The Design and Testing of the Gravity Probe B Suspension and Charge Control Systems

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Abstract. The Relativity Mission Gravity Probe B (GP-B), is designed to verify two rotational effects predicted by gravitational theory. The GP-B gyroscopes (which also double as drag free sensors) are suspended electrostatically, their position is determined by capacitative sensing, and their charge is controlled using electrons generated by ultraviolet photoemission. The main suspension system is digitally controlled, with an analog backup system. Its functional range is 10 m/s^2 to 10^{-7} m/s^2. The suspension system design is optimized to be compatible with gyroscope Newtonian drift rates of less than 0.1 marcsec/year (3×10^{-12} deg/hr), as well as being compatible with the functioning of an ultra low noise dc SQUID magnetometer. Testing of the suspension and charge management systems is performed on the ground using flight gyroscopes, as well as a gyroscope simulator designed to verify performance over the entire functional range. We describe the design and performance of the suspension, charge management, and gyroscope simulator systems.

I. INTRODUCTION

The Relativity Mission, also known as Gravity Probe B (GP-B), is first in a series of challenging basic science space space-experiments. Taking advantage of the space environment to reduce gravitational disturbances, these missions are designed to measure relativistic effects with an accuracy of four to seven orders of magnitude better than those achievable on the ground. State of the art technology must be developed, to meet the challenge of attaining the experimental accuracy and to compensate for the demanding space environment.

GP-B (1) is a test of the rotational effects of gravity designed to measure the geodetic and frame dragging relativistic rotational precessions. The local frame of reference in a polar orbit of 650 km, determined by high precision gyroscopes, is compared with the fixed frame of reference of distant stars, determined by a telescope. Figure 1 is a schematic representation of the GP-B experimental concept. In General Relativity the magnitudes of the geodetic and frame dragging precessions are 6.6 arcsec/yr and 0.042 arcsec/yr, to be measured in the Relativity Mission with an accuracy of 0.3 marcsec/yr or better. STEP and LISA, two major space tests of gravitational theories presently in progress, will utilize technologies similar to those developed for GP-B.

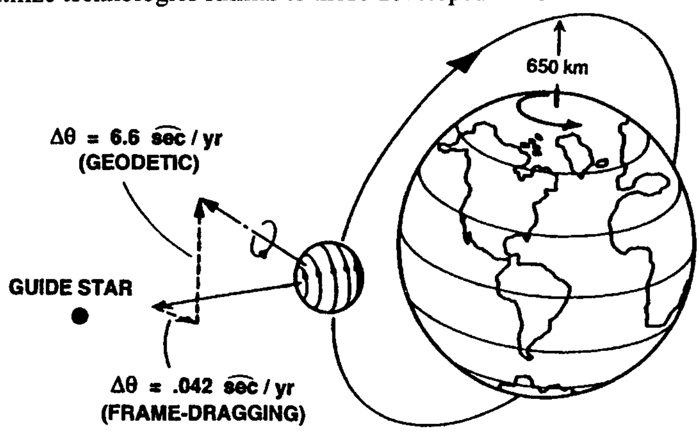

Figure 1. GP-B experimental concept

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Chapter II describes the gyroscopes, their Newtonian disturbances, and the requirements they impose on the suspension system. Chapter III contains the requirements, implementation, and performance of the Gyroscope Suspension System (GSS), while chapter IV details the testing approach of the GSS. We describe the charge measurement and control method, using UV photoemission, in chapter V.

II. GYROSCOPES / DRAG-FREE SENSORS

The most demanding goal of the Relativity Mission is the measurement of the parameterized post-Newtonian parameter _ to one part in 10^5; with _ determined from the measurement of the geodetic effect in Earth orbit. The knowledge of _ to one part in 10^5 will extend the search for a possible scalar interaction in gravity by two orders of magnitude, and allow a test of the critically damped version of the Damour-Nordtvedt (2) "attractor mechanism". This goal implies a measurement of the geodetic precession to 0.67×10^{-5}, and combined gyroscope drift and read-out noise of less than 50 μarcsec/yr (1.7×10^{-12} deg/hr). GP-B system testing shows that the instrument meets all requirements, and is expected to achieve the stated goal. Results from more than 100,000 hours of gyroscope operation indicate that residual Newtonian drift is less than 0.14 marcsec/yr for a supported gyroscope in 10^{-9} m/s^2, and less than 0.02 marcsec/yr for a fully inertial orbit. Low temperature bake-out is used in conjunction with a sintered titanium cryopump to achieve a vacuum level measured to be less than 3×10^{-12} Pa (2×10^{-14} torr).

The gyroscope readout system is based on measuring their London moment using dc-SQUID magnetometers and has demonstrated a noise performance of 5×10^{-29} J/Hz at 5 mHz (the spacecraft roll frequency). This is equivalent to an angular resolution of 1 marcsec for an integration period of four hours, thus fully meeting GP-B requirements. Through the use of normal and superconducting shields, the dc magnetic field of the science instrument is reduced to less than 10^{-7} G, with an attenuation of the ac field in excess of 10^{13}.

