Gravity Probe B: Countdown to Launch

C.W.F. Everitt¹, S. Buchman¹, D.B. DeBra¹, G.M. Keiser¹, J.M. Lockhart¹², B. Muhlfelder¹, B.W. Parkinson¹, J.P. Turneaure¹, and other members of the Gravity Probe B team

¹ W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
² Physics Department, San Francisco State University, 1600 Holloway Ave., San Francisco, CA 94132, USA

Abstract. NASA’s Gravity Probe B Mission is a test of two predictions of Einstein’s General Theory of Relativity based on observations on very precise cryogenic gyroscopes in a satellite in a 650 km polar orbit about the Earth. Construction and the first round of testing of the flight payload was completed in December 1999. Of the 32 planned qualification tests 28 were passed with complete success, meeting or in several instances surpassing the program requirements. However, one test very unexpectedly revealed a problem in the thermal performance of the Dewar/Probe system which has required a significant redesign and rework, now successfully completed. Gravity Probe B is scheduled for launch on April 1, 2002. This article reviews from the physicist’s viewpoint the experience of living through a space flight program.

1 Gravity Probe B: An Experiment in Physics – and Management

To physicists trained in ground-based research the thought of carrying out an experiment in space is a daunting prospect. The laboratory experiments we are accustomed to seldom work at a first attempt: many stages of redesign and reconstruction are necessary before the desired performance can be met. Space is different. Space experiments of their very nature have to be designed and built so that once on orbit they will work first time. Furthermore the design has to be ‘robust’. Robustness means introducing redundancy into areas that might fail. Redundancy, however, adds complexity. Striking the right balance between these competing requirements is critical to any successful space mission. By now, after forty years of space flight, considerable experience exists about how to approach such issues (not least how to bring together the right mix of science, engineering and management skills to do so).

The NASA/Stanford Gravity Probe B Mission (GP-B) is a Fundamental Physics experiment designed to provide two extremely precise tests of Einstein’s theory of gravitation, General Relativity, based on observations of electrically suspended gyroscopes in a satellite in a 640 km circular polar orbit around the Earth, see Fig.1. It will measure the geodetic effect due to the curvature of space–time by the Earth to approximately 2 parts in 10⁵ and the frame–dragging effect, with its subtle connections to gravitomagnetism and Mach’s principle, to an accuracy approaching 0.3%.
A crucial feature of GP-B is that it is ‘a controlled physics experiment’. It is so in two senses. In the first place the two relativistic effects dominate the data: error terms such as the Newtonian drifts of gyroscopes are reduced to negligible values. Second, no less important, designed into the experiment is a rigorous program of on–orbit verification and calibration in which mission parameters are varied in a controlled way to check and, if necessary, remove specific sources of error.

After many years of technology development, GP-B is now nearing completion. Final assembly of the payload with the spacecraft takes place in March 2001. Launch is scheduled for May 1, 2002.

It was not until late in 1959, 44 years after Einstein published his theory, that any conceptually new test of General Relativity was proposed. It was then that two men, Leonard Schiff and George Pugh, in complete independence of each other, were able to define one, or rather two, fundamentally new tests based on observations of non–Newtonian precessions of gyroscopes in Earth orbit. Remarkably, almost at the same time a number of other tests of the theory were conceived including the Shapiro time delay experiment and redshift tests leading to the Gravity Probe A sub–orbital clock experiment. Then came various new or extended theoretical approaches, best known of which is the parameterized post–Newtonian (PPN) formalism due mainly to Kenneth Nordtvedt and Clifford Will. PPN provides a framework for comparing metric theories of gravitation; it has also suggested interesting new null experiments.

It is no accident that Schiff and Pugh came to their ideas just two years after Sputnik. Both recognized that an orbiting gyroscope would experience the geodetic and frame–dragging effects. They also saw that the performance of a gyroscope in space is potentially much better than on Earth because of the reduction in support force. Schiff’s principal contribution was to provide the first elegant and correct derivation of the two effects. Pugh in a striking, too little known paper (November 1959) gave an impressively complete error analysis of a possible experiment. In particular he suggested for the first time the brilliant
and far-reaching concept of a drag-free or drag-compensated satellite. Gravity Probe B has evolved out of these early thoughts, together with discussions Schiff had at Stanford in 1959–60 with William Fairbank of the Physics Department and Robert Cannon of the Department of Aeronautics and Astronautics. From there GP-B became a cooperative effort between the two departments, a most fortunate occurrence.

Indeed, without a collaboration of this kind it is hard to imagine even attempting a program involving so many diverse technologies. In this test of Einstein, physics and engineering are inextricably linked. Important also has been the presence on the Stanford campus of an infrastructure capable of making the collaboration effective, provided by the interdisciplinary Hansen Experimental Physics Laboratory (HEPL) with its long history of developing medium-scale, long-term scientific programs. HEPL has proved to be an ideal administrative vehicle for a mission of this complexity. In addition, a rarity on university campuses, it offers an extended building with flexible high bay space and crane coverage. To have such a building within easy walking distance of the two departments so that physics and engineering students, academic staff and faculty can come together in a common enterprise is an extraordinary benefit. This happy combination of circumstances, not planned in advance, deserves reflection. Others intending to perform fundamental space experiments may find it wise to think through not only the experiment itself but the structures and expertise that will be needed to make it happen.

No less important is to think through, in conjunction with NASA or the relevant space agency, the relationships between academia and aerospace industry. On GP-B with invaluable support from NASA Marshall Center, excellent working relations were established with Ball Aerospace in the early study phase of the program and subsequently in flight contracts with Lockheed Martin. In establishing the university–industry relation it is essential to formulate a clear plan of what should be done in academia and what in industry, and to devise a suitable contractual vehicle for managing the industrial effort. In facing, as one must, technical surprises, it is well to be prearmed as much as possible against the contractual surprises that too often accompany them.

2 Shape of the Experiment

The GP-B Science Instrument Assembly (SIA) is illustrated schematically in Fig. 2. It comprises four gyroscopes with their spin axes aligned parallel to the line of sight to the guide star and mounted in line in a quartz block structure, to which is attached a reference telescope, all operating at a temperature of 1.8 K. The gyroscopes are fused quartz spheres 38 mm in diameter, coated with a 1.25 µm film of superconducting niobium, suspended electrically within fused quartz housings by voltages applied to three mutually perpendicular saucer-shaped electrodes, as illustrated in Fig. 3. To support the rotor on Earth the voltage required over the 32 µm gap is 650 V. In space it is reduced to 0.1 V. The gyroscopes are spun up on orbit to about 100 Hz by means of helium gas at
a temperature of 6.5 K running at sonic velocity through a differentially pumped channel in one half of the housing.

The gyro readout is based on a special property of superconductors known as the London moment. A spinning superconductor develops a magnetic field aligned with its instantaneous spin axis, and this serves as a magnetic ‘pointer’ even in a perfectly round, perfectly uniform sphere. The direction of the London moment, and therefore of the spin, is measured magnetically by a SQUID magnetometer connected to a four–turn superconducting loop sputtered on to the parting plane of the housing. Because the spacecraft rolls around the line of sight to the star the signal is chopped at roll rate, reducing limits on measurement from $1/f$ noise. The roll period is between one and three minutes (17 to 5.5 mHz). At 5.5 mHz the noise performance is about $7 \times 10^{-29}$ J/Hz, equivalent to resolving 1 mas\(^1\) in an integration time of 7 hours, meeting the GP-B mission goal of 1 mas in 10 hours.

More generally, rolling the spacecraft proves to be a very important overall symmetrizing principles, averaging out other potential sources of error in Gravity Probe B: drifts in the telescope readout, and many of the Newtonian drift torques on the gyroscope.

