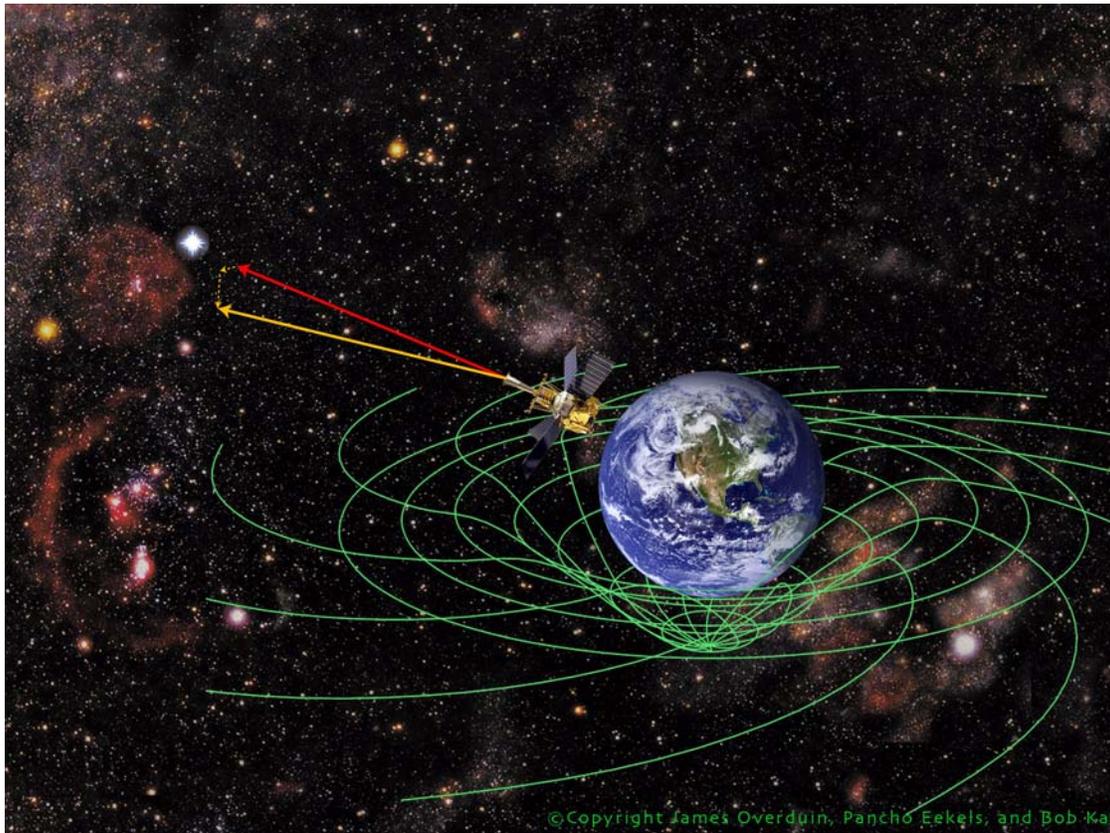


# The Gravity Probe B EXPERIMENT

" TESTING EINSTEIN'S UNIVERSE "



## Post Flight Analysis — Final Report

Preface & Executive Summary

October 2006



# Preface

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Gravity Probe B (GP-B) is a test of Einstein's General Theory of Relativity based on orbiting gyroscopes. NASA technology funding commenced in March 1964. After a long development process, reaching completion in 2003 to 2004, the mission was successfully launched on April 20, 2004—almost exactly 40 years later. This Post-Flight Analysis Report provides a coherent overall final account of all aspects of GP-B, except the science results which are now planned for publication in April 2007.

GP-B has been a collaborative program between two Stanford University Departments, Physics and Aeronautics-Astronautics. Since 1965, it has also involved a continuous collaboration between Stanford and George C. Marshall Space Flight Center in Huntsville, Alabama. A payload subcontract was let from Stanford to Lockheed Martin in November 1984; the spacecraft contract, also to Lockheed Martin, was let in October 1993. The GP-B story is, therefore, a complex one, in fact, seven interfolded stories:

1. About testing Einstein
2. About the invention of many new technologies
3. About a collaboration between university departments
4. About highly successful student involvement in a long-running space program
5. About a remarkable range of spin-offs, including drag-free technology, Autofarm® GPS-based precision tractor control, a novel quartz bonding technique, and the porous plug device for controlling superfluid helium in space which made possible the IRAS, COBE, WMAP and Spitzer missions
6. About collaboration between NASA and academia
7. About the challenge of managing a flight program with a very highly integrated payload and spacecraft which led the then-NASA Administrator, Mr. James Beggs, in 1984, to say that GP-B was not only a fascinating physics experiment but also a fascinating management experiment.

We, at Stanford, feel profound appreciation to NASA Marshall Center and also many friends at NASA Headquarters who have helped to make this challenging mission possible. Credit for coordinating, assembling, and editing this report goes to our GP-B Public Affairs Coordinator, Bob Kahn.

Francis Everitt & Bradford Parkinson

August 2006

# 1

## Executive Summary

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## 1.1 What is Gravity Probe B?

Gravity Probe B (GP-B) is a NASA physics mission to experimentally investigate Albert Einstein's 1916 general theory of relativity—his theory of gravity. GP-B uses four spherical gyroscopes and a telescope, housed in a satellite orbiting 642 km (400 mi) above the Earth, to measure in a new way, and with unprecedented accuracy, two extraordinary effects predicted by the general theory of relativity (the second having never before been directly measured):

1. The geodetic effect—the amount by which the Earth warps the local spacetime in which it resides.
2. The frame-dragging effect—the amount by which the rotating Earth drags its local spacetime around with it.

The GP-B experiment tests these two effects by precisely measuring the precession (displacement) angles of the spin axes of the four gyros over the course of a year and comparing these experimental results with predictions from Einstein's theory.

GP-B is actually the second dedicated NASA physics experiment to test aspects of general relativity. The first, Gravity Probe A, was led in 1976 by Dr. Robert Vessot of the Smithsonian Astrophysical Observatory. Gravity Probe A compared elapsed time in three identical hydrogen maser clocks—two on the ground and the third traveling for two hours in a rocket, and confirmed the Einstein redshift prediction to 1.4 parts in  $10^4$ .

## 1.2 A Quest for Experimental Truth

The idea for testing Einstein's general theory of relativity with orbiting gyroscopes was suggested independently by two physicists, George Pugh and Leonard Schiff, in late 1959-early 1960. Schiff, then chairman of the Stanford University Physics Department, published a paper summarizing the experiment, "Possible New Experimental Test of General Relativity," in *Physical Review Letters* (March 1960). Also during this time, Schiff teamed up with two colleagues from the Stanford faculty: low-temperature physicist William Fairbank and gyroscope expert Robert Cannon of the Department of Aeronautics & Astronautics. Thus was born the collaboration between the Stanford Physics and Aero-Astro departments which has been essential to the success of GP-B.

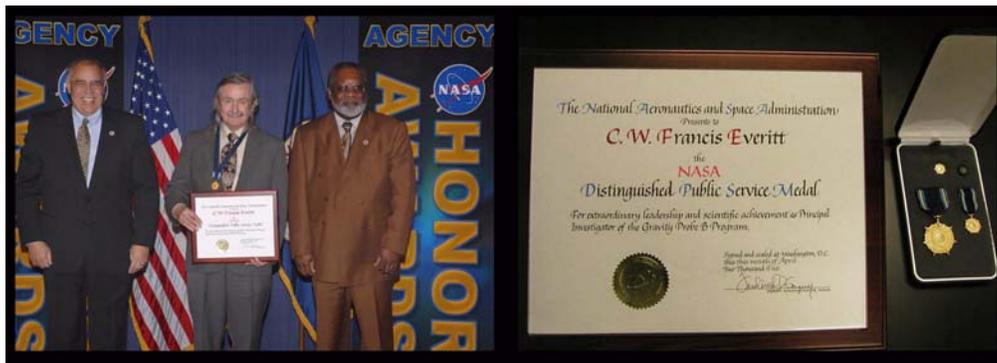
In 1962, Professor Fairbank invited Francis Everitt to come to Stanford as the first full-time academic staff member on the experiment. NASA's Office of Space Sciences, under the leadership of Dr. Nancy Roman, provided research funding in 1964, with Fairbank and Cannon as Co-Principal Investigators and Schiff as Program Advisor. Initial funding was direct from NASA Headquarters to Stanford. In 1971, program oversight was transferred to NASA Marshall Space Flight Center (MSFC) where some engineering collaboration had already begun. Also in 1971, in parallel with the technology development, MSFC funded an in-depth Mission Definition Study by Ball Brothers Research Corporation (BBRC, now Ball Aerospace), performed in close collaboration with Stanford, the starting point of all future flight studies.

Between 1978 and 1984, following in-house Phase A and Phase B studies at MSFC, the experiment was re-structured as a NASA flight program. An important step between 1982 and 1984 was the definition of a technology development program for GP-B to be performed on the Shuttle in 1989—the Shuttle Test Of the Relativity Experiment (STORE), followed two years later by a satellite launch from the Shuttle. In 1981, Francis Everitt became Principal Investigator, the position which he still holds, and in 1984, Stanford Professor Bradford Parkinson (Aero-Astro) joined GP-B as Program Manager, and also as Co-PI, along with Co-PI's John Turneure (Physics) and Daniel DeBra (Aero-Astro).

