THE GRAVITY PROBE B RELATIVITY MISSION

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ABSTRACT

The NASA/Stanford Relativity Mission Gravity Probe B (GP-B) experiment will provide two extremely precise tests of General Relativity based on observations of electrically suspended gyroscopes in a satellite in a 650 km circular polar orbit around the Earth. The project is now nearing completion. Final assembly of the instrument will take place later this year and launch is scheduled for October 2000. GP-B will provide a very accurate measurement of the frame-dragging effect, with its subtle connections to gravitomagnetism and Mach's principle. In addition to measuring frame dragging to 0.3%, it will measure the geodetic effect to approximately 1 part in 10^5. GP-B is a controlled physics experiment where error terms such as the Newtonian drifts of gyroscopes are reduced to negligible values, and where the apparatus is under the experimenters' control.

OVERVIEW

Using electrostatically suspended precision gyroscopes GP-B (Turneaure *et al.*, 1989) will measure very precisely the frame dragging and geodetic effects predicted by gravitational theories. In the framework of Einstein's General Relativity, Schiff (1960) has calculated the relativistic precession of a gyroscope in a circular Earth orbit to be:

$$\overline{\Omega}=\left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}\left(\overline{R}\times\overline{\mathrm{v}}\right)+\left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot\left(\overline{\omega}_e\cdot\overline{R}\right)-\overline{\omega}_e\right] \tag{1}$$

Here $\overline{R}$ and $\overline{\mathrm{v}}$ are the orbital location and velocity of the gyroscope, and I, M, and ω_e are the moment of inertia, the mass, and the angular velocity of the Earth. The PPN parameters γ and α_1 modify Schiff's original result in order to account for alternative metric gravitational theories, and are equal respectively to 1 and 0 in General Relativity. The first term in Eq. 1 represents the geodetic effect that yields a 6.6 arcsec/yr precession in the plane of the orbit for a 650 km polar orbit. This effect is due to the motion of the gyroscope through the curved space-time around the Earth, and will be measured to about one part in 10^5 providing the most precise test to date of any of the non-zero predictions of General Relativity. The second term represents the precession due to the dragging of the inertial frame by the rotation of the Earth, and equals 0.042 arcsec/yr for a gyroscope spin axis lying in the equatorial plane. GP-B will measure the frame dragging effect with a precision of about three parts in 10^3.

The geodetic and frame dragging precessions are measured by comparing the local frame of reference, determined by electrostatically suspended gyroscopes, to the reference frame of the distant stars, determined by a telescope pointed to the star HR8703, a relatively bright optical star that is at the same time a radio-star. The proper motion of the star represents one of the main sources of error for the experiment. HR8703 was chosen for its brightness, its location near the equator, and the fact that being also a radio source enables its proper motion to be determined with great accuracy in a separate astrometry measurement. GP-B will be placed in a drag free satellite (DeBra, 1970) thus minimizing the Newtonian disturbances exerted by the suspension system on the gyroscopes. As shown schematically in Figure 1, the polar orbit will result in orthogonal geodetic and frame dragging precessions, thus significantly simplifying the data analysis.

GP-B will perform three secondary relativity experiments in addition to the primary measurements. These are the measurement of the gravitational deflection of light to an accuracy of 5×10^{-3}, the determination of the relativistic perigee precession to better than 3×10^{-3}, and a test of the null gravitomagnetic effect to better than 6×10^{-4}.

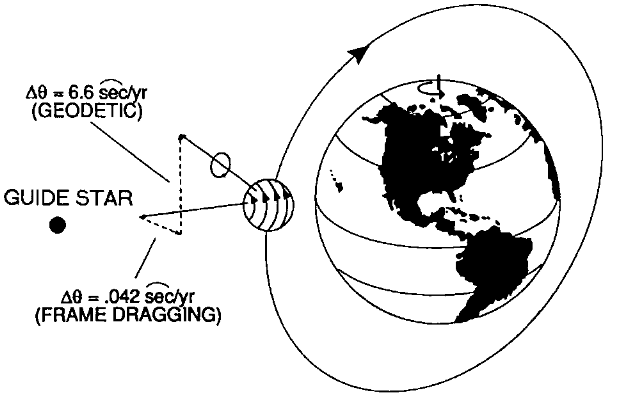

Fig. 1. GP-B experimental concept showing the geodetic and frame dragging precessions predicted by General Relativity for a 650 km polar orbit

