Refinement of the Geoid—The Gravity Probe B Experiment

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Author's note: In 2004, I wrote a web-exclusive article about a science experiment that was attempting to verify Einstein's General Theory of Relativity. In addition to the cool science needed to mount the experiment, there were several aspects I felt surveyors would enjoy, such as the needed angular accuracy, etc. The results of the experiment were released last week, and can be found here: **http://einstein.stanford.edu/highlights/status1.html**. A 218Kb PDF of the article, complete with lots of images, can be found **HERE**.

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Long before GPS and the reliance on geoids to establish orthometric heights, surveyors' plumb lines were being affected by local gravity variations, such as nearby mountains. Today, about the best angular accuracy we can achieve is on the order of tenths of a second. Stanford University's Gravity Probe B, with its capability of resolving angles to the tenth of a millarcsecond, will explore the fine structure of the Earth's gravitational field.

Whether you first learned it in an early science class, or recall it twirling across the opening episodes of The Twilight Zone, Einstein's $E=mc^2$ formula expressed a special theory of relativity. Based on that theory, the development of nuclear energy was made possible, and with it, the atomic bomb.

But it is Einstein's general theory of relativity that has been more difficult to understand. Proposed more than 40 years ago, and based on work stretching back to the 1800s and Einstein's 87-year-old theory, the Gravity Probe B (GP-B) experiment brings together an incredible array of new technology, without which the experiment would not be possible.

From a layman's point of view, Einstein's lesser-known theory postulates that as an object in space (such as the Earth) travels though space, it drags space-time along with it. It may be hard to conceive of the applications for this verification here on Earth, but it has enormous implications for understanding our universe—such things as black holes, for example. The theory also suggests that the planets are not moving in elliptical orbits around the Sun, but rather are following straight lines through curved space-time.

Twisting the Fabric of Space-Time
A relatively simple explanation of Einstein's general theory appeared in a recent issue of Popular Science (Nov 2003), called Einstein 101: "The general theory of relativity says that massive bodies distort the shape of space-time. When light from a distant star passes another star, for example, its path curves because the star's gravity has curved the surrounding space, not because the light is being pulled inward. This warping will also affect an orbiting body. Gravity Probe B will be the first test of frame-dragging, the theory that a massive spinning body twists the fabric of space-time. Like a whirlpool in water,

Earth's rotation doesn't stir up distant space; the effect is greatest near the planet's surface."

Another perspective comes from Stanford University's website: "One way to think about space-time is as a large fishing net. Left unperturbed and stretched out flat, it is straight and regular. But the minute one puts a weight into the net, everything bends to support that weight. This is the geodetic effect. A weight that was spinning would wreak even more havoc with the net, twisting it as it spun. This is frame-dragging. The mass-energy of the planet earth represents a 'weight' in our net of space-time, and the daily revolutions of the earth, according to Einstein's theory, represent a twisting of local space-time. GP-B will search for this twisting effect, which has never before been measured." (**http://einstein.stanford.edu**)

The seeds for the GP-B experiment were sown a half-century ago. In the late 1950s, a Stanford scientist and a Defense Department scientist came up with the idea of launching an extremely stable gyroscope into an orbit that would cross the planet's poles. If Earth was twisting space-time, the gyroscope's axis of rotation would tilt. By keeping the gyroscopes precisely pointed at a distant star, any variation in the axes of the gyroscopes would be detected. In polar orbit, with the axes of the gyros pointing at the star, the geodetic and frame-dragging effects would show up at right angles to the axes.

Several technologies had to be developed to make the experiment possible. First, the creation of the gyroscopes themselves. After much experimentation, scientists decided to use fused silica and single crystal silicon as the moving part, or rotor. Twenty spheres were created, of which four were selected, two of fused silica and two of silicon. The spheres were ground and polished to within 0.01 microns of perfect sphericity. If enlarged to the size of the Earth, the highest mountains and deepest valleys would be within eight feet of sea level. To create the magnetic field which could be monitored within the gyroscope, each sphere was coated with a very thin layer of niobium. To shield the gyroscopes from the effects of Earth's magnetic field, the entire gyroscope assembly was surrounded with lead bags. For the experiment to work it would have to be in a super-cold, weightless environment.