The SIA is enclosed in a cylindrical cryogenic vacuum ‘probe’, 0.3 m in diameter and 2.4 m long, inserted into the inner well of a dewar vessel containing 2400 l of superfluid helium (Fig.4). The dewar, which maintains cryogenic temperatures on orbit for 18 months, serves as the main structural element of the spacecraft. Boil–off gas from the dewar, vented through proportional thrusters, provides thrust authority for attitude, translational, and roll control. Also shown in Fig.4 is a sunshade that prevents scattered sunlight entering the telescope.

\[^1\text{1 mas} = 1 \text{ milli–arc–second.}\]
An essential feature of the experiment is the provision of both dc and ac magnetic shielding. For the London moment readout to work, the field trapped in the gyro rotor during cooling through its superconducting transition temperature must be below the extremely low value of $3 \times 10^{-10}$ T – well below the limit achievable in practice by conventional ferromagnetic shields. Equally important is to eliminate ac disturbances from external magnetic fields such as the Earth’s: the required ac shielding factor is $10^{12}$. These requirements are met by surrounding the instrument with a nested series of conventional and superconducting magnetic shields, and placing rigorous constraints on the magnetic properties of the probe and SIA. To produce the required ultralow magnetic field use is made of a technique developed originally by B. Cabrera, based on expanding a succession of superconducting lead shields in the inner well of the dewar. A conventional ‘cryoperm’ shield produces an initial ambient field in the well of about $10^{-6}$ T. Because the quantity conserved in superconductors is magnetic flux (field times area), if a folded lead bag is cooled in this low field and then expanded, the new field level will be substantially lower. The process is then repeated with a second lead bag to obtain an even lower field. In practice, with three expansions, field levels as low as $10^{-11}$ T are regularly obtained.

In their earliest proposals for an orbiting gyroscope experiment Pugh, and independently Schiff and his colleagues, recognized that the performance of a gyroscope would be greatly improved by operating in the low g environment of space. The reason is simple. By far the most precise kind of gyroscope, then and now, is an electrically supported spinning sphere. The simplest of the torques...
acting on such a suspended sphere is the ‘mass–unbalance’ torque which occurs when an acceleration acts on a sphere that is perfectly round but not quite perfectly homogeneous. The drift–rate $\Omega$ caused by an acceleration $f$ at right angles to the spin axis is

$$\Omega = \frac{5}{2} \frac{f \delta r}{v_s r}$$  \hspace{1cm} (1)$$

where $r$ is the radius and $v_s$ the peripheral velocity of the spinning sphere, and $\delta r$ is the distance between center of mass and center of support. For a sphere homogeneous to 1 part in $10^6$ with a peripheral velocity of 20 m/s the resulting mean transverse acceleration required to reduce the drift–rate to 0.03 mas/yr is $4 \times 10^{-12}$ g. This is an instructive number. It demonstrates the insight of George Pugh – and also of B.O. Lange, who independently advanced the same idea in August 1961 – in recognizing the need for drag compensation. The acceleration levels on satellites at the GP-B altitude with normal area/mass ratios are typically of the order $10^{-8}$ g. In Gravity Probe B as a drag–free satellite rolling about the common axis of the gyroscopes the mean cross–track acceleration will be below $10^{-12}$ g.

Arguments of the same kind developed in detail by G.M. Keiser and A. Silbergleit, and discussed further in Section 4 below, establish that torques due to the action of the suspension voltages on the out–of–roundness of the gyroscope are reduced to similarly acceptable levels. In all, three different classes of errors have to be considered in Gravity Probe B: gyro drift errors, gyro readout errors, uncertainty in the proper motion of the guide star. Fig.5 gives current estimates
of each of these terms and the result for an overall experiment with one, two, three, and four gyroscopes.

The spacecraft carrying electronics, telemetry, solar panels, mass trim mechanisms, a sunshield for the telescope, and other support equipment, fits around the dewar. Fig. 6 is a general view of GP-B in orbit.

3 Incremental Prototyping

From 1964 to 1984 the main effort on Gravity Probe B went to advanced technology development, along with Mission Definition and Phase A studies and an in-house Phase B study performed at NASA Marshall Center. In US fiscal year 1985 NASA decided to proceed with an instrument development program, the Shuttle Test of the Relativity Experiment (STORE). As first conceived, the object of STORE was to fabricate the Science Payload, and then launch it on Shuttle for a seven-day rehearsal experiment that would test all systems in space and operate the gyroscopes at Shuttle acceleration levels. The Payload would then be returned to Earth, mounted into the spacecraft, and launched once more by Shuttle from the SL-6 Western Test Range at Vandenberg Air Force Base in California for release into a free-flying polar orbit.

STORE provided the essential mechanism for developing the Gravity Probe B Payload. However, with the Challenger accident in 1986 and subsequent closure of the Western Test Range the planning had to be rethought. The new constraints on Shuttle payloads and the fact that it was no longer possible to launch Shuttle into a polar orbit were serious complications. A modified program was therefore devised with an increased emphasis on incremental prototyping. Although the main design principles of the Science Instrument Assembly were
well established by 1985, the engineering challenge was formidable. Equally challenging was the design of the cryogenic vacuum ‘probe’ containing the SIA which is complex and has many features unique to GP-B. Thus the neck tube of the probe must contain cooled radiation windows to intercept infrared radiation that would otherwise be a severe heat load on the SIA and dewar. On the other hand, it also must serve as a high speed pumping line to exhaust gas at low pressure from differential pumping of the gyro spin system. It was by no means obvious in advance how these two requirements could be reconciled.

Nor could the sophistication of the GP-B dewar be underestimated. Though there was important engineering and flight heritage for superfluid helium dewars from the IRAS and COBE programs, some of GP-B’s most critical features were unprecedented in space. A major issue was the ultralow magnetic field requirement, which demands having a permanently cold superconducting lead bag in the inner well of the dewar and therefore inserting the warm probe into the cold dewar. This is an intricate process in which it is necessary to mount a temporary airlock on top of the dewar to prevent solid air from condensing into the inner well. Once in place, the probe has to be locked down thermally and mechanically at appropriate points in the dewar. Incremental prototyping has helped immensely in arriving at a sound design and establishing correct insertion procedures.

Incremental prototyping attacks the hardest engineering problems first by using full-size flight prototypical designs with flight interfaces, but with reduced

---

2 Following standard cryogenic engineering practice, reference is made in this paper to three successive cryogenic ‘probes’ to be inserted into the dewars, Probe-A, Probe-B, Probe-C; this terminology is not to be confused with the use of the word ‘probe’ in Gravity Probe B.
functionality and without costly flight build standards. Specifically, three full-sized payload system tests have been conducted with the three ‘probes’ of increasing fidelity just referred to (A, B, C), where Probe-A is a pre-prototype; Probe-B (designated as the backup flight probe) is essentially of flight-quality; Probe-C is the actual flight probe. These have been evaluated in the following successive ground-based tests:

A. **First Integrated Systems Test (FIST) 1990–1991.** FIST consisted of a demonstration test of Probe-A in a semi-prototypical Engineering Development Dewar (EDD) with science-mission–like interfaces. Probe-A incorporated a prototypical quartz block but no telescope and only two gyroscopes. It operates in a magnetic field of about $10^{-6}$ T obtained with conventional shields. The use of only two gyroscopes made additional electrical and other connections available for instrumentation to investigate the thermal and vacuum performance of the probe.

B. **Ground Test Unit GTU-0 1991–1994.** GTU-0 was also performed with Probe-A and the EDD but with an ultra-low magnetic field shield ($10^{-11}$ T) installed in the dewar. Cold insertion of the probe into the dewar by means of the airlock resulted in low trapped flux in the gyroscopes.

