showed that primary digital suspension system and the backup analog suspension system were working reliably and the transition between these modes could easily be made. During these tests the average voltage applied to the electrodes was 10 volts, which was subsequently reduced to 0.2 volts. The differential control effort required to keep the four gyroscopes centered in the housing agreed well with the expected force from the gradient of the Earths gravitation field. While the gyroscopes are being spun up to the full spin speed, the force of the spinup gas on one side of the housing requires a higher voltage to keep the rotor centered. Tests of this digital spinup mode as well as its analog backup showed that it was performing reliably and that transitions between these various operating modes occurred smoothly.

When each of the four gyroscopes were initially levitated, the rotor potential was found to be several tenths of a volt as expected. Since this rotor potential is larger than the planned control voltage for the electrostatic suspension system, the ultraviolet charge control system was used to reduce the rotor potential to within the required 10 millivolts of zero.

Initial measurements of the variation of the magnetic flux through each of the four pickup loops indicated that the magnetic flux trapped in the superconducting coating of some of the four gyroscopes was higher than the required value. This increase in the magnetic trapped flux had been anticipated because similar results were found during the prelaunch acoustic tests of the spacecraft. To reduce this magnetic trapped flux, each of the four gyroscopes and the entire quartz block were heated above their superconducting transition temperature and then allowed to cool slowly through the transition temperature. Because the magnetic field within the superconducting shield is less than several microgauss, the magnetic field trapped in the rotors after cooling was expected to be at about the same level. This was confirmed with measurements of the slowly spinning rotors after their temperatures were cycled about the superconducting transition temperature.

To reduce the force required to maintain each gyroscope at the center of its housing, and thereby reduce the torques acting on each of the gyroscopes, the satellite has the capability of using one of the gyroscopes as a drag-free sensor to control the translation of the spacecraft. There are two different operation modes of the drag-free control system. In the standard drag-free control, the spacecrafts translation control system uses the output of the gyroscopes position sensing capacitance bridge to control the acceleration of the spacecraft. In this operating mode the gyroscope rotor is maintained at the center of its housing by controlling the satellite to chase the gyroscope which has been designated as the drag-free sensor. There are no electrostatic forces which need to be applied to the rotor, and the gyroscope torques are thereby reduced. To the extent that the drag-free control system reduces the spacecraft acceleration due to the residual atmosphere and the solar radiation pressure, the forces and torques on the other gyroscopes will also be reduced. In the second operating mode of the drag-free control system, the electrostatic suspension system maintains control of the drag-free sensor, but the spacecraft translation control system minimizes the force required by the electrostatic suspension system to keep the rotor centered. During the initialization phase, tests were made of both of these operating modes, and the second mode was selected for the science data collection period because of its greater reliability.

The spinup of each of the four gyroscopes occurred in three steps. Initial tests were made with the gyroscopes spinning at several tenths of a Hz. At this spin speed, extensive tests of the various operations planned for the gyroscopes at the higher spin speeds were made. After these tests were completed, the gyroscopes were spun for 90 seconds using the maximum flow rate of approximately 700 sccm, which brought each of the gyroscopes to a spin speed of approximately 3 Hz. After confirming that each of the four gyroscopes had a spindown rate commensurate with the pressure in the vacuum probe, all the four gyroscopes were spun to their final spin speed. As each subsequent gyroscope was spun up, the spindown rate of the other three gyroscopes increased because of the increase of the gas pressure due to leakage of gas from the spinup channel. Following the spin up of each of the four gyroscopes, the interior of the probe and the cryopump were heated to 6 K as described above and the gas was evacuated to space. The vent was closed and the temperatures were reduced to their values of approximately

2.5 K. The final spin speeds of the four gyroscopes are 79.4, 61.8, 82.1, and 64.9 Hz. The measured spindown rates of three of the four gyroscopes are less than 1 μHz/hr while the fourth gyroscope is slightly over this value. This spindown rate corresponds to a spin down time constant of 15,000 years and a residual gas pressure of less than 1.5×10^{-11} torr.

To reduce the gyroscope torques and minimize potential systematic readout errors, the spin axes of each of the four gyroscopes were aligned so that their expected average position over the course of a year would lie within 10 arc-seconds(as) of the average direction to the guide star. Since these gyroscopes had been deliberately designed to minimize the potential classical torques which could change the orientation of the spin axis, very different operating conditions were necessary to nudge the spin axis into its final alignment [11]. An electrostatic torque due to the equatorial bulge of the spinning gyroscopes combined with a deliberate imbalance in the average electric field on two electrode axes which lie at 45° to the gyroscope spin axis was used for the final alignment. The voltages on the electrode were increased from 0.2 to 40 V and the average electric fields on two axes were deliberately modulated by 30% at the satellite roll frequency. The direction of the gyroscope drift under these conditions is determined by the phase of the modulation. After spinning up the gyroscopes with the gas spinup system, each of the spin axes was oriented from 100 to 200 as from the direction to the guide star. By deliberately applying this electrostatic torque to each of the four gyroscopes, their spin axes were gradually aligned in the desired direction at a rate of several arc-seconds per day. Because the aberration of starlight from the guide star due to the Earths motion about the Sun has a magnitude of ~ 20 as in an East-West direction in late August, each of the four gyroscopes were aligned 20 as from the measured direction to the guide star, so that over the course of one year their average direction would lie within 10 as of the satellite roll axis.

After the spin up and final alignment of the spin axes of each gyroscope, the electrode voltages were reduced to 0.2 V volts. The gyroscopes are expected to remain in this condition for most of the remainder of the mission. Data from the satellite is collected and reviewed every day and the analysis of the data to determine the drift rate of the gyroscopes in underway. The analysis of this data will also more tightly constrain potential systematic experimental errors. Several weeks before the liquid helium is exhausted, a number of operations are planned which will deliberately enhance potential systematic errors in an effort to place stringent limits on these errors. The latest measurements indicate that the liquid helium will last through July

2005.

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