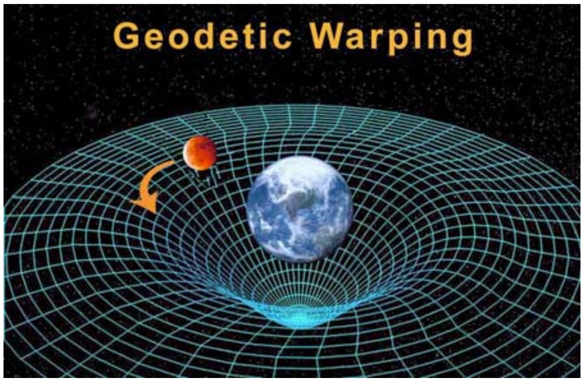
Gravity Probe B

Photos: (Left) Russ Underwood, Lockheed Martin Corporation; (Right) Boeing Corporation

Launch Companion

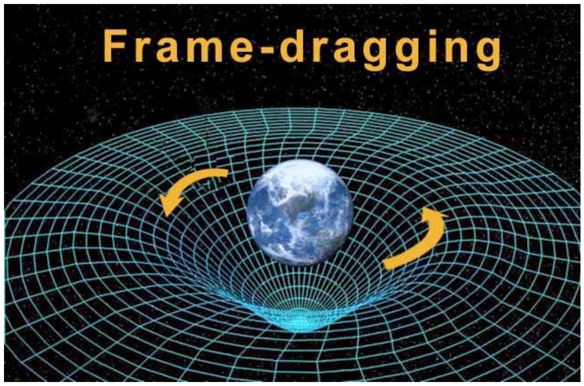
Gravity Probe B in a Nutshell

In 1916, in what has been called one of the most brilliant creations of the human mind, Albert Einstein formulated his general theory of relativity, which stands as one of the foundational theories of modern physics. The stuff of both hard science and science fiction, Einstein's theory weaves together space, time, and gravitation, and predicts such bizarre phenomena as black holes and the expanding Universe, yet it remains arguably the least tested of scientific theories. Now, 88 years later, a team from Stanford University, NASA, and Lockheed Martin is poised to launch the Gravity Probe B spacecraft to measure two of Einstein's oddest predicted effects.



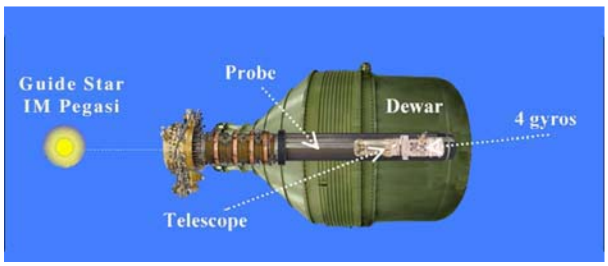
The first of these effects, known as the geodetic or curved spacetime effect, postulates that any body in space warps or curves its local spacetime. This is Einstein's theory that gravity is not an attractive *force* between bodies, as Isaac Newton believed, but rather the product of bodies moving in curved spacetime. One way to visualize this effect is to think of local spacetime as a flat bedsheet and the Earth a bowling ball lying in the middle. The heavy ball warps or puts a dent in the bedsheet, so that a marble (another celestial body) moving along the bedsheet will be inexorably drawn down the warped slope towards the massive ball. The geodetic effect being measured by Gravity Probe B is the amount of the tiny angle by which the Earth is warping its local spacetime.

The other effect, known as "frame-dragging," was postulated by Austrian physicists Josef Lense and Hans Thurring two years after Einstein published his general theory of relativity. It states that as a celestial body spins on its axis, it drags local spacetime around with it, much like a spinning rubber ball in bowl of molasses drags around some of the molasses as it spins.

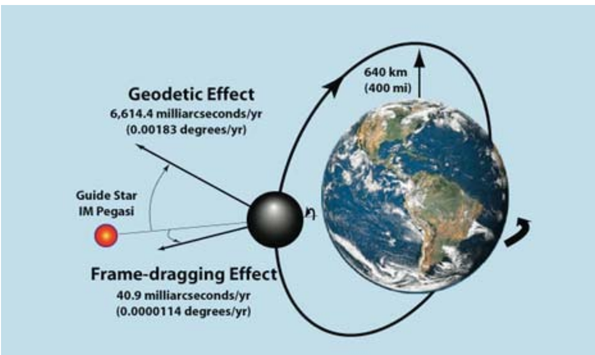


Particularly intriguing, the frame-dragging measurement probes a new facet of general relativity—the way in which space and time are dragged around by a rotating body. This novel effect closely parallels the way in which a rotating electrically charged body generates magnetism. For this reason it is often referred to as the "gravitomagnetic effect," and measuring it can be regarded as discovering a new force in nature, the gravitomagnetic force.

The experiment aboard the Gravity Probe-B spacecraft is designed to measure these effects with unprecedented precision and accuracy. Basically, the spacecraft consists of a polar-orbiting satellite containing four ultra-precise spherical gyroscopes and a telescope—which is like saying that an aircraft carrier consists of a some sophisticated fighter planes and a floating runway. In other words, there's a whole lot more going on.



The gyroscopes must be maintained in a pristine environment, in which they can spin in a vacuum, unhindered by any external forces, magnetic disturbances from Earth, or disturbances from the satellite itself. At the beginning of the experiment, the telescope (and satellite) are aligned with a distant “guide” star. The gyroscopes are aligned with the telescope, so that initially, their spin axes also point to the guide star. The gyroscopes are spun up, and over the course of a year, while keeping the telescope (and satellite) aligned with the guide star, the gyroscopes’ spin axes are monitored to detect any deflection or drift due to the geodetic and frame-dragging relativistic effects.



If the predictions based on Einstein’s theory are correct, the gyroscopes’ spin axes should slowly drift away from their initial guide star alignment—both in the satellite’s orbital plane, due to the curvature of local spacetime, and perpendicular to the orbital frame due to the frame-dragging effect. While physicists believe that the effects of relativity—especially the frame-dragging effect—are enormous in the vicinity of black holes and other massive galactic bodies, around a small planet like Earth, these effects are barely noticeable. For example, the predicted angle of spin axis deflection due to the frame-dragging effect corresponds to the width of a human hair as seen from 1/4 mile away!

When Stanford physicist Leonard Schiff (and independently, George Pugh at the Pentagon) first proposed this experiment in 1960, America had just created NASA, launched its first satellite, and entered the space race. Landing men on the Moon was still 10 years away. At the time, this experiment seemed rather simple, but it has taken over four decades of scientific and technological advancement to create a space-borne laboratory and measurement instrument sophisticated and precise enough to quantify these minuscule relativistic effects.

Gravity Probe-B’s measurement of the geodetic effect, the larger of the two, will be to an accuracy of 0.01%, which is far more accurate than any previous measurements, and will provide the most precise test ever of general relativity. The frame-dragging effect has never directly been measured before, but Gravity Probe-B is expected to determine its accuracy to within 1%.

At least nine new technologies had to be invented and perfected in order to carry out the Gravity Probe B experiment. The spherical gyroscopes have a stability more than a million times better than the best inertial navigation gyroscopes, and the magnetometers, called SQUIDs (Super-Conducting Quantum Interference Devices), that monitor the spin axis direction of the gyroscopes, can detect a change in spin axis alignment to an angle of approximately 1/40,000,000th of a degree. These advances were only possible through GP-B’s unique combination of cryogenics, drag-free satellite technology and new manufacturing and measuring technologies.

Over its 40+ year lifespan, spin offs from the Gravity Probe B program have yielded many technological, commercial, and social benefits. The technological benefits include cryogenic products used in other NASA missions, Global Positioning Satellite (GPS) products used in aviation and agriculture, optical bonding and fused quartz technologies that have commercial applications, and photo diode detectors that have ramifications for digital camera improvements.

Less tangible, but perhaps most important, the Gravity Probe B program has had a profound effect on the lives and careers of numerous faculty and students—both graduate and undergraduate, and even high school students, at Stanford University and other educational institutions. Nearly 100 Ph.D. dissertations have been written on various aspects of this program, and GP-B alumni include the first woman astronaut, the CEO of a major aerospace company, professors at Harvard, Princeton, Stanford and elsewhere, and a recent Nobel Laureate in Physics.

Gravity is the most fundamental force in nature; it affects all of us all the time. But, gravity is still an enigma—we don't completely understand it. Einstein's 1916 general theory of relativity forever changed our notions of space and time, and it gave us a new way to think about gravity. If the Gravity Probe-B experiment corroborates the two predictions of general relativity, then we will have made the most precise measurement of the shape of local spacetime, and confirmed the mathematics of general relativity to a new standard of precision. If on the other hand, the results disagree with Einstein's theoretical predictions, then we may be faced with the challenge of constructing a whole new theory of the universe's structure and the motion of matter. Whatever the result, Gravity Probe B will provide us another glimpse into the sublime structure of our universe.