C. **Ground Test Unit GTU-1 1994–1995.** GTU-1 was the first use of Probe-B. It included: (a) operation with all four gyroscopes and a mass model of the telescope; (b) achieving a $< 0.1$ nT trapped dipole in the gyro rotor; (c) test of the fully coupled dc SQUID readout; (d) electromagnetic interference (EMI) tests; (e) operation at ultra high vacuum with a sintered titanium cryopump. Also performed at room temperature was a successful protoqual shake test of the probe with the telescope mass model and caged gyroscopes, fully confirming the reliability of the design.

D. **Ground Test Unit GTU-2 1997.** GTU-2 was performed again with Probe-B but mounted in the Science Mission Dewar (SMD). This provided a verification of a complete payload integration and test procedures using the SMD together with a full functional test of all subsystems (SIA, Probe and Dewar) before and after an integrated system shake test at protoqual levels.

E. **First Complete Payload Test August–December 1999.** Results of this test are discussed in Section 5.

4 Risk Mitigation and Verification Matrix

Developing a flight mission compels the physicist to address two interrelated sets of problems very different from traditional laboratory experience. An apparatus has to be made that will survive launch and function in the unfamiliar environment of Earth orbit or outer space. It also has to work even though not all aspects of its performance can be verified experimentally on the ground. Addressing these two issues requires, in the first place, systematic thought about principles of risk mitigation and the concept of a verification matrix. Secondly it requires a well-ordered test plan to assure that the risks and uncertainties have indeed been properly accounted for.
From an engineering standpoint ‘risk mitigation’ means first that the experiment has to be designed conservatively to withstand the vibration of launch and the temperature conditions and charged particle environment encountered on orbit. In each case it is necessary to think not only of the design but of the testing necessary to verify that the completed payload meets the engineering and scientific requirements. Some of the following observations should be regarded as general space practice; others are specialized to Gravity Probe B.

A. Surviving Launch: The Tradeoff Between Strength and Weight.
The recipe for surviving the hostile launch environment might seem simple – extreme over-design so that the apparatus cannot possibly break. The flaw in this simple nostrum is that there is another constraint, weight. It seems almost a law of human nature that during the development of any spacecraft its weight will grow beyond the capability of the launch vehicle. Always at some point a strenuous program of weight reduction becomes necessary. In Gravity Probe B the largest contributing factor was the heavy outer shell of the dewar, especially the two end-domes. After investigating several options, including the use of special low-density alloys we chose the well established but sophisticated method in which the inner surface is relieved with suitably-patterned rib structures (an ‘isogrid’ design). The final effect was a reduction of dewar weight of about 18 percent. Another frequently encountered weight penalty, surprising to the laboratory physicist, is from the electrical harnesses. Long experience has shown that these are always underestimated. In Gravity Probe B we were fortunate to begin harness layout early and were thus subject to less surprise than some programs have been.

More generally, the physicist engaged in a space program is impressed to observe that through all the development a constant weekly watch has to be kept on weight and power budgets.

B. Temperatures of Electronics Boxes: Two Issues and Their Resolution.
The conditions under which electronics boxes have to function in space are very different from those typical of ground-based laboratories. In Gravity Probe B the surface temperature of the spacecraft is around 220 K (−50°C). Also as it rolls around the line of sight to the star the electronic boxes will heat and cool in the presence of the Sun. This is a critical point in the design because it limits the accuracy of our earlier statement that rolling the spacecraft eliminates readout errors and gyro suspension torques. Obviously, if the temperatures of key components vary at roll-rate the statement is no longer quite true. In building the electronics, therefore, thermal risks of two distinct kinds must be mitigated. They must have the engineering robustness to work under extreme conditions. They must also have the scientific refinement to maintain temperatures within a very narrow and known range over each roll cycle. Both constraints must be met in a situation where the electronics components are functioning in hard vacuum: any heat has to be removed by radiation or solid conduction, there is no atmospheric convection to aid us. These conditions require a ground verification program
of very considerable sophistication and have a critical influence on spacecraft design. Key electronics boxes are enclosed in a Forward Electronics Enclosure (FEE) at the front end of the spacecraft with passive temperature control; within the individual boxes active temperature control is applied to certain particularly sensitive elements. As part of the on–orbit verification, temperature data is telemetered to ground.

C. The Charged Particle Environment. The presence of the Van Allen belts at or a little above the 640 km Gravity Probe B orbit altitude places requirements on the GP-B electronics different from anything encountered on Earth. Particularly critical are the effects, well known to space engineers but less familiar to most physicists, of the South Atlantic Anomaly (SAA). The old discovery by Gauss in the 1840s that the Earth’s magnetic field can be represented by a tilted dipole displaced toward North modifies the lives of space scientists. Over the South Atlantic there is a region where for a period of 5 to 15 minutes the spacecraft encounters a much higher density of charged particles than elsewhere in its orbit. Since the Earth is rotating the SAA does not affect GP-B in every orbit; nevertheless there are several each day in which the charged particle environment is hostile. An obvious question is what effect this may have on the gyro and telescope readouts. Tests of the SQUID magnetometers in a special facility at the Paul Scherr Institute in Villingen, Switzerland designed to provide in a few hours a particle dosage equivalent to a year’s passage through the SAA were pleasantly reassuring. The SQUIDS continued to function with only a small and acceptable number of measurable ‘flux–jumps’. On the other hand, with the telescope detectors some periods of interruption will certainly take place. Throughout the electronics ‘rad–hardened’ components must be used in all critical areas, and the design must be made ‘robust’ so that any temporary electronics failure will not have catastrophic effects. Most critical of all is the digital gyro suspension system. To guard against upsets of the computers controlling the suspension it is designed with two parallel control computers, a backup analog suspension system, and an arbiter to monitor performance and determine which system shall be used. Such are the complexities of gyro suspension. In addition, it is necessary to prevent excessive charging of the rotor itself. For this purpose the charge on the rotor is measured by injecting a signal into the suspension system and the information so obtained is used to control an ultraviolet discharge mechanism based on the photoelectric effect.

D. Electromagnetic Interference (EMI) and Compatibility (EMC). The issue of electromagnetic interference is familiar to physicists engaged in ground–based experiments. Nevertheless space in general, and Gravity Probe B in particular, have special problems. The compactness of the spacecraft means that unusual care is needed to insure that signals from the telemetry of the science data to Earth do not interfere with the payload electronics. There is also the bizarre–seeming fact that in low–Earth orbit signals from television stations on the ground can be a formidable problem. In Gravity Probe B a special issue is that the gyroscope readout based on the London
moment depends on accurately measuring very minute changes in magnetic fields and therefore extremes of magnetic shielding. In addition, each gyroscope must be shielded from the next and the readout of each must be shielding from its own gyro suspension signals. Without superconducting shielding and frequency separation between the suspension and readout signals, these requirements could probably never have been met. The fact that they were, as demonstrated in the tests of Probe-C discussed below, is one of the most reassuring results of the GP-B development. It is a success critically dependent on incremental prototyping.

Mitigating risk is a total process requiring judgments of many diverse kinds. Risks need to be identified but they need also to be weighed intellectually and sometimes even literally. If a particular mitigation adds to the weight of the spacecraft, it may in that form be impracticable. Then there is the complicated question of complexity. Does the mitigation achieved by introducing a redundancy so increase the complexity that in the end it increases rather than reduces risk? All such issues have to be addressed in a context of cost, recognizing that in space programs cost penalties are of two kinds. There is the immediate cost of designing, fabricating, and testing some previously unplanned part or system but there is also the secondary, often far greater, problem of the ‘marching army’. Any schedule delay increases cost far more than one at first imagines because it entails keeping a large spacecraft team together longer than originally planned.