NASA initiated funding of STORE in FY 1985, following receipt in November 1984 of a Stanford proposal, with Stanford as prime contractor, and Lockheed Missiles and Space Company (LMSC, now Lockheed Martin) as subcontractor to Stanford. In this proposal, Lockheed held principal responsibility for developing the unique 650-gallon dewar and probe—the cryogenic apparatus that houses the telescope and four gyroscopes. After the

Challenger disaster in 1986 and the subsequent closure of NASA's West-Coast, polar-orbiting shuttle launch facility, it was necessary to recast the mission as the launch of a dedicated satellite from its own expendable launch vehicle, without losing the technology funding. Eventually, after extended NASA review and two competitive industrial Phase A studies and proposals, Stanford selected LMSC to build the space vehicle and associated control systems that would contain the dewar and probe in orbit.

William Fairbank once remarked: “No mission could be simpler than Gravity Probe B. It's just a star, a telescope, and a spinning sphere.” However, it took the exceptional collaboration of Stanford, MSFC, Lockheed Martin and a host of others almost two more decades to finally bring this “simple” experiment to the launch pad in April 2004. Over this period, as construction of the payload and spacecraft commenced, the GP-B team expanded, reaching a peak of approximately 100 persons at Stanford, and eventually some 200 persons at Lockheed Martin. Six scientists, each with a different area of specialization, became Co-Investigators: Saps (Sasha) Buchman, George (Mac) Keiser, John Lipa, James Lockhart, Barry Muhlfelder, and Michael Taber. In 1998, Bradford Parkinson stepped aside as Program Manager, to be succeeded first by John Turneure, and then in turn, Sasha Buchman, Ronald Singley, and Gaylord Green for the flight program, and William Bencze for the data analysis phase of the mission. Throughout this period, Tom Langenstein served as the Deputy Program Manager, with responsibility for resources and procurements.



**Figure 1-1.** GP-B Principal Investigator, Francis Everitt, receiving the NASA Distinguished Public Service Award at an awards ceremony at NASA Headquarters in April 2005

However, if there is one person who, along with William Fairbank has proved to be the driving force of GP-B since his arrival in 1962, it is Francis Everitt. His leadership has markedly advanced the state of the art in the areas of cryogenics, magnetics, quantum devices, telescope design, control systems, quartz fabrication techniques, metrology and, most of all, gyroscope technology. The fact that GP-B survived no fewer than seven potential cancellations, finally launched in April 2004, successfully completed a 17-month flight mission, and is now in the final stages of analyzing the relativity data is a direct tribute to Everitt's leadership, tenacity, and dogged pursuit of the experimental truth. It was in recognition of these seminal contributions that, in April 2005, NASA awarded Everitt the Distinguished Public Service Medal—the highest award that NASA can confer upon a non-government employee.

### 1.3 The GP-B Flight Mission

On April 20, 2004 at 9:57:24 AM PDT, a crowd of over 2,000 current and former GP-B team members and supporters watched and cheered as the GP-B spacecraft lifted off from Vandenberg Air Force Base. That emotionally overwhelming day, culminating with the extraordinary live video of the spacecraft separating from the second stage booster meant, as GP-B Program Manager Gaylord Green put it, “that 10,000 things went right.” The orbital insertion was within a few meters of a perfect “bull's eye,” and thus no orbit trim was required during the initialization and checkout phase of the mission.

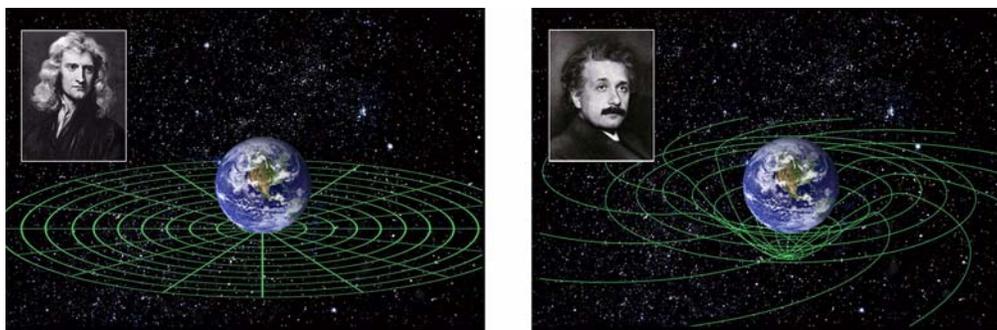
Once in orbit, the spacecraft first underwent a four-month Initialization and Orbit Checkout (IOC), in which all systems and instruments were initialized, tested, and optimized for the data collection to follow. The IOC phase culminated with the spin-up and initial alignment of each of the four science gyros early in August 2004.

On August 28, 2004, the spacecraft began collecting science data. During the ensuing 50 weeks, the spacecraft transmitted over a terabyte of science data to the GP-B Mission Operations Center (MOC) at Stanford, where it was processed and stored in a comprehensive database for analysis. On August 15, 2005, the GP-B flight team finished collecting science data and began a planned set of essential calibration tests of the gyros, telescope, and SQUID readouts that lasted six weeks, until the liquid helium in the dewar was exhausted on September 25, 2005. (The helium actually lasted about three weeks longer than expected, allowing for extra calibration tests to be made.)

As of summer 2006, the GP-B science team is working through the second phase of a three-phase analysis of the data. It is currently anticipated that the data analysis will be concluded in early 2007. At that time, the analysis and results will undergo a careful and critical review by the GP-B external Science Advisory Committee (SAC), as well as by other international experts. During the latter part of 2006 and 2007, members of the GP-B team will also be preparing a number of scientific and engineering papers for publication, as well as working with NASA in planning a formal public announcement of the results of this unprecedented test of General Relativity. It is currently anticipated that the results of GP-B will be announced in April 2007.

## 1.4 The Two Einstein Effects

Newton believed that space and time were absolute or fixed entities and that gravity could be represented as an attractive force that somehow acted instantaneously between objects. In Newton's universe, the spin axis of a perfect gyroscope orbiting the Earth would remain forever fixed with respect to absolute space. Einstein determined that space and time are relative entities, interwoven into a “fabric,” which he called spacetime, and he realized that no force—not even gravity—could act faster than the speed of light. In Einstein's universe, the presence of celestial bodies causes spacetime to warp or curve; and gravity is not a force, but rather the product of bodies moving in curved spacetime (Figure 1-2). Thus, in Einstein's universe, the spin axis of a perfect gyroscope orbiting the Earth will precess over time with respect to the distant universe, as it follows the warping and twisting curvature of spacetime.



**Figure 1-2.** Newton's flat and fixed space and time (left) vs. Einstein's warped and twisted spacetime (right)

GP-B is measuring both the predicted geodetic effect, the amount by which the Earth's presence is warping its local spacetime. Concurrently, and even more important, GP-B is measuring the predicted frame-dragging effect, deduced in 1918 as a corollary to general relativity by Austrian physicists Josef Lense and Hans Thirring, and never before directly measured. It states that massive celestial bodies, like the Earth, drag their local spacetime around with them as they rotate. This effect of a moving “gravitational charge” is often compared to

the generation of a magnetic field by a moving electric charge, and is often referred to as *gravitomagnetism*. Physicists and cosmologists are particularly interested in frame-dragging because it may account for the enormous power generation in the most massive and explosive objects in the universe, such as black holes.

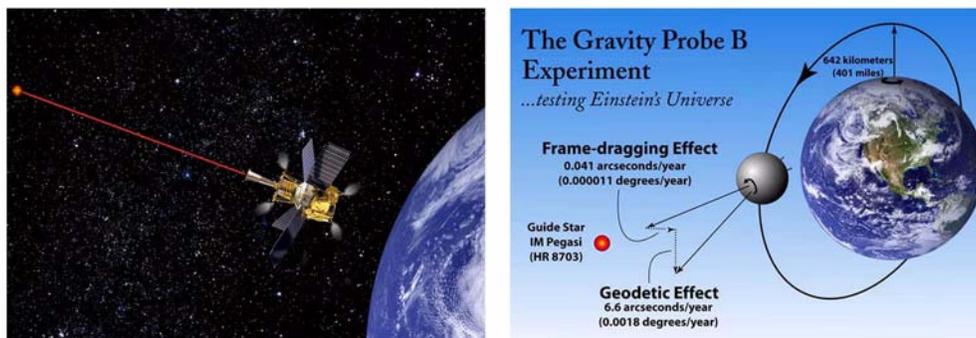
## 1.5 Why Perform Another Test of Einstein?

While it has become a cornerstone of modern physics, general relativity has remained among the least tested of all theories in physics, because, as Caltech physicist Kip Thorne once put it: “In the realm of black holes and the universe, the language of general relativity is spoken, and it is spoken loudly. But in our tiny solar system, the effects of general relativity are but whispers.”

And so, any measurements of the relativistic effects of gravity around Earth must be carried out with utmost precision. Over the past 90 years, various tests suggest that Einstein was on the right track. But, in most previous tests, the relativity signals had to be extracted from a significant level of background noise. The purpose of GP-B is to test Einstein's theory by carrying out the experiment in a pristine orbiting laboratory, reducing background noise to extremely low levels and enabling the experiment to examine general relativity in new ways. If GP-B's results corroborate the predictions of general relativity, we will have made the most precise measurement of the shape of local space-time, and confirmed the theory of general relativity to a new standard of precision. If on the other hand, the results disagree with Einstein's theoretical predictions, theoretical physicists may be faced with the challenge of constructing a whole new theory of the structure of the universe and the motion of matter.

## 1.6 Experimental Design & “Near Zeroes”

Conceptually, the GP-B experiment is simple (Figure 1-3): Place a gyroscope and a telescope in a polar-orbiting satellite, 642 km (400 mi) above the Earth. (GP-B actually uses four gyroscopes for redundancy.) At the start of the experiment, align both the telescope and the spin axis of each gyroscope with a distant reference point—a guide star. Keep the telescope aligned with the guide star for a year, and measure the precession change in the spin-axis alignment of each gyro over this period in both the plane of the orbit (the geodetic precession) and orthogonally in the plane of the Earth's rotation (frame-dragging precession).