Four high precision cryogenic gyroscopes are used in GP-B to determine the inertial reference frame in the vicinity of Earth. Three of the gyroscopes are electrostatically suspended, while the fourth is used as the drag free sensor for the experiment. (Note that we use the term gyroscope interchangeably for gyroscopes and drag free sensor, unless clarification is required.) Residual torque is reduced to a minimum by compensating for the drag of the satellite (3) and by carefully controlling the sphericity of the gyroscope and its housing. Figure 2 shows a schematic view of an exploded gyroscope.

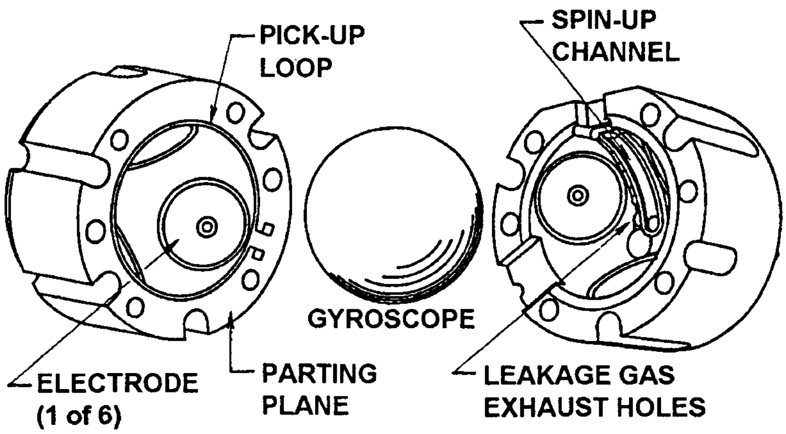

Figure 2. Schematic view of gyroscope

Table 1 summarizes the disturbance precessions for supported and unsupported gyroscope (4). The unsupported gyroscope, also used as the drag free sensor, does not need electrostatic support, thus eliminating the largest disturbance precession. Note however that the largest disturbances for both the supported and unsupported gyroscopes are due to electrostatic suspension and rotor-charge induced torques, emphasizing the need for optimization of both the electrostatic suspension and the charge control systems. Ground testing of the gyroscopes has shown performance consistent with the Relativity Mission requirements, indicating that the performance of the unsupported gyroscope will allow the measurement of _ to one part in 10^5.

Table 1. Gyroscope disturbance precessions

	GYROSCOPE SUPPORT	
DISTURBANCE TYPE	**Supported (marcsec/yr)**	**Unsupported (marcsec/yr)**
Mass Unbalance (12nm)	< 0.007	< 0.001
Electrostatic Suspension	< 0.140	< 0.010
Residual He Gas(10^{-11} torr)		
Differential Damping	< 0.006	< 0.006
Brownian Motion	< 0.001	< 0.001
Rotor Charge (10pC)	< 0.010	< 0.010
Gravity Gradient	< 0.001	< 0.001
Cosmic Radiation	< 0.001	< 0.001
Magnetic	< 0.001	< 0.001
Photon Gas	< 0.001	< 0.001
ROOT SUM SQUARE	**< 0.140**	**< 0.016**

III. GYROSCOPE SUSPENSION SYSTEM (GSS)

As shown in the previous section, the gyroscope suspension system (GSS) is the primary source of disturbance torques on the gyroscopes during the Science Mission phase of the GP-B experiment. The key challenge for the GSS design is to hold these disturbance torques to Science Mission compatible levels, while always maintaining positive suspension of the gyroscope under the effects of on-orbit disturbances and within the constraints imposed by the experimental apparatus.

To meet the overall objective set for the GP-B mission, the forces that the GSS needs to exert the gyroscope must span a huge dynamic range – eight orders of magnitude – and the system must compensate for a diverse set of disturbances during the various phases of the mission. It is not practical to span this large force and disturbance space with a simple, fixed control scheme. Thus, a multi-level scheme has been developed to address the pertinent requirements in each of three control modes: 1) Science Mission, 2) Spin-up and alignment, and 3) Ground-Test. Figure 3 presents a visual picture of the GSS controller set, the specific forces and electrode voltages required in the various modes, and the regions of influence of the primary disturbances operating during the mission.

The suspension system operates by generating electrostatic forces on the rotor via the application of a coordinated set of quasi-static voltages to the six electrodes on the gyroscope housing; see Figure 2. Since the three electrode axes are orthogonal, a judicious choice of the electrode voltage set allows the force on one axis to be decoupled from the other two, thus simplifying the design of the controller dynamics into an identical set of three one-DOF controllers rather than a single three-DOF controller. Even in this case, the resulting voltage-to-force map is still highly non-linear in both rotor position and in the magnitude of the applied voltage. An active non-linearity inversion scheme is employed to linearize the dynamics of the gyroscope plant to that of a simple inertial mass. This further simplifies the design of the controller dynamics, especially in the analog backup modes. The position of the rotor is measured with three capacitance bridges, one per axis, using a 40 mV-pp (400 mV-pp in the Spin-up and Ground Test modes), 34 kHz sinusoidal sense signal superimposed onto the drive electrodes. The high precision, low-noise design of the bridge results in an operational noise floor of 0.1 nm/√Hz, a resolution that allows the control system to meet the rotor centering requirements for the mission. The magnitude and frequency of the sense signal was chosen to be compatible with the ultra low noise operation of the SQUID magnetometers used to measure the orientation of the rotor's spin axis.

