ON-ORBIT PERFORMANCE OF THE GRAVITY PROBE B DRAG-FREE TRANSLATION CONTROL SYSTEM

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The Gravity Probe B satellite, which uses ultra-stable electrostatically suspended gyroscopes as an experimental test of General Relativity, was flown in 2004-5. Support forces on the gyroscopes must be minimized or they become a significant source of torques which may corrupt the experimental results. Placing the gyroscopes in an orbital environment is the first step, which reduces the acceleration by seven orders of magnitude or more when compared with the acceleration of 1 g on the ground. The acceleration is reduced further by operating the satellite "drag-free". We describe the implementation and the on-orbit performance of the Gravity Probe B drag-free control system from launch on 20 April 2004 to the exhaustion of the helium cryogen that was also used as the control propellant on 29 September 2005.

INTRODUCTION

The Relativity Mission Gravity Probe B (GP-B) is a NASA-sponsored astrophysics satellite, built by Stanford University and the Lockheed Martin Corporation, which is designed to test two of the predictions of Einstein's theory of General Relativity. During the course of the satellite's mission, this experiment measures both the Geodetic and Frame-dragging effects predicted by General Relativity 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. [Turneaure 1996] The precessions, as predicted by General Relativity, are shown in Figure 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, California, and started to collect science data on 28 August 2004. Science data collection was completed on 29 September 2005 when the superfluid helium dewar was depleted after 17.3 months of on-orbit operation.

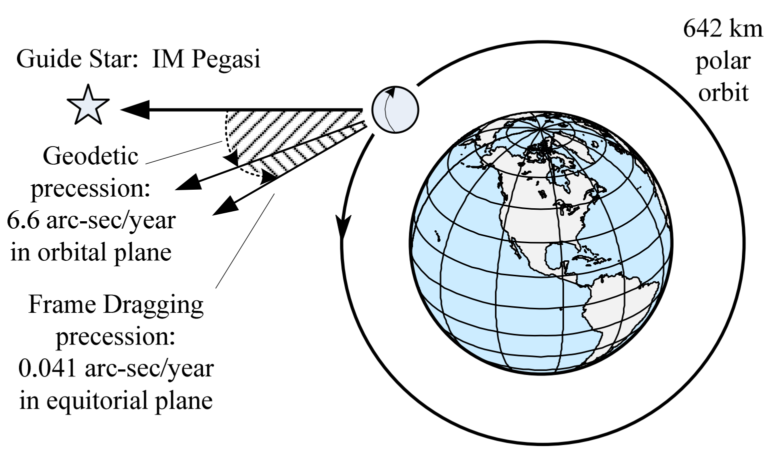

Figure 1 - The Predicted Relativistic Precessions: Geodetic and Frame-dragging

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DRAG-FREE SATELLITE TECHNOLOGY

A drag-free satellite uses an internal shielded proof mass as a reference for applying thrust to cancel external disturbances. George Pugh [1959] proposed a 'tender' satellite for the first proposed gyroscope test of General Relativity. He also recognized the drag-free satellite could be used to get improved tracking for geodesy, and from the compensatory forces needed to cancel drag, one can determine the orbital atmospheric density. Lange [1964] provided the first definitive design study of a drag-free satellite which led to the addition of a DISturbance Compensation System (DISCOS) to the Navy's Navigation Satellite, *Transit* [1974]; see Figure 2. *Transit I* was segmented into three parts: power supply at the top (left), electronics for the navigation function at the bottom (right), and DISCOS unit in the center. On *Transit*, a 22 mm spherical proof mass floated freely in a 40 mm diameter cavity (9 mm gap). *Transit* was controlled in six degrees of freedom (three in translation by cold gas propulsion, two with one axis controlled to the vertical by gravity gradient, and one, the rotation about the vertical controlled by the addition of a constant speed wheel spinning about the axis normal to the orbit plane). By canceling the disturbances, the orbit was more predictable and ephemeris updates were only required on a weekly basis as opposed to twice a day. It achieved a level of disturbance cancellation to 5×10^{-11} m·sec^{-2} and was designed to insure that gradients in internal disturbing forces were less than 1×10^{-7} sec^{-2}. Subsequent flights of the DISCOS for the *Transit* were for drag compensation in one axis along the orbit direction [Eisner 1982] and based on the results of the first flight the drag-free requirements were relaxed by an order of magnitude.