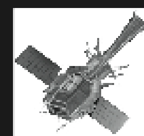
Gravity Probe B Quick Facts

Spacecraft	
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
Dewar	
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)
Telescope	
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)
Gyroscopes (4)	
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
Launch Vehicle	
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
Mission	
Launch Date	April 19, 2004
Site	Vandenberg Air Force Base, Lompoc, CA
Duration	12-14 months, following 40-60 days of checkout and start-up after launch
Orbit	
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
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°
Measurements	
Predicted Drift-Geodetic Effect	6,614.4 milliarcseconds or 6.6 arcseconds (1.83×10^{-3} degrees)
Predicted Drift - Frame-Dragging	40.9 milliarcseconds (1.14×10^{-5} degrees)
Required Accuracy	Better than 0.5 milliarcseconds (1.39×10^{-7} degrees)
Program	
Duration	43 years from original conception; 40 years of NASA funding
Cost	$700 million dollars

The History of Gravity Probe B

2010

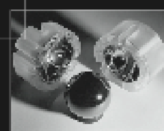
2005
GP-B flight concludes; analysis begins



2004
Gravity Probe B launches from Vandenburg AFB

2000

1999
World's roundest gyroscopes are flight- ready



1992
Purified fused quartz delivered to GP-B

1990

1980
NASA Rosendhal Committee confirms GP-B technological readiness

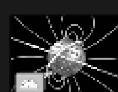
1980

In the first two decades of the 20th century, Albert Einstein presented his theories of relativity, which revolutionized our understanding of the structure of space. Central to these theories was the idea that the motion of moons and planets is directed by the curve of spacetime. Soon after two physicists concluded that spacetime must be "twisted" by the rotation of planets and stars.

In 1960, Stanford University physicist Leonard Schiff (and, independently, Defense Department physicist George Pugh) suggested that the presence of local spacetime could be "seen" by using a gyroscope. Four decades later, this concept is coming to fruition and scientists will be able, for the first time, to see direct empirical evidence of the curve of spacetime.

1973
NASA funds flight mission "Gravity Probe B"

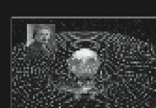
1970



1964
NASA funds GP-B technology development

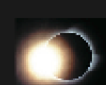
1960

1958
NASA created by Eisenhower



1920

1919
Einstein's "starlight deflection" confirmed



1916
Einstein publishes General Theory of Relativity

1918
Lense & Thirring predict "frame-dragging"

1910

1905
Albert Einstein publishes Special Theory of Relativity

1900

The Space Vehicle

All of the Gravity Probe B technologies are integrated into one of the most elegant and sophisticated satellites ever to be launched into space. Over four decades in development, the GP-B space vehicle is a marvel of engineering and truly a beautiful sight to behold.

From it largest to smallest parts, it is filled with the cutting edge technologies and materials described in the previous section, many of which were invented specifically for use in the Gravity Probe B mission.

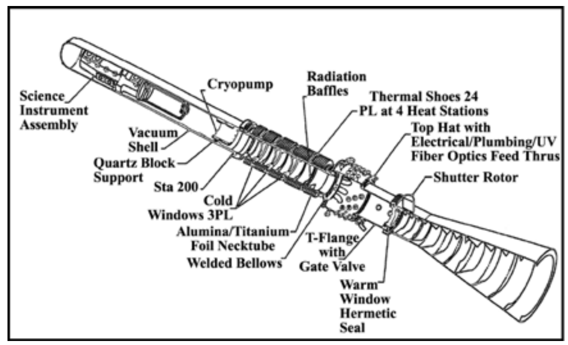
Inside the Dewar

A Dewar is a sophisticated Thermos bottle for holding cryogenic liquids. The Gravity Probe B Dewar will be one of the largest and most sophisticated ever put into space. It is nine-feet tall and forms the main structure of the space vehicle. The vacuum area just inside the Dewar's shell contains multiple reflective surfaces that cut down on heat radiation. The Dewar also contains vapor-cooled metal shields that help maintain its internal cryogenic temperature and slosh baffles that help suppress tidal motions in the superfluid helium inside. When cooled to almost absolute zero temperature, liquid helium transforms into a state called "superfluid," in which it becomes a completely uniform thermal conductor. Only helium exhibits this, and other special properties of superfluidity.

Inside the neck area of the Dewar is a doughnut-shaped tank called the "guard tank." Once the Dewar has been conditioned for launch—an iterative process of successive evacuations and fills that transforms the liquid helium inside the Dewar to the superfluid state—the guard tank keeps the Dewar supercooled for weeks, without the need for additional conditioning, while the space vehicle is being readied for launch.

Science Instrument Assembly—Quartz Block and Telescope

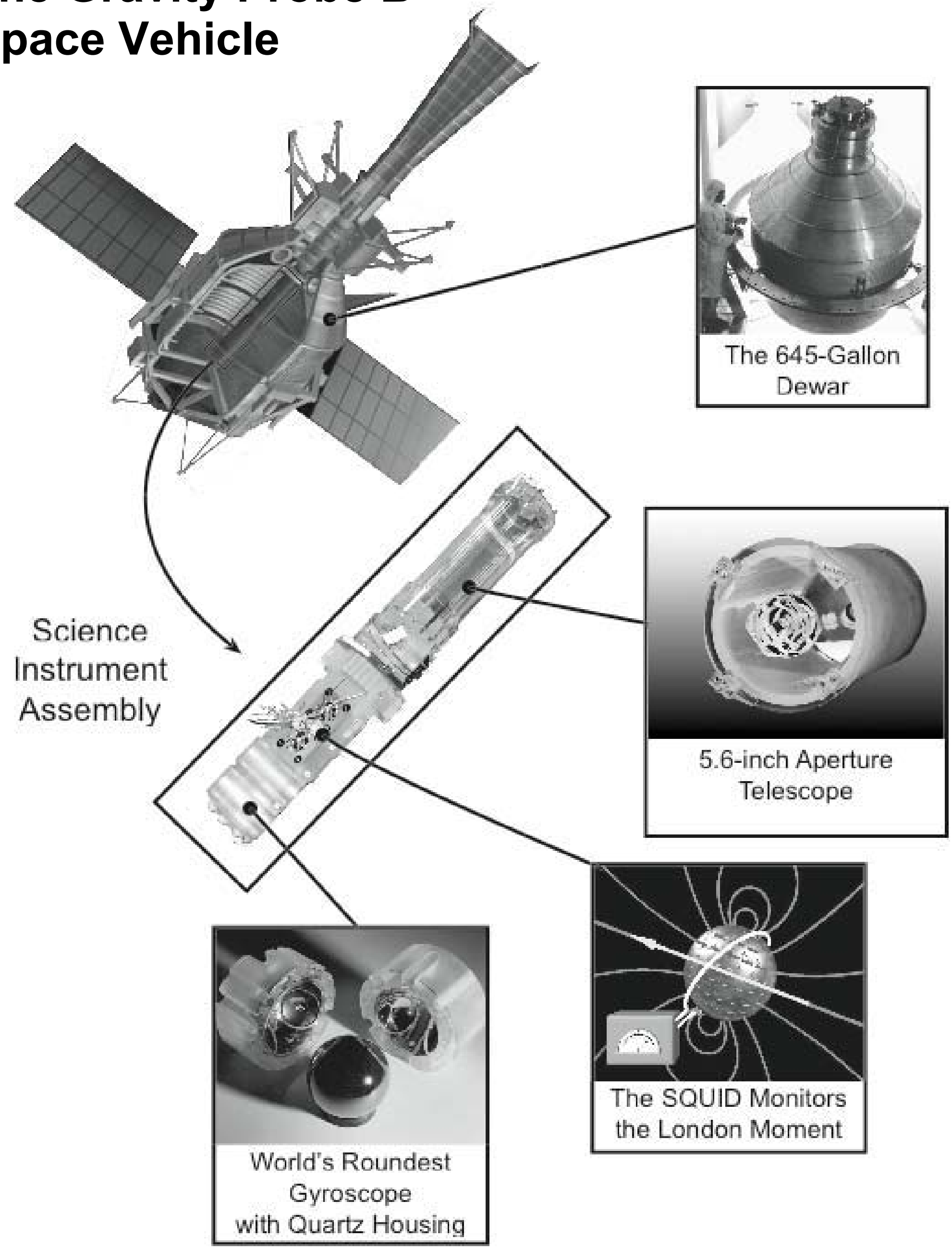
The Science Instrument Assembly (SIA) contains the quartz block and the telescope. The SIA is located at the center of mass of the Dewar, along its main axis. It is mounted inside a vacuum canister called the probe (described in the next section).