Figures 4 and 5 present a detailed block diagram of the GSS for a single gyroscope; each gyroscope is suspended by its own suspension electronics set. The overall design is partitioned into two physical enclosures. Figure 4 shows the makeup of the Forward Suspension Unit (FSU) enclosure. It primarily houses the precision analog electronics suite needed by the suspension system but also contains a bank of 16-bit A/D and D/A converters to translate the analog drive and position sense signals to their digital equivalents for use in the aft-mounted computer. Extensive internal shielding is employed to minimize the propagation of high-frequency digital noise to the sensitive analog electronics set. Thermal stability of the analog electronics is of a prime concern, especially in a space environment. This stability is achieved through a passive, multi-layer insulation scheme that will hold the electronics to within

0.05 K at the critical roll period of the spacecraft (1-3 min). The FSU also includes a multiplexed A/D converter for telemetry monitoring of the main control signals in the forward enclosure.

A radiation-hardened configuration register holds the state of all the configurable elements of the FSU enclosure. The 16-bit data word is stored in a set of radiation-impervious latching relays, which is changed only after a successful majority-voted succession of update commands to this register sent from the computer. It is powered independently of the computer; thus aft power failures or computer faults will not affect the configuration of FSU.

The aft block diagram presented in Figure 5 shows the bulk of the digital circuitry of the GSS system. At the heart of the Aft Control Unit (ACU) is a RAD6000-based CPU which acts as a DSP for control calculations, as well as a system monitoring and communication channel to the main spacecraft computer. This enclosure includes spacecraft timing synchronization circuitry to lock the computer clock and all derived clocks to the master spacecraft timing generator. This circuitry also generates the A/D sample and D/A convert triggers for the converter bank in the FSU and also performs a telemetry data gathering function via another multiplexed A/D converter in the aft enclosure. The GSS processor communicates with the FSU via the aft portion of the GSS Forward/Aft Bus, or GFAB.

Power is generated for the GSS by a very low noise DC-to-DC converter system mounted in its own enclosure next to the aft box. It generates a warm-redundant set of analog and digital supply voltages for the FSU, a non-redundant set of voltages for the ACU, and survival heater power to keep both the forward and aft electronics warm enough so that they will reliably start on orbit. The aft-created set of FSU supply voltages are further filtered and regulated forward to ensure that conducted EMI is minimized.

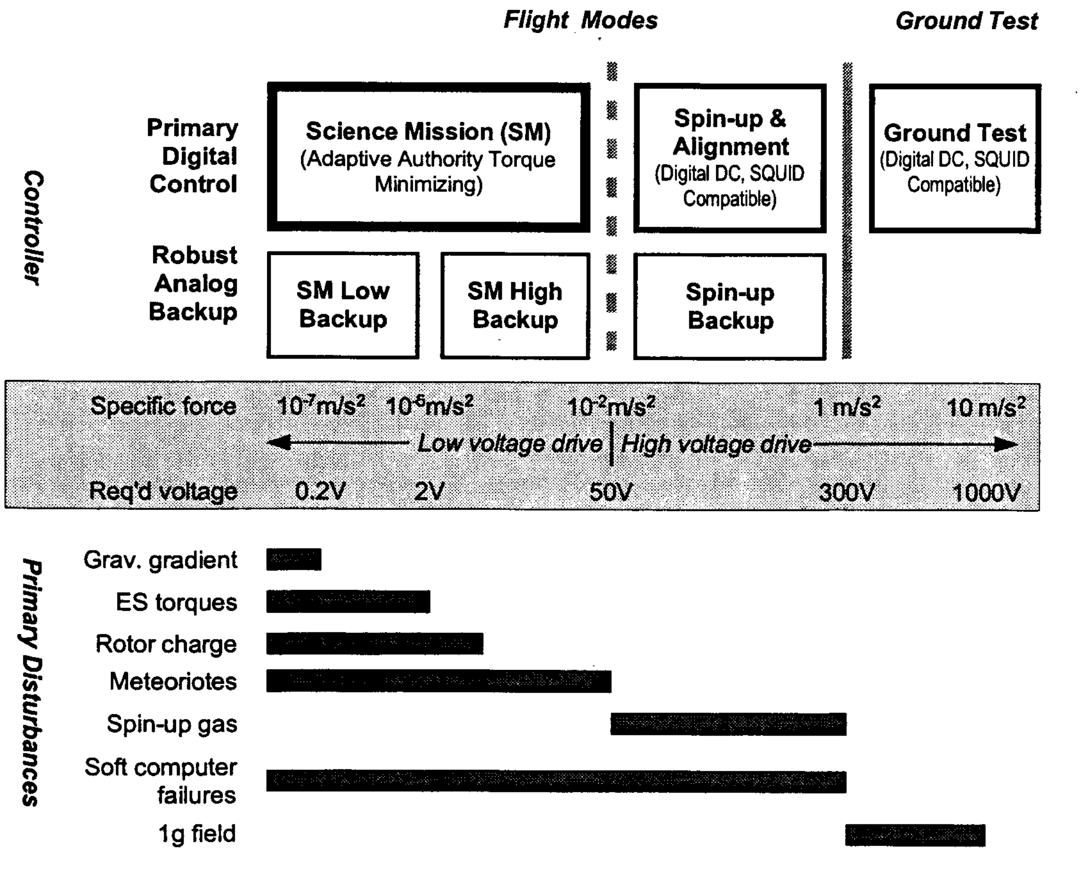

Figure 3. GSS controller set, required forces/voltages by mode, and primary disturbance set