Figure 2 - Artist's rendition of the *Transit* satellite deployed in orbit (ca. 1972)

There are two equivalent ways of canceling the spacecraft disturbances. First, the spacecraft can fly to follow an internal unsupported proof mass by minimizing the relative position of the spacecraft with respect to the proof mass (this is called a "primary" or "unsuspended" drag-free), and second by suspending the internal proof mass and controlling the spacecraft to keep the suspending forces a minimum (called "backup" or "suspended" drag-free). These are equivalent in function, but the backup mode is more robust especially when the clearance between the spacecraft and the proof mass must be minimized to achieve an accurate relative orientation measurement, as is necessary in the GP-B case.

GP-B MISSION REQUIREMENTS

On GP-B, four spherical mechanical gyroscopes are spun up so that their spin axes point nominally toward a reference or "guide" star, IM Pegasi (HR 8703). Their orientation is measured with respect to the guide star during a year. To be interesting scientifically, the drift rate of the gyroscopes together with in instrument's ability to measure their orientation must be better than 10 marcsec/yr (3.2×10^{-10} deg·hr^{-1} or 1.5×10^{-15} rad·sec^{-1}). The GP-B performance goal is 0.5 marcsec (2×10^{-9} rad) of drift with respect to the reference direction over the course of the year long experiment, which provides a 1 part in 100 resolution of the predicted Frame-dragging effect. To achieve this, the gyroscope drift rate must be less than 1×10^{-11} deg·hr^{-1} (7×10^{-17} rad·sec^{-1}). On the ground the very best uncorrected drift rate of gyroscopes is only slightly less than 1 deg·hr^{-1}. In a fundamental physics experiment such as GP-B, there should be no modeling of gyroscope drift to insure that some science is not accidentally modeled out of the observations whereas for navigation and attitude control, improvements of several orders of magnitude can be achieved beyond the raw accuracy of the device. Needless to say, every effort is made to prevent the satellite environment from creating a torque that might be confused with or mask the science measurement. Drag-free control of the GP-B spacecraft is employed to minimize the support forces, which in turn minimized support induced torques on the rotor.

Inevitably there are interactions at some small level between the gyroscope's housings and the rotors that might produce a torque. To mitigate this, the satellite is rolled about the axis pointing toward the guide star which averages these effects. In body axes this means the drag-free must be most effective at the roll frequency at which torques would produce a secular drift of the gyroscope spin axis in inertial space. The drag-free requirements for GP-B are broadly 1×10^{-9} m·sec^{-2} with a tighter requirement for 1×10^{-11} m·sec^{-2} in a narrow band centered at the roll frequency (13 mHz;77.5 sec period) transverse to the direction of gyroscope spin. The spectral shifting due to roll considerably eases the requirements for disturbance reduction especially from internal forces such as mass attraction since roll averages body fixed forces transverse to the roll axis.

General Relativity predicts a linear drift rate of a gyroscope in a polar orbit. If this theory is correct, the effect is a very low frequency phenomenon. Therefore, the primary interest in collecting data is to look for very low frequency effects that would include a constant drift during the year.

To help make this measurement, the spacecraft rolls about the line of sight to the guide star, as noted above. In the spacecraft frame of reference the science information, which accumulates slowly in inertial space, is now modulated at the vehicle roll rate. The spectral shifting due the vehicle roll however does not occur for the sensor noise since the sensor is fixed in the space vehicle. The science data can be transformed back into the inertial frame and the sensor noise is then spectrally shifted to a higher frequency and can easily be separated out by filtering.

Since the experiment's science data is at 13 mHz ± 1×10^{-7} Hz and the drag-free control bandwidth is approximately 1 Hz, the effectiveness of the drag-free control system is fundamentally limited. A notch filter has been introduced at the space vehicle roll rate in the space vehicle's Attitude and Translation Control (ATC) command path to help limit the vehicle-induced disturbances at this frequency. However, since the drag-free system cancels the principal external disturbances that drive the control system, it allows the electrostatic suspension to operate at very low average force levels. This consequently reduces the required electric fields used by the suspension system to a sufficiently low level to meet the overall drift requirements for the gyroscopes.

INERTIAL PROOF MASS: SCIENCE GYROSCOPE

The proof mass used for the drag-free proof mass for GP-B is one of the four redundant mechanical science gyroscopes used to measure the effects of General Relativity. Each gyroscope consists of a 38 mm diameter, 63.5 g, metallized fused quartz sphere that is spherical to better than 1 part in 10^6 (20 nm). It is suspended electrostatically in a spherical cavity across a 32 μm gap - small in comparison to *Transit's* 9 mm gap - via voltages provided through six dish-shaped electrodes located on the housing wall arranged in opposing pairs along three orthogonal axes. To operate as a gyroscope, the suspended rotor is spun to ~4500 RPM (~75 Hz) via a tangential helium gas jet which flows in a channel in the housing, as shown in Figure 3.