**Figure 1-3.** The GP-B spacecraft in orbit and the two measurements being made with the gyroscopes on-board

The predicted geodetic gyro-spin-axis precession is a tiny angle of 6.6 arcseconds (0.0018 degrees) in the orbital plane of the spacecraft. The orthogonal frame-dragging precession is a minuscule angle of 0.041 arcseconds ( $1.1 \times 10^{-5}$  degrees)—about the width of a human hair viewed from  $\frac{1}{4}$  mile away, or four feet at the Earth's radius. GP-B's measurement of the geodetic effect has an expected accuracy of better than 0.01%. The frame-dragging effect has never directly been measured, but Gravity Probe-B is expected to determine its accuracy to  $\sim 1\%$ .

Designing a physics experiment involves a basic choice: maximize the effect to be measured, or minimize the “noise” that obscures it. For the Gravity Probe-B experiment, that choice was moot because Einstein's relativistic effects that literally “roar” near black holes whisper almost inaudibly here on earth. Thus, implementing the experimental design described above required meeting seven near-zero design constraints—three near-zero constraints on the gyro rotors, which had to be near-perfect spheres, with uniform superconductive coatings and virtually no imperfections in shape and density, and four near-zero constraints on the pristine space-borne, cryogenic laboratory, which housed the gyros and shielded them from any sources of noise or interference that might distort the results—solar radiation, atmospheric friction, magnetic fields, electro-magnetic signals radiating from Earth, and so on. [Table 1-1](#) summarizes these seven near-zero constraints, showing the tolerance required and the tolerance actually achieved for each one during the mission.

**Table 1-1.** GP-B Seven Near Zeros

| Experimental Variable                   | Tolerance Requirements  | Tolerances Achieved During Mission                                 |
|---|---|--|
| <b>Gyroscope Rotor Near Zeros</b>       |   |  |
| Mechanical Sphericity                   | 50 nanometers (2 micro inches)                                      | <10 nanometers (< 0.4 microinches)                                 |
| Material Homogeneity                    | 3 parts in $10^6$   | 3 parts in $10^7$  |
| Electrical Sphericity                   | 5 parts in $10^7$   | <5 parts in $10^7$   |
| <b>Probe Environment Near Zeros</b>     |   |  |
| Temperature                             | 1.95 kelvin (-271.2° degrees Celsius or -456.2° degrees Fahrenheit) | 1.8 kelvin (-271.4° degrees Celsius or -456.4° degrees Fahrenheit) |
| Non-Gravitational Residual Acceleration | Less than $10^{-10}$ g  | Less than $5 \times 10^{-12}$ g                                    |
| Background Magnetic Field               | $10^{-6}$ gauss   | Less than $10^{-7}$ gauss  |
| Probe Pressure                          | $10^{-11}$ torr   | Less than $10^{-11}$ torr  |

## 1.7 Unique and Extraordinary Technologies

While the concept of Gravity Probe B is relatively simple, carrying out the experiment required some of the most accurate and sophisticated technology ever developed. In fact, scientists and engineers from Stanford, Lockheed Martin, and NASA had to invent about one dozen totally new technologies in order to meet GP-B’s near-zero constraints, because much of this technology simply did not exist when the experiment was first suggested in late 1959 - early 1960. Einstein, himself once a patent clerk, would have enjoyed reviewing these extraordinary technologies.

### 1.7.1 The World’s Most Perfect Gyroscopes

To measure the minuscule angles predicted by Einstein’s theory, the GP-B team needed to build a near-perfect gyroscope—one whose spin axis would not drift away from its starting point by more than one hundred-billionth of a degree each hour that it was spinning. By comparison, the spin-axis drift in the most sophisticated Earth-based gyroscopes, found in high-tech aircraft and nuclear submarines, is seven orders of magnitude (more than ten million times) greater than GP-B could allow.

To accomplish this exceptional challenge, the GP-B gyroscope rotors ([Figure 1-4](#)) had to be perfectly balanced and homogenous inside. They had to be free from any bearings or mechanical supports, and they had to operate in a near-perfect vacuum.

After years of work and the invention of new technologies and processes for polishing, measuring sphericity, and thin-film coating, the result was a homogenous 1.5-inch sphere of pure fused quartz, polished to within a few atomic layers of perfectly smooth. In fact, the GP-B gyro rotors are now listed in the Guinness Database of World Records as being the roundest objects ever manufactured; they are topped in sphericity only by neutron stars. The spherical rotors are the heart of each GP-B gyroscope. The raw quartz material was mined in Brazil, and then fused (baked) and refined in a proprietary process at Heraeus Amercil in Germany. The interior composition of each gyro rotor is homogeneous to within two parts in a million. On its surface, each gyroscope rotor is less than three ten-millionths of an inch from perfect sphericity. This means that every point on the surface of the rotor is the exact same distance from the center of the rotor to within  $3 \times 10^{-7}$  inches. If a GP-B gyroscope rotor were enlarged to the size of the Earth, its tallest mountain or deepest ocean trench would be less than eight feet!



**Figure 1-4.** A GP-B niobium-coated gyro rotor and housing (left), the Guinness Database record for roundness (center), and measuring the sphericity of a gyro rotor (right)

Finally, a GP-B gyroscope is freed from any mechanical bearings or supports by levitating the spherical rotor within a precisely machined fused-quartz housing cavity. Six electrodes, evenly spaced around the interior of the housing, keep the rotor levitated in the housing cavity. During the IOC phase of the mission, a stream of pure helium gas was used to spin up each of the four gyroscopes to approximately 4,000 rpm. After that, all but a few molecules of the helium spin-up gas was evacuated from the housings, and the gyroscopes were left spinning—a mere 32 microns (0.001 inches) from their housing walls, free from any mechanical or fluid supports. During the experiment, the near-perfectly spherical and homogeneous rotors, combined with the highly sophisticated Gyro Suspension System (GSS), resulted in an average spin-down time constant of approximately 15,000 years for the four GP-B gyros.

### 1.7.2 Gyro Suspension System (GSS)

The GSS, that electrostatically suspends the science gyroscopes within their housing cavities and enables them to spin freely with minimal friction and torque, is a marvel of engineering in its own right. To perform its mission successfully, the GSS had to satisfy a number of requirements:

1. Operate over 8 orders of force magnitude. The same system must be able to suspend the gyroscopes on Earth in a 1 g field as well as generate minimal disturbances at the  $10^{-8}$  g level during data collection.
2. Suspend or levitate the gyroscopes reliably. The system must *never* let a spinning rotor touch the housing. There is sufficient mechanical energy in a rotor spinning at 4,000 rpm to effectively destroy the rotor and housing in such an event.

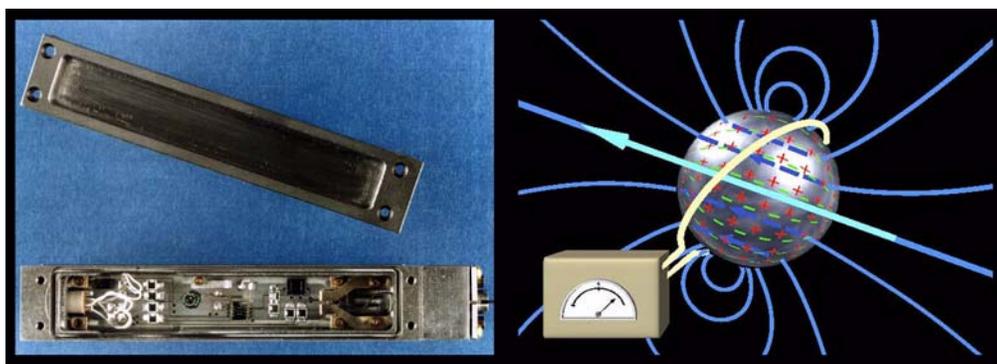
3. Operate compatibly with the SQUID readout system. The SQUID magnetometers are extremely sensitive. Thus, the suspension system must not interfere with these sensors, both during ground and on-orbit operation.
4. Minimize electrostatic torques during science data collection. The suspension system must meet centering requirements with absolutely minimal control effort, and thereby with minimal residual torques on the rotors.
5. Apply controlled torques to the rotor for calibration and initial rotor spin-axis alignment.
6. Act as an accelerometer as part of the “drag-free” translation control system to further minimize classical torques on the rotors by another factor of  $10^6$ .

All of these requirements were met during the GP-B flight mission. Furthermore, the suspension systems continue to operate well following the depletion of helium from the dewar, since they do not require cryogenic electronics to function.

### 1.7.3 SQUID Magnetometers for Gyro Orientation Readout

How can one monitor the spin-axis orientation of a near-perfect spherical gyroscope without any physical marker showing the location of the spin axis on the gyro rotor? The answer lies in a property exhibited by some metals, called “superconductivity.” At temperatures slightly above absolute zero, many metals completely lose their electrical resistance and become superconductive. Furthermore, as predicted in 1948 by theoretical physicist Fritz London, a spinning superconductor develops a magnetic moment—created by the electrons lagging the lattice of the superconducting metal—which is therefore exactly aligned with its instantaneous spin axis.

What is wonderful about this phenomenon (and most fortunate for GP-B) is that the axis of this magnetic field lines up exactly with the physical axis of the spinning metal coating on each rotor. Here was the “marker” Gravity Probe B needed. Each spherical GP-B quartz gyroscope rotor is coated with a very thin layer of superconducting niobium (1,270 nanometers thick). When each niobium-coated gyroscope rotor is spinning, a small magnetic field surrounds it. By monitoring the axis of the magnetic field, Gravity Probe B knows precisely which direction the gyroscope's spin axis is pointing, relative to its housing. This is one of the many technologies invented and developed specifically for GP-B.