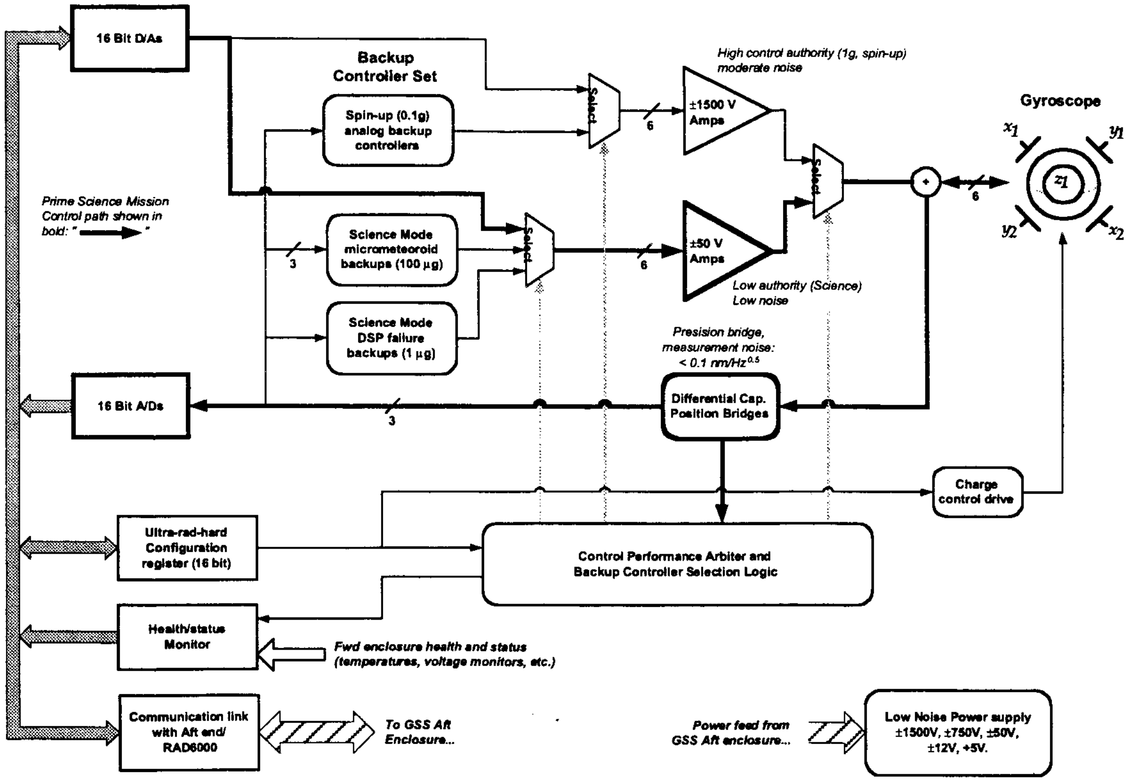

Figure 4: Block diagram of the forward GSS electronics enclosure (FSU)