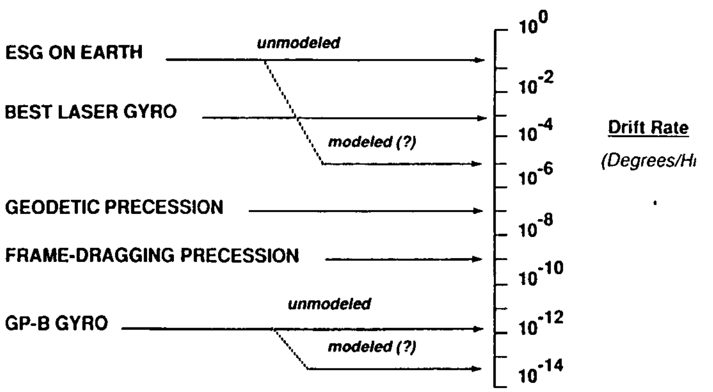

Fig. 2. Performance of gyroscopes on Earth, GP-B gyroscopes, and magnitude of the geodetic and frame dragging precessions.

Damour and Nordtvedt (1993) have shown that tensor-scalar theories of gravity can result in deviations from zero of the PPN parameter γ of up to $\gamma\text{-}1 \leq 4\times10^{-5}$. These theories contain a damping mechanism that drives the world towards General Relativity, with the above deviation a result of the finite time elapsed since the end of the radiation-dominated era. This provides additional incentive to increase the measurement accuracy in order to add the test of this prediction to the GP-B tests (Everitt, 1991).

EXPERIMENTAL REQUIREMENTS

The main requirement is the measurement using a single gyroscope of the precession of the local inertial frame (650 km polar orbit) with respect to the frame of the distant stars with an accuracy better than 0.5 marcsec/yr. Note that a single gyroscope provides all the information necessary to complete the experiment. GP-B has set the goal (versus the 0.5 marcsec/yr requirement) of an overall measurement accuracy of better than 0.1 marcsec/yr. This goal is made achievable by a) the use of four redundant gyroscopes, b) the use of one gyroscope as the drag free sensor, thus eliminating electrostatic suspension disturbances, and c) the possibility to calibrate and subtract from the data the classic disturbances. The 0.5 marcsec/yr error budget is distributed roughly equally among the three main error sources: gyroscope drift (0.3 marcsec/yr), readout system noise (0.3 marcsec/yr), and proper motion of the guide star (0.2 marcsec/yr). Figure 2 shows the relative performance of gyroscopes on Earth, GP-B gyroscopes, and the geodetic and frame dragging precessions (0.3 marcsec/yr = 10^{-11} deg/hr).

GP-B must function for about two years in the space environment, survive launch loads, and achieve compatibility of its various systems, thus imposing demanding engineering requirements on the instrument. The 650 km orbit exposes the spacecraft and instrument to cosmic radiation, making it necessary to construct radiation hardened electronics and to implement an electric charge management system for the gyroscopes (Buchman *et al.*, 1995). Ground testing imposes the requirement that instrument (in particular gyroscope) functionality covers the range 10^{-8} g to 1 g, while non-functional survivability of loads of about 8 g is required for launch capability. The London moment based gyroscope readout system using very high sensitivity SQUID magnetometers imposes stringent restrictions on the amplitude and frequency of the electrical signals in the entire instrument. At the same time the readout system requires both very low static magnetic fields and very high attenuation of variable magnetic fields. These requirements impose the need for complex magnetic shielding and very careful selection and screening of non-magnetic materials for the instrument. The angular accuracy of the experiment is achieved by ensuring the very high mechanical stability of the telescope and the gyroscopes, as well as their connecting structure.

MAIN EXPERIMENTAL FEATURES

Four electrostatically suspended cryogenic gyroscopes whose spin axes are aligned with the line of sight to the guide star measure the local frame of reference. The gyroscopes are 3.8 cm diameter fused quartz spheres coated with a 1.25 μm film of niobium. Spin-up to about 100 Hz is achieved using 6.5 K helium gas. UV photoemitted electrons control the charging caused by cosmic radiation. Alignment of spin axis to star direction, to about 1 arcsec, is achieved by modulation of the electrostatic support force at satellite roll-rate. The gyroscope housing is also fabricated of fused quartz, and supports electrostatic suspension, position sensing, charge management, helium spin-up, and thermometry. The expected gyroscope disturbance drift rate is about 0.2 marcsec/yr for the suspended gyroscopes and less than 0.02 marcsec/yr for the non-suspended (drag free sensor function) gyroscope.