The quartz block houses the four gyroscopes and SQUID readout instruments (Super Conducting Quantum Interference Devices—the magnetometers that read the gyroscopes' spin axis orientation). Each gyroscope is enclosed in a quartz clamshell housing, mounted in the quartz block and surrounded by antimagnetic shielding. The gyroscopes are electrically suspended with only 0.001 inch clearance from the housing walls, and they spin at up to 10,000 rpm during the science phase of the mission.

Optically bonded to the top of the quartz block is the quartz reflecting Cassegrain astronomical telescope, which focuses on the guide star, IM Pegasi. Optical bonding is a patented method of fusing together quartz parts, without the use of any "glue" or fasteners to ensure that the SIA does not distort or break when cooled to cryogenic temperatures. The line of sight of the telescope is rigidly aligned to the SQUID readout loop of each gyroscope. As such, the quartz telescope provides the frame of reference for measuring any drift in the spin axis of the gyroscopes.

The Gravity Probe B Space Vehicle



The Probe

The SIA is mounted in a cigar-shaped canister, called the "probe," which is inserted into the Dewar. The probe is an amazing feat of cryogenic engineering, designed by Lockheed Martin Space Systems in Palo Alto, California. It provides both mechanical and structural stability for the SIA. The probe is designed to provide a free optical path for the telescope to view distant space through a series of four windows, mounted in its upper section. These windows also serve to reduce thermal conductivity into the Dewar.

The inside of the probe is maintained at an extremely high vacuum—much greater than the vacuum of space. The probe is surrounded by a superconducting lead bag between it and the Dewar. The superconducting lead bag provides an impenetrable shield from electromagnetic signals that could disturb the gyroscopes.

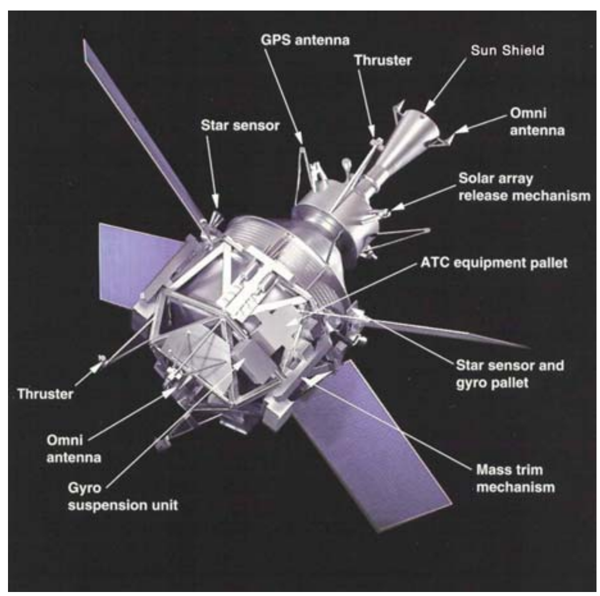
Taken together, all of these measures create an ultra pristine, cryogenic environment, free of any external forces or disturbances, in which the gyroscopes spin.

At the upper end of the probe, capping off the Dewar, is the "top hat." The top hat serves as a thermal interface for connecting over 450 plumbing and electrical lines, that run from various electronics and control systems, mounted on the space vehicle's truss system outside the Dewar, to the cryogenic vacuum chamber inside the probe and Dewar.

Before Gravity Probe B was completely integrated, each component went through years of testing and construction. Some parts even had to be de-constructed and rebuilt. The entire probe was assembled in a Class-10 clean room, as any particles larger than a single micron would disrupt the precise structure.

Outside the Dewar

Outside the Dewar are all of the systems that provide power, navigation, communication, and control of the space vehicle.



Sun Shield

The sun shield is a long, conical tube that keeps stray light from entering the telescope. Inside the sun shield are a series of black, metal baffles that absorb incoming stray light before it can reach the telescope. In addition to blocking out stray light from the Sun, the sun shield also blocks stray light from the Earth, Moon, and major planets.

Proportional Micro Thrusters

The proportional micro thrusters on the space vehicle provide a very means of controlling its attitude or orientation in space. In the case of Gravity Probe B, an unprecedented amount of on-orbit control is required for the vehicle to maintain its drag-free orbit. This is accomplished by harnessing the helium gas that continually evaporates from the Dewar's porous plug and venting it as a propellant through eight pairs of opposing or balanced proportional micro thrusters.

These micro thrusters continually meter out a flow of helium gas—at the rate of about $1/100^{th}$ the amount of a human "puff" exhalation that one might use to clean eyeglasses. This metered flow of helium keeps the space vehicle's center of mass balanced around one of the gyroscopes, called a "proof mass"—a predetermined test mass that serves as a reference for measurement. The thrusters are set up in pairs, so that they counterbalance each other. As long as the same amount of helium is flowing from two opposing thrusters, the space vehicle will not change its position along that axis. However, if the telescope or the SQUID readout for the proof mass gyroscope requires the space vehicle's position to change, it is simply a matter of unbalancing the flow, ever so slightly, in the appropriate thruster pair to move the vehicle in the desired direction. These proportional micro thrusters also control the roll rate of the GP-B space vehicle.

Solar Arrays

Solar arrays convert energy from the Sun into electrical power that is stored in the space vehicle's two batteries and then used to run the various electrical systems on board. The position of each solar array can be controlled to maximize its power output.

GPS Sensors & Antennae

GPS (Global Positioning System) sensors calculate and transmit information about the space vehicle's position. In the case of the Gravity Probe B space vehicle, the number and placement of the GPS sensors provide positioning information that is over 100 times more accurate than traditional ground-based GPS navigation systems. For example, a high quality handheld GPS sensor on Earth can locate your position to within about a meter, whereas the GPS sensors onboard the GP-B space vehicle can locate its position to within a centimeter.

Telemetry & Communications Antennae

These antennae enable both inbound and outbound communications with the space vehicle—this includes communications with ground stations and with orbiting communications satellites in the Tracking Data Relay Satellite System (TDRSS). Telemetry data from the space vehicle and science data from the experiment are transmitted to ground stations using these communications systems. These systems also enable the GP-B Mission Operations Center (MOC) to send daily batches of commands to the space vehicle. Communications between the space vehicle and orbiting satellites is limited to a 2K data format, whereas communications with ground stations uses a 32K data format, enabling far more data to be transmitted per unit of time.

Star Trackers

A star tracker is basically a camera and pattern matching system that uses constellations and stars to determine the direction in which a satellite is pointing. The Gravity Probe B satellite contains two star trackers—one wide field and one narrow field (called the star sensor). The wide field star tracker is used to locate the general region of the heavens containing the guide star, and then the narrow field star tracker helps align the space vehicle with the guide star.

The Gravity Probe B on-board telescope basically performs the same function, but it uses a different technique, and it is orders of magnitude more precise and more accurate. The narrow field star tracker has a field of view on the order of one degree (60 arcminutes), and it can focus to a position within perhaps one arcminute—about the same as the whole field of view of GP-B on-board telescope, which can pinpoint the guide star's position to within a milliarcsecond.

With such a small field of view, it would be nearly impossible to locate the guide star using only the onboard telescope, so the star trackers function like “spotting scopes” for initially pointing the space vehicle towards the guide star. Once the narrow field star tracker has focused on the guide star, the onboard telescope takes over the job of maintaining the precise alignment required for measuring gyroscope drift.

Navigational Gyroscope

GP-B uses a standard, flight-qualified gyroscope, equivalent to those found on other spacecraft (and also airplanes, ships, and other vehicles). This gyroscope is not part of the relativity experiment, but rather it is part of the general navigation system used for monitoring the general direction and position of the space vehicle.

Electro-mechanical Control Systems

Surrounding the Dewar, is a lattice of trusses that forms the structure of the space vehicle. Attached to these trusses are a number of electrical and mechanical systems that control the operation of space vehicle and enable the relativistic measurements to be carried out. These control systems include the following:

- **Attitude Control System (ATC)**—Controls all of the proportional micro thrusters that determine and maintain the space vehicle’s precise positioning.
- **Mass Trim Mechanism (MTM)**—A system of movable weights that can be adjusted during flight to restore 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. The GSS control boxes are mounted in the truss work, outside the Dewar. The wiring goes through the top hat section of the probe and down to each gyroscope.
- **Gas Management Assembly (GMA)**—A very complex set of valves, pipes, and tubing, that runs from a triangular assembly on the truss work, through the top hat and down the probe to each of the gyroscopes. The critical job of the GMA is 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.
- **Experiment Control Unit (ECU)**—The ECU controls many of the systems onboard the space vehicle, including the GMA, the UV system, and various thermal devices.

The Mission

The GP-B Space Vehicle will be launched from the Vandenberg Launch Facility at Vandenberg Air Force Base (VAFB) in California. GP-B will be launched on a Delta II 7920-10 rocket from launch pad SLC-2W into a polar circular orbit of 640 km (400 mile) altitude. The Space Vehicle is launched with the Command/Control Computer Assembly, Command and Data Handling subsystem, and Attitude Control Electronics powered on; command and telemetry links should be established from the Mission Operations Center (MOC) at Stanford University as soon as the fairing separates—about 5 minutes after launch. The Launch Vehicle will release the Space Vehicle in the desired attitude and at the desired roll rate. Solar arrays are deployed soon after launch.

