PROBING THE FABRIC OF SPACE: FROM FOUCAULT'S GYROSCOPE TO GRAVITY PROBE B

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Abstract

Foucault's original gyroscope in 1852 and the gyroscopes in NASA's Gravity Probe B satellite were both conceived with the same goal of probing the nature of space in the vicinity of the Earth.

Introduction

When the 19th century dawned, the learned world held no doubt but that the Earth turned on its axis. Evidence included the polar flattening and equatorial bulge predicted by Newton and confirmed by 18th-century expeditions to Lapland and Peru. However more direct proofs were lacking: weights dropped down mineshafts had failed to provide conclusive evidence of the expected eastward deviation. It is for this reason that Léon Foucault caused such a sensation when he set up his famous giant pendulum experiment in the Panthéon in Paris in 1851. The inertia of the pendulum—-its resistance to change in its acquired motion—caused its swing plane to remain fixed in space (but see the caveat below). In a phenomenon that could be perceived with the naked eye, the slow clockwise veering of the swing plane revealed to the assembled spectators that the Earth was turning anticlockwise beneath them.

Foucault's gyroscope of 1852

However, Foucault's pendulum has a flaw—or rather a difficulty—as a demonstration of the Earth's rotation. At the poles, the vibration locks to the frame of reference defined by the stars, and it takes one sidereal day, or 23h 56m, for the swing plane to make a complete circuit of the horizon. At lower latitudes, however, the veering is no longer synchronized with the Earth's rotation but is slowed by a factor that is equal to the sine of the geographic latitude. A Foucault pendulum in Nelson, for example, would take over 36h to make a complete circuit. This is because the pendulum oscillations are not completely free. Rather, the suspension point is dragged around with the Earth and the direction of the restoring force on the bob, gravity, is likewise changing. As the British mathematician J.J. Sylvester wrote in *The Times*, "…many persons…think it a hard tax upon their faith to believe that when the earth has gone once fairly round the *status quo* as between the horizon and the plane of vibration should not be restored."

An apparatus was needed that was unaffected by the latitude. This is what Foucault produced in 1852, and it was based on the immobility of the axis of a rotating mass.

Unlike the pendulum, the idea was not new, for it had long been suggested that the inertia of rotating discs might provide artificial horizons at sea, and it was also known that the north-south axis of the spinning Earth defined a fixed direction in space. However, exquisite construction was required, because if a spinning disc is not perfectly balanced, a torque (or turning force) will cause the direction of its spin axis to change in an effect known as precession. (In fact, lunar-solar torques on the Earth's equatorial bulge cause the axis of the Earth to precess. This is the precession of the equinoxes in which the Earth's axis sweeps out a cone of half-angle 23.5° every 26 000 years.) Foucault's genius was that he—along with his instrument maker, Gustave Froment—was able to make a precision device that was unaffected by precession. Foucault dubbed his instrument the gyroscope, from Greek words meaning to look at the rotation, and once set going, the axis of its spinning rotor stayed locked to the stars, just like an equatorial telescope drive. The rotor ran down after about ten minutes, but had it continued turning for a sidereal day, it would have returned to the initial orientation with respect to the Earth. No one's faith needed to be taxed! Crucially, whether the gyroscope rotor was spun clockwise or anticlockwise, its axis appeared to move in the same direction, showing that its slow creep really was a reflection of the Earth's rotation, and was not the result of poor balance, which would have reversed the resulting precession.

Interpretation of the pendulum and gyroscope motion

For Foucault, it was simple to interpret the pendulum and gyroscope motions in terms of Newton's absolute space. The pendulum and gyroscope probed nearby space and found that the Earth was rotating in it. But later in the 19th century, the Moravian physicist Ernst Mach found Newtonian space to be a 'conceptual monstrosity'. In particular, Mach did not like the idea that space acted on masses by giving them their inertia, but was not acted upon in return. He hoped to establish a dynamical theory in which only relative positions and motions mattered, a dynamics in which there would be no observable or conceptual difference between a rotating Earth in a stationary universe and a stationary Earth in a rotating universe. Einstein was greatly influenced by Mach's thoughts, but ultimately rejected them. In his General Theory of Relativity, Einstein re-established space as space-time, in which rotations are absolute. The interaction between space-time and matter is no longer asymmetric. The warp of space-time tells matter how to move, while matter bends space-time.

Gravity Probe B

In about 1960, Leonard Schiff at Stanford University realised that a gyroscope in low Earth orbit could be used test two predictions of General Relativity. The first prediction concerns the warping of space by the Earth's mass such that the circumference of a circular, low-Earth orbit should be about an inch less than 2π times its radius. The second prediction is that space-time should be dragged around by the rotation of the Earth. This frame-dragging was predicted by the Austrian physicists Hans Thirring and Josef Lense soon after publication of Einstein's theory.

NASA's Gravity Probe B satellite aims to test these predictions. The effects however are tiny. Because of the warping, or geodetic effect, a gyroscope spin-axis should veer by about 6.6 arcsec over the interval of a year compared to an external reference direction defined by the distant universe, which in practice means a quasar. At right angles to this, the frame-dragging should cause a gyroscope deviation of a mere 0.041 arcsec/year for the orbit adopted by Gravity Probe B. There have in fact already been tests of the geodetic effect: GP-B's major purpose is to search for the Lense-Thirring effect.

