

THE PROMISE AND CHALLENGE OF GRAVITATIONAL EXPERIMENTS IN SPACE: GP-B AND ITS LESSONS FOR LISA, AND STEP

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The Relativity Mission, Gravity Probe B (GP-B) is the most complex gravitational space experiment to date. Launched on April 20, 2004 it has successfully taken science data from August 29, 2004 to August 15, 2005. GP-B has demonstrated that very complex physics experiments can perform flawlessly in space. It is the first experiment to see General Relativity directly as the main effect of the measurement. We present data from GP-B and its impact on the design and development of technology for the Laser Interferometer Space Antenna (LISA) and the Space Test of the Equivalence Principle (STEP).

1 Introduction

GP-B, LISA, and STEP are three ultra untypical physics experiments that can meet their precision requirements only by using the quiet environment of space. GP-B is measuring two rotational effects predicted by gravitational theories; the geodetic precession due to the distortion of space by a massive body, and the frame dragging precession, a twisting of space caused by the rotation of the body.^{1,2} Earth is the massive body, with the experiment in a 642 km polar orbit. Figure 1a shows the GP-B concept. The frame of reference in the field of the Earth, measured by gyroscopes, is compared to the reference frame of distant stars determined by a telescope locked on the guide star HR 8703 (IM Pegasi). Equation 1 gives the two precessions as computed in General Relativity and expanded in the Parameterized Post Newtonian (PPN) formalism used for metric theories in weak gravitational fields. The geodetic precession in the plane of the polar orbit, first term, and the frame dragging orthogonal to the orbit plane, second term, are proportional respectively to the mass and the moment of inertia of the Earth.

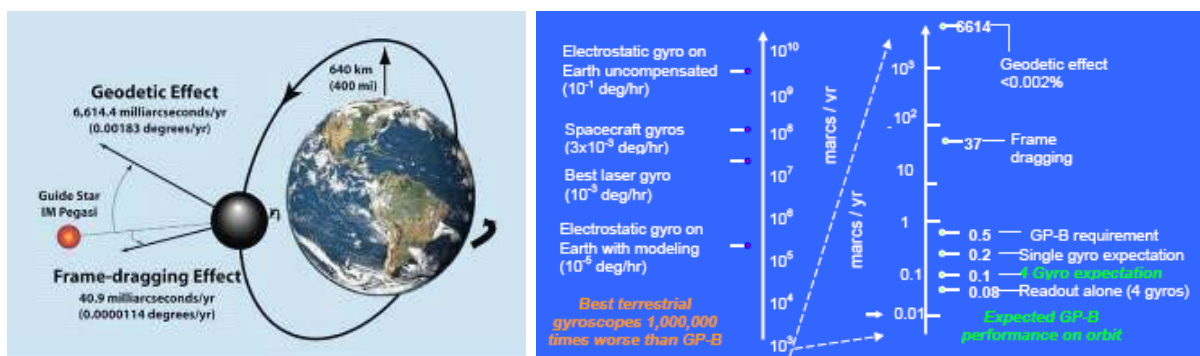


Figure 1: a) GP-B concept,

b) Gyroscope performance: GP-B versus ground based

$$\bar{\Omega} = \left(\gamma + \frac{1}{2} \right) \frac{GM}{c^2 R^3} (\bar{R} \times \bar{v}) + \left(\gamma + 1 + \frac{\alpha_1}{4} \right) \frac{GI}{2c^2 R^3} \left[\frac{3\bar{R}}{R^2} \cdot (\bar{\omega}_e \cdot \bar{R}) - \bar{\omega}_e \right]. \quad (1)$$

GP-B is a unique gravitational measurement in space, as a controlled physics experiment with an apparatus specifically designed for the purpose with fully determined parameters. While based on a simple concept, the precision requirements make GP-B a very complex experiment based on cutting edge technology, never before used in space. Its superb performance demonstrates that such complex experiments can and will work and greatly increases the confidence in the success of future experiments in space. In particular, the significant technologies overlap of GP-B, LISA,³ and STEP⁴ present us with the opportunity to greatly enhance the probability of success for LISA and STEP by judiciously using the lessons learned from GP-B. Section 2 introduces the subject of the advantages of gravitational experimentation in space and a summary description of the LISA and STEP missions. Section 3 details the requirements and performance of the main GP-B systems. Section 4 discusses the lessons learned from GP-B and their application to the LISA and STEP missions.