The gyroscope's spin axis orientation is sensed from measurements of the rotor's London Moment, a dipole magnetic field created by a spinning superconductor whose axis is perfectly aligned with the rotor's instantaneous spin axis. To activate the superconducting coating, the gyroscopes are cooled to ~2.0 K in a superfluid liquid helium dewar. A superconducting pickup loop on the housing parting plane couples this magnetic field into a Superconducting QUantum Interference Device (SQUID), magnetometer for measurement [Wellstood 1984]. From these measurements over multiple satellite roll periods, the direction of the gyroscope spin axis can be determined with respect to the spacecraft-fixed frame. Using the guide star tracking telescope and star trackers that roll with the spacecraft, the orientation of the gyroscope in the local inertial frame can be measured with respect to a distant inertial frame. This system is able to resolve the angle between the rotor spin axis and the space vehicle roll axis to a noise level of ~200 marcsec·$Hz^{-1/2}$ (1 μrad·$Hz^{-1/2}$)

Figure 3 - Science Gyroscope and Drag-Free Proof Mass. 4 of the 6 electrodes and the cigar-shaped spinup channel (right half) are clearly seen.

GYROSCOPE SUSPENSION SYSTEM (GSS)

The Gyroscope Suspension System (GSS) primary functions are to 1) center the rotors electrostatically in the housing and minimize suspension-induced torques on the rotor during science data taking periods, 2) position and hold the gyroscopes close to the spinup channel during gas spinup operations, 3) and transmit position and control effort data to the space vehicle attitude and translation control (ATC) system to implement drag-free control.

The GSS measures the position of the rotor along 3 axes using a three-phase capacitance bridge running at 34.1 kHz at amplitude of 20 mV; this frequency and amplitude were chosen to minimize interference with the SQUID magnetometers used for gyroscope orientation measurement. The position of the rotor can be measured to a noise floor of 1.5 nm·$Hz^{-1/2}$, and is quantized by the GSS at the 1 nm level. The primary suspension scheme is a digital implementation of an adaptive LQE (Linear Quadratic Estimator) algorithm that minimizes electrostatic torques on the gyroscope by minimizing the electric field strengths between the electrodes and rotor. The 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. To guard against a computer failure, each gyroscope is equipped with a high-authority backup analog PD (proportional + derivative) control system, which is engaged by an independent suspension arbiter circuit. This arbiter monitors computer health and gyroscope position and engages the backup control loops when a computer fault or a large position excursion (> 10 μm) is detected [Bencze 2003].

In its role as a drag-free inertial sensor, the GSS can be commanded to send to the ATC system either measurements of the rotor's position in the cavity (for unsuspended, or "primary" drag-free) or the associated control efforts required to keep the designated proof mass centered in the cavity (for suspended, or "backup" drag-free).

HELIUM SUPPLY

The propellant for the drag-free control system is derived from exhaust gas boil-off from the spacecraft's 2400 liter superfluid helium dewar. The dewar is required to maintain the science gyroscopes and associated orientation readout electronics at superconducting temperatures for proper operation as well as to maintain the integrity of the superconducting magnetic shielding that surrounds the science instrument.

The dewar's main tank vents through a porous-plug superfluid phase separator that was designed to provide flow rates between 4 to 16 $mg{\cdot}s^{-1}$ over a temperature range of 1.6 to 2.0 K without choking or breakthrough, and operates with sufficient back pressure (5 to 17.5 torr) so that the vented gas may be used by the ATC system. The plug was sized so that the average flow rate during the science phase of the mission is in the range of 6 to 7 $mg{\cdot}s^{-1}$. The plug was fabricated from 316L sintered powered stainless steel, 6.35 mm thick and a diameter of 69 mm, with a permeability of $3.8{\times}10^{-8}$ mm^2 [Parmley 2003]

The dewar temperature is regulated by controlling the net mass flow from the main tank and venting this flow in the force and torque null space of the thruster system; any combination of change of flow through the thrusters that does not change the force or torque on the spacecraft is said to be a "null space" command. A heater in the main tank is also provided to supply energy to the helium bath should it be necessary to increase the pressure in the main tank and thruster manifold during high flow conditions. During on-orbit operations, the 125 mW nominal heat leak into the dewar was sufficient to supply enough boil off gas for the operation of the thruster system without the need for additional heat.