The Space Vehicle is configured for science mission operations during the Initial Orbit Checkout (IOC) phase, which is scheduled for the first 40-60 days after launch. Many important things happen during IOC. Subsystem boxes are powered on and verified. As soon as the orbit is determined, the Attitude and Translation Control subsystem (ATC) is commanded to begin making the necessary orbit corrections. The low thrust of the propulsion system requires that corrections be started as soon as possible so that the correction doesn’t delay the start of the science mission. The attitude is confirmed using the telescope. The science gyros are turned on and SQUIDs tested. The drag free operation of the spacecraft is tested and verified, and the spacecraft is balanced using the mass trim mechanisms. Calibrations are made, and the gyros are spun up. The orbit is finalized, the spacecraft rebalanced, and gyros are then precisely set for nominal science operations. The 60-day initialization schedule contains 20 days of contingency, and funding allows for an additional 15 days if required.

Once the spacecraft and payload are configured, with the gyros suspended and spinning, and the ATC autonomously providing attitude and drag-free orbit control, the science mission begins. Nominally three to four Ground Network tracks per day will allow a daily upload to the flight computer to control the spacecraft and payload configuration and return data. Occasional data base updates may be made. The space Network TDRSS will provide two passes a week for orbit determination and as required for contingency operations.

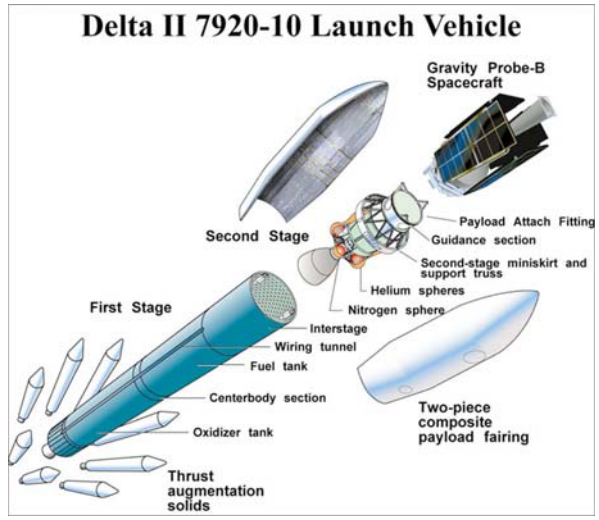
When it is determined that there is only a 1-2 months of helium left to maintain the required superconducting temperatures, the mission will shift to the post science calibration phase. During this phase, recalibrations will be performed and intentional disturbances will be introduced to ensure that the flight data is well understood and valid. The nominal total mission time is 18 months.

Launch Site & Vehicle

The spacecraft will be launched from Vandenberg Air Force Base, CA, on a Delta II 7920-10 launch vehicle. Overall, the rocket is 38.6 meters (126.5 feet) long, 3 meters (10 feet) in diameter and weighs 231,821 kilograms (511,077 pounds or 255.5 tons). It has nine strap-on solid rocket motors. The Delta's first stage burns kerosene and liquid oxygen propellant, and produces 890,000 newtons (200,000 lbs.) of thrust. The second stage burns hydrazine and nitrogen tetroxide propellant, producing a thrust of 43,400 newtons (9,750 pounds).

Launch Period

The daily launch period opens on Monday, April 19, 2004. If launch does not take place then, GP-B can be prepared to launch on two consecutive days, but needs each third day for re-servicing of its helium guard tank. Launch opportunities from April 19-21 will use an inclination of 90.011 degrees; from April 22-30, the inclination would be 90.007. Both inclinations are almost due South.



Daily Launch Time

There is one 1-second launch opportunity each day during the launch period. On April 19, the launch time is at 10:01:20 a.m. PDT. (On April 20 and later, the launch time is earlier by almost 4 minutes a day.

Television Coverage

The Delta rocket will carry two video cameras, which will record the separation of the 2nd stage of the launch vehicle from the GP-B Space Vehicle.

Mission Operations

Mission operations will be conducted from the Gravity Probe B Mission Operations Center (MOC), located in the Gravity Probe B building at Stanford University, Stanford, California. Spacecraft communications will be conducted through NASA's Space Network (TDRSS).

Mission Time Line

This mission time line is divided into four main phases:

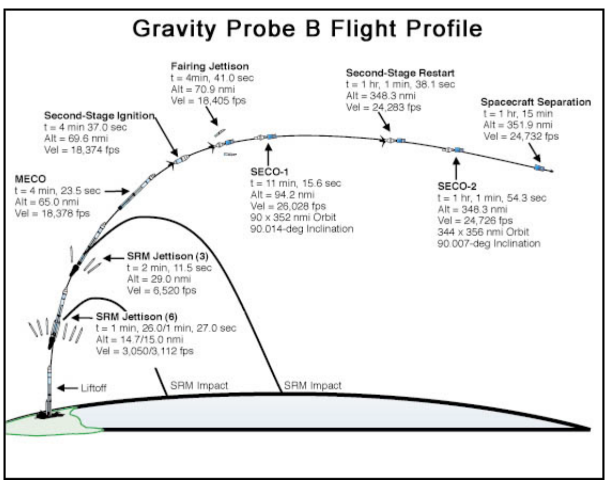
1. Launch and Early Orbit (L&EO) Phase
2. Initialization and Orbit Checkout (IOC) Phase
3. Science Phase
4. Post-science Calibration Phase.

Each of these phases is described in more detail below.

Launch and Early Orbit Phase

This phase covers the period of time immediately prior to launch through the first day of flight operations. The Gravity Probe B space vehicle will lift on a Delta II 7920-10 rocket from launch pad SLC-2W at Vandenberg AFB, CA. Into a polar circular orbit of 640 km (400 mile) altitude.

The Delta's main engine cutoff will occur at about 263 seconds. The second stage engine will ignite about 277 seconds, and cut off for the first time at about 11 minutes after launch. After coasting, the second stage will restart at launch plus about 62 minutes, and will burn for about 16 seconds. At 75 minutes after launch, the Gravity Probe B Space Vehicle will separate from the second stage. The second stage will perform a maneuver to move away from the Space Vehicle to avoid future contact and possible contamination. After separation from the second stage, the Space Vehicle will orient itself towards the guide star.



The Mission Operations Center (MOC) at Stanford University will be able to command and monitor telemetry from the space vehicle at VAFB. The baseline plan is for the pre-launch stored program commands and launch time to be loaded by the computers at the launch site, with telemetry monitoring at the MOC. As soon as the fairing separates, the stored program commands will power on the space vehicle transmitter, starting a telemetry link through a tracking data relay satellite (TDRS) to the MOC. Commanding is also possible at this time, if required.

The nominal timeline below summarizes the main events of the launch/ early orbit phase.

Gravity Probe B — Launch & Early Orbit Nominal Timeline

Time from Launch	Event
0	Launch on Delta II at VAFB
48 sec	Maximum Dynamic Pressure
1 min 26-27 sec	First 6 solid rocket booster motors separate
2 min 12 sec	Last 3 solid rocket booster motors separate
4 min 24 sec	Main Engine Cutoff (MECO)
4 min 31 sec	Stage II separates from Stage I
4 min 37 sec	Stage II ignition
4 min 41 sec	Jettison Fairing
5 min 5 sec	Power on star sensors; set Attitude Control (ATC) I/O directives
11 min 16 sec	First Cutoff — Stage II (SECO-1)
1 hr 1 min 38 sec	Stage II Restart Ignition (orbit circularization)
1 hr 1 min 54 sec	Second Cutoff — Stage II (SECO-2)
1 hr 6 min 50 sec	Begin solar panel deployment
1 hr 11 min 40 sec	End solar panel deployment
1 hr 15 min 0 sec	GP-B Spacecraft separation from Stage II
1 hr 15 min 1-42 sec	Stage II Retro
1 hr 16 min 37 sec	Begin attitude capture
1 hr 17 min 32 sec	Enable survival heaters for battery, ECU, SRE, & GSS
1 hr 26 min 43 sec	GPS Side A/B power on
1 hr 31 min 45 sec	Third Cutoff — Stage II (SECO-3)
1 hr 38 min 20 sec	Restart 3 — Stage II
1 hr 44 min 19 sec	Aft SQUID Readout Electronics (SRE) power on
1 hr 57 min 18 sec	Electronic Control Unit A (ECU-A) power on
5 hr 0 min 6 sec	Proton Monitor on
5 hr 9 min 6 sec	Telescope Detectors on
6 hrs 33 min 28 sec	Gyro Suspension System 2 (GSS-2) power on

Initialization and Orbit Checkout (IOC) Phase

The IOC phase is planned to last between 40 and 60 days. Payload activities during this phase of the mission include calibration and measurements of on-orbit performance of the payload instrumentation and uncaging, levitation, and a slow spin (~1 Hz) of the gyroscopes. Spacecraft activities include deployment of the solar arrays, acquisition of the guide star, and final orbit trim. During this phase extensive testing of the on-orbit performance will require frequent commands to the spacecraft and careful evaluation of the telemetry. The initialization phase will conclude when the gyroscopes are spun up to full speed and aligned with the satellite roll axis and the satellite is commanded to its main science phase roll rate. The table below provides a nominal timeline of the IOC activities.