2 GP-B, LISA, STEP

Deciding on performing a space experiment requires the careful balancing of the advantages and disadvantages of space. Such experiments are costly and of very long duration, require survivability in the severe launch environment, are a single opportunity endeavor with any major anomaly potentially causing total mission loss, and are handicapped by limitations in communications. However, low seismic noise in the frequency region below 1 Hz, the low gravity environment, long interferometry baselines, and long integration times make space the only possible way of achieving the requirements for a number of experiments including GP-B, LISA, and STEP. Figure 1 shows a) the GP-B concept and b) the rationale behind going to space. Only the very low gravity of space allows the gyro performance required for the measurement of the relativistic precessions. GP-B is the first experiment to directly measure gravitational relativity as the main measured effect. Figure 2a shows the preliminary analysis results (April 2007) of the direct measurement of the geodetic effect, the north-south inertial orientation of the four gyroscopes to $\pm 1.5\%$ (± 97 marcsec/year); figure 2b is the drag-free performance data..

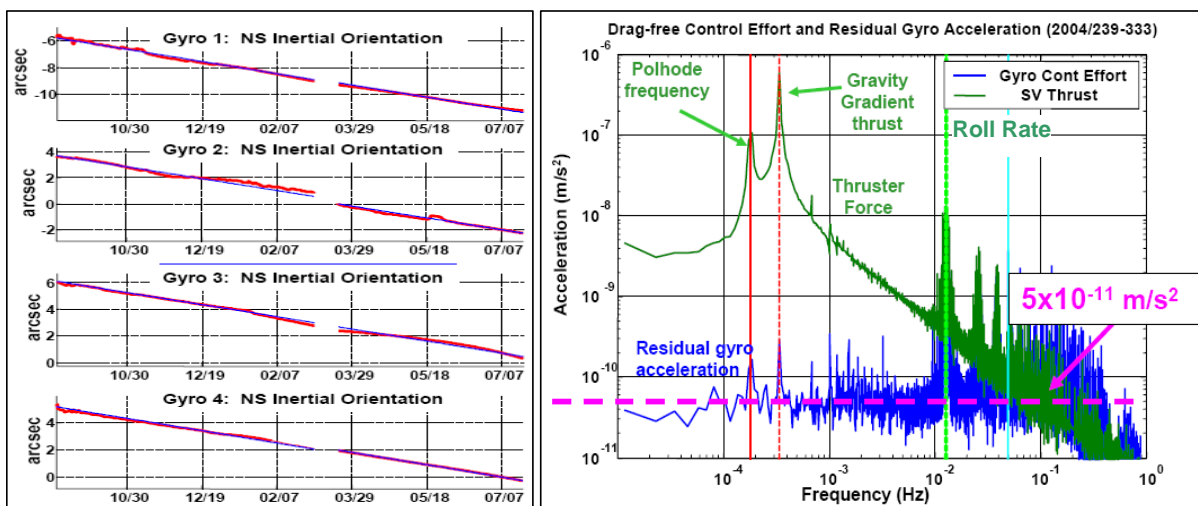


Figure 2: a) Flight data: Red: Flight data, Blue: After torque correction. b) GP-B drag-free performance.

LISA is a space gravitational wave observatory based on the interferometric measurement of the distances between three spacecraft placed in an equilateral triangle with five million

kilometers side. The formation center is twenty degrees behind the Earth on its solar orbit and inclined sixty degrees to the ecliptic. Its bandwidth is 3×10^{-5} Hz to 1 Hz, complimentary to the ground gravitational wave detectors. LISA takes advantage of the low gravitational environment and the very long baselines available in space. The main GP-B heritage technologies are the gravitational reference sensor (GRS), the high stability optical benches and telescopes, the drag free technology, and the multiple degrees of freedom controls systems.