PROPORTIONAL COLD GAS THUSTERS

The design of the GP-B spacecraft evolved over a period of more than 40 years. In 1965, the helium thrusters were originally to be as simple as possible considering the technology of the period. The initial design had two nozzles with a differential solenoid spool valve that would open one nozzle while closing the other. Thrust would be produced without changing the helium flow and therefore not influence the dewar temperature. The low flow corresponded to a Reynolds number of as small as 10 and there was a serious question of whether the gas would provide a significant specific impulse, I_{SP}, for propulsion. Bull [1973] designed the first model and experimentally established that the I_{SP} was 130 sec which was surprisingly close to the theoretical value. Chen [1983] improved the modelling of the flow including slip and free molecular in the valve and nozzle, optimized the geometry to minimize the variation in flow as the thrust required was varied. He also redesigned the solenoid actuator for minimum power and maximum ruggedness. Wiktor [1989] developed the concept of maximizing the minimum authority and showed the differential thrusters sacrificed too much authority. Lee [1992] developed a wide dynamic range single nozzle thruster that used the throttling valve of Bull and Chen for normal actuation but increased the throat area for greater dynamic range. Jaffry [1992] completed the modeling with plume studies that established the accommodation coefficient in the nozzle to be unity. He showed plume impingement would be minimal in space and worked with Vanden Beukel (Lockheed Martin Corp.) to verify I_{SP} again for the flight designs. This team also recognized the need for the thrust to be independent of the temperature of the helium gas, so pressure feedback was introduced to make the thrusters thrust-command devices [Dougherty 1995].

A diagram of the flight thruster is shown in Figure 4. Helium enters the thruster via a port on the side of the unit, and then flows through a restrictor formed from a orifice and piston. A voice coil controls the gap between the piston and the orifice to control the flow through the unit. Following the orifice, the helium then enters a chamber upstream of the nozzle. Here, the stagnation pressure of the helium is measured by a pressure transducer before leaving the thruster via the nozzle. This thruster is designed to operate under choked flow conditions where the thrust produced is a direct function of the upstream stagnation pressure. In operation, an analog control loop is used to modulate the helium flow to maintain a commanded stagnation pressure at the pressure sensor. In this way, the thrust of the unit is decoupled from the supply line pressure and is insensitive to the local helium temperature.

The nozzle was sized to supply a required 2.5 mN of thrust at the minimum helium supply pressure of 5 torr (665 Pa). This results in a 3.5 mm throat diameter, slightly oversized to provide a 20% margin above the maximum required thrust. The thrusters are calibrated to operate over supply pressures of 5 to 17.5 torr (665 to 2333 Pa) and mass flows of 4 o 16 $mg{\cdot}s^{-1}$. A typical operating point for the thruster is 8.5 mN thrust for a mass flow of 6 $mg{\cdot}s^{-1}$ at a supply pressure of 12.5 torr (1667 Pa) with a stagnation pressure set at 6 torr, (800 Pa); this represents a specific impulse, I_{SP}, of 130 s. Thrust noise for these units has been measured to be 25 $\mu N{\cdot}Hz^{-1/2}$ and exhibit a unit-to-unit thrust variation of less than 0.2 mN and a thrust scale factor variation of less than 6%.

In addition to the pressure feedback mode of operation, the thruster may be operated open loop, independent of the pressure sensor. In this mode, voice coil current commands, rather than nozzle pressure setpoint commands, are generated by the flight software. For redundancy, two voice coils are provided for each thruster, with independent drive electronics and control loops; One pressure sensor is used jointly for both drive systems.

Installed upstream of each thruster in an thruster isolation valve (TIV) that can be used to completely isolate the thruster from the helium supply manifold in flight in the event of a mechanical failure of a thruster. [DeBra 2006]

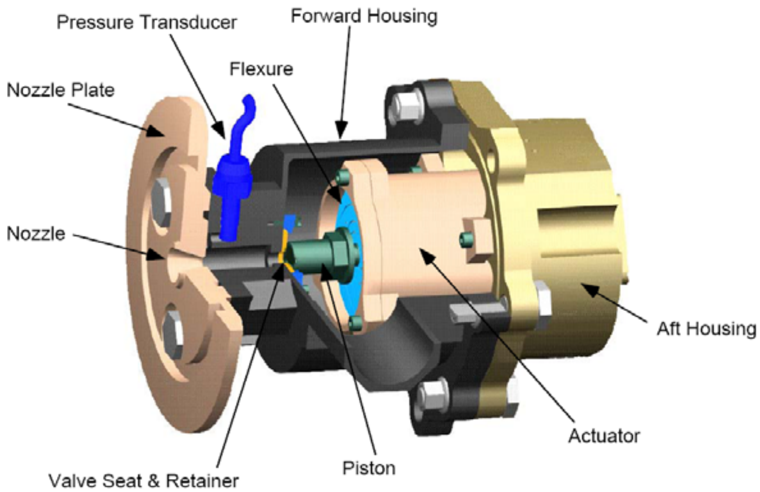

Figure 4 - GP-B Flight Thruster, cutaway view (1 of 16 units)

The arrangement of the thrusters on the space vehicle is shown in Figure 5. The thrusters are installed in four clusters of four thrusters each. Each cluster is arranged so that a pair of thrusters is aligned along the vehicle Y axis, and one thruster each is aligned along an X and Z direction, for a total of 8 along the Y axes, 4 each along the X and Z axes across the vehicle. The arrangement provides full 6 degree of freedom of control of the space vehicle orientation and position in orbit.

