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THE GRAVITY PROBE B RELATIVITY GYROSCOPE PROGRAM

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I. OVERVIEW OF PROGRAM

The idea of testing general relativity through observations on Earth-orbiting gyroscopes was suggested in 1959-1960 independently by G. E. Pugh (1959) and L. I. Schiff (1960). Both recognized that the direction of spin of a suitably oriented gyroscope should change with respect to the line of sight to a guide star for two reasons: a geodetic effect from the motion of the gyroscope through the curved space-time around the Earth, and a frame-dragging effect from the Earth's rotation. In a 600-km polar orbit, the predicted effects are respectively 6.718 arcsec/yr and 0.043 arcsec/yr.

NASA began supporting laboratory research on the experiment, now called Gravity Probe B, in 1964. Technologies for it were progressively established in the 1960's and 1970's, and an error analysis, completed in 1974 (Everitt 1974), demonstrated the potential of measuring frame-dragging to 1% to 2% and the geodetic effect to 1 part in 10^4. Later analyses, discussed below, suggest possibilities for further improving those precisions each by a further factor of 10.

In 1984, after technical and scientific reviews by the Space Science Board and other bodies, and completion by NASA Marshall Center of a Phase B Study, the NASA Administrator approved the start of a program known as STORE (Shuttle Test Of the Relativity Experiment). The purpose of STORE is to verify the final Gravity Probe B science payload, perform on the Shuttle a 7-day "experiment rehearsal" (including sophisticated gyro tests in low gravity), and then return the payload to Earth for refurbishment and integration into the Science Mission spacecraft.

The payload (Figure 1) comprises four gyroscopes, a telescope, and a "drag-free proof mass," all mounted in a "quartz block assembly" within an evacuated magnetically shielded probe, which in turn is inserted into a 10-ft long, 6-ft diameter liquid helium dewar, operating at 1.8° K and maintaining low temperature for 2 years. Stanford is responsible for developing the quartz block assembly; Lockheed, under contract to Stanford, developed the dewar and the probe. STORE is manifested on Shuttle OV-105, for launch MSSN 69 in February 1993. The Science Mission is set tentatively for June 1995.

II. THE GYROSCOPE

The gyroscope is a sphere of fused quartz 38 mm in diameter, coated with a thin (~1 μm) layer of superconducting niobium, and suspended within a spherical cavity by voltages applied to 3 mutually perpendicular saucer-shaped electrodes. The rotor-electrode gap is about 40 μm; the support voltages about 1 kV on Earth and 0.1 V in space. The rotor is spun up to 170 Hz through a differential pumped channel inside the housing, after which the pressure is reduced to about 10^{-11} torr and the rotor coasts freely. The spin-down rate, governed by gas damping, is about 0.0025% per year.

The gyroscope's most novel feature is its "London moment readout." A spinning superconducting sphere of radius r, angular velocity ω_s develops a magnetic moment $M_L = (mc/2e)r^3\omega_s$ G-cm^3 aligned with its instantaneous spin axis. This magnetic marker is read out by surrounding the sphere with a tightly coupled superconducting loop (Figure 2) connected to a SQUID (Superconducting QUantum Interference Device) magnetometer. The London moment readout has four key merits: (1) it can be applied to an ideally round and homogeneous rotor, (2) it offers 1 milliarcsec resolution in a 2-hour observation period, (3) it is insensitive to miscentering of the ball in the loop, and (4) it causes negligible readout reaction torque.

Since 1975, we have gained some 20,000 hours of gyro test data, with speeds up to 179 Hz, precise London moment readout, and drift performance corresponding to 0.6 milliarcsec/yr at 10^{-10} g.

III. PERFORMANCE LIMITS ON THE EXPERIMENT

A sound experiment needs: (1) drift-free gyroscopes, (2) precise determination of the gyro spin directions with respect to a guide star, and (3) knowledge of the star's proper motion with respect to distant quasars. Current uncertainty in the proper motion of our guide star, Rigel, sets limits on the experiment at 0.9 to 1.7 milliarcsec/yr, but since future astrometric missions (HIPPARCOS and POINTS) should remove that problem, we ignore proper motion and ask what the internal limits on the experiment are.