Gravity Probe B — Nominal Timeline of IOC Activities

Time From Launch	Activity
2 hours	Dewar vent, Orbit Acquisition (Completion of task)
1 day	Start Orbit trim (Completes many days later)
2 days	Power-On and Set-Up Of Payload Electronics Boxes
2 days	Flux lock SQUIDs
2 days	Guard tank runs out of helium
2 days	Acquire guide star (Confirmation: 4 days)
3 days	Drag Free (Gyro #2 acts as “proof mass”)
8 days	Gyro checkout: Low voltage on 4 gyros, High voltage gyro 3
10 days	Start Dewar pressure control
18 days	Mass Trim Sequences (balancing vehicle) Completed
18 days	Space Vehicle Spin Up & Helium Bubble Wrap
20 days	Trapped flux measurement/reduction/re-measurement
22 days	1 Hz spin all gyros (plus High Voltage check gyros 1, 2, 4)
23 days	5 Hz spin gyros 3, 4
31 days	Gyro health check, practice spin alignment & post science calibrations completed
32 days	5 Hz spin gyros 1, 2
36 days	High speed spin gyros 4, 3, 1, 2
38 days	Spin axis alignment polarity
43 days	Spin axis alignment completed
43 days	Low Temperature Bakeout
44 days	Transition to Science Phase of Mission

Following is a more detailed description of the main IOC activities.

Orbit Trim Maneuver (L+1 Day)

Because the launch vehicle does not place the space vehicle exactly into the orbit plane required for the science phase of the mission, it will be corrected during IOC. Ground generated command parameters will be used to automatically command thruster firings. The orbit trim process includes review of orbit data as determined by Doppler and GPS data, calculation of the required parameters for the orbit trim flight software, transmission of these parameters, and initiation of the automatic orbit trim maneuver. For large (3-sigma) launch errors, the time required to correct planar errors may be the longest activity in the IOC phase, so an early determination of the launch orbit and initiation of its correction will be important. Nominally, orbit correction sequences are expected to begin within 24 hours after achieving orbit. A one-sigma error can be corrected in 10-14 days.

Guide Star Acquisition (L+2 Days)

About 24 hours after launch, the flight software automatically begins the process of acquiring the guide star. No real-time commanding or special telemetry requirements are expected to complete this activity, although the sequence can be broken into steps requiring initiation commands from the ground, if required. Guide star acquisition consists of determining the initial attitude using the star sensors, measuring gyro biases, performing a course attitude maneuver using thrusters, and then refining the attitude based on data from the onboard science telescope.

Mass Trim Sequences (Completed L+18 Days)

After launch, the center of mass and products of inertia of the space vehicle can be corrected by moving some or all of the seven mass trim mechanisms (MTM). The process to operate the MTMs includes analysis on the ground of ATC data (to see what forces and torques are required to hold attitude), generation of commands, and then execution of special mass trim sequences. The baseline timeline shows several MTM events throughout the IOC period to allow refinement of the mass properties, beginning with a coarse trim on day 6. Final mass trim cannot be completed until the vehicle is operating in drag-free mode. It is expected that mass trim refinements will be required occasionally throughout the mission as helium is depleted or thermal properties change.

Space Vehicle Spin Up / Helium Bubble Wrap (Completed L+18 Days)

The space vehicle is separated from the launch vehicle rolling at 0.1 rpm. During IOC the roll rate is sequentially increased to 1.0 rpm for two reasons:

1. Get better insight into adjusting the Mass Trim Mechanisms (MTM)
2. Mass balance the space vehicle by wrapping the liquid helium bubble uniformly around the Dewar chamber.

The space vehicle is then spun down to 0.6 rpm for the first gyro spin up interval. Just prior to commencing the science phase of the mission, the final roll rate will be determined and set (the value is expected to be between 0.3 rpm and 1.0 rpm).

Drag Free Operations (Starts L+ 3 Days)

Drag free operations are practiced beginning on Day 3 of IOC. Towards the end of IOC, the vehicle is commanded to fly drag free for the duration of the science phase of the mission. There is no real-time commanding required for this process. The Attitude Control Electronics (ACE) uses position data from science gyro #2, which has been designated as a "proof mass," and commands the thrusters to maneuver the vehicle to maintain this gyro in the center of its housing.

Gyro Spin Up (Starts L+22 Days)

Spinning up the Gravity Probe B gyroscopes is a delicate and complex process that requires more than half of the IOC mission phase. Each of the four science gyros undergoes a series of four spin-up and testing sequences, gradually increasing its speed to the final spin rate required for the science phase of the mission.

The first spin up sequence involves using the Gyro Suspension System (GSS) to levitate and position each gyro—one at a time—in its nominal spin up position. For each gyro, the Gas Management Assembly (GMA), which flows ultra pure helium gas through the spin up channel in one half of the gyro's housing, is operated; however no gas is flowed over the gyro during this first spin up sequence.

The second spin up sequence repeats the first one; however in this case, a small amount of gas is flowed over each of the gyros—again, one at a time. This results in each gyro reaching a spin rate of approximately 1 Hz (60 rpm).

In the third spin up sequence, the GMA flows a somewhat larger amount of helium gas over each gyro, resulting in a spin rate of approximately 5 Hz (300 rpm).

The fourth and final spin up sequence increases the gyro's spin rate to full speed. This requires the GMA to flow helium gas over each gyro continually, for a period of 1-2 hours. At the conclusion of this sequence, each gyro will be spinning at up to 150 Hz (9,000 RPM).

Spin Axis Alignment (Starts L+38 Days)

After gyro spin up, the spin axis direction of each gyro must be closely aligned to the guide star. This is accomplished by torquing or twisting the rotor in a methodical manner, using the Gyro Suspension System (GSS) electronics. There are two phases to this alignment process—coarse and fine. During the coarse alignment, as much as one degree of spin axis orientation correction is achieved. The fine axis alignment then provides the final orientation accuracy of better than 10 arcseconds relative to the guide star.

Low Temperature Bakeout (L+43 Days)

Also following gyro spin up, is the low temperature bakeout process. The gyro spin up process leaves residual helium gas in and around each of the science gyros. If not removed, this helium would reduce the accuracy of the experimental data collected during the Science Phase of the mission. The low temperature bakeout process involves applying a *very* mild heat cycle to the Science instrument Assembly, briefly raising its temperature from 1.8 Kelvin to approximately 7 Kelvin. The net effect of this procedure is to remove nearly all of the residual helium. A cryogenic pump, comprised of sintered titanium in a sponge-like form, getters the remaining helium from the gyro housings. After low temperature bakeout, the SIA temperature is restored to 1.8 Kelvin.

Science Phase

After the gyroscopes are spun up to full speed, the mission enters a phase where the essential science data are collected. During this period there will be a minimal number of commands sent to the satellite, and the acquisition and telemetry of the data will follow a routine pattern. The telemetry during this phase will include health and safety data, basic science data, and additional data necessary for the evaluation of potential systematic experimental errors This phase is expected to last between 13 and 15 months.

Post-Science Calibration Phase

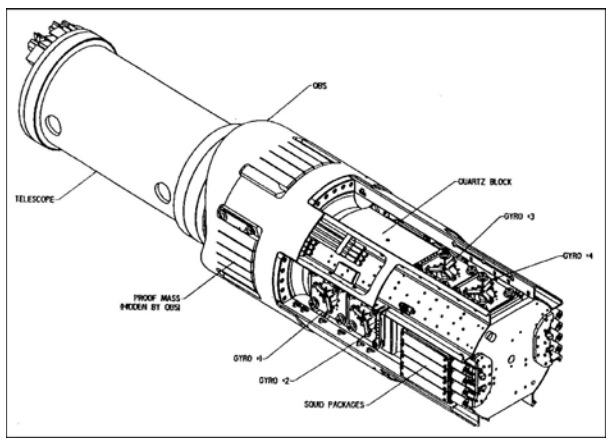
An essential part of the mission is the post-science calibration phase where the disturbing torques on the gyroscopes and potential systematic measurement errors are deliberately enhanced. During this period, commands will be sent to the satellite more frequently. The information collected during this period will be used to place limits on the systematic experimental errors. This phase is expected to last between two and three months. Measurement of the remaining superfluid helium will be used to time the transition from the Science Phase to the Calibration Phase.