The gyroscope readout is based on the detection of the London magnetic dipole moment created by the spinning superconducting niobium film coated on the gyroscope. Precession of the angular momentum results in the precession of the magnetic dipole and induces variation of the flux threading a 4-turn superconducting loop concentric to the gyroscope. This variation is then measured by a SQUID magnetometer. Rolling of the satellite around the gyroscope spin axis results in a readout signal at this same roll frequency. Readout accuracy is dominated by 1/f noise, making it desirable to use the highest roll-rate compatible with overall experimental constraints. GP-B is designed for roll periods of one to three minutes, 17 mHz to 5.6 mHz. At a 5 mHz detection frequency the noise performance of the read-out in the flight system is about 7×10^{-29} J/Hz. This is equivalent to a resolution of 1 marcsec for an integration time of seven hours, fully meeting the GP-B requirements.

The very small magnitude of the London moment readout requires an ac magnetic shielding factor for the gyroscopes of 10^{12}. In order to meet the requirement for a low trapped flux in the rotors, 3×10^{-10} T, the residual dc magnetic field at the gyroscopes must be less than 10^{-10} T. These requirements are achieved by using a system of superconducting magnetic shields, in conjunction with controlling the magnetic properties of the instrument materials, resulting in dc field values of about 5×10^{-11} T, and ac attenuation of 10^{12}.

A cryogenic Casegrainian telescope, with a 381 cm focal length and an aperture of 14.4 cm, provides the reference to the fixed frame of the distant stars. The telescope and the quartz block mounting the four gyroscopes are bonded and maintained at cryogenic temperatures, thus ensuring the ultra-low mechanical drift between these instruments. The telescope detector uses photodiodes with JFET amplifiers functioning at 70 K, resulting in a pointing noise for the instrument of less than 10 marcsec/$\sqrt{\text{Hz}}$. Accurate repeatable mounting of the detector package assembly on the telescope is achieved using a precision-mounting fixture. A set of four optical windows, one sapphire and three quartz, allow the light of the star to reach the cryogenic telescope. The window system ensures optical transmission of at least 70% in the 400 nm to 1000 nm band, 50 dB EMI rejection, 10^{-9} Pascal ultra high vacuum for the experiment, and minimal optical distortions induced by thermal gradients.

The main components of the GP-B Science Instrument Assembly (SIA), including telescope, quartz block, and four gyroscopes, must maintain high mechanical stability with respect to each other in order to achieve the required measurement accuracy. Advanced material science, machining, and mechanical mounting techniques have been developed to achieve these goals. All quartz interfaces are precision machined and optically polished to allow bonding. Figure 3 is a schematic representation of the SIA. Telescope and gyroscopes are mounted to the quartz block by potassium hydroxide bonding and special mechanical mounts ensuring an angular stability between the readout loops of the gyroscopes and the telescope axis of better than 0.1 marcsec/yr, and an alignment better than 5 arcsec. In order to minimize the centrifugal forces on the gyroscopes caused by the satellite roll, all four gyroscope centers are aligned to the roll axis to better than 0.1 mm, while their spacing along the telescope axis is controlled to better than 1 mm.

The science instrument is mounted to the cryogenic probe via a quartz-to-aluminum interface with special mechanical fasteners and molybdenum thermal shoes in order to meet the thermal conductivity and mechanical stress requirements. Assembled at room temperature for use at 2 K, the entire probe science instrument structure is designed to withstand cycling over the 350 K to 2 K thermal range. Cryogenic temperatures for the GP-B experiment are maintained by 2300 liter capacity superfluid helium flight dewar with a nominal lifetime of 16.5 months. A normal helium guard tank, placed at the neck of the dewar, makes it possible to maintain the main tank full for extended periods on the launch pad. A 'porous plug' maintains the helium bath at superfluid temperatures. This plug consists of a calibrated superfluid leak, ensuring well-defined high gas flow rates over a range of temperatures, while inhibiting superfluid breakthrough.

The GP-B spacecraft is tailored to support the high accuracy cryogenic experiment. The proportional thrusters that control the attitude, roll, and drag free functions of the spacecraft utilize the venting helium as propellant. Star trackers are used to control roll rate, while rate gyroscopes support pointing and roll when the Earth occults the guide star. The star trackers and rate gyroscopes are mounted on precision instrumentation platforms connected to a graphite ring in the dewar structure, ensuring a rigid and stable mechanical reference to the science instrument. Particle detectors and magnetometers monitor the space environment, making possible direct correlation of the science data with anomalous radiation or magnetic events. A global positioning system, GPS receiver, ensures accurate orbit insertion and trim. Orbit parameters will be continuously monitored by the GPS receiver and by laser ranging to a set of retro-reflectors mounted on the spacecraft. All spacecraft systems are designed to meet the high reliability appropriate for this type of experiment. Figure 4 is a schematic representation of the GP-B satellite.

Detailed descriptions of the gyroscopes, charge management system, read-out system, telescope, payload, space vehicle, and GPS are given in accompanying papers in this journal, while the gyroscope suspension system is described in detail by Buchman *et al.* (1998).