To detect such small angles has required the development of numerous new technologies in an instrument in which classical effects have been reduced to below the expected relativistic ones. The gyroscopes, which perform some million times better than the best navigational gyroscopes, comprise niobium-covered quartz spheres which are the roundest objects ever made by man. There are four gyroscopes for redundancy. Cooled by liquid helium to a temperature of 1.8 K, the niobium becomes superconducting and acquires a magnetic field aligned with the rotation axis. Sensors called SQUIDs can measure the orientation of the rotation axes relative to the satellite with an accuracy of 0.0001 arcsec. A 142-mm optical tracking telescope and helium thrusters lock the orientation of the satellite onto a guide star, IM Pegasi. The direction defined by IM Peg is variable, however, because of parallax and proper motion, because IM Peg is a flare star (which displaces its photometric centre) and because it is an unresolved binary. However it is angularly close to a quasar, and radioastronomers are following its motion via Very Long Baseline Interferometry (VLBI).

Gravity Probe B was launched on 2004 April 20. This was four decades after funding began, and is a tribute to the tenacity of the project's principal investigator, Francis Everitt of Stanford University. Science operations began at the end of August and by the time this article is published should have ended with calibration measurements prior to exhaustion of the liquid helium coolant in 2005 August. The satellite and VLBI teams have worked independently and will only then combine their measurements to eliminate the motion of the guide star in order to fnd whether the gyroscopes have behaved as predicted by General Relativity. It would be fitting if the result were announced within the World Year of Physics, but realistically it will be early 2006 before we know whether the gyroscope shifts are in accord with Einstein's Relativity or not.

Conclusion

In 1852 Foucault used his gyroscope to make the gross test of whether the Earth was turning in space or not. Gravity Probe B is testing subtler questions of whether space-time is warped and dragged by the Earth. We see that the fundamental aim was the same in both the 19th and 21st centuries: probing the fabric of space near the Earth.

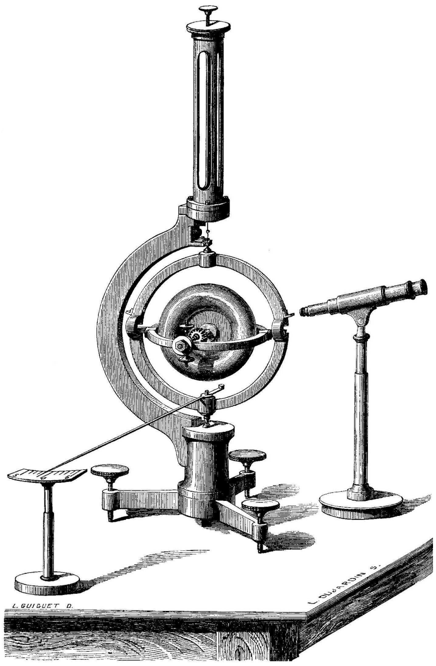
Further Reading

Fuller details of Foucault's pendulum and gyroscope can be found in W. Tobin & B. Pippard, "Foucault, his pendulum and the rotation of the Earth" *Interdisciplinary Science Reviews,* **19,** 326-337 (1994) and in W. Tobin, *The Life and Science of Léon Foucault,* Cambridge University Press (2003), which was reviewed by Clive Rowe in *Southern Stars,* **44,** (1) 37-38 (2005).

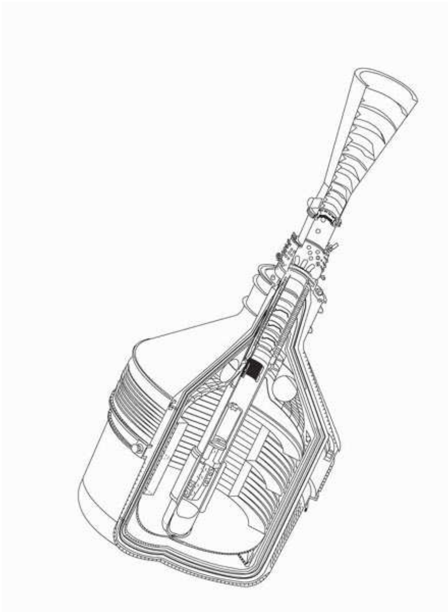
For Gravity Probe B, visit `http://einstein.stanford.edu` and `http://www.gravityprobeb.com`

Figures

The French physicist Léon Foucault (1819-1868). Foucault is best-remembered for his pendulum experiment in 1851, which provided the first direct dynamical demonstration of the Earth's rotation. The following year he devised the gyroscope to furnish a demonstration that was conceptually even simpler.



Foucault's gyroscope. Once the central, doughnut-shaped rotor had been set spinning, its axis remained fixed in space. The resultant motion of the low-friction gimbals was a reflection of the Earth's rotation and could be monitored with the pointer or microscope.



Cutaway of the Gravity Probe B payload. The main vessel or dewar (lower) held an initial charge of 2400 litres of liquid helium coolant. A tube along the central axis holds the quartz gyroscope housings and a 142-mm telescope, which points through the neck of the dewar and through the conical sunshade (upper) to track the guide star. GP-B was launched into a polar orbit of 642 km altitude from Vandenberg Air Force Base on 2004 April 20 by a Delta II rocket.

The GP-B gyroscopes are 38.1-mm diameter quartz spheres covered with a 1.27-µm layer of niobium.   Their sphericity is only some 40 atomic layers from perfect. Only neutron stars are rounder.