The world's largest dewar (essentially, a giant 9-foot tall Thermos bottle) was built and filled with 650 gallons of liquid helium. The dewar will keep the assembly in a vacuum near absolute zero (1.8º Kelvin or -271º Celsius). A special challenge was created by the fact that as the satellite passes from shadow to intense sunlight, onboard temperatures will change dramatically. If the temperature of the assembly varies by as much as one degree, it will fail, so special features have been incorporated to handle temperature stabilization. A new "porous plug" was created for the tank that allows evaporating helium gas to escape, while keeping the liquid inside. The gas is used to start the gyroscopes spinning at 10,000 rpm, and to power the satellite thrusters that keep the satellite precisely pointed at the star. Once up to speed, which will take a half-hour, the gas will be pumped out, and the resulting vacuum will be lower than that of space surrounding the satellite. The scientists estimate that the low vacuum would enable the gyros to lose less than 1% of their starting speed, even after 1,000 years. The separation between the spheres and the fused quartz block enclosing them is measured in millionths of an inch. Inside each housing, three electrodes suspend the spheres. Detectors (called Superconducting QUantum Interference Devices, or SQUIDS) in the housing can sense any change on the magnetic field created by the spinning spheres. Two of the spheres will rotate in one direction while the other two rotate in the opposite direction, thus providing canceling effects.

Assembling the telescope itself presented several challenges. 14 inches long, with a 5.6 inch aperture (focal length 12.5 feet), it will be able to pinpoint the center of IM Pegasus to within 0.1 millarcseconds. The entire probe was assembled in a Class-10 clean room, capable of eliminating any particles larger than a single micron. To put the tiny tolerances and design objectives into perspective, consider the following: the detection capability of the assembly is less than 0.002% of a degree, which corresponds to a gyro tilt of 0.1 millarcsecond. Per Einstein's theory, the predicted amount of the geodetic effect is 6600 millarcseconds, and the frame-dragging effect is 42 millarcseonds. Accordingly, the experiment has been designed to detect twisting at the 0.5 millarcsecond level. To put this in human perspective, the distance subtended by this angle would be like looking at the edge of a piece of paper 100 miles away. Similarly, this subtended angle would result in a distance of five feet if it were extended to the moon.

The gyroscopes must provide a reference system stable to 10-12 degrees per hour, a million times better than the best inertial navigation gyroscopes. Two factors combine to make the experiment possible: the weightlessness of space and near-zero temperatures. Six requirements must be met: a drift-free gyroscope, a method for determining changes in the spin angle to 0.1 milliarcseconds, a system for referencing the gyro to the guide star, a star of which its motion and position is precisely known, a data processing technique to allow the separation of the geodetic and frame-dragging effects, and a credible calibration scheme. The last requirement is particularly interesting because once the satellite is on orbit, the experiment will require almost a year to calibrate and prepare to make the observations. After approximately two years, the satellite will run out of helium, and then become space junk.

The system developed to keep the probe precisely centered on a star in the Pegasus constellation involves beam-splitting and perfectly matching two halves of the star. Minute thruster firings will ensure that the telescope remains pointed at the star. Much more technology is involved, for instance, the joining of the telescope to the gyro assembly. Using a technique known as optical contacting, the two parts use no cement or mechanical attachment. Instead, the mating surfaces are so flat and clean that they join through molecular adhesion.

The GP-B experiment is not without controversy due to its cost of $700 million, but if it succeeds, spin-off benefits for surveyors will include a dramatic refinement of our wildly undulating geoid. Also of interest to surveyors is the incredible accuracy and precision that will be needed to detect the tiny effects predicted by the theory.

GP-B, with its capability of resolving angles to the tenth of a millarcsecond, makes our work today look coarse, to say the least. The experiment will explore the fine structure of the Earth's gravitational field. As we learn to deal more and more with a geoid which undulates across the landscape, any refinements in the geoid will be welcome.

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