DRAG-FREE IMPLEMENTATION

Both “prime” and “backup” drag-free modes were part of the ATC design and have been exercised on orbit. Implementation details for both modes are given below:

Unsuspended or “prime” drag-free mode:

In this mode, the suspension system of the drag-free reference gyroscope is placed in a standby mode and the rotor is allowed to freely float while the vehicle flies to keep the rotor at the center of the housing cavity. The GSS monitors the position of the gyroscope in the housing and only allows rotor position excursions of approximately ±4μm from center of the 32μm rotor/electrode gap prior to disabling the drag-free mode and re-centering the gyroscope electrostatically. At 4500 RPM, there is sufficient mechanical energy in the rotor to destroy the gyroscope assembly should the rotor come into contact with the housing wall. Therefore, conservative limits have been built into the suspension system to preclude this possibility during normal operation.

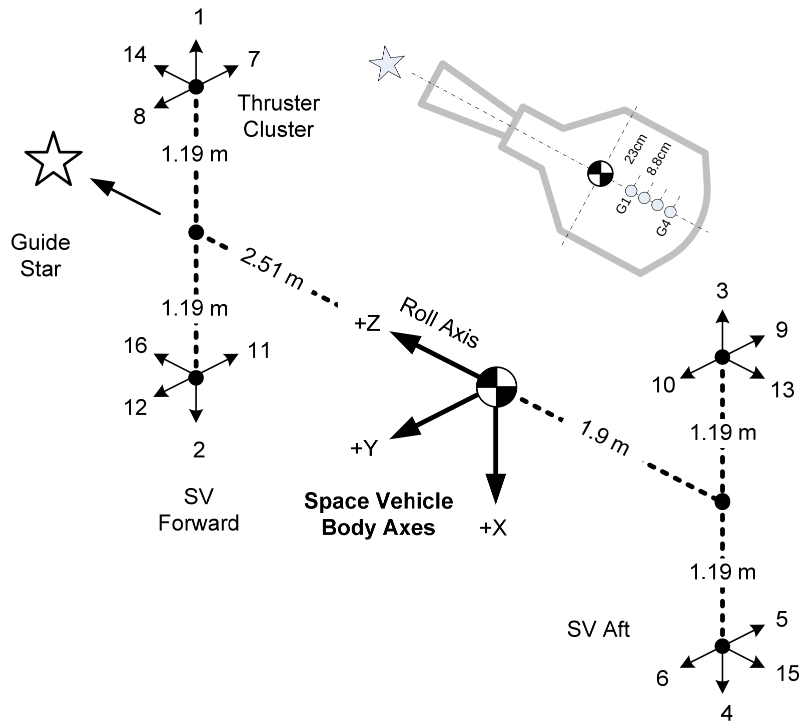

Figure 5 - Physical arrangement of thrusters on the space vehicle. Location of the gyroscopes relative to the CM is shown at the upper right corner of the figure.

The ATC system regulates the position of the inertial mass of the spacecraft, ***R***, with respect to the position of the gyroscope, ***r***, as shown in Figure 6. The GSS passes rotor position information to the ATC controller through the interface gain **K1**. The controller is implemented as a 3-axis PID controller with sufficient gain at the space vehicle roll frequency to meet its 1×10^{-11} m·sec^{-2} residual acceleration requirement. Calculations are performed in the nadir frame and are rotated into the vehicle body frame for application.

All drag-free sensors are subject to a gravity gradient force since 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 (see Figure 5). The gravity gradient acceleration is on the order of 4×10^{-7} m·s^{-2} on the rotor closest to the vehicle mass center (gyroscope 1) and increases linearly with distance to the other gyroscopes. Drag-free operation in effect moves the vehicle point of free fall to the location of the drag-free gyroscope, thereby reducing the gravity gradient acceleration on the other gyroscopes as well.