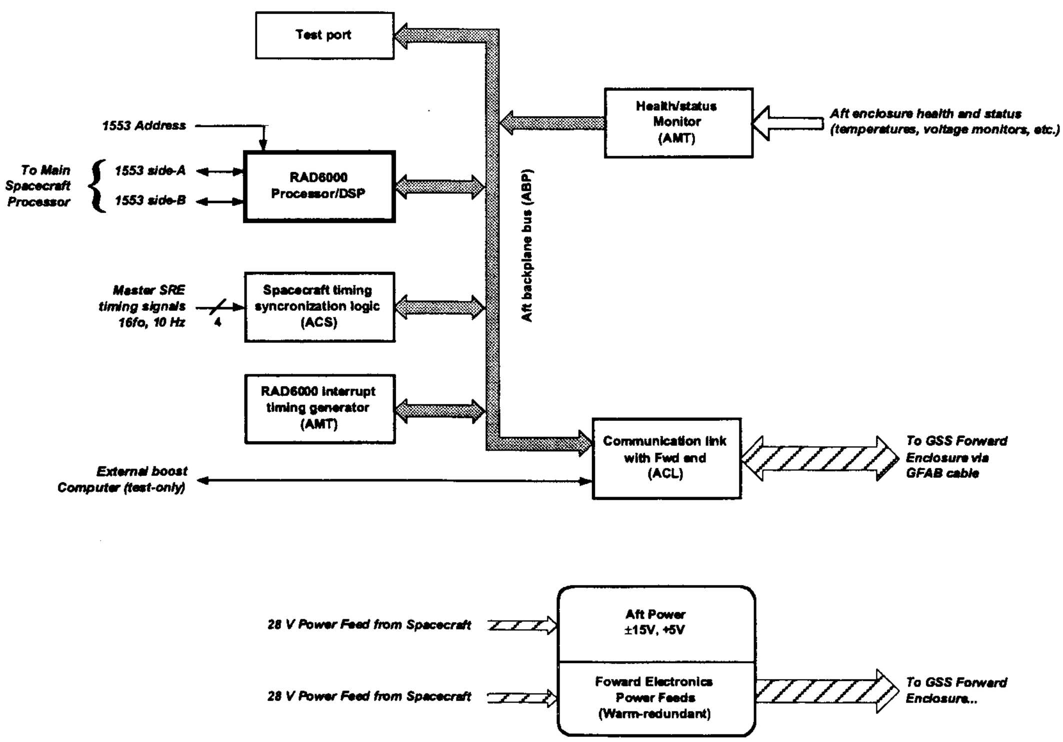

Figure 5: Block diagram of the aft GSS electronics enclosure (ACU)

The primary controller for the GSS system – the controller which shall be operating 99%+ of the mission – is the Science Mission digital controller running the GSS computer. The primary function of this controller is to minimize the electrostatic suspension-generated torques acting on the gyro, but it must also effectively handle the disturbance set active in this mode. This set consists primarily of slowly time-varying gravity gradient accelerations and the effects of rotor charging as well as the impulsive disturbances of micrometeoroid impacts. It adjusts to these disturbances by actively adjusting the bandwidth of the control loop so as to provide the minimum needed integrated force on the gyroscope to keep it within its centering requirements. At each control sample, it computes an electrode voltage set which provides the required force vector on the rotor while minimizing the maximum magnitude of the control voltages. These two strategies minimize the operational torques on the gyroscope.

This controller adapts to the disturbance environment and becomes increasingly aggressive as the magnitude of the disturbance increases. It smoothly transforms itself from a soft, linear controller to a maximum authority *bang-bang* controller to handle disturbances from micrometeorites with momenta as large as 1.0 kg-m/s; these occur with a probability of less than once per mission for the GP-B orbit. The prime science drive path is shown with a bold line in Figure 4. The D/A converters directly drive a low voltage (±50V), low noise amplifier to the gyro and the bridge feeds the position measurement to the A/D converter set for use by the control algorithm in the aft-located processor.

The primary Spin-up and Ground Test controllers are also implemented in the GSS processor, but are of a less sophisticated design. The main character of both of these modes is that they must handle a quasi-DC disturbance as part of their nominal operation. The Spin-up controller is required to hold the rotor near the spin-up channel in the presence of a specific force on the order of 1 m/s^2 during the time spin-up gas is flowing. In a similar way, the Ground Test controller must suspend the gyroscope against the 9.81 m/s^2 acceleration of the Earth's gravitational field in the laboratory. These high specific forces require high suspension voltages, and thus, a Spin-up/Ground Test high voltage amplifier is needed to provide the necessary voltages. During spin-up, the amplifier is designed to provide up to ±750 V to the electrodes, while on the ground up to ±1500 V is required for suspension. The aft-mounted power system will provide these voltages when needed, but will be shut off during the bulk of the mission in order to save power.

While it is desired to run the entire mission via the digital control algorithms in the GSS processor, radiation-induced soft failures of the processor which require a full reboot are likely to occur 1 to 3 times per mission per gyroscope. Thus a backup control system is required. In the Science Mission mode, two separate backup controllers are provided. A low control authority controller is provided to take over from the processor during normal operation where only gravity gradient and rotor charge disturbances are in effect. This controller is a simple PD (proportional-derivative) linear controller that will generate specific forces on the rotor up to the order of 10^{-5} m/s^2. While the torque performance of this simple PD controller is worse than that of the baseline digital algorithm, it is designed to meet as nearly as possible the Science Mission specifications. It is predicted that the gyroscope can remain in this low backup mode for 1-2 months before adversely affecting the precision of the measurement.

Though the low backup controller is nearly Science Mission compatible, it is unable to handle the random impulsive disturbances caused by micrometeoroid impacts. For this case, and aggressive high authority backup controller is included. This controller aggressively catches and re-centers the gyroscope in the event of a large micrometeoroid impact. It is a *bang-bang* controller and is constructed to use the full ±50 V range of the low-noise science drive amplifier. While greater control forces can be generated through the use of the high voltage amplifier, the system is designed so that it will never need to use these amplifiers in an emergency situation. Similarly, the primary digital spin-up controller also has a PD backup control system in the event of a soft computer failure during spin-up operations.

The selection of which controller is in operation at any one time is determined by the control system arbiter, a simple, robust analog computer in the forward electronics enclosure. This arbiter continuously monitors computer activity as well as the position of the gyroscope. In the event of a computer failure or a gyro excursion out of a pre-determined safety zone about the center of the cavity, the arbiter autonomously will switch between from prime digital controller to one of its backup systems. It will return control of the gyroscope to the computer only after it confirms that the computer is operational and is functioning properly. It is powered separately from the processor by the FSU warm-redundant power supply, and thus will faithfully execute its function regardless of the condition of the aft electronics set.

