Relativity's most elaborate test

A project to test the general theory of relativity is still going after a quarter of a century. The physics is such fun that the travelling may be better than the arrival.

Stanford, California

How do you make into a perfect sphere a lump of fused quartz the size of a ping-pong ball with an accuracy of one part in 10^7? How do you suspend that electrically in a cavity hardly any bigger, and set it spinning so as to function as a nearly perfect gyroscope? And then do all this in a satellite at an altitude of more than 500 km? And why, in any case, do you bother?

These questions have for thirty years preoccupied the Stanford-centred group of physicists and engineers designing what must be the most elaborate of all experiments in physics — the measurement of the precession of a nearly-perfect gyroscope moving through the Earth's gravitational field. The declared objective is to test Einstein's theory of gravitation in a way that has not previously been possible. The hidden agenda may be to push a constellation of exacting technologies further than has previously been done.

Since the earliest days of general relativity, it has been clear that a gyroscope should precess (drift) in the gravitational field of a rotating object such as the Earth, but the Stanford project was inspired by the late Leonard Schiff, who calculated explicitly the rate of precession of a gyroscope in free fall around the Earth.

There are two effects, one called goedetic precession and caused merely by motion through the gravitational field, the other due to the angular rotation of the Earth and called motional precession. The first effect is analogous to spin-orbit coupling in the calculations of the energy levels of atoms, the second to the spin-spin coupling between the nucleus and the electrons of an atom which is responsible for the hyperfine structure of atomic spectra.

Both effects are tiny. Geodetic precession should amount to 6.9 seconds of arc a year for a satellite at an altitude of 550 km, motional precession to a mere 0.044 arc-seconds a year. Fortunately, the two effects are at right angles and so may be separated by a single measurement. The objective of the Stanford measurement is to obtain the motional precession to within 1 per cent, which requires an underlying accuracy of 0.3 milliarc-seconds a year — the angle subtended by the width of a human hair at a distance of 10 miles.

The refinements elaborated in the past thirty years have been dictated simply by this goal. The project calls for a gyroscope with an inherent drift-rate nine orders of magnitude less than that of the instruments now used for the inertial navigation of nuclear submarines. The only hope of achieving such stability is in an orbit about the Earth, for otherwise even the best suspensions will yield an unacceptable amount of drag. The evolution of this project shows what happens when people set outrageously ambitious goals, promising themselves that they will solve whatever unanticipated problems arise. This is how the project has moved from one apparently insuperable obstacle to another:

- The original decision that the gyroscope should be a spinning sphere has not been seriously reconsidered. Fused quartz is used chiefly for strength and homogeneity. Electrostatic suspension is achieved by coating the sphere with a superconducting material (niobium). The space between the sphere and its spherical housing is typically 40μm. Three pairs of electrodes sputtered on the surface of the housing are used to keep the sphere at the centre of the cavity and also, as capacitors, to sense departures from positions. In the satellite, there will be two pairs of gyroscopes mounted in a line, spinning in pairs parallel and anti-parallel to each other. Making spheres of quartz accurate to one part in 10^7, which has been done by two special lapping machines at NASA's Marshall Space Flight Center at Huntsville (Alabama), is slightly less difficult than the measurement of departures from roundness, made possible by means of a computerized mechanical stylus built by Rank Taylor Hobson (from Leicester, England) to a design developed at the University of Aberdeen.
- Superconducting skins make essential liquid helium temperatures, which in any case help to reduce random noise. So the spacecraft will be built around a huge Dewar vessel, containing 1,295 litres of liquid helium, like that used successfully in the infrared astronomy satellite IRAS.
- To measure the drift of the gyroscopes relative to the fixed stars, there must be a telescope — one of 400 cm focal length fashioned from fused quartz with folded optics (three coaxial mirror surfaces). The reference point will be the bright star Rigel in Orion.
- Spinning a spherical superconducting sphere cannot be accomplished electromagnetically because of the obdurate diamagnetism of the material, so that the housing is to contain a system of channels for allowing helium gas to flow past the sphere, using friction to get them spinning. The awkward tradeoff that must be made is between the acceleration of the sphere by the gas jets and its deceleration by gas escaping from the channelled flow. Residual helium is removed by raising the ambient temperature from 1.5 to 3.5 K, whimsically called "baking-out". The intention is that the axes of the gyroscopes should be along the apparent line of sight (uncorrected for aberration) to Rigel, which will entail a complicated sequence of approximations in which the spin axes of the four gyroscopes are alternately adjusted by gas jets and rolling of the spacecraft.
- Sensing the direction in which a nearly perfect spinning sphere is pointing obviously cannot be accomplished optically. Mercifully, F. London showed in 1957 that a superconducting object set spinning should have a characteristic magnetic moment, essentially the external macroscopic magnetic field compensating for the angular momentum imposed by spinning on quantum states of individual electrons. But the London moment is tiny, so it is necessary not merely to exclude all magnetic material from the structure but to isolate the gyroscopic assembly from the external magnetic field. Shifts in the direction of the London moment are to be detected by a pair of superconducting coils and measured with the help of the superconducting devices called SQUIDs.
- Even at 550 km, atmospheric drag will cause the spin axes of the gyroscopes to drift. So it is planned to compensate for drag by placing near the centre of the spacecraft a free-falling metal ball, then using helium jets to keep the spacecraft on the freefall path. This technique was used in the US Navy's navigation satellite TRIAD I to keep the acceleration of that spacecraft below 5×10^{-12} of the acceleration at the surface of the Earth.

The long history of this elaborate project has not been free from trouble, but William Fairbank, professor of physics at Stanford, now thinks the doubters have been won over. NASA has promised space for a proving flight on the shuttle in 1988, and there is a prospect that the satellite may be launched (into an accurately polar orbit) in 1991.

Fairbank says that the outcome may not be just another test of general relativity but perhaps a pointer to the physics that will have to be understood before gravitation can be quantized. If it works, it should help further to make general relativity part of ordinary physics.

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