To aid the controller in rejecting this significant disturbance, a gravity gradient feed-forward signal, scaled by the distance from the vehicle center of mass to the center of the gyroscope housing, is generated and added to the thrust commands send to the space vehicle. In this case, the controller works primarily to reject the effects of vehicle resonance modes (minimal) and external disturbances from aero drag, solar pressure, and other environmental disturbances.

The main advantage of this mode is that the rotor is free-floating, and thus it represents the purest implementation of a drag-free system and, in principle, to the greatest extent minimizes the torques on the rotors – a great value for this experiment. However, this topology does have some particular disadvantages for GP-B.

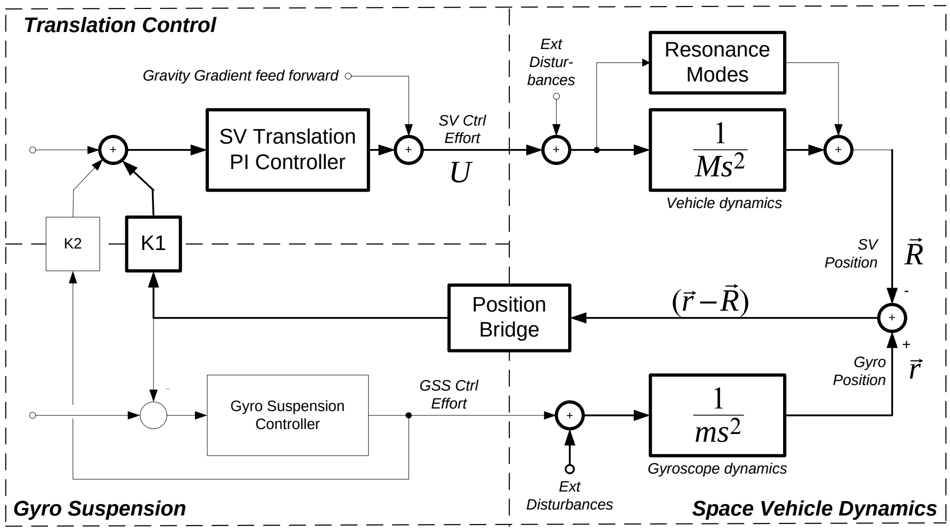

Figure 6- Unsuspended or "prime" drag-free control topology.

Because of the need to protect the spinning rotor, the drag-free system is only allowed to operate in a relatively narrow dead band around the center of the housing. This leads to more frequent drag-free shutdowns by the GSS when the vehicle encounters external environments that temporarily overwhelm the capability of the ATC system, approximately 5 mN per vehicle axis.

This mode also does not allow for acceleration bias compensation in the sensor since it relies on relative position of the rotor and housing as its input. Any force (due to an electrical patch charge, for example) between the rotor and housing will cause the rotor to accelerate toward the housing. In turn, the vehicle will accelerate to follow. To hold the rotor at a fixed position in the housing, the ATC system would need to apply a constant acceleration the vehicle which would change the orbit over time.

Suspended or "backup" drag-free mode:

In this mode, the gyroscope is suspended in science configuration by the GSS and the drag-free system flies the vehicle to minimize the measured suspension forces on the gyroscope. The ATC system works to drive the measured control effort on the proof mass, ***u***, to zero via translation control commands, ***U***, as shown in Figure 7. The GSS passes rotor control effort information to the ATC controller through the interface gain **K2**; any accelerometer biases are removed on the translation control side of the interface. At low frequency, near space vehicle roll rate, the transfer function from ***U*** to ***u*** is simply a constant, and in principle, a simple integral control is all that is required to minimize ***u***. The controller is implemented in the same structure as the suspension-off drag-free mode, but with different coefficients. Gravity gradient feed forward is again applied to compensate for known large disturbance acceleration.

The chief advantage of this mode is that the spinning gyroscope is always actively centered by the GSS, and thus is at minimal risk of contacting the housing wall. In addition, acceleration is measured directly and thus a post-measurement accelerometer bias adjustment can be readily made in the ATC system; this feature was exercised on orbit as noted below.

The disadvantage to the science measurement is that the drag-free gyroscope is always suspended, and thus is subject to greater electrostatic torques than a free-floating gyroscope due to the active suspension. However, this is not a significant disadvantage, since three of the four gyroscopes in primary drag-free mode need to be suspended against gravity gradient in any case, and the experiment error due to these residual forces has been shown to be well within the requirements.