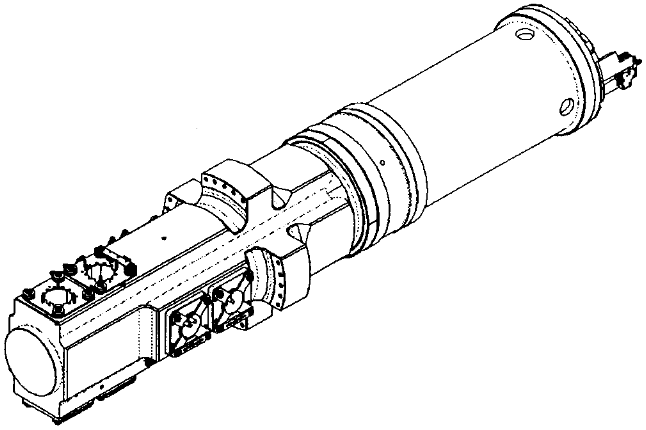

Fig. 3. Schematic view of GP-B Science Instrument Assembly.

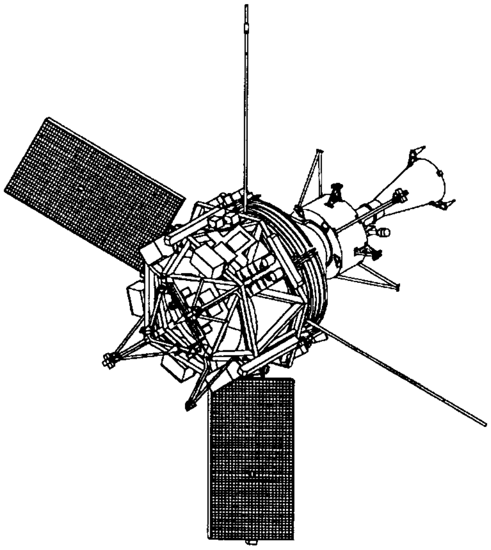

Fig. 4. Schematic view of GP-B Spacecraft

PROGRAM STATUS AND CONCLUSIONS

GP-B has developed a complete set of flight and science mission data analysis algorithms, as well as a comprehensive error-tree analysis system. End to end analysis of simulated data through flight algorithms has verified the software and confirmed the 0.1 marcsec/yr analytically calculated prediction for the expected experimental accuracy. Measurements of the proper motion of the guide star HR 8703 (IM PEG) are continuing, with the expectation that the accuracy of this measurement will exceed 0.1 marcsec/yr by 2002. A highly elaborate operational time line has been developed for the mission. A complex 40-60 day initial calibration and setup, incorporating in excess of 1000 events, is followed by 13-15 months of science data acquisition and a 30-day post-mission calibration period comprising about 100 events. The telemetry of the 26 kbit/sec data (15 kbit/sec science and 11 kbit/sec house keeping and transient event data) is supported by the NASA ground network as well as by the TDRSS network.

All science instruments: gyroscopes, SQUID sensors, and telescope have been commissioned for flight and are meeting all requirements. The flight dewar and probe are completed and ready for final integration. SIA integration and payload (SIA, probe, and dewar) integration are planned for early 1999, with payload verification and payload electronics completion scheduled for mid-1999. The end of 1999 will see the completion of the spacecraft and the space vehicle (payload and spacecraft) integration. Space vehicle verification and launch are planned respectively for the first and last part of the year 2000.

GP-B has developed and implemented a large number of technologies with direct application to future precision space experiments in general, and to the Satellite Test of the Equivalence Principle (STEP) and the Laser Interferometer Space Antenna (LISA) missions in particular. The program has also perfected the incremental prototyping approach to hardware and integrated testing, thus ensuring the successful development of the complex instruments needed for this class of experiments.

ACKNOWLEDGMENTS

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REFERENCES

DeBra, D.B., DISCOS Description, Private communication, Stanford University, (1970).
Buchman, S., T. Quinn, G.M. Keiser, D. Gill and T.J. Sumner Rev. Sci. Instrum. **66**, 120 (1995)
Buchman, S., William Bencze, Robert Brumley, Bruce Clarke, and G.M. Keiser, Second International LISA Symposium, AIP Conference Proceedings **456**, 178 (1998)
Damour, T., K. Nordtvedt, Phys. Rev. Lett. **70**, 2217 (1993).
Everitt, C.W.F., Proc. VI Marcell Grossmann Meeting, Kyoto, Japan (1991).
Schiff, L.I., Proc. Natl. Acad. Sci. **46**, 871 (1960).
Turneaure, J.P., C.W.F.Everitt, and Brad Parkinson, Adv. Space Res. **9**, 29 (1989).