Earlier analyses of gyro drift performance were deliberately conservative. Take the simple but critical mass-unbalance torque due to variations $\Delta\rho/\rho$ in the density of the gyro rotor. It causes a drift-rate $\Omega_\rho < 0.25\ (\Delta\rho/\rho)\ f/\omega_s$, where ω_s is the gyro angular velocity and f is the mean transverse acceleration on the spacecraft. With $\Delta\rho/\rho \sim 3\times10^{-7}$ and $f \sim 10^{-10}$ g, the drift-rate is 0.05 milliarcsec/yr - essentially the result used, with other error terms, to compute the earlier overall estimated worst-case Newtonian drift of 0.3 milliarcsec/yr. Now, Gravity Probe B is a drag-free satellite, and it rolls (10-min period) about the line of sight to the guide star, which is also the gyro spin axis. In that configuration, the assumption of a 10^{-10} g mean transverse acceleration is extraordinarily conservative. Even 10^{-11}g is conservative. This term can safely be reduced by least a factor of 10, though it should be added that, as of now, nonuniformities in the rotor coating would make a larger (0.06 milliarcsec/yr for 10^{-11} g) contribution to gyro drift.

Other refinements to the error budget come from (1) a greatly improved understanding of gyro suspension torques, (2) a demonstrated capability of operating at pressures as low as 10^{-11} torr (as compared with the earlier 10^{-10} torr), and (3) a decision to fly Gravity Probe B in an orbit (established via an on-board Global Positioning System sensor) whose mean is within 100 m of the poles. A revised analysis, to be published elsewhere, yields a worst-case total Newtonian drift no higher than 0.06 milliarcsec/yr.

The issues in determining the gyro spin direction with respect to the guide star are somewhat different. Here the analysis combines gyro readout noise, telescope errors, calculation of the gyro scale factor (achieved by using the aberration of starlight as a "natural yardstick"), and calibration of the spacecraft roll orientation. In earlier Kalman filter covariance analyses (Vassar *et al.* 1980), the limits dominated by SQUID noise in the gyro readout were in the range of 0.6 to 0.9 milliarcsec/yr. A recent analysis by J. V. Breakwell and X. H. Qin, taking into account already demonstrated improvements in SQUID technology plus the extension of the mission lifetime from 1 to 2 years, reduces this figure in measurement of the frame-dragging effect to 0.06 to 0.13 milliarcsec/yr for a single gyroscope.

It would be premature to offer a final revised figure for the overall performance of Gravity Probe B, but an improvement by as much as a factor of 10 over earlier estimates is not out of the question.

IV. INTEGRATION AND IN-FLIGHT CALIBRATION

The STORE program commenced in February 1985. The main tasks so far have been to develop flight quality gyroscopes and design and build a First Integrated Systems Test (FIST) (Bardas *et al.*). The FIST comprises a full-scale dewar probe/quartz block assembly (Figure 1, inner part), interfaceable with the flight dewar, for use in ground tests in a laboratory dewar of comparable length but smaller diameter. First cool down is June 1989. Design of the science payload/Shuttle test unit begins September 1988, fabrication February 1990. Between February 1989 and September 1990, competing spacecraft predesign studies will be performed by two yet-to-be-selected aerospace companies.

In-flight calibration is a critical issue for the Science Mission. Gravity Probe B is unusual among tests of general relativity in that it is a physics experiment rather than an observation of given astrophysical or solar system phenomena. The system is under experimenters' control and allows a profusion of reliability checks. Some deliberately enhance certain errors for brief periods, for example, by introducing an inertially fixed 10^{-7} g bias into the drag-free controller to magnify and calibrate mass-unbalance and suspension torques. Others, such as the use of starlight aberration to calibrate the gyro scale factor, are built into the experiment. Six distinct principles of in-flight calibration have been established (Everitt 1988) to form a comprehensive validation scheme.