**Figure 1-5.** A GP-B SQUID module (left) and a diagram of the magnetic pickup loop and London moment

The spinning rotor’s magnetic field axis is monitored with a special type of magnetometer, called a SQUID (Superconducting QUantum Interference Device, shown in [Figure 1-5](#)). The SQUID is connected to a superconducting niobium pickup loop, deposited on the flat surface at the outer edge of one optically flat mating surface of the quartz housing in which the gyro rotor spins. Thus, the loop, which senses the gyro’s spin-axis orientation, is located on the planar surface where the two halves of the gyro housing are joined. When the spin

axis of a gyroscope rotor changes its orientation, the London moment magnetic field moves with it, passing through the superconducting loop. This causes a quantized current to flow in the loop, and the SQUID detects this change in magnetic field orientation. The SQUID magnetometers are so sensitive that a field change of only  $5 \times 10^{-14}$  gauss (one ten-billion<sup>th</sup> of the Earth's magnetic field) and corresponding to a gyro deflection of 0.1 milliarcseconds ( $3 \times 10^{-8}$  degrees)—is detectable.

### 1.7.4 The Pointing Telescope

A 36 centimeter (14 inch) long Cassegrain reflecting astronomical telescope (Figure 1-6) with a focal length of 3.8 meters (12.5 feet), mounted inside the GP-B Probe along the central axis of the spacecraft and dewar, provided the experiment's required reference to a distant "guide star." Any change in spin-axis orientation of each of the gyros, as they traveled through the warped and twisted spacetime around the Earth, was measured against this guide star reference to distant spacetime. During the science phase of the mission, the telescope's job (in conjunction with the ATC) was to keep the entire spacecraft precisely pointed at the center of the guide star with a pointing deviation in the range of approximately  $\pm 200$  milliarcseconds ( $\pm 6 \times 10^{-5}$  degrees).

To satisfy these precision pointing requirements, it was necessary to locate the optical center of the guide star image in the telescope to an accuracy of 0.1 milliarcseconds ( $3 \times 10^{-8}$  degrees). The diffraction limit size of the GP-B telescope is approximately 1.4 arcseconds, which is about 14,000 times larger than the required pointing accuracy, and this presented a formidable challenge to the GP-B team. The solution was to precisely split the image into equal x-axis and y-axis components, and then to divide each of the axis components into two half images whose brightness values could be compared.



**Figure 1-6.** A pre-flight prototype of the GP-B telescope and diagram of its image-centering operation

GP-B accomplished this task by focusing the mirror-reflected starlight onto an Image Divider Assembly (IDA) at the telescope's front end. In the IDA, the starlight was first passed through a beam-splitter (a half-silvered mirror), that forms two separate images, one for the horizontal (x) axis and one for the vertical (y) axis. The half beam from each axis was then focused onto a roof-prism (a prism shaped like a peaked rooftop). Each roof prism sliced its portion of the starlight beam into two half-disks, which were focused onto a pair of silicon photo diodes.

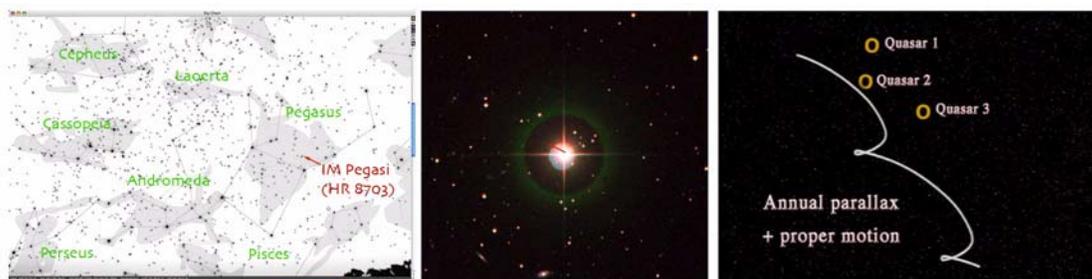
The photo diodes converted the light signals from each half-disk to electrical signals which were then compared. If the signals were not equal, the roof-prism was not slicing the image precisely in half. The orientation of the entire spacecraft was then readjusted in real time until the signals were equal and the image was split right down the middle. When this was accomplished for both the x-axis and y-axis halves of the starlight beam, the telescope was locked on the exact center of the guide star. Once tuned up, the Attitude and Translation Control (ATC) system on-board the spacecraft was capable of locking the telescope onto the guide star in less than a minute each time the spacecraft emerged from behind the Earth over the North Pole and the guide star came into view. Once the telescope was locked onto the guide star, the telescope pointing signals were used to compensate for the small pointing deviation to an accuracy of better than 0.1 milliarcseconds ( $3 \times 10^{-8}$  degrees).

### 1.7.5 Relating the Guide Star’s Motion to a Distant Quasar

Ideally, the telescope would be aligned with a distant quasar, because quasars are so distant from the Earth that they appear to be fixed in their relative position and would thus provide an ideal, stable reference point for measuring changes in gyroscope spin-axis orientation. However, quasars are too dim for any optical telescope this size to track. So, instead, the telescope was focused on a brighter, nearby guide star whose motion could be mapped relative to quasars separately. As such, the frame of reference of the Gravity Probe B gyroscope measurements will ultimately be related to the far distant universe.

In order to precisely map the motion of a guide star relative to a quasar, it was necessary to select a guide star that was in the correct position for tracking by the on-board telescope, shines brightly enough for the on-board telescope to track accurately, can be tracked by radio telescopes on Earth, and is visually located within a fraction of a degree from a reference quasar. Out of 1,400 stars that were examined, only three matched all the necessary criteria, and the star that was chosen as the GP-B guide star is named IM Pegasi (HR 8703).

Thus, throughout the science phase of the mission, the GP-B science telescope was tracking a very slowly moving star, but the gyros were unaffected by the star's so-called “proper motion;” their pointing reference was IM Pegasi’s position in the celestial sphere. Consequently, in the gyro precession data, it is necessary to subtract out the displacement of the original guide-star orientation so that the angular displacements of the gyros can be related to the guide star’s initial position, rather than to its current position. For this reason, a very accurate map of the proper motion of IM Pegasi is required in order to complete the GP-B data analysis.

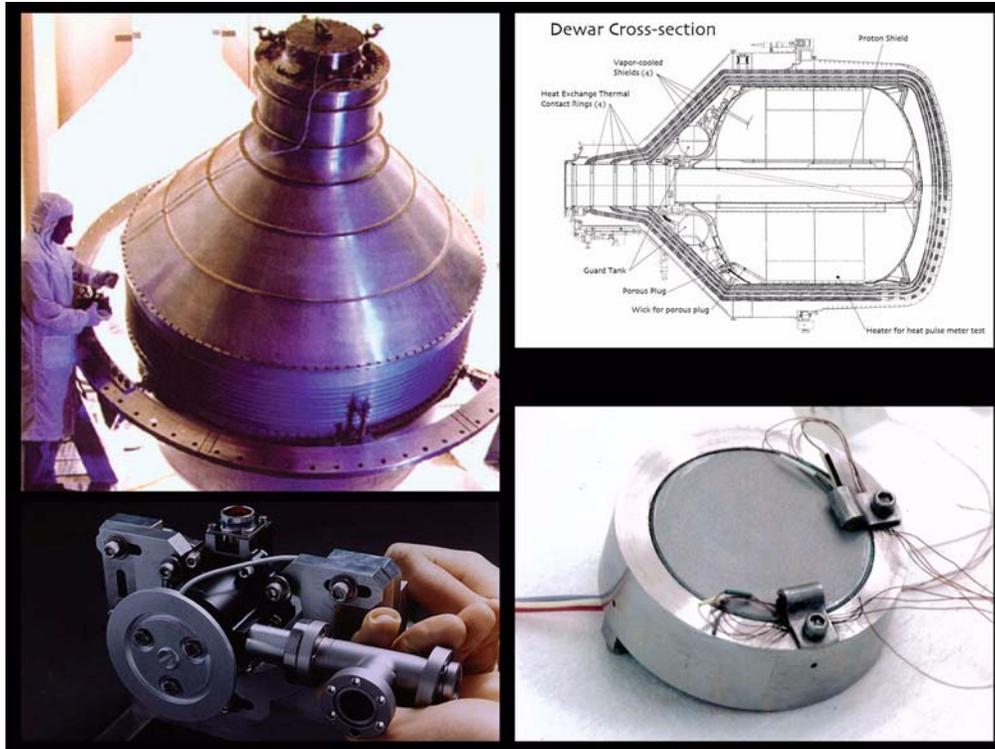


**Figure 1-7.** Guide Star IM Pegasi (HR 8703) sky location (left), photo (center) and proper motion (right)

Because IM Pegasi is a radio source, its proper motion can be tracked by a sophisticated world-wide network of radio telescopes, through a technique called Very Long Baseline Interferometry or VLBI. A team at the Harvard-Smithsonian Center for Astrophysics (CfA) led by astrophysicist Irwin Shapiro, in collaboration with astrophysicist Norbert Bartel and others from York University in Canada and French astronomer Jean-Francois Lestrade, have now mapped the motion of IM Pegasi with respect to a reference quasar over a number of years to an unprecedented level of accuracy. With these measurements the motions of the GP-B gyroscope spin axes can now be precisely related to the reference quasar in the far distant universe.