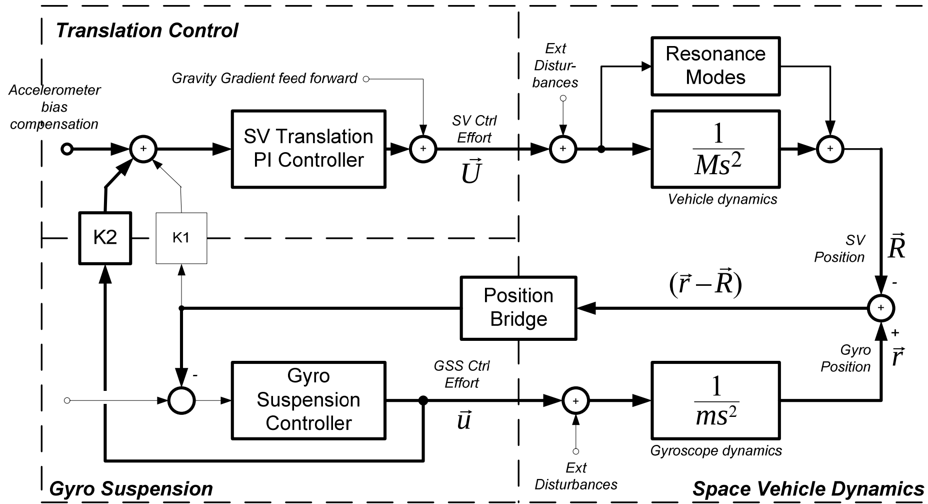

Figure 7 - Suspended or "backup" drag-free control topology.

FLIGHT PERFORMANCE

The design of the space vehicle permits any gyroscope to act as the drag-free reference; on orbit, the selection of the gyroscope to serve as the drag-free sensor was largely driven by practical, operational concerns. To minimize the overall residual gravity gradient acceleration the gyroscopes, Gyroscopes 2 or 3 (near the center of the linear array) are preferable. Gyroscope 4 is the furthest from the center of mass of the vehicle, and thus would require the most thrust – helium usage – to force the space vehicle to free fall around its center. Gyroscope 2, early on, required some control system tuning to optimize suspension performance and thus was not used for drag-free control during testing. Thus, drag-free testing and optimization was done with Gyroscopes 3 and 1.

Both the primary and the backup drag-free control modes were tested on the vehicle. Figure 8 shows an example transition sequence from non-drag-free, to suspended (backup) drag-free to free-floating (primary) drag-free control. During these transitions, the transfer of the gravity gradient acceleration moves from the gyroscope to the space vehicle ATC system as the space vehicle is forced to free-fall about the drag-free sensor. In prime drag-free mode, the suspension control efforts are disabled, so the vehicle must fly around the position of the rotor. Additional control effort activity in the ATC system is seen during this period.

Though prime drag-free is the preferred operational mode, it was not used during the science data gathering phase of the mission. After on-orbit calibration, it was found that some gyroscopes exhibited a small acceleration bias, up to 20 nN, that the prime drag-free system would track; though this bias would have no effect on the drift performance the gyroscopes, the ATC control action over time would slowly change the space vehicle's orbit. The backup drag-free system could properly compensate for these biases and showed acceptable performance for the mission during testing, thus it was selected as the baseline drag-free mode during science data collection.