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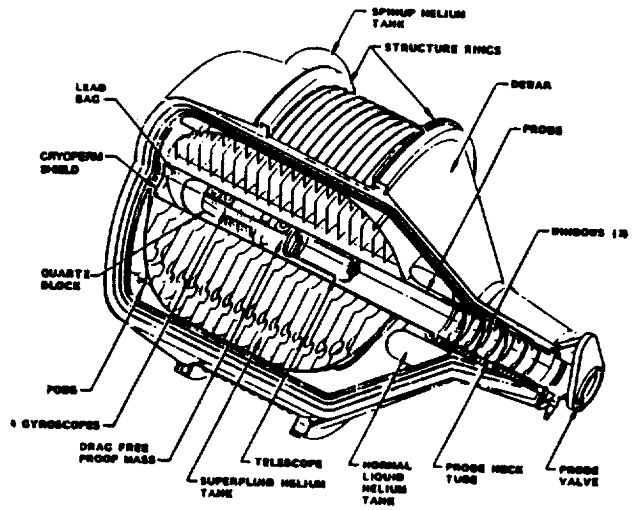

FIG. 1. — Gravity Probe B Science Payload as Tested on Shuttle in the STORE program.

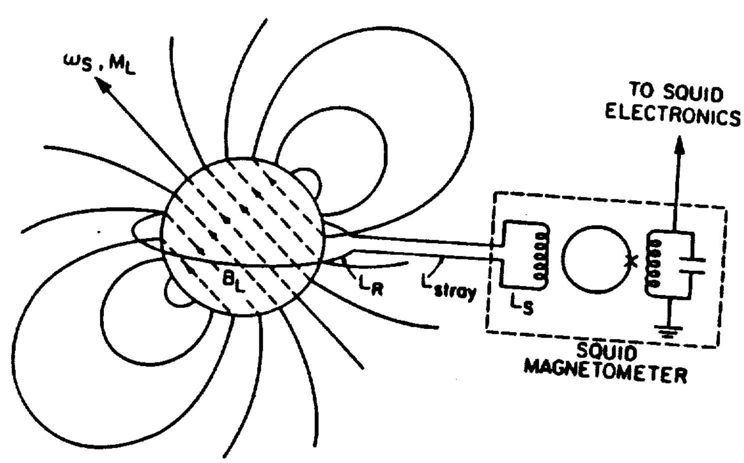

FIG. 2. — Reading Out the Gyro Spin Axis via the London Moment.

DISCUSSION

SHAPIRO: What tests will be performed on the 7-day shuttle flight of the gyroscope experiment?

EVERITT: The Shuttle flight fulfills two functions. First is an "experiment rehearsal" that will enable us to evaluate the overall performance of the dewar instrumentation package under semi-realistic space conditions. In that mode we will go through the fairly complex logistics of gyro spin-up, alignment, and low gravity operation; and also study a large number of mundane but important operational parameters such as gyro pressures and temperatures, dewar boil off, performance of the multilevel suspension system under different acceleration conditions, SQUID performance, response of system to launch environment, and so forth. Second, the Shuttle flight provides the first opportunity for extended gyro tests under low gravity conditions. These will be based on intercomparisons between the gyros. To enhance the information gained from the gyro tests we have reached agreement in principle with the Shuttle program office to have two two-hour periods per day in which the Shuttle will be rolled slowly (10 minute period) approximately about the gyro spin axes. We plan also to spin two gyros at full speed and two at reduced speed. Some consideration has been, and will continue to be given, to reducing the mean transverse acceleration on the gyros by applying the gyro suspension signals to the Shuttle control system, in order to make the Shuttle quasi drag-free. This data has interest for many other people besides ourselves, but we may suspect that in the end the bureaucracy will prevent it from happening.

SHAPIRO: What changes of the individual gyroscopes might be made (one with respect to another) to eliminate possibly important common-mode errors?

EVERITT: As the basic operation of the gyroscope we have four gyros all aligned essentially parallel with the line of sight to the guide star, two spinning clockwise and two counterclockwise; each with its own unique mass-balance, asphericity, and surface patch effect patterns. Having the gyroscopes in two opposed pairs makes them respond oppositely to certain classes of disturbance; for example, any effect of the Earth's gravity gradient on the centrifugally induced oblateness of the gyro star (but see answer to Ciufolini's first question below), and magnetic torques from the interaction of the London Moment with some common-mode transverse magnetic field (though the only known example of such a field that can begin to cause error, trapped flux in the surrounding magnetic shield, is heavily averaged by the roll of the spacecraft). Conversely, having innate differences in asphericity, mass-unbalance, etc. for the individual gyroscopes, means that they will respond differently to mass-unbalance and suspension torques generated by transverse accelerations on the spacecraft. If, therefore, in basic gyro operation, all four gyroscopes are seen to agree with each other to the performance level calculated in advance, significant constraints will have been established on any common mode errors from these known sources.