STEP will improve the measurement of the equivalence principle by five orders of magnitude; from 10^{-13} to 10^{-18} . The experiment compares the rate of fall of different materials and relies on the low gravity and the long integration times in a 450 km orbit. The science signal is modulated at orbital frequency. GP-B technologies used for STEP are the cryogenic, magnetic-shielding, drag-free, multiple degrees of freedom controls, and cold gas thrusters systems, the dc SQUID read-out, and the high stability optical bench.

3 GP-B Performance

From launch until Science Mission start, on August 29, 2004, the experiment underwent a period of 128 days of initialization that included instrument calibrations, guide-star acquisition, spacecraft rolling, drag-free set-up, spin-up of gyroscopes and their alignment with the roll axis, and low-temperature bake-out. The 128 days was triple the expected duration of 40 days. Thus, the first GP-B lesson is to allow for a factor of three contingency in the planned experiment initialization period. The science data collection phase lasted for 353 days until August 15, 2005. In addition to the collection of science data, redundancy and internal cross-checks of these data were performed. The 46 day calibration phase, ending with the depletion of the liquid helium on September 29, 2005, consisted of repeat calibrations while deliberately enhancing the disturbing effects.

The Science Instrument Assembly (SIA) contains four electrostatically suspended cryogenic gyroscopes, four dc SQUID read-outs, and a 14 cm aperture 380 cm focal length Cassegranian telescope, mounted in a quartz block that ensures accurate and stable alignment. Each gyroscope is sufficient for the GP-B experiment, thus the local frame is measured with quadruple redundancy while the telescope has double redundancy for measuring the far-stars reference frame. The SIA is mounted in the cryogenic probe, that is in turn inserted in the dewar. The spacecraft systems are mounted around the dewar that supplies the mechanical core of the space vehicle.

We present the GP-B instrumental performance in terms of the cutting edge technologies for the mission. Table 1 lists the ten “Near-zeroes and Superlatives”, their performance requirements and their actual measured performance in orbit. All requirements were achieved or surpassed.

Sphericity uniformity is critical to the performance of the gyroscopes by minimizing the torques caused by the electrostatic fields. The gyroscopes are 3.9 cm diameter fused quartz spheres coated with $1 \mu\text{m}$ thick Niobium film of 2% uniformity. Quartz substrate sphericity is $2 \cdot 10^{-7}$ of diameter or less than 10 nm peak-to-valley. The centered gyroscopes are spaced at $32 \mu\text{m}$ from the suspension electrodes with a maximum clearance of $20 \mu\text{m}$ from other housing features. In order to reduce precession the center of mass coincides to the center of geometry (mass unbalance) to $2 \cdot 10^{-7}$ of diameter. The actual mass unbalance measured in orbit was between 3.3 nm and 6.9 nm, the ground estimates were about 15 nm.

The GP-B gyroscopes were spun up in orbit with Helium gas warmed to 6.5 K, below the superconducting transition of the Niobium their coating. Figure 3a shows the spin-up of gyroscope #1; its spin-up causes some spin down of the other gyroscopes. Table 2 gives the science mission average spin-speed and spin-down rates for each of the four gyroscopes.

The gyroscope charge was controlled to less than 15 pC; equivalent to a potential of 15 mV. Charge was managed by UV generated photoelectrons from the gyroscope and housing, which

Table 1: GP-B critical “near-zeros” and superlatives: requirements and performance in orbit.

#	Systems	Requirement	In orbit performance
1	Rotor asphericity	< 50 nm	< 10 nm
2	Rotor inhomogeneity	< 25 nm	< 7nm
3	Electric charge	< 15 pC	<15 pC
4	Residual acceleration	< 10^{-12} m/s ² at roll	< 10^{-12} m/s ² at roll
5	Gas pressure	< 10^{-11} torr	< 10^{-14} torr
6	Magnetic field	< 9 μ G in rotor	< 3 μ G in rotor
7	Low-noise SQUID	< 200marcs/ $\sqrt{\text{Hz}}$ at roll	< 190marcs/ $\sqrt{\text{Hz}}$ atroll
8	Sensitive star-tracker	0.1 marcs	0.1 marcs
9	Largest flight dewar	2,500 l, 16.5 month, 1.8K	2,500 l, 17.3 month, 1.8K
10	Star proper motion	< 0.3 marcs/year	< 0.15 marcs/year