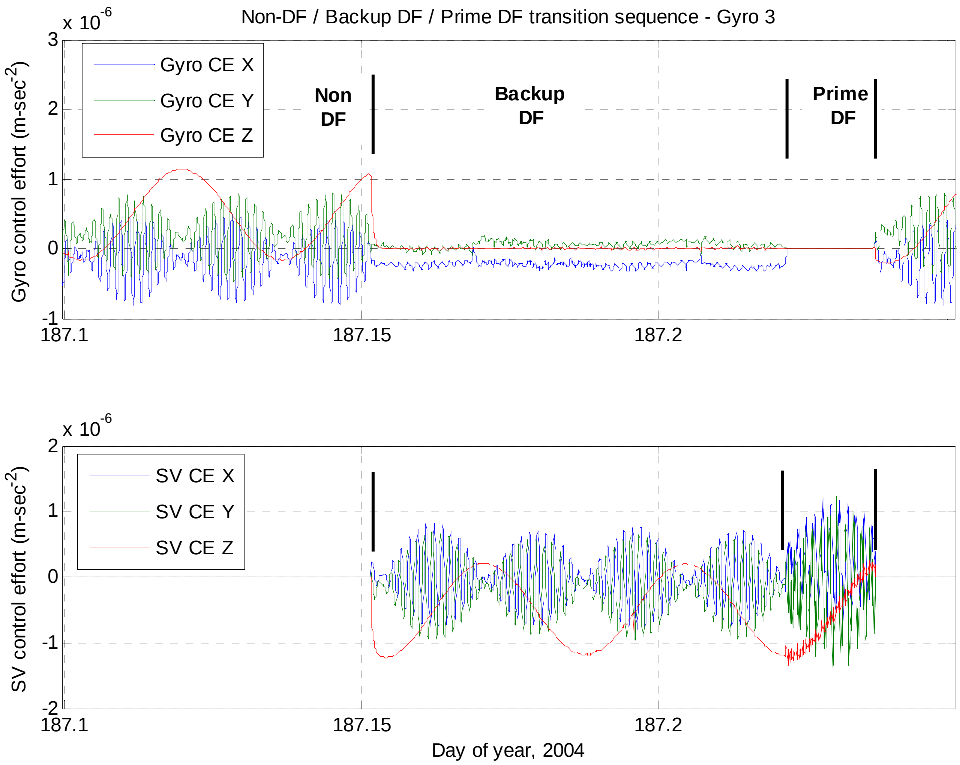

Figure 8 - Example transition sequence from non-drag-free to backup drag-free to prime drag-free operation.

Representative backup drag-free performance is shown in Figure 9. The top curve shows the spectrum of the space vehicle translation control effort showing the twice-orbit frequency gravity gradient signature at 3.4×10^{-4} Hz (red line); 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 4×10^{-11} m·s^{-2} from < 0.01 mHz to 10 mHz in inertial space (averaging period: 24 hours). If the gyroscope is viewed as an accelerometer, the acceleration measurement 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 sensing bridge, as required for compatibility with the SQUID readout system. 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 and remove force biases in both the ATC and GSS systems

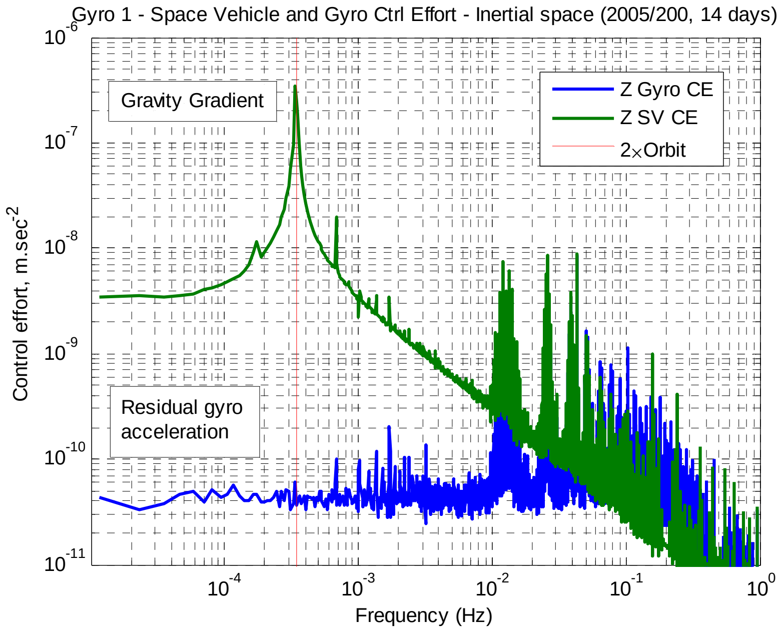

Figure 9 - Representative drag-free performance together with gravity gradient acceleration on the space vehicle

CONCLUSIONS

Drag-free control for the Gravity Probe B satellite functioned well on orbit, giving a residual acceleration on the space vehicle of 4×10^{-11} $m\cdot s^{-2}$ from < 0.01 mHz to 10 mHz in inertial space. The boil-off gas from the 2440 liter superfluid helium dewar was an effective source of propellant for the space vehicle's attitude and translation control system, always providing sufficient mass flow to control the vehicle in 6 degrees of freedom. The Lockheed Martin designed proportional helium thruster was successful providing reliable and accurate response to commands with a specific impulse of up to 130 sec. Overall, the drag-free system reduced the gravity gradient and environmental forces on the space vehicle by a factor of ~10,000 below ambient orbit environmental conditions. This reduced to an insignificant level a primary source of torque on the gyroscopes, and thus it eliminated an important error source for the measurement of the effects of General Relativity in the GP-B experiment.

This research was supported under NASA contract NAS8-39225. The proportional helium thruster, thruster isolation valve, and the remainder of the ATC system were developed for GP-B together with our partners at Lockheed Martin Corporation, Advanced Technology Center, Palo Alto, CA. [Dougherty 1995] We would like to particularly acknowledge the contributions of Jeff Vanden Beukel for the design and testing of the flight proportional helium thrusters and isolation valves, and Jon Kirschenbaum for the design of the space vehicle Attitude and Translation Control System. More information on the Gravity Probe B project can be found at http://einstein.stanford.edu.

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