Another built-in difference among the four gyroscopes is that each is at a different distance (ranging from 10 cm to 45 cm) from the spacecraft center of mass. Hence we get a further autocratic check (of a very favorable kind) on mass-unbalance and suspension torque terms. The reasoning is as follows. Although we tune up the orbit initially so that its mean plane over the lifetime of the experiment is very exactly polar and aligned with the line of sight to the guide star, the orbit-plane is subject to lunisolar perturbations that make it oscillate back and forth, principally with respect to the line of sight, with 14 days and 6 month periods. These motions introduce transverse accelerations, different for each gyro, because of the gyros' displacement from the orbit plane. These accelerations give rise to very small drift terms, with six month and fourteen day periodicities, in the plane of the geodetic precession. (Note that there is no such effect in the plane of the frame dragging precession). Both terms are small, (the fourteen day one exceedingly so) but by searching for them we set a definite upper limit on such torques (from a criteria different from these described above) and so strengthen confidence in the experimental result. Alternatively if the observed were much larger than anticipated, one could attempt to diagnose their cause, and apply corrections to back out the relativity data.

The question of deliberately applying changes to the system, different for each gyroscope, is part of the larger question of post-flight calibration tests discussed by Everitt (1988). There is a balance, discussed in that paper, between the physicist's desire to vary every parameter he can, and the engineer's desire not to mess with a working system. It is easy enough to raise the suspension preload voltages on each gyro independently and thereby change a certain class of suspension torques; it is also easy to apply known magnetic fields to each gyro to find any anomalous magnetic disturbances. On the other hand, we should be considerably more cautious about changing rotor speed after spin-up. See Everitt (1988) for further discussion.

CIUFOLINI: Another possible use of the GP-B experiment outcome may be to place limits on the existence of torsion (antisymmetric connection), that may propagate in vacuum in some gravity theories. A part of the eventual torsion may in fact comply with the spin of the gryoscope and give a precession, additional to the Lense-Thirring-Schiff and De Sitter precessions.

EVERITT: This comment is appreciated. I hope Dr. Ciufolini will continue his researches into these interesting theoretical questions.

CIUFOLINI: What is the order of magnitude of the spin precession of the gyroscope due to the coupling between the static part of the Earth field and the quadrupole moment of the quartz sphere due to its rotation?

EVERITT: For a gyroscope with quadrupole coefficient J_2, in circular orbit about a spherical central body, the secular component of drift for gravity gradient coupling is, by Laplace's formula, W = 3/4 or $3J_2\ g'/4w_sP\ \sin 2\alpha$, where R is the orbit radius, α the angle between spin axis and orbit plane, g' the gravitational acceleration at altitude R, and w_s the gyro's angular velocity. For the Gravity Probe B gyroscopes the centrifugally induced J_2 with w_s = 1068 rad/s (170 Hz) is 3×10^{-6}; there is also an intrinsic J_2, because of mass inhomogeneities, of order 10^{-7}. For an orbit whose mean inclination and alignment are, as indicated in the response to Shapiro's second question above, within 100 m of the Earth's polar axis and line of sight to the star, the resulting near precession rate of the gyro spin axis for the centrifugally induced J_2 is 4.6×10^{-4} marc-s/yr. There are also minute six month and fourteen day periodic terms in the orbit plane from the effects of lunisolar perturbations discussed above.

CIUFOLINI: What is the current value of the altitude at which the gyroscope should be injected?

EVERITT: Relativity makes it desirable to have a low altitude; atmosphere drag, which affects the amount of gas required for drag-free control, to have a higher altitude. Current discussion ranges from 550 km - 650 km, with the most likely value being 600 km as specified in the text of the paper.