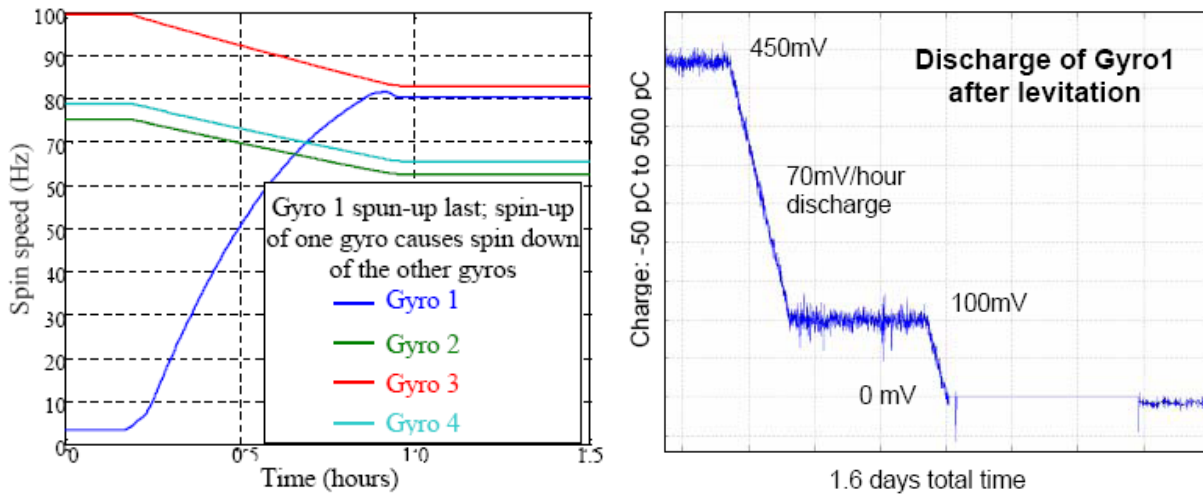


Figure 3: a) Gyroscope spin-up. b) Discharge of gyroscope #1 after levitation.

were moved onto or away from the gyroscope by the appropriate electrostatic bias.⁵ The charge was measured to better than 2 pC. In order to achieve science electrostatic suspension mode this charge needed to be reduced to less than 15 pC. Two discharge operations were required during the mission, at 3 months and 7 months after science start. Figure 3b shows the discharging of gyroscope #1 after levitation.

Gyroscope performance is dependent on the level of drag-free the control systems are reaching.⁶ By controlling the position of the spacecraft around a test mass, drag-free technology reduces the disturbing acceleration effects in orbit as caused principally by radiation pressure and residual gas. The average acceleration transverse to roll axis was less than 10^{-11} m/s², figure 2b.

To remove the residual spin-up Helium, the entire apparatus is heated to 6 K, evacuated to space, about 10^{-8} torr, isolated from the environment by closing all exhaust valves, and cooled down to the 1.8 K science working temperature. The spin-down periods after bake-out were between 7,200 years and 26,400 years..

GP-B’s magnetic readout requires both ultra-low magnetic field at the instrument location and very high magnetic shielding of outside sources. Taking advantage of the conservation of magnetic flux in a superconducting loop, magnetic fields of less than 10^{-7} gauss are achieved by the expansion of a series of nested lead bags. A system of magnetic shields, including the lead bag, attenuates the external field by 120 db. The trapped field in the gyroscopes superconducting

Table 2: Spin speed and spin-down rates.

Gyro #	Spin-speed (Hz)	Spin-down rate ($\mu\text{Hz}/\text{hour}$)
1	79.4	0.57
2	61.8	0.52
3	82.1	1.30
4	64.8	0.28

coating was less than $3.0 \mu\text{gauss}$. The spinning superconducting gyroscopes develop magnetic dipoles, also called the London moment, aligned with the spin axis and, for the uniform spherical gyroscopes, with the angular momentum. This dipole is used for the read-out of the gyroscope angular momentum.

