



The Gravity Probe B in a Nutshell

EXPERIMENT



LOCKHEED MARTIN

" T E S T I N G E I N S T E I N ' S U N I V E R S E "

What is Gravity Probe B?

Gravity Probe B (GP-B) is a NASA physics mission to experimentally investigate 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, with unprecedented accuracy, two extraordinary effects predicted by the general theory of relativity: 1) the *geodetic effect*—the amount by which the Earth warps the local spacetime in which it resides; and 2) the *frame-dragging effect*—the amount by which the rotating Earth drags its local spacetime around with it. GP-B 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.

A Quest for Experimental Truth

The idea of testing general 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 Bill Fairbank and gyroscope expert Bob 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, Francis Everitt was invited 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. In 1971, program management was transferred to NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL.



Between 1977 and 1984, the experiment was restructured as a NASA flight program, with Lockheed Missiles & Space Company (LMSC, now Lockheed Martin) sub-contracting to Stanford to build the experiment's unique 650-gallon dewar and probe. Later, LMSC was also selected to build the spacecraft and associated control systems to house the dewar and probe in orbit. In 1981, Francis Everitt became Principal Investigator, the position which he still holds, and in 1984, Stanford Professor Brad Parkinson (Aero-Astro) joined GP-B as Program Manager, and also a Co-PI, along with professors John Turneure (Physics) and Dan DeBra (Aero-Astro).

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 more than four decades to develop the ultra-precise gyroscopes and the other cutting-edge technologies necessary to carry out this "simple" experiment.

The GP-B Flight Mission & Data Analysis

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."

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 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 database for analysis. On August 15, 2005, the GP-B Mission Operations team finished

collecting science data and began a planned set of calibration tests of the gyros, telescope, and SQUID readouts that lasted six weeks, until the liquid helium in the dewar was exhausted at the end of September.

In October 2005, the GP-B science team began a three-phase data analysis process that was initially expected to yield a final result towards the end of 2006. However, two complications significantly extended the data analysis phase.

From 2006-2008, we investigated the physical mechanisms underlying these complications and developed techniques for resolving them. We announced first results at the American

Physical Society's April 2007 annual meeting and presented dramatically improved results at the International Space Sciences Institute (ISSI) Gravity Workshop in October 2008. NASA funding ended in September 2008, and from 2008-2010, GP-B was funded through a collaboration between Stanford and the King Abdulaziz City for Science and Technology (KACST) in Saudi Arabia. Data analysis was completed in December 2010.

The final results of this landmark experiment have been published in *Physical Review Letters*, and publicly announced in a press and media event at NASA Headquarters on May 4, 2011. See the GP-B website for details: <http://einstein.stanford.edu>



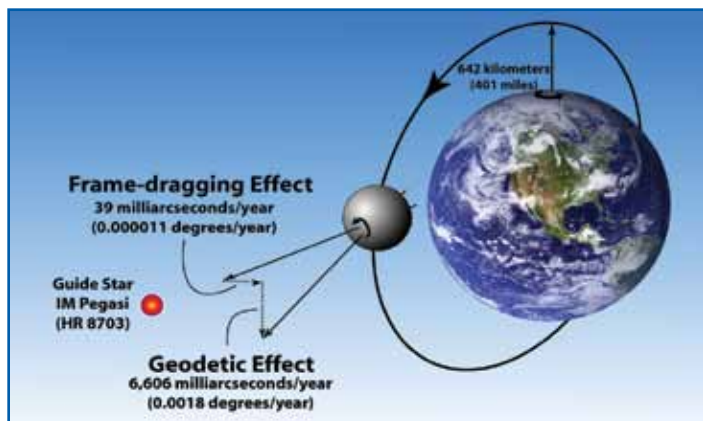
The Two Einstein Effects

Newton believed that space and time were absolute or fixed entities and that gravity was an attractive *force* between objects. In Newton's universe, the spin axis of a perfect gyroscope orbiting the Earth would remain unchanged forever. Einstein realized that space and time are relative entities, interwoven into a "fabric," which he called *spacetime*. In Einstein's universe, the presence of celestial bodies causes spacetime to warp or curve, and gravity is the product of bodies moving in curved spacetime. Based on predictions of Einstein's theory, GP-B is first measuring the geodetic effect, the amount by which the Earth is warping its local spacetime. In addition, and more important, GP-B is measuring the frame-dragging effect, postulated in 1918 as a corollary to general relativity by Austrian physicists Josef Lense and Hans Thirring. It proposes that massive celestial bodies, like the Earth, drag their local spacetime around with them as they rotate. Physicists and cosmologists are particularly interested in frame-dragging because it may account for the enormous power generation in some of the most explosive objects in the universe.

The Experimental Design

Conceptually, the GP-B experiment is simple: 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 the 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 the gyros 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).

The predicted geodetic gyro spin axis precession is a tiny angle of 6,606 milli-arcseconds (0.0018 degrees) in the orbital plane of the spacecraft. The orthogonal frame-dragging precession is a minuscule angle of 39 milli-arcseconds (0.000011 degrees)—about the width of a human hair viewed from 1/4 mile away. GP-B's measurement of the geodetic effect has an expected accuracy of better than 0.01%, far more accurate than any previous measurements. The frame-dragging effect has never directly been measured, but Gravity Probe-B is expected to determine its accuracy to better than 1%.



The Extraordinary Technology

All of the Gravity Probe B technologies are integrated into one of the most elegant satellites ever launched, filled with cutting-edge technologies, many of which simply did not exist in the 1960s. Einstein, himself once a patent clerk, would have enjoyed reviewing these extraordinary technologies.

The spacecraft is built around a 9' tall, 650-gallon dewar (thermos bottle), the largest and the most sophisticated ever flown. Before launch, it was filled with liquid helium, cooled to a superfluid state 1.8 K [$=^{\circ}$ C] above absolute zero (-456° F). Embedded along its central axis, a cigar-shaped canister called the *Probe* contains 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 is made up of the telescope and the quartz block, optically bonded together. The quartz block contains the four gyros and SQUIDs—Superconducting QUantum Interference Devices (digital magnetometers) that monitor the spin axis orientations of the gyros. During the 17-month mission, the Probe was maintained at 1.8 K in a vacuum.



The slowly escaping helium also served as the propellant for 16 micro-thrusters that kept the spacecraft pointed towards the guide star, and maintained its drag-free position in orbit and constant roll rate. Outside the dewar, mounted to the spacecraft frame are all the systems that provide power, navigation, communication and control of the spacecraft.

The Broader Legacy

At least a dozen new technologies had to be invented and perfected to carry out this experiment. For example, the spherical gyros are over a million times more stable 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 detect a gyro tilt corresponding to 0.1 milliarcsecond. Over its 40+ year life span, spin-offs from GP-B have yielded many technological, commercial, and social benefits—e.g. GP-B's porous plug for controlling helium in space was essential to several other vital NASA missions. 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 PhD dissertations at Stanford and 13 elsewhere. GP-B alumni include the first U. S. woman astronaut, an aerospace CEO, and a Nobel laureate.