Mitigation involves assessment and planning; it also involves verification. Reflection on that fact leads to the important concept of a ‘verification matrix’. In any actual spacecraft there are many systems. Some have been flown many times. Others are new but very similar to systems that have been flown before. Others again are new but capable of being tested with greater or lesser completeness in the laboratory. Finally, others may not be capable of being tested at all before launch and can only be verified through calculation. The idea of a verification matrix is to lay out in an orderly way all the systems, their requirements and the nature of the verifications to be performed: inspection, similarity, analysis, test, and once that is done to establish, and where necessary enhance, the realism of the verification process.

As an example consider Newtonian disturbances of the Gravity Probe B gyroscopes. Almost by definition gyro performance cannot be fully verified until GP-B is on orbit: if it could, one would be seeking to perform the experiment in a ground-based laboratory. That, however, does not preclude a rationally conceived and experimentally well-founded verification process. During the long history of Gravity Probe B an exhaustive error analysis has been conducted identifying no fewer than 120 different known class gyro torques, most of them exceedingly small. The verification questions are whether all these have been calculated correctly and whether any significant torques might have been left out.

A broader view reveals that the torques can be classified in a number of ways which allow plausible comparisons of their relative values and aid in setting reasonable limits on unknown terms. One distinction is between support-dependent
torques (which decrease in space) and support-independent ones. Another is between torques due to pressures on the surface of the gyro rotor and those arising from momentum transfer through the volume of the material. A third is between torques varying linearly with time and those like Brownian motion, photon bombardment, and the impact of cosmic rays on the rotor which tend to cause ‘random-walk’ effects evolving as the square root of time. Simple as these distinctions are, they throw a flood of light on the expected performance of the experiment.

Thus, the two obvious classes of torque involving surface pressure are those from gyro suspension and from residual gas in the housing. The ‘electrical pressure’ has to be such as to apply to the rotor accelerations of order $10^{-8}$ g. At the planned operating gas pressure ($10^{-12}$ torr) the corresponding acceleration under the extreme assumption that all the pressure acts on one side of the rotor is $10^{-13}$ g. Hence, it is inherently plausible – and true – that gas-pressure torques are negligible and all our attention should be focused on electrical pressures, i.e. on the suspension torques.

In fact, the suspension torques dominate the gyro performance. The analysis by Keiser and Silbergleit demonstrates that these electrical suspension torques are governed by 15 distinct coefficients. A laboratory verification, therefore, should evaluate each one and establish their consistency with other measured parameters, e.g. out-of-roundness of the gyro rotor, rotor centering, spin-axis alignment, etc. Measurements on a flight type gyroscope suspended against 1g, performed at Stanford by Dr. Yoshimi Oshshima, have successfully determined all 15 coefficients.

With the coefficients known, classical electrical formulae based on Coulomb’s law determine the resultant gyro drifts to be expected on orbit. This is a powerful verification. Fig. 7, based on the analysis of G.M. Keiser and Silbergleit, gives the top eight non-relativistic terms contributing to the precession of the gyroscope in the plane of the frame-dragging effect.

Of these no fewer than seven are support dependent torques and of the seven, four originate in imperfect roll-averaging due to heating and cooling of the electronics as the spacecraft rolls in the presence of the Sun. We are thus led to a further verification. By determining in the laboratory the temperature coefficients of key electronics systems, one can set criteria on their allowed temperature variations in space. This, in turn, leads to an on-orbit verification through measuring and transmitting to Earth a record of the temperatures. It is even possible to use this record as a mode of on-orbit calibration allowing errors to be backed out by calculation after the fact.

Although the argument from pressure eliminates the most obvious gas torque it does not guarantee that the residual gas has no effect. Molecules continually moving back and forth between the rotor and housing cause the gyroscope to slow down. If there is any asymmetry in this process it will result in a gyro drift due to ‘differential damping’. At $10^{-12}$ torr the characteristic spin-down time of the gyroscope is 320,000 years. For GP-B the rolling of the spacecraft around the line of sight to the star has a powerful symmetrizing effect and the
A. Support–dependent torques from temperature variations of suspension electronics at spacecraft roll–rate (1,5,7,8)

1. Roll–variation of preload voltage difference ($h_a - h_b$)
2. London moment coupling to local magnetic shield–gyro axis misaligned with line of sight to star
3. Gyro spin axis misaligned with spacecraft roll axis
4. Constant transverse acceleration on gyro parallel to Earth’s gravity gradient. Acting through misalignment between orbit plane and line of sight to star.
5. Fixed sums of preloads ($h_a + h_b, h_c$)
6. Sagging of gyroscope at twice orbital period due to Earth’s gravity gradient
7. Roll–variation of sensing bridge voltages
8. Roll–variation of preload sums ($h_a + h_b, h_c$) plus fixed miscentering of rotor

Note: all above are conservative upper limits, awaiting calibration of flight Electronics. Also, temperature variations of electronics will be measured on orbit.

B. Support–dependent torques from non–temperature–dependent effects (3,4,6)

3. Gyro spin axis misaligned with spacecraft roll axis
4. Constant transverse acceleration on gyro parallel to Earth’s gravity gradient. Acting through misalignment between orbit plane and line of sight to star.
6. Sagging of gyroscope at twice orbital period due to Earth’s gravity gradient

C. Support–independent torque (2)

2. London moment coupling to local magnetic shield–gyro axis misaligned with line of sight to star

Fig. 7. The Top Eight Gyro Drift Torques.

computed value of this differential damping torque is below 0.0001 mas/year. While this in itself is beyond ground verification, there is an important ground verification related to it, namely, to measure the characteristic spin down time of the gyroscope under laboratory conditions. The measurements confirm the accuracy (at low temperature) of the gas drag formula. They also provide a crucial check on whether any debris are present in the housing.
5 Probe-C Assembly March–August 1999

Assembling the SIA and the Flight Probe has been a lengthy process, lasting more than 6 months. Individual systems and subsystems had to be fully qualified before assembly, all under the discipline of record keeping and Quality Assurance unfamiliar to most physicists. In total Gravity Probe B had 32 distinct mechanical and electrical systems that required verification through the Probe-C tests. It is only through dealing with an apparatus of this sophistication that the physicist comes to realize the benefits of the rigorous QA procedures developed through hard–won experience in the aerospace business.

Among the systems tests that were performed before the assembly of the SIA and Probe-C began some of the more important were as follows:

A. Gyro Qualification. To date, more than 110,000 hours of gyro testing have been conducted in a variety of cryogenic and room temperature test facilities. The final qualification of the individual gyroscopes to be inserted in Probe-C was carried out in a special Gyro Acceptance Facility designed to allow the verification that each gyroscope meets five flight requirements: (1) asymptotic spin speed > 100 Hz; (2) spin–down rate after evacuation < −2 mHz/hr (verifying gyro cleanliness); (3) low trapped magnetic field < 3 × 10−10 T; (4) discharge rate by ultraviolet system > 10 fA/µW (in combination with the charge measurement system, this will allow the mean rotor voltage to be kept < ±10 mV); (5) SQUID–dc coupling < 1% decay of 200 flux quanta after 15 min (verifying integrity of the readout loop).

B. Qualification of SQUID Assemblies for Gyro Readout. Each SQUID assembly consists of a SQUID microchip sensor mounted on a sapphire circuit board with a superconducting thin–film input transformer, electronic components, and connectors, filter components for rejection of electromagnetic interference, all contained within a superconducting box made of “reactor grade” niobium and sealed with an indium alloy gasket. The SQUID chip was initially selected for low noise by cryogenic testing. It was then mounted into the SQUID assembly, which was subjected to cryogenic qualification testing to determine sensor noise, linearity, transfer function, temperature sensitivity, bias current level, stability, the superconducting persistence of the input circuit, and magnetic and EMI attenuation. Only assemblies that meet all qualification criteria are accepted for use in Probe-C, and only SQUID sensors that have remained stable through multiple thermal cycles to cryogenic temperatures are incorporated in these assemblies.