Laboratory tests to date indicate that this system will meet the overall gyroscope suspension, calibration, and operational needs of the GP-B experiment.

IV. GSS TESTING

A significant problem facing GP-B, is checking the performance of the suspension system levitating the on-orbit gyroscopes without actually having to perform an additional full fledged space experiment. It is necessary to test the closed-loop response of the electrostatic suspension, in order to determine the subtleties of the integrated system and to verify compliance with all flight requirements. While the gyroscopes are designed for ground levitation capability needed for functionality checking, the four orders of magnitude separating the ground and on-orbit suspension voltages (1000 V versus 0.1 V) make the ground testing unsuitable for complete verification of on-orbit performance. Computer simulations, with their dependence on idealized models, would provide a less than satisfactory test of the systems.

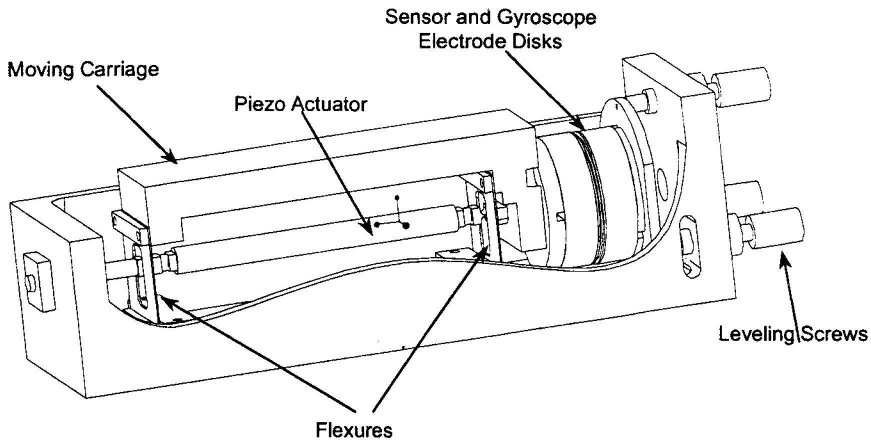

Figure 6. Schematic view of testbed actuator design

The solution implemented combines precision engineering with modern control techniques, to create a device with the dynamics of a gyroscope, which operates in a fully defined and controllable environment. The gyroscope 'testbed' consists of six electrode pairs on quartz disks that simulate the six gyroscope electrodes, by generating the required electrode to gyroscope capacitance. Piezoelectric actuators control the spacing between the quartz disk pairs, using the position information supplied by additional 'measurement' electrodes. Complex shielding between the gyroscope and the measurement electrodes on the quartz disks is needed in order to minimize cross talk between the two feedback systems. Figure 6 shows a schematic view of a complete testbed actuator.

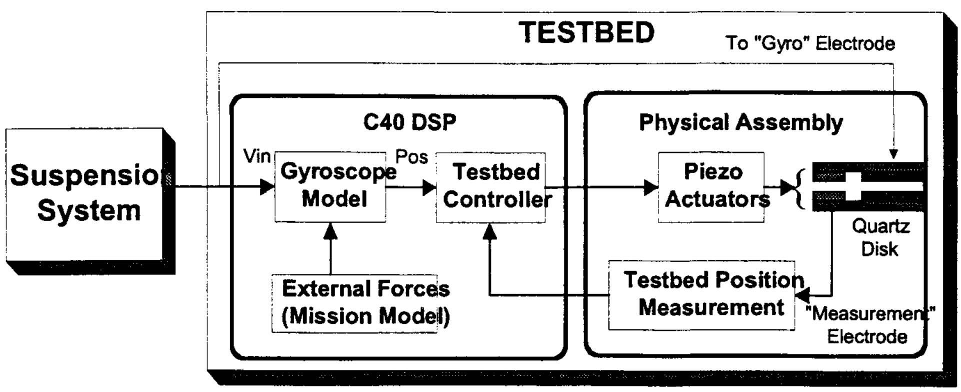

Figure 7. Schematic view of testbed concept

A C40 DSP contains the testbed controller, the gyroscope model, and a science mission model including all on-orbit disturbances, while the suspension system couples directly into the testbed. Figure 7 shows a representation of the entire testbed concept. The testbed allows the integrated testing of all functions of the suspension system, including position measurement and control, charge measurement and control, and spin axis alignment using space vehicle roll rate modulation of the suspension voltages. It also allows the testing of all suspension regimes from 1 g to 10^{-7} g, while incorporating all on orbit disturbances during both the initial setup and gyroscope spin-up stages, as well as the Science Mission data acquisition period.

Figure 8 demonstrates that the position resolution of the testbed is better than 0.1 nm, by showing the result given by the measurement electrodes for a commanded 0.3 nm peak-to-peak sinusoid. Verification of the testbed functionality is performed by comparing the gyroscope positions for all three axes during ground 1 g levitation of a real gyroscope and of the testbed. Figure 9 shows the results of this test.