### 1.7.6 The Dewar

One of the greatest technical challenges for Gravity Probe B was keeping the probe and science instrument precisely at a designated cryogenic temperature, just above absolute zero, of approximately 2.3 kelvin (-270.9 degrees Celsius or -455.5 degrees Fahrenheit) constantly for 16 months or longer. This was accomplished by integrating the probe into a special 2,441 liter (645-gallon) dewar, or thermos (Figure 1-8), about the size of a mini van, that is filled with liquid helium, cooled to a superfluid state. This nine-foot tall Dewar comprised the main structure of the GP-B satellite itself.



**Figure 1-8.** Clockwise, from top left: The dewar, a cross-section of the dewar, the porous plug, and one thruster

Through a combination of multi-layer insulation, vapor-cooled shields, and a unique porous plug, the dewar's insulating chamber was maintained in a cryogenic vacuum throughout the mission. While virtually no heat could penetrate from the outside wall through the vacuum and multi-layer insulation inside, a small amount of heat was continually conducted from the neck of the Dewar and from the heat-trapping windows inside the probe into the superfluid helium inside the dewar chamber. This very slight, but continual warming caused the superfluid helium to slowly vaporize into helium gas, which needed to be vented continually from the dewar chamber through the porous plug.

Invented at Stanford, and engineered for space at the NASA Marshall Space Flight Center, Ball Aerospace, and the Jet Propulsion Laboratory, the porous plug controls the flow of this evaporating helium gas, allowing it to escape from the Dewar, but retaining the superfluid helium inside. The plug is made of powdered titanium that has been sintered (heated) until it coalesces into a sponge-like pumice with very tiny pores. The evaporating helium gas climbed the side of the dewar near the plug and collected on the plug's surface, where it evaporated through the pores in the plug, much like sweating in the human body, drawing heat out of the liquid helium remaining in the Dewar, and thereby balancing the heat flow into the Dewar. The helium gas continually escaping through the porous plug was cycled past the shields in the outer layers of the Dewar, cooling them (thus the name, "vapor-cooled shields.") Moreover, it then was used as the propellant for eight pairs of micro thrusters, strategically located at the extremities of the spacecraft and used by the Attitude and Translation Control system (ATC) for high-precision pointing and positional control. Thus, not only did the dewar serve as the means of maintaining a cryogenic environment for the experiment, it was also the sole source of propellant for the ATC system.

### 1.7.7 Spacecraft Control—Nine Degrees of Freedom

GP-B is the first spacecraft ever launched requiring six degrees of freedom in active attitude control—three degrees of freedom in pointing control to maintain its guide-star pointing orientation (pitch and yaw) plus its constant roll rate, and three degrees of freedom in translational control (up-down, front-to-back, and side-to-side), to maintain a drag-free orbit throughout the 17-month flight mission. In addition, the Gyro Suspension System (GSS) for each gyroscope required three degrees of freedom in controlling the location of the spherical rotor within its housing. Thus, in total, the GP-B experiment required nine degrees of freedom for controlling the spacecraft—a truly demanding and remarkable accomplishment.

The term “drag-free” refers to a body that is moving without any friction or drag, and thus its motion is affected only by gravity. A drag-free satellite refers to a feedback system consisting of a satellite within a satellite. The inner satellite, often called a proof-mass, is typically a small homogeneous object, such as a spherical GP-B gyroscope, totally shielded from air drag and solar pressure. The position of the outer shielding satellite must be tightly controlled to prevent it from ever touching the proof mass. This is accomplished by equipping the outer satellite with sensors that precisely measure its position relative to the proof mass and a set of thrusters that automatically control its position, based on feedback from the sensors. Through this feedback system, the satellite continually “chases” the proof-mass, always adjusting its position so that the satellite remains centered about the proof mass, which is orbiting the Earth in a constant state of free fall—i.e, a purely gravitational orbit.

In the GP-B spacecraft, the drag-free feedback system was based on data from the Gyro Suspension System (GSS) for the science gyro that was serving as the drag-free proof mass. Based on this feedback, the ATC system metered the flow of the escaping helium gas through the 16 micro-thrusters in order to precisely control the spacecraft’s position. In fact, the location of the entire spacecraft was continually balanced around the proof-mass gyroscope by increasing or decreasing the flow of helium through opposing thrusters, to maintain a drag-free orbit. The drag-free feature of the GP-B spacecraft was critically important to the experiment because external drag on the spacecraft would otherwise cause an acceleration that would obscure the minuscule relativistic gyro precessions being measured.

GP-B’s ATC system, designed by Lockheed Martin, was truly an engineering “tour-de-force.” It took a considerable amount of time during the 4-month Initialization and Orbit Checkout (IOC) phase of the mission and part of the science phase of the mission for the GP-B and Lockheed Martin Mission Operations Team to master all the subtleties of this complex system.

## 1.8 The Management Experiment

GP-B was not a packaged experiment carried into orbit by a space-cargo vehicle. Rather, the GP-B spacecraft was a total system, comprising both the space vehicle and its unique payload—an integrated system dedicated as a single entity to making the measurements of unprecedented precision required by the experiment. To accomplish this goal, it was crucial that the whole system be developed by a strong and cohesive team.

In 1984, GP-B began the transition from program definition to payload and spacecraft design. Francis Everitt had become Principal Investigator in 1981, and with the anticipated increase in staff and activity required for design and development, he recruited Bradford Parkinson to join GP-B as Program Manager and also as a Co-PI, along with Co-PI’s John Turneure (Physics) and Dan DeBra (Aero-Astro). At that time, GP-B was defined as a two-phase Space Shuttle mission: first, a technology readiness demonstration (STORE—Shuttle Test of the Relativity Experiment) to be launched in 1989, followed two years later by the actual experiment, a satellite to be launched from a polar-orbiting Shuttle. For a number of reasons including the interdependency of the payload and spacecraft and the high level of technology development required, Samuel Keller, then Deputy Director of the NASA Office of Space Science Applications, decided to make Stanford NASA’s prime contractor on the GP-B mission. James Beggs, then the NASA Administrator, concurred with this decision and remarked that in addition to being a physics experiment that needed to be carried out in space, GP-B was equally interesting as a

“management experiment.” This was one of the first, and largest NASA missions, in which a university was given the prime role of managing the development of an entire space flight mission—science instrument, spacecraft, operations and data analysis.

Following the Challenger disaster in 1986 and the subsequent closure of NASA's West Coast, polar-orbiting shuttle launch facility, it became necessary to re-cast the GP-B mission as a satellite to be launched from its own expendable rocket. From 1992-1994, Stanford conducted a thorough source selection process from which LMSC was chosen to build the space vehicle into which the dewar and probe would be integrated. During the ensuing years, Stanford led the combined team, with oversight from NASA's Marshall Space Flight Center (MSFC), in developing and perfecting each of the components of the payload and spacecraft.

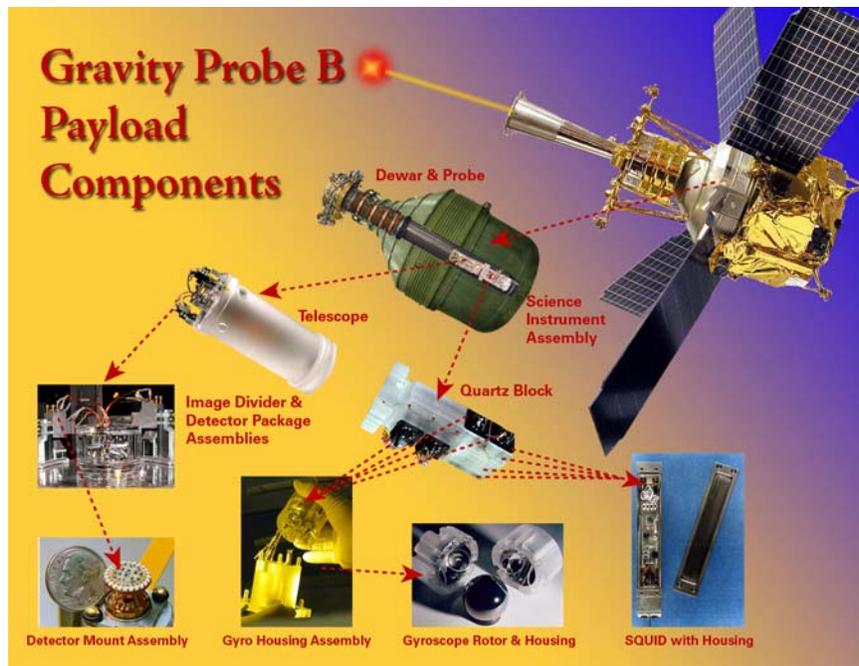
In the late 1990s, it was time to transition GP-B from a research and development program with limited NASA oversight to a classical NASA flight program that would culminate in the complete integration and testing of the payload-spacecraft system, followed by a successful launch, on-orbit operations, and subsequent data analysis. This shift in focus from maximizing advances in research and development to minimizing the risks in producing a flight-ready spacecraft was a difficult transition for GP-B. It took the exceptional insight and leadership of Rex Geveden, then NASA's GP-B Program Manager at MSFC (now Associate Administrator at NASA Headquarters), in collaboration with Principal Investigator Francis Everitt and other senior management at Stanford, LMSC, and NASA to arrive at an effective, minimum-risk-based management plan that would ready the GP-B spacecraft, payload and operations team for the flight mission.

Given the success of the GP-B launch and 17.3-month flight mission, the management experiment was also a success. It showed that a university, in close partnership with NASA and an experienced aerospace sub-contractor, can effectively develop and operate a sophisticated integrated satellite, and it provided NASA with invaluable management insights for future missions.