The GP-B telescope, has a folded Cassegranian configuration, where a tertiary mirror returns the image to the front end. Image dividers split the beam in orthogonal components with double redundancy read-out. The sensors are silicon detectors working at 72 K; with two sensors per detector assembly. The telescope measurement precision is 0.1 marcs, with its pointing of $34.5 \text{ marcs}/\sqrt{\text{Hz}}$ determined by the Helium thruster noise.

The proper motion of the guide star HR8305 (IM Pegasus) was determined to better than $0.15 \text{ marcs}/\text{year}$ by Very Large Baseline Interferometry using the radio emission of this binary system.

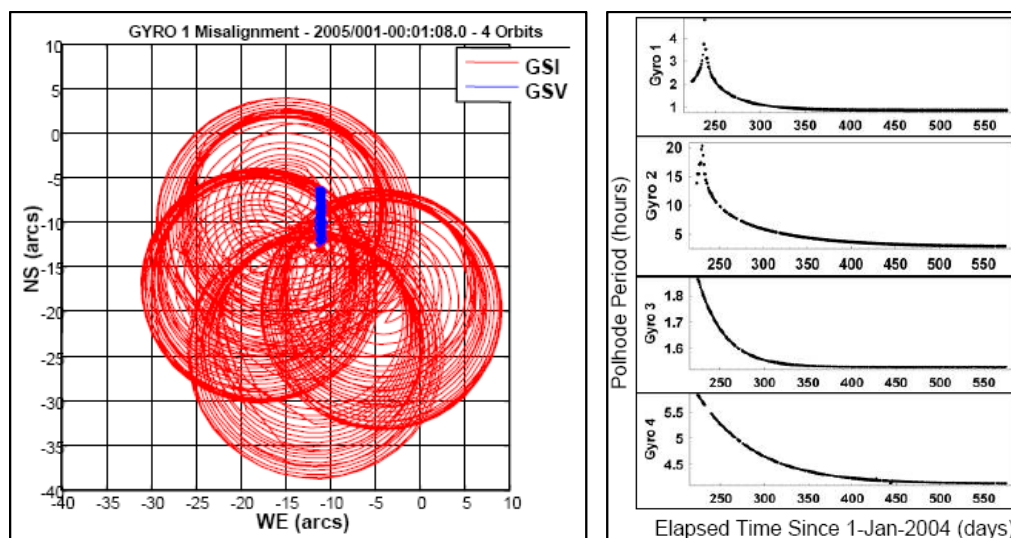


Figure 4: a) Misalignment angle GS valid and invalid. b) Polhode period variation.

The main unexpected experimental observation was the spatial extent of the patch effect on both gyroscopes and housings. Patch effects are spatial variations in surface potential caused by non-uniform dipole layers. Ground data indicated that the electrostatic patches are of micron size. In orbit it was determined that the size of the patches was up to the order of centimeters. The cause for the patches on the gyroscope was most likely the coherence of the crystalline structure of the thin films over large numbers of single crystals. Misalignment torques, polhode damping and spin-down were the main results of the patch effect.

Misalignment torques cause precession orthogonal to the plane of the misalignment; defined by the gyroscope spin axis and the spacecraft roll axis. Only relativity effects will contribute to angular momentum changes in the misalignment plane. Therefore the accurate measurement of the misalignment angle, including guide star occulted periods makes it possible to separate

Table 3: Comparison of significant features of GP-B, STEP and LISA.

	GP-B	STEP	LISA
Measurements/Controls	6	13	16×3
Communications	Ground + TDRSS	Ground + TDRSS	DSN
Drag -free sensors	1	2	6
Formation flying	No (1 satellite)	No (1 satellite)	Yes (3 satellites)
Frequency band	13 mHz	0.18 mHz	3·10 ⁻⁵ Hz to 1 Hz
Drag-free level in band	10 ⁻¹² m/s ²	10 ⁻¹¹ m/s ²	10 ⁻¹¹ m/s ² /√Hz
Cryogenics	Yes	Yes	No

the precessions due to misalignment torques from those caused by relativity; figure 4a. The misalignment during occultation is measured using the science gyroscopes themselves.