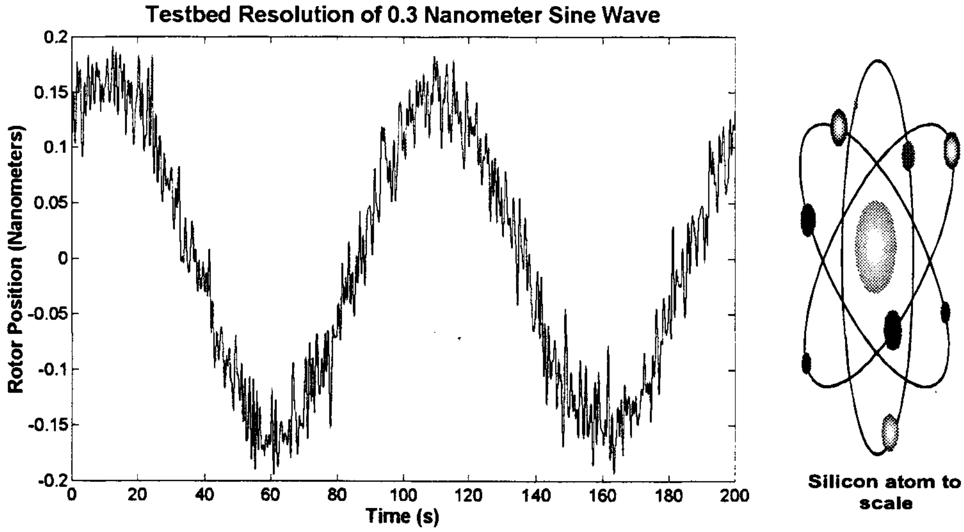

Figure 8. Testbed resolution of 0.3 nm sinusoid

V. CHARGE MEASUREMENT AND CONTROL

In the 650 km polar orbit used by GP-B the main contributions to the radiation environment are due to charged particles trapped in the Earth's magnetic field (5) and to charged particles generated by solar flares (6). Note that mainly proton trapping affects the gyroscopes, causing the cosmic radiation charging to be positive. The shielding provided by the spacecraft stops most primary electrons, while secondary emission of electrons has a yield of less than unity for the GP-B environment. During experiment-initialization stages two additional mechanisms can cause gyroscope charging: the separation of dissimilar metals during gyroscope levitation off the housing, and charge deposition by ionized helium during the spin-up of the gyroscopes. The polarity of the charging due to gyroscope levitation and spin-up are difficult to predict, making it necessary for the charge control technique to have bipolar capability.

In order to reduce heating and charging during solar flares, a radiation shield of 10 $g \cdot cm^{-2}$ was added, resulting in a total shielding for the gyroscopes of 20 $g \cdot cm^{-2}$ aluminum equivalent. Standard space technology is used to mitigate the effects of cosmic radiation on the electronics, the cryogenic probe, and the satellite. However, the gyroscope rotors are mechanically isolated systems spinning in ultrahigh vacuum, thus making it necessary to use non-contact methods for charge control and to rely on thermal radiation for cooling.

Gyroscope requirements, due to torque and acceleration considerations, limit the rotor charge to 10 pC, or equivalently to a 10 mV potential (for the 1 nF rotor capacitance). The total charge accumulation over the 1.5 year mission is about 600 pC making it necessary to monitor the gyroscope potential and use active charge control.

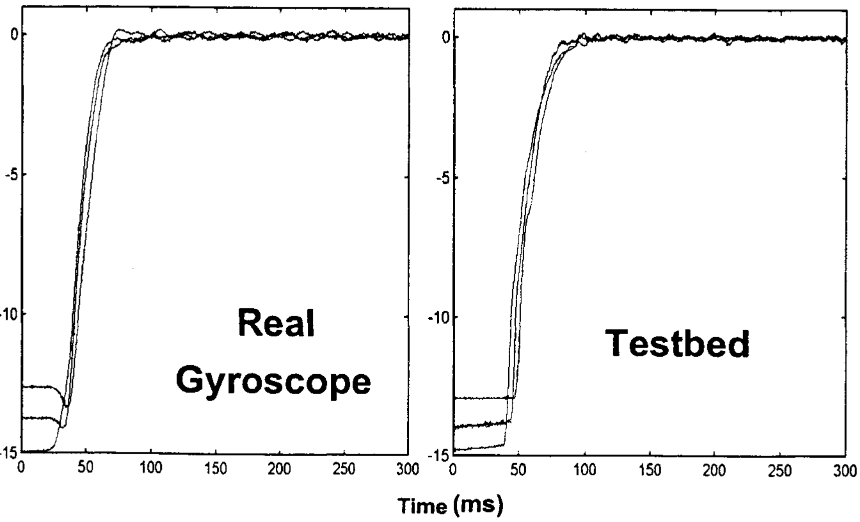

Figure 9. 1 g testbed suspension results

The force modulation technique is insensitive to gyroscope miscentering, is independent of the ambient acceleration, and achieves an accuracy of better than 5 mV for an integration time of 100 s, making it suitable for use for the GP-B mission. GP-B uses two levels of charge measurement excitation. a) A 10 mV level for continuous monitoring that achieves the 5 mV accuracy in 100 s. b) A 100 mV level for measurements during active control using the UV system, which achieves the 5 mV accuracy in about 1 s, thus making the control loop much simpler to implement.