## 1.9 The GP-B Spacecraft

All of the Gravity Probe B technologies were integrated into one of the most elegant satellites ever launched ([Figure 1-9](#)). The spacecraft was built around the dewar. Embedded along the dewar's central axis was a cigar-shaped canister called the Probe which contained a series of heat-absorbing windows, a helium-adsorbing cryopump, and the Science Instrument Assembly (SIA)—the pristine space-borne laboratory for making the GP-B experimental measurements.

The SIA comprised the telescope and the quartz block, optically bonded together. The quartz block contains the four gyros and SQUIDs that monitor the spin-axis orientations of the gyros. The telescope and all four gyros were precisely aligned along the long, central axis of the spacecraft, around which the spacecraft rolled continuously at 0.77 rpm (77.5 seconds per revolution) throughout the science phase of the mission.



**Figure 1-9.** The GP-B spacecraft and its main payload components

Outside the dewar, mounted to the spacecraft frame are all the systems that provide power, navigation, communication and control of the spacecraft, including:

**Sun Shield.** This is a conical tube, attached to the probe, that kept stray light from entering the telescope.

**Proportional Micro Thrusters.** Eight pairs of balanced, proportional thrusters provided very precise attitude and position control in orbit during the flight mission. (Now that the helium is exhausted from the dewar, these micro thrusters are no longer functional, and only a set of magnetic torque rods control the spacecraft's attitude, with much less precision than the thrusters provided.)

**Solar Arrays.** These four arrays convert energy from the Sun into electrical power that is stored in the spacecraft's two batteries and then used to run the various electrical systems on board. Because the orbit plane of the GP-B spacecraft always contained the guide star, the position of each solar array was precisely canted to maximize the power output as the spacecraft rolled and changed position with respect to the Sun over the course of the mission.

**GPS Sensors & Antennae.** Four GPS (Global Positioning System) antennas on-board the spacecraft—two at the forward end of the spacecraft and two at the aft end—transmit information about both the spacecraft's position and its attitude.

**Telemetry & Communications Antennae.** These fore and aft antennae enable both inbound and outbound communications with the space vehicle, including communications with ground stations and with orbiting communications satellites in the Tracking Data Relay Satellite System (TDRSS).

**Two Star Trackers.** Basically, these are telescopes with cameras and pattern-matching systems that use constellations and stars to determine the direction in which the satellite is pointing. During the mission the star trackers functioned like "spotting scopes" for the science telescope. Once the star trackers had oriented the spacecraft within a degree of the guide star, the telescope took over the job of achieving and maintaining the precise alignment required for measuring gyroscope precession.

**Attitude-Control Gyroscopes.** Two pairs of standard, flight-qualified rate-sensing gyroscopes, equivalent to those found on other spacecraft (and also airplanes, ships, and other vehicles) were included as part of the general navigation system used for monitoring the orientation of the spacecraft.

**Electro-mechanical Control Systems.** Surrounding the dewar, a lattice of trusses forms the outer structure of the spacecraft. Attached to these trusses are a number of electrical and mechanical systems that control the operation of the spacecraft and enabled the relativistic measurements to be carried out. These control systems include the following:

- **Attitude & Translation Control System (ATC)**—Uses feedback from the gyro suspension system (GSS), the SQUID readout system (SRE), the telescope readout system (TRE), the star trackers, magnetometers, and rate-sensing navigational gyroscopes to control the proportional micro thrusters and magnetic torque rods that determine and maintain the spacecraft’s precise attitude and position relative to one of the science gyro rotors that serves as the drag-free proof mass.
- **Magnetic Torquing System (MTS)**—A set of long electromagnets that push or pull against the Earth’s magnetic field to orient the spacecraft’s attitude.
- **Mass Trim Mechanism (MTM)**—A system of movable weights that can be adjusted during flight to restore precise rotational balance of the space vehicle (similar to spin balancing the tires on an automobile)
- **Gyro Suspension System (GSS)**—The electronics that levitate and precisely control the suspension of the four gyroscopes at the heart of the Gravity Probe B experiment.
- **Gas Management Assembly (GMA)**—A very complex set of valves, pipes, and tubing that was used to spin up each of the four gyroscopes by blowing a stream of 99.99999% pure helium gas over them, through a channel built into one half of each gyroscope’s quartz housing. (Subsequently, all but a few molecules of the helium gas were removed from each housing; the gyro rotors spun in a near-perfect vacuum.)
- **Experiment Control Unit (ECU)**—The ECU controls many of the systems on-board the space vehicle, including the GMA, the ultraviolet light system used to remove electrostatic charge from the gyro rotors, and various thermal devices.

## 1.10 On-Orbit Operations

With a typical spacecraft, the mission operations team spends a considerable amount of time after launch learning how the spacecraft behaves and responds. Once the team has become comfortable operating the vehicle, the more sophisticated experimental operations are then attempted. In contrast, GP-B required that a number of very complex operations be carried out during the Initialization and Orbit Checkout (IOC) mission phase immediately following launch, because the dewar’s lifetime was limited to approximately 16-17 months and a year’s worth of experimental data had to be collected while there was still liquid helium in the dewar. With all of the unique features and cutting-edge technologies embodied in the GP-B spacecraft, it became apparent early on that the GP-B mission operations team would have to “hit the ground running.” To accomplish this goal, a sophisticated mission operations plan was created. Detailed procedures with contingencies, were developed, and the GP-B mission operations team went through rigorous training. One of the hallmarks of the GP-B mission operations team was “test it as you fly it, and fly it as you test it.” This meant that all of the ground test software and procedures used were essentially the same as those used in flight. The GP-B team also worked through a number of pre-launch simulations, with the test program being based on expected mission operations. Thus, by the time of launch, the team was already well-rehearsed and ready to tackle real issues and anomalies.

Launch operations proceeded like clockwork, with virtually perfect orbit insertion. The team then immediately set to work performing IOC initialization and checkout procedures. Activities during the IOC phase included tuning the ATC system to set the spacecraft's roll rate, capturing the guide star at the top of each orbit in less than one minute, and establishing and maintaining drag-free control. In addition, it was necessary to balance the spacecraft about its center of mass by adjusting the Mass Trim Mechanisms on the spacecraft frame and to uniformly wrap the helium bubble inside the dewar by briefly increasing the spacecraft's roll rate.

However, the most delicate and painstaking operations concerned the four science gyros, for which there were no precedents in any other space mission. First, the gyro suspension system had to be checked out and calibrated for each of the four gyros. Then, the gyros were spun-up, one by one, by blowing a stream of pure helium gas through a spin-up channel in each rotor housing. The spin-up was accomplished gradually, in three stages that lasted over a month, ultimately resulting in the final gyro spin rates averaging 4,000 rpm. The spin-up operations were among the most stressful and risky of the entire mission. Following gyro spin-up, it was necessary to "bake out" excess helium molecules remaining in the Probe from the spin-up gas. It was then necessary to align the spin axis of each gyro with the guide star—another set of painstaking procedures. Finally, gyro #3 was designated as the "proof mass" to be used by the ATC system to maintain the spacecraft in a drag-free orbit. At last, on August 28, 2004, the spacecraft and payload were ready to begin collecting science data.



**Figure 1-10.** The GP-B Mission Operations Center (MOC) during gyro spin-up (left) and end of helium (right)

The IOC phase was followed by an 11 month science-data-taking phase. In comparison to IOC, this period was relatively straightforward and routine. By the start of the science phase, the team was very well trained; each team member knew well his or her responsibilities, thus further easing the effort. Moreover, while most days were uneventful, an "all-hands" meeting was held every day to ensure that the team remained focused on the status of the total system—spacecraft and payload. The all-important science data were transmitted to the ground four times a day. The engineering and science teams reviewed the data on a daily basis and provided top-level feedback on the previous day's data at the daily meeting.

The science mission concluded with a 6-week instrument calibration phase. The purpose of this phase was to help evaluate sources of systematic experiment error and to allow the team to place limits on possible gyroscope torques. Although many operations were performed during this period, the implementation was performed nearly flawlessly.

Ever since the launch of the spacecraft in April 2004, the Mission Operations Center (MOC) at Stanford ([Figure 1-10](#)) was the lifeline to the spacecraft. Mission operations personnel in the MOC were always focused on the current vehicle status. Typically, the vehicle would be "green" and the MOC would verify this status with a real-time monitoring system. In a typical "green" day, the daily 10 am "all-hands" meeting would inform the team of the previous day's events and planned future operations. Following the all-hands meeting, mission planners would meet with subsystem specialists to develop the detailed plan for the next day. In practice, much of the planning already had been developed long before, and only rearrangement of the order of tasks was required. When new products were required, the Integrated Test Facility (ITF), a ground-based computerized model of all systems on-board the GP-B spacecraft, was used for verification prior to use on the vehicle.

Any significant deviation from “green” would immediately “trump” other program activities. An efficient electronic communication-information system allowed for rapid response. Telemetry information from the MOC, as well as information determined from off-line analysis, were in near-constant review. Deviations from a “green” or expected result would cause the immediate initiation of an in-house anomaly resolution process, described in the next section.

By the end of mission, the GP-B team had become very skilled at both operating the spacecraft and handling anomalies. Thus, there was some sadness—as well as the thrill of accomplishment—when the mission ended and members of this truly remarkable mission operations team moved on to new jobs and other missions in their careers.



**Figure 1-11.** NASA GP-B Program Manager, Tony Lyons, from the Marshall Space Flight Center in Huntsville, AL, presents a NASA Group Achievement Award to the entire GP-B team in November 2005.