C. Magnetic Qualification of Probe Components. Control of the magnetic properties of materials and assemblies used in Probe-C is essential for the London moment readout. To meet the necessary stringent requirements, a Magnetic Control Plan was set up dividing the Probe into magnetic zones based on distance from the gyroscope rotors. Within each zone, limits were placed on the residual magnetic moment and magnetic susceptibility of each component, and on the maximum level of stray ac magnetic field. Samples of the actual material stocks, from which probe components had been fabricated, were characterized magnetically at temperatures down to 2 K using a
Fig. 8. GP-B Telescope: The cylindrical structure in the center contains the image dividers. The mirror on top of it aids in telescope testings. The two DPA’s, each with redundant detectors, are mounted in the two structures set at 90 degrees of each other on the edge of the telescope.

SQUID magnetometer. Once fabricated, the assemblies were further tested for magnetic cleanliness with a SQUID gradiometer to verify that machining and assembly operations did not introduce unacceptable magnetic contamination.

D. Telescope Qualification. Fig. 8 illustrates the front end of the completed Flight Telescope, fabricated entirely of fused quartz and held together by a silicate bonding technique invented by Dr. Jason Gwo. It is a folded Cassegrainian system, of 3.75 m focal length and 0.15 m aperture, and a physical length of 0.32 m. Two star images are formed, one for each readout axis; the images are divided at two orthogonal roof prisms and the intensities of the divided beams are compared in redundant Detector Package Assemblies (DPA), operating at a temperature of about 70 K, mounted on the front end of the Telescope.

The Flight Telescope was the third in a series whose evolution is another illustration of incremental prototyping. In fact, incremental prototyping appears equally in testing the telescope testing. No fewer than three artificial
stars have been constructed to evaluate its performance. The one used for qualification was the second, on which a vibration–isolated dewar vessel was mounted to allow testing both at room temperature and low temperatures. Tests of the DPAs were performed separately to determine noise performance prior to their installation on the telescope. Linearity measurements with the artificial star demonstrated that the telescope would remain linear to $< 3 \text{ mas}$ over a range of $\pm 20 \text{ mas}$, meeting the requirements of spacecraft pointing control.

With the individual systems for the Probe and SIA all qualified, it became possible to proceed to final assembly conducted in a class 10 clean room at Stanford. The Quartz Block/Telescope structure was inserted into an inner framework (the ‘bird–cage’) in the Probe, followed by the exacting process of inserting and aligning the gyroscopes into the Quartz Block with their centers within 50 $\mu$m of a common line. (Hence, when the spacecraft has been mass–balanced on orbit, the gyroscopes will be within that 50 $\mu$m radial distance from the roll axis, minimizing the centrifugal acceleration to which they are subjected). Fig. 9 illustrates the SIA in an advanced stage of assembly showing the suspension cables, SQUID assemblies, gyro caging line, and fiber optic cable for uv charge control. The final tests performed before inserting the Probe in the dewar were a room temperature spin test for all four gyroscopes, measuring the spin–down rate after evacuation and thus verifying once more that the gyro os were free from particle contamination, and a telescope field–of–view test.

Fig. 9. SIA in Advanced Stage of Assembly: Note the suspension cables and two of the four SQUID boxes mounted on the upper side of the ‘bird–cage’. 
Because the ultra low magnetic field shield is maintained permanently in the inner well of the SMD, the process of inserting the Probe is, as remarked earlier, an unusual one. Whereas in almost all cryogenic systems the probe is inserted before the dewar has cooled down, here a method had to be developed for inserting a warm probe into a cold dewar. In doing so, it is essential to avoid condensing any solid air into the dewar well. The method (devised by B. Cabrera) is to make use of a cylindrical air lock within which the probe is fitted with a tight piston seal. By mounting the probe and air lock on top of the dewar it is then possible to pump out any air and backfill the air lock with helium gas prior to insertion. Insertion has to be performed sufficiently slowly not to generate excessive heat and warm up the superconducting lead shield. To aid in this process, the dewar well is filled temporarily with liquid helium prior to insertion. Fig.10 shows Probe-C mounted in the airlock ready for placement on the dewar in its vertical position.

Probe-C was inserted into the Science Mission Dewar on August 24, 1999 and testing was continued until December 15. Fig.11 shows the assembled probe and dewar under test at Stanford in a horizontal position.

At an early stage it became clear that there was a significant, quite unexpected anomaly in the thermal performance of Probe-C, which would require a recycling to room temperature. However, rather than immediately warming up we decided to ‘retire risk’ by completing the entire range of planned qualification tests on every one of the 32 major subassemblies contained in Probe C and the SMD. 28 out of 32 met or surpassed the stated requirements; 3 more
Fig. 11. Probe-C under test in the SMD in a Horizontal Position: The dewar can be tilted through a range of angles to perform different tests.

discrepancies (1 significant, 2 minor) were uncovered in addition to the thermal anomaly named above. These discrepancies were of a character that would not have prevented launching a successful mission but the necessity of warming up has given the opportunity to address them all.

A. SIA. Tests of the SIA covered 7 major subassemblies and 1 systems test as follows:

- **Telescope:** testing with artificial star # 3 (designed to mount on the SMD) verified performance under final operating conditions. The optical transmissivity and the strehl ratio (which measures the quality of the final image) surpassed the requirements. All 8 detectors in the two DPAs functioned correctly. The noise performance for the selected guide star HR 8703 meets the 10 mas/√Hz pointing requirement.

- **SQUIDs:** all 4 SQUIDs function correctly, with noise performance meeting, and in 2 of the 4 surpassing, the requirement by a factor of 4. In separate tests of electromagnetic compatibility (EMC) with the Gyro Suspension System the shielding was shown to fully meet stated requirements.

- **Gyro levitation and spin–down:** all 4 gyroscopes met the levitation requirements and the stated spin–down requirements, showing that at low
temperature as well as in the earlier room-temperature tests the gyros were free from particle contamination\(^3\).

- **Gyro caging:** tests of the caging mechanism met requirements both at room temperature and low temperature.

- **Gyro uv charge control system:** all 8 systems (2 per gyro for redundancy) functioned correctly yielding a photocurrent \(> 100\text{fA}/\mu\text{W}\), surpassing the requirement by more than a factor of 3.

- **Gyro readout coupling:** for 3 of the 4 gyros (## 1, 2, 3) the coupling of the SQUIDs to the readout loop met the superconducting requirement; for # 4 it showed resistance \(> 1,000\ \Omega\) which is unacceptable.

- **SIA sensors and wiring:** all of the thermometric and other sensors on the SIA functioned correctly, and all of the wiring met specifications; there was one electrical short on the gyro # 4 suspension shields, which, however, had no practical impact.

- **Trapped flux in gyro rotors:** As noted in C below, the ambient field in the lead bag was \(< 2 \times 10^{-10}\ \text{T}\). Trapped fields in 3 of the 4 gyroscopes were below the \(3 \times 10^{-10}\ \text{T}\) requirement but in gyro # 1 (the one nearest the top of the bag) field levels were anomalously high \((10.6 \times 10^{-10}\ \text{T})\).

**B. Probe-C.** The 3 principal system entities: (1) plumbing; (2) sensors and wiring; (3) radiation windows, met their requirements, with the exception of minor leaks in the caging lines and one valve. The practical impact of these minor leaks would have been negligible but since the probe has been warmed up they are being repaired. Transmission through the windows exceeded 80%. The vacuum integrity of the probe fully met its requirement. The failure in thermal performance is discussed below.

**C. Dewar.** The 4 principal system entities: (1) plumbing; (2) sensors and wiring; (3) low-temperature valves; (4) ultralow magnetic field shield met all their requirements. The magnetic field level in the lead shield was \(< 2 \times 10^{-10}\ \text{T}\). The vacuum integrity and thermal performance also met all requirements.