UV photoemission is the method used by GP-B to generate the electrons used for charge control (7). Rotor and biasing electrode are illuminated with UV light, and the electrons generated by photoemission from both these surfaces are added or removed from the rotor using a dedicated biasing electrode. The direction of the charge flow is controlled by biasing of the charge control electrode to ±3 V with respect to the gyroscope surface. The gyroscope surface is a sputtered thin film of niobium, while the charge control electrode surface is electroplated gold. Experimental considerations pose additional constraints on the hardware near the gyroscope: low remnant magnetization, very high standards of cleanliness, a superconducting transition temperature below 1.5 K, and compatibility with the 2 K GP-B experimental temperature. Figure 10 is a schematic representation of the fixture mounted in the gyroscope housing which directs the UV light onto its inner surface and onto the gyroscope, while also fulfilling the function of the charge control bias electrode.

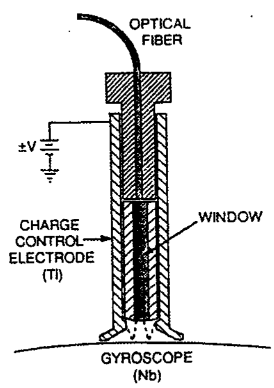

Figure 10. Schematic of UV counter electrode

The UV source is an rf-discharge mercury lamp manufactured by Resonance Ltd. Canada (8). About 10 μW of 254 nm mercury light is coupled from the lamp into each of twelve 300 μm UV fibers. For redundancy GP-B will fly two lamps, with two fibers from each lamp capable to illuminate the two UV fixtures on each gyroscope. Each of the eight fibers going to the four gyroscopes has a UV compatible switch developed by GP-B, thus allowing the choice of one of the two lamps for illumination. The photoemission efficiency is strongly dependent on the exact surface conditions of the transmitting and reflecting system elements, and varies between 50 and 1000 fA/μW for the gyroscope and between 100 and 2000 fA/μW for the UV fixtures.

Ground testing of the charge control system proceeds by two techniques. In the first method the gyroscope is not levitated, and the photoemission current is measured directly through the connection to the ground-plane of the housing on which the gyroscope is resting. Figure 11 gives the photo current as a function of the bias voltage for a flight gyroscope, for room temperature, 300 K, and low temperature, 4 K. The second technique uses the voltages generated by the electrostatic suspension system to measure the gyroscope potential variations under UV illumination. Flight hardware testing confirms that charge management, using measurement by force modulation and electrons generated by ultraviolet photoemission, are the solutions for the GP-B gyroscope-charging problem.

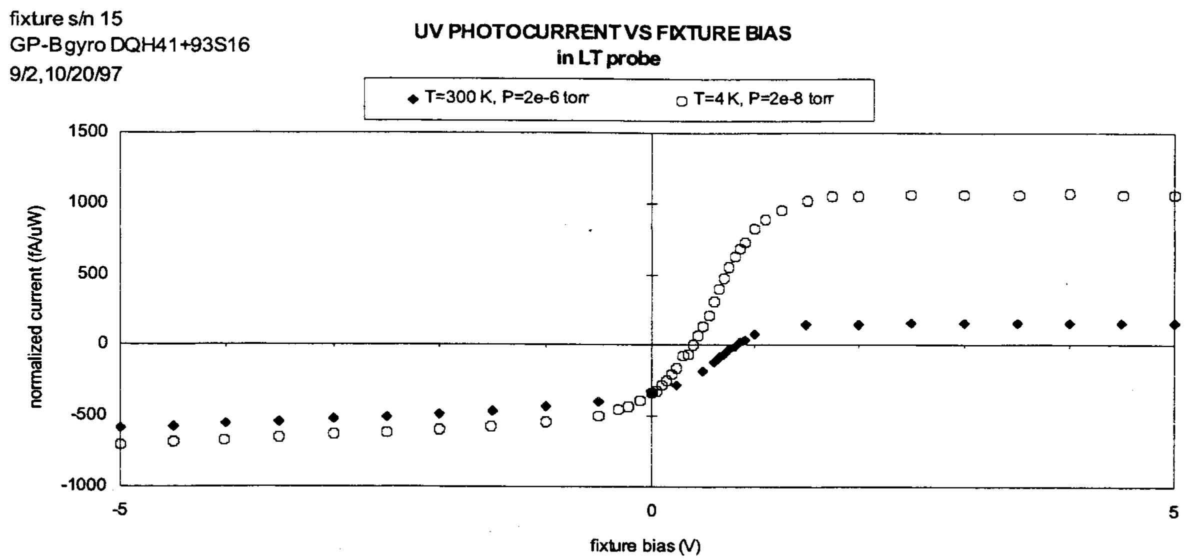

Figure 11. UV photo-current vs fixture bias

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