The Amazing Technology of GP-B

To test Einstein's theory of general relativity, Gravity Probe B must measure two minuscule angles with spinning gyroscopes, floating in space. While the concept of Gravity Probe B is relatively simple in design, the technology required to build it is some of the most sophisticated in the world. Scientists from Stanford University, NASA's Marshall Space Flight Center, and Lockheed Martin Space Systems have drawn from a diverse array of physical sciences, and have invented much of the technology that makes the mission possible. In fact, much of the technology did not even exist when Leonard Schiff (and independently, George Pugh) conceived of the experiment in the early 1960's.

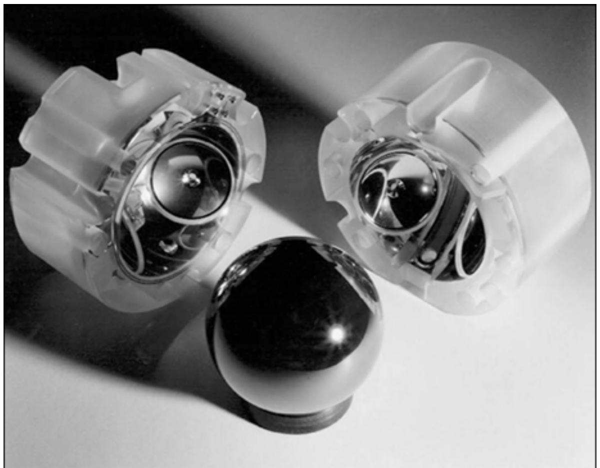
The GP-B Science Instrument

The Gravity Probe B science instrument takes the shape of a long rectangular block with four gyroscopes lined up behind a telescope that peers out the top of the Gravity Probe B satellite. Each gyroscope is suspended in a quartz housing, surrounded by a metal loop connected to a SQUID magnetometer (Super Quantum Interference Device) to monitor its spin axis orientation. The fused quartz gyroscopes sit in a fused quartz block that is bonded to the fused quartz telescope. These three components make up the Science Instrument Assembly (SIA).



World's Most Perfect Gyroscopes

To measure the minuscule angles that Leonard Schiff predicted— 6,614.4 milliarcseconds (6.6 areseconds) per year and 40.9 milliarcseconds per year— Gravity Probe B 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. This was an especially stiff challenge, given that the spin axes of all gyroscopes tend to drift slightly while they are spinning. Even the spin axis drift in the most sophisticated Earth-based gyroscopes, found in missiles and jet airplanes, is seven orders of magnitude greater than GP-B could allow.



Gravity Probe B gyroscope (rotor), with quartz housing halves.

Each glass-like rotor is coated with a sliver-thin layer of niobium, a superconducting metal. Inside each housing, six electrodes electrically suspend the gyroscope, allowing it to spin freely at up to 10,000 rpm. Channels are cut in the quartz housing to allow helium gas to start the rotor spinning. A wire loop, embedded in the housing, acts as a SQUID (Superconducting Quantum Interference Device) to detect any change in direction of the gyroscope's spin axis.

Three physical characteristics of a gyroscope can cause its spin axis to drift:

1. An imbalance in mass or density distribution inside the gyroscope
2. An uneven, asymmetrical surface on the outside of the gyroscope causing air friction
3. Friction between the bearings and axle of the gyroscope.

This means the GP-B gyroscope has to be perfectly balanced and homogenous inside, cannot have any rough surfaces outside, and must be free from any bearings or supports.

After years of work and the invention of numerous new technologies, the result is a homogenous 1.5-inch sphere of pure fused quartz, polished to within a few atomic layers of perfectly smooth. It is the most spherical object ever made, topped in sphericity only by neutron stars.

Inside, the gyroscope is solid fused quartz. It was carved out of a pure quartz block grown in Brazil and then baked and refined in a laboratory in Germany. Its interior parts are all identical to within two parts in a million.

On its surface, the gyroscope is less than three ten-millionths of an inch from perfect sphericity. This means that every point on the surface of the gyroscope is the exact same distance from the center of the gyroscope to within 0.0000003 inches.

Here are two ways to imagine how smooth this is. First, compare the GP-B gyroscope's smoothness with another smooth object—a compact disk. CD's and DVD's both appear and feel incredibly smooth. The pits on the compact disk's surface, which carry the digital information, are less than 4/100,000ths of an inch deep (one millionth of a meter). However, compared to the GP-B gyroscope, the surface of a CD is like sandpaper. The bumps and valleys on the surface of the GP-B gyroscope are 100 times smaller than those on a CD. Viewed at the same magnification, one could barely see any imperfections on the gyroscope's surface.

Alternatively, imagine a GP-B gyroscope enlarged to the size of the Earth. On Earth, the tallest mountains, like Mount Everest, are tens of thousands of feet high. Likewise, the deepest ocean trenches are tens of thousands of feet deep. By contrast, if a GP-B gyroscope were enlarged to the size of the Earth, its tallest mountain or deepest ocean trench would be only eight feet!

Finally, the gyroscope is freed from any mechanical bearings or supports by levitating within a fused quartz housing. Six electrodes evenly spaced around the interior of the housing keep the gyroscope floating in the center. A brief stream of helium gas spins the gyroscope up to 10,000 rpm. After that, the gyroscope spins in a vacuum, a mere 0.001 inches from the housing walls, free from any interfering supports.

Spinning Superconductivity

Each Gravity Probe B gyroscope is nearly perfectly spherical and nearly perfectly homogenous. While this ensures that the gyroscope will spin with near-perfect stability, its "near-perfect-ness" creates a daunting challenge—GP-B scientists cannot mark the gyroscope to see exactly which direction its spin axis is pointing.

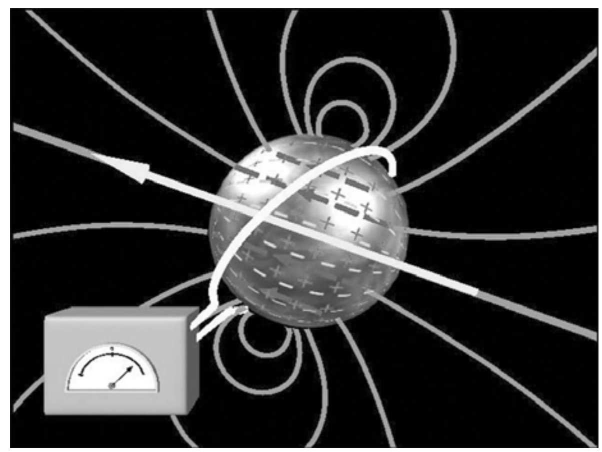
For GP-B to "see" the shape and motion of local spacetime accurately, the scientists must be able to monitor the spin axis orientation to within 0.5 milliarcseconds, and spot the poles of the gyroscope to within one-billionth of an inch.

How can one monitor the spin axis orientation of this near-perfect gyroscope without a physical marker showing where the spin axis is on the gyroscope? The answer lies in a property exhibited by some metals, called "superconductivity."

Superconductivity was discovered in 1911 by the Dutch physicist H. Kammerlingh Onnes. He found that at temperatures a few degrees above absolute zero, many metals completely lose their electrical resistance. An electric current started in a superconductor ring would flow forever, if the ring were permanently kept cold. But, superconductors also have other interesting properties. In 1948, the theoretical physicist Fritz London predicted that a spinning superconductor would develop a magnetic moment, exactly aligned with its instantaneous spin axis. In 1963, three different groups, including a GP-B graduate student, demonstrated the existence of this London moment experimentally.

What is remarkable about this phenomenon (and most fortunate for Gravity Probe B) is that the axis of this magnetic field lines up exactly with the physical axis of the spinning metal. Here was the "marker" Gravity Probe B needed. GP-B scientists coated each quartz gyroscope with a sliver-thin layer of a superconducting metal, called niobium (1,270 nanometers thick). When each niobium-coated gyroscope rotates, a small magnetic field surrounds each gyroscope. By monitoring the axis of the magnetic field, Gravity Probe B knows precisely which direction the gyroscope's spin axis is pointing.

The magnetic field axis is monitored with a special device called a SQUID (Superconducting Quantum Interference Device). The SQUID is connected to a superconducting loop embedded within the quartz housing. When the gyroscope tilts, the London moment magnetic field tilts with it, passing through the superconducting loop. The SQUID detects this change in magnetic field orientation. The SQUID is so sensitive that a field change of 5×10^{-14} gauss (1/10,000,000,000,000th of the Earth's magnetic field), corresponding to a gyro tilt of 0.1 milliarcsecond, is detectable within a few days.



Using the London moment to monitor the gyroscope's orientation is the one readout scheme perfect for Gravity Probe B: extremely sensitive, extremely stable, applicable to a perfect sphere, and—most importantly—exerts no reaction force on the gyroscope at all.