**D. Interfaces.** Interface requirements had to be, and were, met for 3 systems: (1) SIA–to–Probe; (2) Probe–to–Dewar; (3) the Belleville–washer preload system to maintain thermal contact between Probe-C and the SMD.

The foregoing tests were highly successful in retiring risk. At the conclusion of this phase of payload testing 90% of the required systems verifications had been completed.

### 7 The Four Discrepancies and Their Resolution August 1999–June 2000

Considerable work was done to characterize the four discrepancies while Probe-C was still in the SMD. After its removal on December 15, 1999 new diagnostic tests

\(^3\)At a late stage of testing, some contamination from frozen gas occurred in two of the gyros for reasons that are well understood. The gas disappeared on warming to room temperature, leaving the gyroscopes once more free of contamination. Procedures are in place for preventing this contamination happening again.
became possible which further clarified the problems and various experiments and rehearsal tests were performed to validate the redesign. Rework commenced on March 27 and was completed on June 2, 2000. Reinsertion of Probe-C into the SMD will take place before October 18, 2000.

A. Probe-C Thermal Anomaly. To understand the thermal anomaly one needs to grasp the principles governing the design of long hold–time helium dewars.

Liquid helium, because of its quantum mechanical zero point energy, has very low latent heat. Far more cooling–power is available from the warming of the boil–off gas to room temperature than from the latent heat. In designing helium dewars one makes use of this fact by intercepting much of the incoming heat in ‘vapor–cooled shields’. With 3 to 4 suitably spaced shields embedded in the multilayer insulation, it is possible to recover about 35% of the available gaseous refrigeration and increase the dewar hold–time by a factor of about 25.

In Gravity Probe B this vapor–refrigeration must be applied not only to the dewar but also to intercept heat radiated and conducted down the neck–tube of the probe. Accordingly, as Fig.12 shows, radiation windows at 3 locations in the neck are connected to copper rings epoxied to its inner surface. Matching copper rings on the outside of the neck connect these thermally to corresponding cooled rings on the dewar neck. On orbit, where the dewar skin temperature is 220 K, the nominal temperatures of the 3 windows are 33 K, 77 K, and 132 K; a fourth ring (HEX # 4) without a window operates at 157 K. On Earth with a skin temperature of 293 K, the window temperatures are usually slightly higher; however, there is also a special operating condition used mainly on the launch pad, in which the lowest vapor–cooled shield is artificially cooled by means of a ‘guard tank’ full of ‘normal’ (i.e. non–superfluid helium) and therefore to operates at or near 4.2 K. In the experiments to be discussed now, this was in fact the condition and window # 1 should have been at around 6 K.

This sophisticated design was prototyped in Probes A and B, and successfully demonstrated in both the EDD and the Science Mission Dewar. When Probe-C was cooled down, however, very serious temperature anomalies were observed. Instead of being at 6 K, as it should have been with the guard–tank cold, window # 1 ran at 86.5 K! The temperatures of windows # 2 and # 3 and of Hex # 4 were also far too high. These drastic discrepancies strongly suggested that the windows were receiving effectively no cooling from the boil–off gas (in other words that there was a thermal disconnect somewhere between the window and the vapor–cooled shields. A variety of tests pointed to a thermal disconnect internal to Probe-C, probably between the copper rings and the fiberglass–epoxy neck tube. Conclusive evidence came from tests in which helium exchange gas was introduced into the probe at various pressures with the system vertical to prevent convection. At 0.31 torr the temperatures are reduced dramatically: the exchange g as provides an excellent conductive path between the inner ring and the neck tube.
Fig. 12. Schematic of Probe-C Repair: The three radiation windows can be seen within the neck in the main drawing. The left inset shows details of the window frame; the right inset is an enlarged section of the neck-wall and rings.
The conclusion has to be that the epoxying that had worked so well for Probes A and B went wrong in Probe C. The very detailed written and photographic QA record of the construction showed no discernible cause of failure; nevertheless, failure there was, with three very serious implications. First, the loss of thermal conductivity reduces the dewar hold-time on orbit from 19 months to possibly as low as 10 months. Second, just as serious, it reduces the ground hold-time in such a way as to make operations on the launch pad almost impossibly difficult. Third and gravest of all, the break between heat stations and neck tube makes the probe vulnerable to mechanical failure under the vibration of launch.

A failure of this kind puts a space program into a new situation. To disassemble Probe-C and remake the epoxy bonds would take over a year and still not guarantee success. Instead, the method GP-B has adopted is to short-circuit the problem by a redesign which establishes direct thermal links between the outer and inner copper rings. At each heat station four holes are drilled through the outer ring, the neck tube, and the inner ring ending as a ‘blind hole’ that stops just short of penetrating through to the far side of the inner ring. Thermal contact and mechanical integrity are established by means of copper pins inserted into each hole with a tight ‘press-fit’. For technical reasons two of the pins are inserted horizontally and two inclined at 51 degrees. Fig.13 illustrates a cross-section of the pin and ‘blind hole’ for one of the 51-degree pins. Vacuum integrity, which has of course been lost by drilling through the neck tube, is restored by two stages of epoxy seal. A low viscosity epoxy is injected into the hole around the pin and over this, following a standard cryogenic practice, a ‘doubler’ in the form either of a flat copper sheet or copper plug is sealed over each pin with an extremely robust thermally matched epoxy rejoicing in the name “Blue Death”.

To assure success, rehearsals were performed on two prototype assemblies with two alternative pinning procedures. Critical to the pinning solution is the complex drilling process which has to be undertaken to penetrate first a copper ring, then the composite neck tube, then the second ring, all with perfect alignment and without penetrating beyond the blind end of the hole. Since the pin has to be a ‘press-fit’, alignment and finish of the holes are critical; it has been found necessary to drill each hole in six stages, with three different kinds of drill. For the horizontal holes two of the stages required carbide drills which are notoriously brittle; great care had to be applied to avoid breaking off a drill partway through a hole. After many trials the procedure was perfected and demonstrated to meet the three essential re-
requirements, thermal, mechanical, and vacuum. Comparative experiments on Probes B and C provided an unequivocal room–temperature diagnostic to distinguish acceptable and unacceptable thermal performance at low temperature. Mechanical and vacuum integrity were validated as follows: Each prototype assembly was vacuum tested; subjected to a vibration test at flight qualification levels; vacuum tested again; twice cycled to low temperatures; vacuum tested for a third time. Both pinning techniques met all requirements. Finally, on March 23, 2000 Probe C Redesign Readiness Review was held and approval given to proceed with the rework using the particular method discussed above.

In applying to Probe-C the experience gained during the rehearsals, it was essential to take into consideration the issue of cleanliness. Debris or turnings from the drilling process must, at all costs, be prevented from contaminating the gyroscopes or soiling the surfaces of the telescope and radiation windows. The drilling was performed in an ultra high quality (class 10) clean room at Stanford, with the probe in an inverted position and at a slight overpressure to drive any contamination outwards. It was accompanied by a continuous vacuum cleaning around the hole. Drilling proceeded from the outside in, removing one radiation window after another to gain access for measurement of the position and alignment of the inner rings.