At the end of November 2005, shortly after the successful completion of the GP-B flight mission, NASA’s GP-B Program Manager, Tony Lyons from the Marshall Space Flight Center, presented a NASA Group Achievement Award to the entire GP-B science mission team, including, of course, people from both Stanford and Lockheed Martin (Figure 1-11). The award reads: “For exceptional dedication and highly innovative scientific and engineering accomplishments leading to the successful execution and completion of the Gravity Probe B Science Mission.” The award is signed by NASA Administrator Michael Griffin, and an individual citation was given to each and every member of the team.

## 1.11 Anomaly Resolution

In space missions, there are always some problematic events—both anticipated and unexpected. The GP-B mission was no exception. We call these surprising events “observations” and “anomalies.” An important part of the pre-launch preparation for the mission was to set up a formal anomaly review process, including procedures for assembling a quick-response anomaly team at any time—day or night—to work through the anomaly, determine the root cause, and come up with a procedure for addressing the issues and returning the spacecraft to nominal operating mode.

A special room in the GP-B Mission Operations, called the Anomaly Room (Figure 1-12), was the home of the GP-B Anomaly Review Board (ARB), a select group of senior GP-B team members from Stanford, NASA, and Lockheed Martin, who managed the troubleshooting of anomalies and observations. The Anomaly Room, which was located across the corridor from the GP-B MOC, contained a set of spacecraft status monitors, communications and teleconference equipment, computer and voice hookups, a documentation library, white boards, a computer projection system, and an oval discussion table.



**Figure 1-12.** The GP-B Anomaly Room in action

During the flight mission, whenever an anomaly was in the process of being resolved, the Anomaly Room was staffed 24 hours a day, 7 days a week; at other times, it was staffed during normal working hours, with team members on call. When major anomalous events, such as computer reboots, occurred outside normal working hours, the Mission Director on duty activated the Anomaly Room and issued a series of pager and cell phone calls via computer, summoning key staff members on the ARB, along with a selected anomaly team, comprised of resident engineers and engineering specialists, to come in and work through the issue. The group used a technique called “fault tree analysis” to evaluate and determine the root cause of unexpected events.

The first anomaly in orbit occurred just two weeks into the mission at around 3:00 AM, when stray protons from a solar flare struck multiple critical memory cells in the main on-board flight computer, causing an automatic switch-over to the backup computer. The GP-B anomaly team was assembled by 4:30 AM that morning—within 90 minutes of the event—and they immediately began taking corrective action.

Over the course of the flight mission, the ARB successfully worked through 193 observations/anomalies. Of these, 23 were classified as true “anomalies,” five of which were sub-classified as “major anomalies,” including the B-Side computer switch-over and the stuck-open valve problems with two micro thrusters early in the mission, as well as subsequent computer and subsystem reboot problems due to radiation strikes. Of the remaining 18 anomalies, 12 were sub-classified as “medium anomalies” and 6 were sub-classified as “minor anomalies.”

The 170 other issues (88%) were classified—at least initially—as “observations.” These observations typically documented various unanticipated events, sub-optimal parameter settings, and other unusual results that were monitored until their root cause was understood. In several cases, observations were escalated to anomaly status, and then necessary actions were taken first to understand, and then to correct the problem. In all cases, the established anomaly resolution process enabled the team to identify the root causes and provide procedures that led to recovery.

Anomalies on orbit did cause some disruptions in the data collection. Methods of treating these had been identified prior to launch and are currently being systematically addressed in the data analysis.

## 1.12 Managing Program Risks

Through mission development, GP-B instituted a high-visibility risk steering committee, which program management used to evaluate and set overall program priorities. Risk groups met on a monthly basis; both Stanford and MSFC had independent risk evaluation teams, using different processes, that met regularly to share their assessments.

Hardware risks were evaluated on the basis of probability of occurrence, as well as the impact of potential failure, using a complete Failure Modes and Effects Analysis (FMEA) process. Other program risks (e.g., budget, schedule and personnel) were evaluated using a similar method. The committees solicited advice from

independent councils of experts to ensure that our evaluations were correct. Five categories of risk were established, ranging from Level 1 (not likely, little cost or critical path impact, and no compromise in mission performance) to Level 5 (Nearly certain likelihood, very large program cost and critical path impact and loss of mission).

Based on potential impact to the program, each risk was evaluated using a table of risk levels and consequences as a guideline. The risk action was then assigned to one of three categories:

- **Mitigate.** Eliminate or reduce the risk by reducing the impact, reducing the probability or shifting the time frame.
- **Watch.** Monitor the risks and their attributes for early warning of critical changes in impact, probability, time frame, or other aspects.
- **Accept.** Do nothing. The risk will be handled as a problem if it occurs. No further resources are expended managing the risk.

Risks were promoted or demoted as program needs or technical understanding evolved. This risk mitigation process was an exceptionally good example of the complementary skills of the MSFC and Stanford-Lockheed teams, as borne out by the success of the mission.

## 1.13 A Successful Mission

Managing a flight program such as GP-B, in which the spacecraft contained only a single, highly integrated payload proved to be a challenge for NASA, its government overseers, Stanford University as NASA's prime contractor, and Stanford's subcontractor, Lockheed Martin—so much so that in 1984, the then NASA Administrator, James Beggs, remarked that GP-B was not only a fascinating physics experiment, but also a fascinating management experiment. NASA thoroughly addressed these challenges, and the many years of planning, inventing, designing, developing, testing, training and rehearsing paid off handsomely for GP-B, culminating in a highly successful flight mission.

Beginning with a picture-perfect launch, bull's-eye orbit insertion, and breath-taking live video of spacecraft separation, the mission got off to a flawless start. The preparedness of the GP-B mission operations team immediately became evident in its deft handling of two major anomalies that occurred within the first month of the mission—the automatic switch-over from the main to the backup flight computer due to proton strikes induced by solar flares and two micro thrusters that had to be isolated due to stuck-open valves. In both cases, the team's knowledge and well-coordinated responses resulted in efficient mitigation of the problems and timely restoration of nominal spacecraft operations. Furthermore, the experience of working through major anomalies early in the mission provided invaluable experience that enabled the team to handle similar anomalies during the science phase of the mission with even more efficiency.

GP-B is arguably one of the most sophisticated spacecraft ever flown. It incorporated many new technologies—most notably the gyros, their suspension systems, the accompanying SQUID readouts, and the precision-pointing of the spacecraft-fixed telescope—whose debut performance in space occurred during this mission. It is remarkable, and a testament to the preparation, talent, knowledge and skill of the Stanford-NASA-Lockheed Martin development team, that all of these technologies performed exceedingly well on orbit, with some, such as the GSS and SQUID readouts, far exceeding their required performance specifications. Likewise, the GP-B mission operations team was one of the best ever assembled. During IOC, even the most difficult and risky operations, including gyro spin-up, low-temperature bakeout of the excess helium gas, and gyro spin-axis alignment all proceeded smoothly. The one system that required considerable fine-tuning well into the science phase of the mission was the Attitude and Translation Control (ATC) system. Due in large part to solar environment sensitivity of the external Attitude Reference Platform (ARP), on which the ATC's star trackers

were mounted, parameters in the ATC system had to be seasonally adjusted in order for the spacecraft's required precision pointing to be maintained. By April 2005, all of the issues with the ATC had been identified and addressed, and from that time forward, the ATC system performance was quite good.

By the end of IOC in August 2004, GP-B team members had a masterful command and knowledge of the spacecraft's systems and its nuances, and they were well-primed to handle any situation or anomaly that might occur during the ensuing science (data collection) and instrument calibration phases. As it turned out, the helium in the dewar lasted 17 months and 9 days—a month longer than had been anticipated through numerous helium lifetime tests performed throughout the mission by the dewar team. This made it possible to collect science data for 50 weeks, just 14 days shy of the one-year data collection goal, and this was of great benefit to the GP-B science team. In fact the helium lasted long enough for the team to perform many extra calibration tests following the science data collection phase.

During the months after the flight mission, the team performed several feasibility tests of possible post-mission experiments, and then they readied the spacecraft for a hibernation state, from which it can be awakened at any time, in the event that there is interest and funding for post-mission experiments or uses of the spacecraft. (The spacecraft can remain functional in orbit for another ten years or more.)

Following is a list of some of the extraordinary accomplishments achieved by GP-B during the 17 months of its flight mission.

- Over the course of the 17.3-month mission, we communicated with the spacecraft over 4,000 times, and the Mission Planning team successfully transmitted over 106,000 commands to the spacecraft.
- GP-B is the first spacecraft ever to achieve nine degrees of freedom in control. The spacecraft itself maintained three degrees of freedom in attitude control (pitch, yaw, and roll), plus three degrees of freedom in translational drag-free control (front-to-back, side-to-side, and up-down). In addition, the Gyro Suspension System (GSS) for each gyro maintained three degrees of freedom in controlling the location of its spherical rotor within the gyro housing.
- The GP-B gyros, which performed extraordinarily well in orbit, have been listed in the Guinness Database of World Records as being the roundest objects ever manufactured.
- The spin-down rates of all four gyros were considerably better than expected. GP-B's conservative requirement was a characteristic spin-down period (time required to slow down to ~37% of its initial speed) of 2,300 years. Measurements during IOC showed that the average characteristic spin-down period of the GP-B gyros was approximately 15,000 years—well beyond the requirement.
- The magnetic field surrounding the gyros and SQUIDs (Super-conducting QUantum Interference Device) was reduced to  $10^{-7}$  gauss, less than one millionth of the Earth's magnetic field—the lowest ever achieved in space.
- The gyro readout measurements from the SQUID magnetometers had unprecedented precision, detecting fields to  $10^{-13}$  gauss, less than one trillionth of the strength of Earth's magnetic field.
- The gyro suspension system operated magnificently. It had to be able to operate both on the ground for testing purposes prior to launch, as well as in space. This meant that the suspension system had to operate over 11 orders of magnitude—an enormous dynamic control range—and its performance throughout the mission was outstanding.
- The science telescope on board the spacecraft tracked the guide star, IM Pegasi (HR 8703), to superb accuracy, and it also collected a year's worth of brightness data on that star. The brightness data we collected on IM Pegasi represents the most continuous data ever collected on any star in the universe.
- In November 2005, the entire GP-B team was awarded a NASA Group Achievement Award “For exceptional dedication and highly innovative scientific and engineering accomplishments leading to the successful execution and completion of the Gravity Probe B Science Mission.”