Cement Mixer-sized Thermos Bottle

One of the greatest technical challenges for Gravity Probe B is to keep its science instrument constantly supercooled. For the relativity experiment to operate properly, the science instrument must be kept just above absolute zero, at 1.8 Kelvin (-271.4° Celsius or –456.5° Farenheit) constantly for at least a year.

The science instrument is kept at this supercold temperature, by placing it in a special 2,441 litre (645-gallon) Dewar, or Thermos, about the size of the mixing tank on a cement truck, that is filled with liquid helium in a superfluid state. This nine-foot tall Dewar is the main structure of the GP-B satellite itself. In its 640-kilometer (400-mile) high polar orbit, the GP-B satellite is low enough to be subjected to heat radiating from the Earth's surface, and it is also subjected to alternating hot and cold cycles, as it passes from intense sunlight into the Earth's shadow every ninety-seven minutes. Throughout the life of the mission, key portions of the science instrument must be maintained at a constant temperature to within five millionths of a degree centigrade.

The Dewar's inner chamber is a vacuum, which limits the amount of heat penetrating through the outside wall into the inner chamber containing the science instrument. In addition, it includes several other devices for maintaining the necessary supercold temperature:

1. Multilayer insulation—multiple reflective surfaces in the vacuum space to cut down radiation
2. Vapor-cooled shields—metal barriers, suitably spaced, cooled by the escaping helium gas
3. Porous Plug—invented at Stanford, and engineered for space at NASA Marshall Space Flight Center in Huntsville, AL and the Jet Propulsion Laboratory in Pasadena, CA, this plug allows helium gas to evaporate from the Dewar's inner chamber, while retaining the superfluid liquid helium inside.

Virtually no heat can penetrate from the outside wall of the Dewar through the vacuum and multilayer insulation inside. However, a small amount of heat (about as much as is generated by the message indicator lamp on a cell phone) leaks into the Dewar from two sources:

1. Conduction of heat flowing from the top of the Dewar into the liquid helium
2. Radiation leaking down through the telescope bore into the liquid helium.

The porous plug controls the flow of this evaporating helium gas, allowing it to escape from the Dewar, but retaining the superfluid helium. The plug is made of a ground up material resembling pumice. The evaporating helium gas climbs the sides of the inner tank near the plug and collects on its surface, where it evaporates through the pores in the plug, much like sweating in the human body.

The evaporating helium provides its own kind of refrigeration. As the helium gas evaporates at the surface of the porous plug, it draws heat out of the liquid helium remaining in the Dewar, thereby balancing the heat flow into the Dewar. You can feel this effect on your skin when you swab your skin with water. As the liquid evaporates off your skin, it draws heat energy with it, leaving your skin a tiny bit cooler than before.

The helium gas that escapes through the porous plug is cycled past the shields in the outer layers of the Dewar, cooling them (thus the name, "vapor-cooled shields"), and then it is vented out into space through eight pairs of thrusters that are strategically located around the spacecraft.

Based on data from the on-board telescope and the gyroscope that is used as a proof mass, the flow of the escaping helium gas is carefully metered through these thrusters in order to precisely control the spacecraft's position. In fact, the position of the entire spacecraft is balanced around the proof mass gyroscope by increasing or decreasing the flow of helium through opposing thrusters, creating a drag-free orbit. Thus, the Dewar and liquid helium serve two critically important functions in the mission:

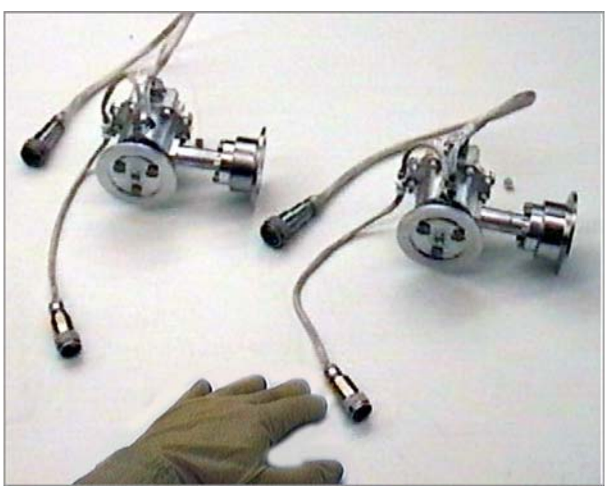
1. Maintaining a supercold temperature around the science instrument.
2. Providing a constant stream of gas propellant for precisely controlling the position and attitude of the entire satellite.

Drag-Free Satellite

As the GP-B satellite orbits the Earth with its four gyroscopes inside, one may assume that the satellite carries the gyroscopes around the Earth in polar orbit. After all, the gyroscopes spin inside four quartz housings that are rigidly attached inside the spacecraft. Whatever orbit the spacecraft follows, the gyroscopes will be forced to follow as well.

In fact, one of the gyroscopes inside the satellite is following an orbit of its own—a near-perfect gravitational free-fall orbit around the Earth. This gyroscope acts as a "proof mass," showing GP-B the path of a near-perfect orbit. This gyroscope spins inside its housing a mere millimeter from the edge. The satellite uses sensors inside the housing to keep the spacecraft perfectly oriented around the spinning gyroscope and, therefore, follows the "proof mass" around the Earth in a near-perfect orbit.

For the most part, the satellite stays on course by following the same free-falling orbit. However, outside the satellite, two factors can alter the satellite's path. The solar radiation streaming from the Sun is enough to knock the satellite askew, and friction from atmospheric gases can slow the satellite down.



GP-B needs extremely sensitive thrusters to re-orient the satellite and keep it on its proper path. Here's where the escaping helium gas that slowly boils off from the liquid helium comes in handy. Minute amounts of gas, 1/10th of a human breath or a few millinewtons of force, provide just the right amount of thrust necessary to adjust the satellite's position. The thrust force of the escaping helium gas provides plenty of force to keep the GP-B satellite in its precise position (within 10 milliarcseconds of a perfect Earth orbit, pointing to within 1 milliarcsecond of the exact center of the guide star).

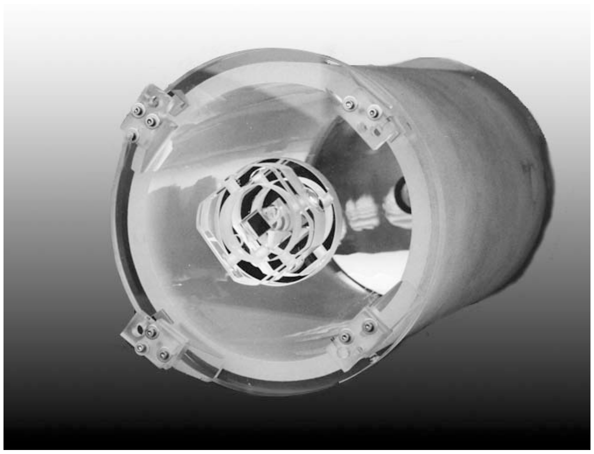
The first drag-free satellite was the U.S. Navy's Triad transit navigation satellite launched in 1972. Transit satellites enable ships to locate their positions on the Earth's surface by reference to orbit data stored on board the satellite, but earlier ones had been limited by uncertainties in orbit prediction arising from atmospheric drag. Triad overcame this uncertainty by incorporating a drag-free controller, the DISturbance Compensation System (DISCOS), developed by Stanford Aero-Astro Department as an offshoot of Gravity Probe B research. Drag-free technology is now standard on transit satellites.

Telescope & Guide Star

In the GP-B science instrument, enclosed within the Probe, along the central axis of the Dewar, a 36 centimeter (14 inch) long Cassegrain reflecting astronomical telescope, with a focal length of 3.8 meters (12.5 feet), is optically bonded to the end of the quartz block that houses the gyroscopes. Together, the telescope and the quartz block form the Science Instrument Assembly (SIA). Optical bonding is a patented method of fusing together quartz parts, without the use of any "glue" or fasteners. This is necessary for the SIA not to distort or break when cooled to the cryogenic temperatures required for superconductivity used by the gyroscopes. The telescope's line of sight provides a frame of reference for measuring any drift in the gyroscopes' spin axis over the life of the experiment.

The telescope must be focused on a distant stable reference point—a guide star—and it must remain fixed on the center of this guide star within a certain range (+/- 20 milliarcseconds) throughout the mission. The resulting telescope signal is continuously subtracted from the gyroscope signal at the 0.1

milliarcsecond level to determine the amount of spin axis drift in each gyroscope.



Ideally, the telescope would be aligned with a distant quasar (massive bodies, located in the most distant reaches of the universe, which put out powerful radio emissions), because they appear to be fixed in their position and would thus provide an ideal, stable reference point for measuring gyroscope drift.