In fact, the entire operation went remarkably smoothly. Pinning was completed on May 15, 2000. After cleaning and reinstallation of the windows the following tests were performed by June 2: (1) a static load test on window frame # 3 at flight qualification levels; (2) the room temperature thermal

Fig. 13. Cross Section of Model of Probe Necktube with 510 Copper Pin. The section shows the pin in position with the blind hole in the inner copper ring. Not shown is the ‘doubler’ which completes the vacuum seal on the outside of the outer ring.
performance test mentioned above; (3) a vacuum integrity test of the entire
probe. Prior to the installation of the pins the thermal conductance between
inner and outer rings was 0.028 W/K, after pinning it was 0. 42 W/K. This
factor of 15 in improvement was in excellent agreement with the data ob-
tained with the earlier validation units. The computed helium hold–time on
orbit (including a 30% allowance for conservatism) is 17 months. Vacuum
performance was excellent: there was no detectable leak even on the most
sensitive $3 \times 10^{-10}$ standard cm$^3$/sec scale of the leak detector, a margin of
at least 4 orders of magnitude on the GP-B requirement.
As of mid–June 2000 Probe C is being prepared for room–temperature spin
tests of the gyroscopes to check whether cleanliness has been properly main-
tained.

B. Gyro # 4 Readout Ring Discrepancy. Beside offering a good oppor-
tunity for scientific detective work, the readout failure for Gyro # 4 nicely
illustrates the range of issues that need to be weighed in executing a space
program.
In the initial planning of Gravity Probe B the decision to have four gyro-
scopes was in some degree arbitrary (a tradeoff between redundancy and
complexity). Obviously, there ought to be more than one, but since each
gyroscope will measure both relativity effects a case can be made for flying
with only three. If there had been no other reason for removing the probe
from the dewar that would almost certainly have been the decision. However,
given the fact that the probe did have to be removed the option of re pair
becomes worth careful consideration.
The tests demonstrated that the entire SQUID readout unit was function-
ing perfectly; the fault lay in the failure of a superconducting bond on the
housing itself. The location of the high–resistance connection in the gyro–to–
SQUID input circuit was determined by measuring the frequency dependence
of the SQUID response to high frequency inductively coupled ac signals. Fre-
quencies above 100 kHz are outside the SQUID feedback circuit bandwidth,
so these measurements were made open loop (i.e., without feedback to the
SQUID). To obtain consistent measurements, the SQUID was dc biased to
the most linear portion of its characteristic curve. Input signals were limited
to no more than one tenth of a SQUID flux quantum in order to obtain a
reasonably linear output. The resulting data of SQUID output amplitude
versus frequency were compared to the predictions obtained from SPICE
circuit simulation results based on a circuit model with a resistive contact at
the gyroscope and a second model with the resistive contact in the SQUID
assembly. The experimental data fit the former model excellently and the
latter model not at all.
It is worth emphasizing that the failure of the superconducting bond on gyro
# 4 was not entirely unexpected. During earlier qualifications of gyroscopes
it had been found that the original design was somewhat unreliable and
occasionally failed on initial cool–down. Accordingly, a new more reliable
design of bond was developed, which has shown no failures, and this was
used for gyros # # 1, 2, and 3. For gyro # 4 a compromise was made. A
gyroscope was available which was so excellent in other respects that we decided to use it despite having a bond of the original design, the argument being that in the past, once such bonds were qualified, they always withstood repeated temperature cycling.

Repairing the bond simply means replacing the gyroscope. Although the SIA is designed to allow such a substitution, the process has never actually been tried and does entail risk. The cables and connections to the old gyroscope have to be severed and unstaked without damaging or contaminating the assembly; the gyro has to be removed and replaced; and numerous tests have to be performed prior to resealing the probe. Before finalizing the decision, a rework team has been set up to rehearse the process in a backup Quartz Block Assembly containing two gyroscopes left over from earlier prototyping activities. The results are encouraging; a decision will be taken in June 2000.

C. **High Trapped Flux in Gyro #1.** The $10.6 \times 10^{-10}$ T trapped field in gyro #1 was rather a surprise because in Probe-B, where less attention had been paid to magnetic cleanliness, there had been little difficulty in obtaining $3 \times 10^{-10}$ T trapped fields in all four gyros. Three possible explanations suggest themselves: (1) a change in magnetic field level in the lead bag; (2) magnetic contamination in the probe; (3) a thermal effect connected with the Probe-C anomaly.

The first conjecture was that there had been a field change in the lead bag. The reason for suspecting this was that during cryogenic operation a ‘thermal spike’ had occurred which could have heated the top end of the bag above its superconducting transition temperature. However, after removing Probe-C from the dewar and carefully remeasuring the field at all levels we found the field completely unchanged. Magnetic contamination remains a possibility, though in view of the extreme care taken in material screening it seems unlikely. The most probable explanation is a temperature effect.

The hypothesized source is the Thomson effect. As is well-known, Thomson in the 1850s showed from thermodynamical reasoning that when any metal is subjected to a temperature gradient, a voltage difference will be established across it. What is less well-known is Thomson’s second discovery (1895) that if the metal is anisotropic circulating currents can be set up generating magnetic fields. At low temperatures, this effect becomes much larger as was discovered by a GP-B graduate student, P.M. Selzer, in 1974. The argument, therefore, is that the thermal anomaly in Probe-C produces just such a temperature gradient in the metal around the SIA, at its upper end, and that the most likely cause of the anomalous field in Gyro #1 is this Thomson–Selzer effect. Final verification will only be possible after insertion of the reworked probe into the SMD.

Two possibilities therefore confront us. First that on cool-down the anomaly will have disappeared. Second that for magnetic contamination or some other reason the trapped field in Gyro #1 will still be anomalously high, in which case the question is, how problematical that will be for the experiment. Detailed analysis by J.M. Lockhart demonstrates that while the $3 \times 10^{-10}$ T nominal requirement remains a desirable goal, the readout is actually more
‘forgiving’ than had originally been thought, and there will be little or no loss in final accuracy of the measurement.

**D. Leaks in Caging Lines, etc.** During the course of the reworking of Probe-C in the clean room at Stanford repairs were effected to the caging lines and these were further secured by the addition of ‘doublers’ similar in principle to the doublers on the pinning system.

8 Spacecraft, Electronics Systems, Integration & Test

Reflection about Gravity Probe B rightly concentrates first on the Science Instrument with its cryogenic and mechanical refinements but no account of a space mission can end there. The following is a brief summary of the main other aspects of the mission.

8.1 Spacecraft

Gravity Probe B is unusual in that its main structural element is the Science Mission Dewar. To it is attached the Spacecraft, a welded aluminum framework that fits around the lower end of the SMD and carries the solar panels, harnesses, spacecraft electronics, and other support equipment Fig. 14.

Mounted on the front end of the SMD in close proximity to Probe-C is a Forward Electronics Enclosure (FEE), which provides a highly stable thermal environment with extensive shielding against electromagnetic interference and coupling for the key payload electronics boxes. Also mounted on the SMD is the telescope sunshield. The combined weight of spacecraft and payload is 3241 kg. The power requirements are 293 W for the spacecraft and 313 W for the payload, (606 W total) during normal operation; during initial setup, however, the requirement rises at certain intervals to 713 W. For an inertially fixed rolling spacecraft such as GP-B the power output from the solar panels at any moment depends on their geometry and the orientation of the spacecraft with respect to the Sun. Allowance has to be made for degradation over the course of the mission. The system, as designed, has beginning–of–life and end–of–life capabilities at worst–case seasonal minimum of 731 W and 703 W respectively. At the currently scheduled May 1, 2002 launch–date the actual capability is 873 W at launch declining to 737 W in early June, a sufficient margin over the 713 W initial requirement.

As of June 2000 the spacecraft is 85% complete. Most of the subsystems, mechanical and electrical, are flight–proven. In total there are 21 electronics boxes representing 12 distinct electrical systems all (except for Attitude/Translational Control) flight–proven or close derivatives of flight–proven systems. All have been installed on the Spacecraft. All electrical harnesses are complete. Two and a half of the four solar panels are complete. The spacecraft flight software coding is complete and in verification test.