Damping of the polhode period changes the trapped flux through the read-out loop and therefore causes variation in the scale factor of the gyroscope. In order to account for this effect in the data analysis high precision knowledge of polhode period and phase is required; figure 4b. These are used as known parameters in the modeling of the gyroscope motion.

The gyroscope spin-down rates (table 2) are equivalent to a gas dissipation pressure of about 10⁻¹¹ torr. However, thermal measurements indicate that the Helium pressure is less than 10⁻¹⁴ torr. The excess spin-down is caused by image charges of the gyroscope flowing through the resistors that ground the housing coatings. Patch effect potentials of 40 mV to 80 mV account for the measured spin-down rates.

4 Lessons learned

GP-B, STEP, and LISA are three ultra-untypical space missions. They have in common sophisticated drag-free attitude and control systems. Their payload and vehicles are integrated in a single instrument. Table 3 compares some of their most significant features.

Lessons learned fall into three main categories; the team, the instrument, and the unexpected. A successful team requires a combination of skills, in this case a close collaboration of physicists and engineers. The approach of designing and building the science payload and the spacecraft separately and then integrating them is unworkable in these experiments where all systems are contributing directly to the experimental error and are expected to perform well beyond the standards of existing space equipment. The lesson is therefore to build a science and engineering collaboration from the start; space experienced personnel are indispensable from the earliest stages of the project. Students, graduate and undergraduate, are essential to the foundation of the team. Their enthusiasm, hard work, and willingness to undertake ‘unsolvable’ problems are at the core of the team’s performance. And, of course, they are the future generation of engineers and scientists. Lastly, it is imperative to keep the core team for the operations and data analysis stages. The GP-B core team, including the developers of the instrument, cryogenic systems, and attitude and control system, was an integral and critical part of the operations, and remains at the center of the data analysis team.

Table 3 illustrates the similarities and differences in technical challenge faced by the three experiments. STEP has the advantage that most technologies involved have been demonstrated by GP-B to the required performance level. LISA does not requiring cryogenics. However, in its present configuration, it faces the technical challenges of the many degrees of control for the six drag-free sensors, a restricted communications channel, the need for formation flying, wide frequency band measurement, three orders of magnitude improved drag-free level and complex optical metrology.

Cutting edge technology, which can only be tested by analysis and simulation on the ground, requires maximum flexibility in the modes of operations, incorporating as many software ‘hooks’ as practical. The experiment must be instrumented as extensively as possible. Space tests are truly a one-shot opportunity and the experimenter needs to understand data, anomalies, and calibrations. For the high accuracy tests discussed, all system interact to large extend and therefore all need monitoring at five to ten times their maximum operating frequency. Snapshots of the parameters of the higher frequency sub-systems are a practical way of understanding their impact on the science data. The GP-B science data was at 13 mHz. Snapshots of the critical electronics, gyroscopes, SQUIDs, and telescope, were collected periodically and for anomalies at sampling frequencies ranging from 220 Hz to 2,200 Hz. These snapshots have proven critical to data analysis and anomaly resolution.

Ground testing should follow the principle “Test it like you fly it”. This includes, the instrument, the environment as practical, the flight software, the telemetry and the ground command systems. A high fidelity simulator with hardware in the loop is an essential development, testing, flight operations, and data analysis tool. Development of the simulator starts with a software simulation, with hardware prototypes included, and ends prior to launch with high fidelity simulations of the instrument using flight hardware software. The simulator includes an identical copy of the mission operations system, making it a virtual science instrument. Following are two, of many, examples of the use of the simulator for anomaly resolution during GP-B operations.