However, quasars are too dim for any optical telescope this size to track. So, instead, we the telescope must be focused on a brighter, nearby star. But, like the Sun, nearby stars move relative to the other stars in our galaxy, and their light diffracts or scatters as it travels through the universe. This situation posed two difficult challenges to the experiment:

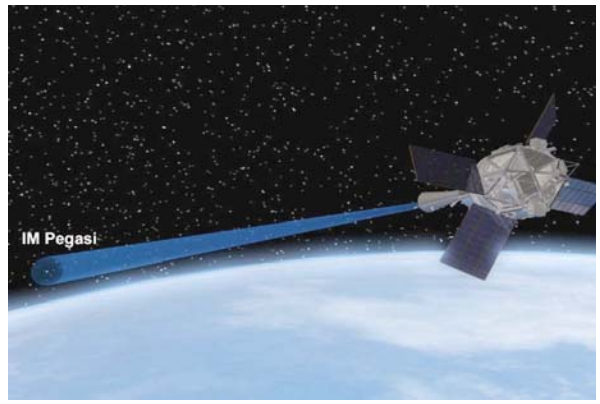
1. Choosing a guide star whose motion can be mapped relative to quasars separately, so that the Gravity Probe B gyroscope measurements can be related to the distant universe.
2. Creating a means for the telescope to find and remain focused on the exact center of a star whose light is widely diffracted.

Choosing and Mapping a Guide Star with VLBI

In order to precisely map the motion of a star relative to a quasar, it was necessary to find a star that meets all of the following criteria:

- Correct position in the heavens for tracking by the on-board telescope (for example, the sun never gets in the way)
- Shines brightly enough for the on-board telescope to track
- Is a sufficiently strong radio source that can be tracked by radio telescopes on Earth
- Is visually located within a fraction of a degree from the reference quasar

It so happens that stars that are radio sources belong to binary star systems. Because almost half the star systems in the universe are binary, it initially seemed that there would be many good candidates for the guide star. However, out of 1,400 stars that were examined, only three matched all four of the necessary criteria. The star that was chosen as the GP-B guide star is named IM Pegasi (HR 8703).



IM Pegasi -- HR8703

IM Pegasi Facts

Distance: ~300 light years

Right Ascension: 22.50'34.4"

Declination: 16.34'32"

Magnitude max. - 5.85

Magnitude min. - 5.6

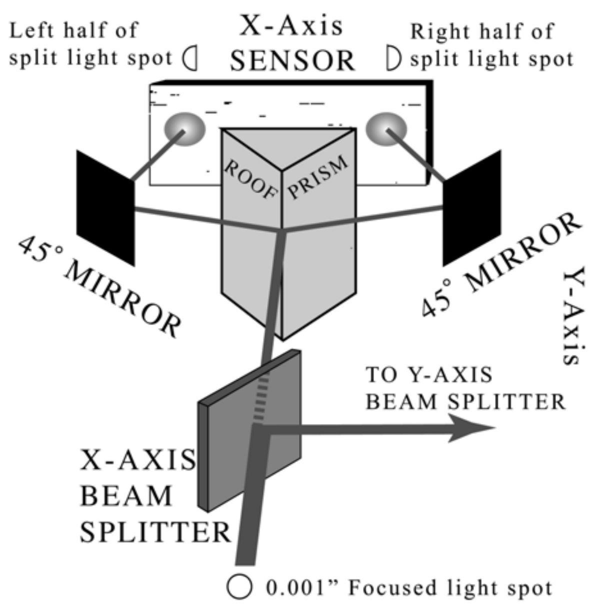
IM Pegasi moves around its binary partner in a spiraling pattern, rather than a linear path. The total motion of IM Pegasi in one year alone is 100 times larger than the smallest gyroscope spin axis drift measurable with Gravity Probe B. Clearly this motion has to be determined with high accuracy for Gravity Probe B to be successful.

Because IM Pegasi is also a radio source, its motion can be tracked by a sophisticated system of radio telescopes, operating in conjunction with each other. This system is called the Very Long Base Interferometry or

VLBI. Radio telescopes from New Mexico to Australia to Germany, acting as a single radio telescope the size of the Earth, focus on IM Pegasi and map its movements. The results are images of IM Pegasi and extremely accurate measurements of its motions with respect to a reference quasar. With these measurements the motions of the gyroscope spin axes can be related to the distant universe.

Splitting the Guide Star Image

Diffraction, the light-scattering phenomenon that produces rings around the moon, spreads IM Pegasi's image to a diameter of 1,400 milliarcseconds, corresponding to a focused image 0.001 inch across. Locating the star's center to 0.1 milliarcsecond means finding the image's optical center to one ten-millionth of an inch—a formidable task.



GP-B accomplishes this task by focusing the starlight in the "lightbox" at the telescope's front end, and passing it through a beam-splitter (a half-silvered mirror). The beam-splitter forms two separate images, each of which falls on a roof-prism (a prism shaped like a peaked rooftop). The prism slices the star's image into two half-disks, which are directed to hit opposite ends of a tiny sensor.

On the sensor, the light signals of each half-disk are converted to electrical signals and then compared. If the signals are not precisely equal, this means that the roof-prism is not splitting the image precisely in half. The entire space vehicle is then adjusted until the signals are equal and the image is split right down the middle. When this is accomplished in both sensors for each axis (x- and y-axes), then the telescope is focused on the exact center of the guide star.

Seven Near Zeroes

Designing an experiment involves a basic choice: maximize the effect to be measured, or minimize the "noise" that obscures it. For the Gravity Probe-B experiments, however, that choice was moot because Einstein's relativistic effects, that literally "roar" near black holes and neutron stars, barely whisper here on earth. The Gravity Probe-B has to turn the volume of the extraneous babble down to zero in order to hear the whisper. It's like asking everyone in a football stadium to sit quietly to hear a bird sing.

The noise affecting near-earth relativistic effects comes from virtually anything that might distort the results. From the slightest amount of heat or pressure, the influence of any magnetic field, any kind of gravitational acceleration, or the tiniest amount of atmospheric turbulence or solar radiation, to the smallest imperfections in the instruments themselves, the tolerances must be at or near zero.

Without seeing them up close it's hard to image the precision of the instruments. Gravity Probe B's four gyroscopes, housings, and telescopes are all carved out of a single purified quartz block, grown in Brazil, refined in Germany, and delivered to GP-B as a trash-can-size crystal. From side to side, the crystalline structure of the quartz is identical and homogenous to within three parts per million. The gyroscope spheres are less than 40 atomic layers from a perfect sphere, the most perfectly round objects ever made by man, so they can spin for over a year without any significant drift. To put that in perspective, if the gyroscopes were enlarged to the size of the Earth, the highest mountain or the deepest ocean trench would be only 8 feet. The electrical charge at the gyroscopes' surface, known as the electric dipole moment, are likewise vanishing small, held to less than five parts in ten million.

The isolation of the instruments from their surroundings is equally impressive. The entire set of instruments is in a near-perfect vacuum, surrounded by 645 gallons of liquid helium cooled to a temperature of 1.8K. The helium's temperature is held constant, just above absolute zero, by insulating the Thermos jug-like Dewar and releasing any evaporating helium through the one-of-a-kind porous plug.

To zero out unwanted magnetic fields, the instruments were built within a cascading succession of four lead bags within bags. After each new bag was inserted, the outside bag was removed, to virtually eliminate any residual magnetic fields. Additionally, while in orbit, the on-board electronics will monitor the position of the spinning gyroscopes by sensing the weak magnetic field produced by each one, and make the necessary corrections. The net result is the absence of any magnetic fields, even from the earth itself, that might affect the results.

Finally, and perhaps most impressive of all, is that the GP-B space vehicle will orbit the Earth in a near-perfect circle, almost completely free from any acceleration due to gravity. Eight opposing pairs of proportional micro thrusters enable the space vehicle to automatically control its attitude or orientation with extreme precision. In addition, the satellite spins continuously to average out various disturbing effects. Floating serenely in orbit, the satellite experiences less than one ten-billionth of the gravity felt on the Earth's surface, and the gyroscopes spin suspended in space touching nothing solid for their entire lifetimes.

Gravity Probe B promises to be the near-perfect instrument placed in a near-zero environment.

GP-B Sever Near Zeroes

Temperature:	1.8 Kelvin (-271.4° Celsius or –456.5 Farenheit)
Gravitational Acceleration	Less than 10^{-10} g
Magnetic Field	Less than 10^{-6} gauss
Pressure	Less than 10^{-11} torr
Material Homogeneity	Less than 3 parts per million
Mechanical Sphericity	Less than 3 ten millionths of an inch
Electrical Sphericity	Less than 5 parts per ten million

Gravity Probe B on the Web

Following are the URLs of several Web sites where you can find more information about Gravity Probe B:

http://einstein.stanford.edu

http://www.gravityprobeb.com

http://www.ksc.nasa.gov/elvnew/gpb/vlcc.htm

http://www.nasa.gov/missions/highlights/launch_update_gpb.html

http://science.nasa.gov/headlines/y2004/26apr_gpbtech.htm?list80268

http://www.spaceflightnow.com/delta/d304/status.html