Straightforward as most aspects of the GP-B spacecraft are, two of the mechanical systems essential to the success of the relativity measurement are decidedly unusual. One is the use of helium proportional thrusters for attitude and
Gravity Probe B

Fig. 14. The GP-B Spacecraft: The spacecraft fits around the lower end of the SMD. Among the items visible in the photo are two long rectangular boxes containing two of the seven mass–trim mechanisms.

translational control; the other is having a set of 7 mass–trim mechanisms to balance and align the principal axes of the spacecraft. Each mass trim mechanism consists of a 20 kg weight mounted in a closed rectangular box and adjusted in position by a lead screw driven by a stepper motor. These mechanisms have been subject to a very extensive qualification program and are now installed on the spacecraft; 4 are mounted transversely to move the axis of rotation laterally until it coincides with the line through the center of the gyroscopes to within 0.8 mm. The other 3 are parallel to the spacecraft axis and adjust the direction of the principal axes of inertia. Trimming is performed intermittently as the helium is depleted, probably a few times during the course of a year.

In most spacecraft with gas–jet attitude control systems constraints on gas consumption set by weight dictate the use of on–off valves fired only on demand. To apply this method to GP-B with its very fine pointing requirement (∼ ±20 mas) would take a space–qualified valve capable of reseating perfectly hundreds of millions of times, a severe reliability problem. Fortunately, there is a way. Already on board is a supply of gas that must be vented – the helium boil–off from the dewar. By directing this continuously through pairs of opposed nozzles operated as ‘proportional thrusters’ one obtains a control system that is at once smoother and mechanically more reliable than the conventional kind. A striking feature is the low Reynolds’ number (∼ 30) in the throat of the valve. Work by
a succession of GP-B graduate students, J.S. Bull, J.–H. Chen, P. Wiktor, and Y. Jafry, has led to a design subsequently further developed and space–qualified by Lockheed Martin that meets all of GP-B’s requirements, provided the orbit altitude exceeds about 600 km. Fig.15 illustrates the flight thrusters.

Control is maintained in all three modes, pointing, drag–free, and roll, from signals derived respectively from: (1) the science telescope, (2) either of two science gyroscopes operated drag–free, (3) conventional rate–gyroscopes mounted on the spacecraft, updated by signals from a ‘star–blipper’ picking up a band of stars spread over the heavens at an angle to the roll axis. The pointing accuracy good to about 10 mas, the residual cross–track average acceleration to better than $10^{-12} \text{g}$, the roll–rate to about 1 part in $10^5$. The translational controller is designed to force the center of rotation of the Spacecraft into coincidence with the line through the gyro centers. The mass–trim mechanism brings it within 0.8 mm; the translational controller brings it to 50 $\mu$m, that is, to within the limit to which the gyros are aligned.

GP-B has 16 thrusters mounted on fixed struts extending out from the Spacecraft, with geometrical and internal redundancies such that any four systems can be allowed to fail with no loss of control performance.

8.2 Payload Electronics

In contrast to the spacecraft electronics, based on flight–proven hardware, almost all of the payload electronics are new. Altogether there are 5 systems, containing a total of 15 electronics boxes distributed between the FEE and a corresponding Aft Electronics Enclosure (AEE) on the Spacecraft (the reason for this division between forward and aft enclosures is that if all the boxes were mounted forward it would unbalance the mass distribution of the space vehicle):

- Telescope Readout Electronics (TRE), 2 boxes, both forward;
- SQUID Readout Electronics (SRE), 4 boxes, 2 forward, 2 aft;
- Gyro Suspension System (GSS), 8 boxes, 4 forward, 4 aft;
- Experiment Control Unit (ECU), 2 boxes, 1 forward, 1 aft;
- Ultraviolet Discharge (UVD), 2 systems, 1 in each aft ECU box.

Only the UVD has been flown before.

An important lesson for the physicist in the world of space electronics is that even when an engineering model of a flight unit has met all requirements
there is still a long way to go before the actual flight unit is ready for installation. Procuring the right space-hardened components, assembling the flight unit under full Quality Assurance, and completing all the tests that are necessary, including vibration tests, is a major task. Among several common surprises is the extraordinarily long procurement times for ‘mil-standard’ components. For GP-B, engineering models of each unit have been fully tested in the laboratory but as of June 2000 the only flight unit available is the TRE. For the other three all components are in-house; the state of assembly is as follows. (1) SRE: all 16 boards complete. Aft-box passed all functional tests except vibration test; forward-box in functional testing. (2) GSS: 10 of 14 boards assembled. For aft-box, all 5 boards tested, conformally coded, and ready for board integration. For forward-box, 4 of 9 assembled, 2 completed testing, 1 also conformally coded. (3) ECU: all 19 boards assembled, tested, and conformally coded. Box testing ready to begin.

The most challenging to design of the Payload Electronics systems is the GSS. It has to support the gyroscope with very low voltage (about 0.1 V) in order not to generate suspension torques yet be able to switch instantly to a higher level in emergencies. During gyro spin-up it has to exert an acceleration of approximately 0.3 g on the rotor to balance the pressure from the spin-up gas. Also during spin-up the center of the rotor has to be displaced in a controlled manner toward the spin-up channel to reduce gas leakage over the wall of the channel. All these operations have to be performed automatically without ever allowing the spinning ball to touch the housing. The final design is a digital system with two separate computers and an analog back-up, with an arbiter to decide which of the three parallel systems should take command. Testing it on Earth has been an interesting task. In addition to high voltage operation with live gyroscopes, a gyro test bed has been constructed in which variable flat plate capacitors driven by piezoelectric actuators mimic the actual gyroscope under controlled conditions.

The current schedule has the GSS completed by December 2000. The GSS and SRE will be used in Probe-C evaluation on the SMD at Stanford early in 2001 prior to shipment of the completed Payload to Lockheed Martin for integration with the Spacecraft in April 2001.

8.3 Integration & Test, Ground Station, and Launch

The process of testing a completed payload and spacecraft is in general terms well-established, though logistically it involves complications that a physicist might hardly expect. For Gravity Probe B, in addition to elaborate acoustic, modal, and end-to-end thermal vacuum tests, very careful spin balancing of the spacecraft is necessary to bring it within the range of the mass-trim mechanisms.

The most unconventional aspect of the GP-B test program is the use of an Integrated Test Facility (ITF) to check software and command-telemetry signals at an early stage prior to transmitting new untested signals to the Spacecraft. From the software point of view GP-B is an unusually complex spacecraft with
7 separate on-board computers, as well as an unusually large number of electronics boxes. To mitigate the difficulty the ITF was commenced very early in the program and brought close to completion in 1998, though even now not all the hardware is installed for verifying performance of the 1553 computer and command and telemetry signals. A constant difficulty in any test program is to separate problems in the electronics from problems in the Test Facility itself. A method of alleviating this has been devised. It consists of mounting in the ITF the already tested engineering models of the different electronics systems, so that it is possible to switch back and forth between them and the flight units.

No less challenging has been the development at Stanford of the Mission Operation Center (MOC) and ground control software. The MOC communicates through NASA Wallops Flight Facility's Ground Network to a series of ground stations located around the Earth. The primary stations in the Ground Network are the Alaska Ground Station and the Svalbard, Norway Ground Station. During set-up and, if necessary, emergency the Ground Network can be supplemented by the NASA Tracking and Relay Satellite System (TRSS) Space Network. And, finally, there is all the planning for the launch. The elaborate preparations required, including safety, preparation of ground support equipment, training of personnel, and the transportation of the spacecraft to the launch site, are a whole story to itself.

Acknowledgement

This work was supported by NASA contract NAS8-39225 through George C. Marshall Space Flight Center, Huntsville, Alabama. We are indebted to the MSFC Gravity Probe B team led by Mr. Rex Geveden. The Lockheed Martin Program Manager is Dr. Hugh Dougherty.