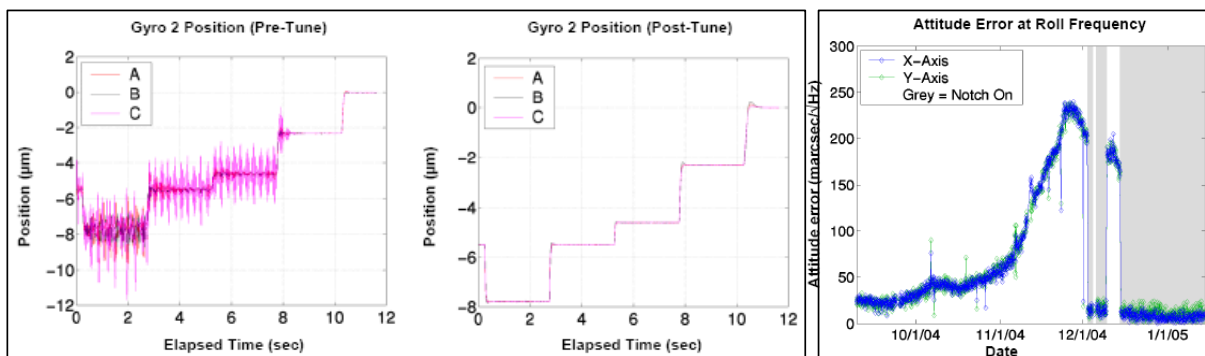


Figure 5: a) Suspension stability pre and post tune. b) Attitude control error at roll frequency; notch filter on in gray areas.

Figure 5a shows the optimization of the in-orbit performance of gyroscope’s #2 suspension system. The simulator accurately reproduced both the anomalous and the optimized performance; the solution was the increase in modulation frequency of the suspension system from 25 Hz to 30 Hz. Note that the anomaly was detected and corrected by the use of gyroscope suspension snapshots, 220 Hz for 12 seconds. The continuous 0.5 Hz data would have clearly been inadequate to the task.

Figure 5b shows the roll frequency component of the attitude control error. The large errors at roll frequency were induced by an anomalous large sensitivity to thermal variations of the platform supporting the navigation instrumentation; the increase in December 2004 coincides with the GP-B spacecraft moving into full Sun illumination. A notch filter at roll frequency, designed and tested with the simulator, was up-loaded into the flight attitude control system, permanently solving the problem.

There are two types of the “unexpected”. Real surprises and standard but consistently underestimated difficulties. Rigorous planning can largely mitigate the second category. Required data and commanding rates will be significantly higher than planned for in the early stages of the experiment design; the standard 50% early development contingency should be increase to as much as 100-200%. In particular the experiment set-up stages and anomaly resolution periods

will require significantly increased data rates. GP-B data was collected both through the space TDRSS network, ~ 12 contacts/day, 20-40 minutes/contact, 1-2 Kbits/sec data rate, as well as the ground based network of NASA ground stations, 4 contacts/day, 10-12 minutes/contact, 32 Kbits/sec data rate. The total stored data, including derived monitors and raw and processed data streams is 1.5 Tbytes.

During the GP-B mission more than 100 anomalies occurred, including the failure of two thrusters, multiple bit upset events (MBE) at ten times the expected rate, computer reboots, antennas and star sensors degradation. A large percentage of anomalies occurred during initialization, a period that required more than 10,000 commands to the space vehicle for experimental set-up and anomaly resolution. Regarding LISA two significant points of reference are the GP-B 128 days commissioning duration and the five year required by the ground based LIGO to achieve design performance. An additional constraint for LISA is the narrow DSN communication bandwidth. LISA requires revolutionary simulation work as well as the development of advanced autonomous software.

Data analysis will always be more complex and time consuming than the most conservative ground estimate, requiring contingency scheduling at factors of two to three beyond what is considered "reasonable" on the ground.

Most systems will work better in this quiet environment, as exemplified by the GP-B gyroscopes, SQUIDs telescope, and cryogenics. Preparing for the "unknown unknowns", the real surprises, requires extensive instrumentation, comprehensive data, and the help provided by the experience of the core team.

5 Conclusions

GP-B has demonstrated that complex physics experiments do work in space. Preliminary results set the measurement accuracy at ± 97 marcs/year or about 1.5% of the geodetic effect. Further improvement in accuracy is expected before the end of 2007. LISA and STEP are space physics experiments significantly similar in many features to GP-B. The main lessons that GP-B can convey are: a) a strong core team of scientists and engineers with space experience that works from design to data analysis, b) a flexible, comprehensively monitored and diagnosed instrument, c) significant longer schedule contingency for operations and data analysis, and d) extensive calibrations to ensure results credible to the science community and the experimental team.

Acknowledgments

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