## 1.14 The Broader Legacy of GP-B

At least a dozen new technologies had to be invented and perfected to carry out this experiment. For example, the spherical gyros, at  $10^{-8}$  g, are better than ten million times more accurate than the best navigational gyros. The ping-pong-ball-sized rotors in these gyros had to be so perfectly spherical and homogeneous that it took more than 10 years and a whole new set of manufacturing techniques to produce them. They're now listed in the Guinness Database of Records as the world's roundest man-made objects. The SQUIDs are so sensitive that they can digitally detect a gyro tilt of 0.1 milliarcseconds ( $3 \times 10^{-8}$  degrees).

Over its 40+ year life span, spin-offs from the GP-B program have yielded many technological, commercial, and social benefits. For example, GP-B's porous plug for controlling helium in space was essential to several other vital NASA missions, including IRAS (Infrared Astronomical Satellite) and COBE (COsmic Background Explorer). Most important, GP-B has had a profound effect on the lives and careers of numerous faculty and students—graduate, undergraduate and high school—including 79 Ph.D. dissertations at Stanford and 13 elsewhere. GP-B alumni include the first U. S. woman astronaut, an aerospace CEO, and a Nobel laureate.



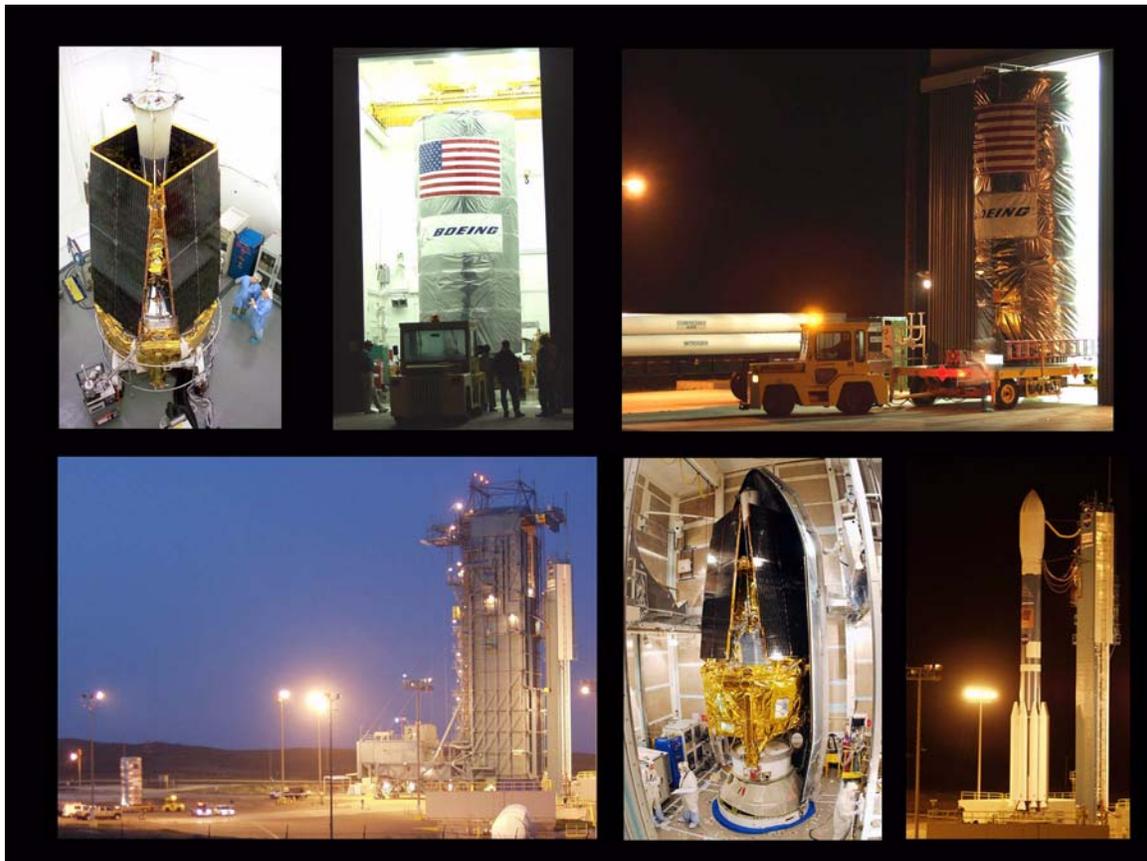
**Figure 1-13.** Stanford GP-B/GPS graduate students and a faculty member pose next to a GPS-controlled tractor (left); Clark Cohen and Brad Parkinson receive awards from the Space Technology Hall of Fame

One interesting GP-B spin-off story is automated precision farming. Under the supervision of GP-B Co-PI Brad Parkinson, centimeter-accurate Global Positioning Satellite (GPS) technology, originally developed for attitude control of the GP-B spacecraft, was re-purposed for other automated guidance and control applications in the early 1990's by Clark Cohen and a group of his fellow GP-B/GPS graduate students at Stanford. After receiving his Ph.D., Cohen founded a company, now Novariant Corporation, to develop precision GPS guidance and control applications, such as an automatic aircraft landing system and automated precision farming. In May 2006, Novariant's Autofarm technology was inducted into the Space Technology Hall of Fame, and individual awards were given to Cohen and several colleagues at Novariant, along with Parkinson and Stanford's GP-B and Hansen Experimental Physics Lab (HEPL) for their role in supporting this technology development.

# A

## Gravity Probe B Quick Facts

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## Gravity Probe B Quick Facts

| <b>Spacecraft</b>     |   |
|-----------------------|---|
| Length                | 6.43 meters (21 feet)   |
| Diameter              | 2.64 meters (8.65 feet)   |
| Weight                | 3,100 kg (3 tons)   |
| Power                 | Total Power: 606 Watts (Spacecraft: 293 W, Payload: 313 W)  |
| Batteries (2)         | 35 Amp Hour   |
| <b>Dewar</b>          |   |
| Size                  | 2.74 meters (9 feet) tall, 2.64 meters (8.65 feet) diameter   |
| Contents              | 2,441 liters (645 gallons) superfluid helium @ 1.8 Kelvin (-271.4°C)  |
| <b>Telescope</b>      |   |
| Composition           | Homogeneous fused quartz  |
| Length                | 35.56 centimeters (14 inches)   |
| Aperture              | 13.97 centimeter (5.5-inch)   |
| Focal length          | 3.81 meters (12.5 feet)   |
| Mirror diameter       | 14.2 centimeters (5.6 inches)   |
| Guide Star            | HR 8703 (IM Pegasi)   |
| <b>Gyroscopes (4)</b> |   |
| Shape                 | Spherical (Sphericity < 40 atomic layers from perfect)  |
| Size                  | 3.81 centimeter (1.5-inch) diameter   |
| Composition           | Homogeneous fused quartz (Purity within 2 parts per million)  |
| Coating               | Niobium (uniform layer 1,270 nanometers thick)  |
| Spin Rate             | Between 5,000 – 10,000 RPM  |
| Drift Rate            | Less than $10^{-11}$ degrees/hour   |
| <b>Launch Vehicle</b> |   |
| Manufacturer & Type   | Boeing Delta II, Model 7920-10  |
| Length                | 38.6 meters (126.2 feet)  |
| Diameter              | 3 meters (10 feet)  |
| Weight                | 231,821 kg (511,077 lbs or 255.5 tons)  |
| Stages                | 2   |
| Fuel                  | 9 strap-on solid rocket motors; kerosene and liquid oxygen in first stage; hydrazine and nitrogen tetroxide in second stage |
| <b>Mission</b>        |   |
| Launch Date           | April 20, 2004  |
| Site                  | Vandenberg Air Force Base, Lompoc, CA   |
| Duration              | 12-14 months, following 60-90 days of checkout and start-up after launch  |
| <b>Orbit</b>          |   |
| Characteristics       | Polar orbit at 640 kilometers (400 miles), passing over each pole every 48.75 min.  |
| Semi-major axis       | 7027.4 km (4,366.8 miles)   |
| Eccentricity          | 0.0014  |

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**Gravity Probe B Quick Facts**

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|----------------------------------|--|
| Apogee altitude                  | 659.1 km (409.6 miles)   |
| Perigee altitude                 | 639.5 km (397.4 miles)   |
| Inclination                      | 90.007°  |
| Perigee Arg.                     | 71.3°  |
| Right Ascension of asc. node     | 163.26°  |
| <b>Measurements</b>              |  |
| Predicted Drift- Geodetic Effect | 6,614.4 milliarcseconds or 6.6 arcseconds ( $1.83 \times 10^{-3}$ degrees) |
| Predicted Drift - Frame-Dragging | 40.9 milliarcseconds ( $1.14 \times 10^{-5}$ degrees)                      |
| Required Accuracy                | Better than 0.5 milliarcseconds ( $1.39 \times 10^{-7}$ degrees)           |
| <b>Program</b>                   |  |
| Duration                         | 43 years from original conception; 40 years of NASA funding                |
| Cost                             | \$750 million dollars  |

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