

## A STATUS REPORT ON THE RELATIVITY MISSION

B. MUHLFELDER\*, C.W.F. EVERITT\*, B.W. PARKINSON\*, J.P. TURNEAURE\*, D. BARDAS\*, S. BUCHMAN\*, D.B. DEBRA\*, H. DOUGHERTY†, D. GILL\*, G.B. GREEN\*, G.M. GUTT\*, J. GWO\*, N.J. KASDIN\*, G.M. KEISER\*, T. LANGENSTEIN\*, J.A. LIPA\*, J.M. LOCKHART\*\*, R.T. PARMLEY‡, M.A. TABER\*, R.A. VAN PATTEN\*, Y.M. XIAO\*, S. WANG\*

\*W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, U.S.A.

\*\* Physics Department, San Francisco State University, San Francisco, CA 94132, U.S.A.

\*NavAstro, 204 More Avenue, Los Gatos, CA 95030, U.S.A.

†Space Systems Division, Lockheed Martin, 2690 Hanover Street, Palo Alto, CA 94304, U.S.A.

‡Research and Development Div., Lockheed Martin, 3251 Hanover Street, Palo Alto, CA 94304, U.S.A.

### ABSTRACT

The Gravity Probe B Relativity Mission will measure the geodetic and frame-dragging precession rates of gyroscopes in orbit about the earth. The goal is to measure the geodetic effect to 2 parts in  $10^5$  and to measure the frame-dragging effect to 3 parts in  $10^3$ . The measurement will be done by comparing the orientation of several gyroscopes to a distant reference star. This paper will describe the main experimental systems including the gyroscopes, gyroscope readout, telescope, and an integrated, cryogenic test system. Experimental results for these systems will be described. These results are consistent with the overall experiment goal as quoted above. Measurements will be presented for the gyroscope's mass unbalance by observation of precession rates, gyroscope readout noise measurements of  $135 \text{ marcsec}/\sqrt{\text{Hz}}$ , demonstration of dc magnetic fields of  $1 \times 10^{-7} \text{ G}$  and telescope readout noise of  $2 \text{ marcsec}/\sqrt{\text{Hz}}$ .

### 1. Introduction

In 1960 L.I. Schiff<sup>1</sup> predicted that a gyroscope in orbit about the Earth would exhibit geodetic and frame-dragging effects as given by General Relativity. The purpose of the GP-B Relativity Mission is to measure these two effects. Figure 1 gives a schematic representation of the two effects for a polar orbit configuration. Since 1960, a number of

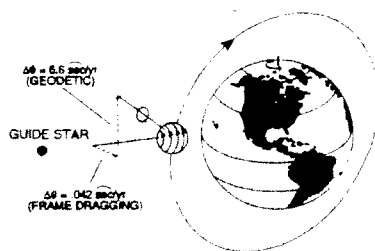


Fig. 1 The geodetic and frame-dragging effects for a gyroscope in a 650-km polar orbit about the earth.

alternative theories<sup>2,3</sup> have been proposed which give varied amplitudes for the geodetic and frame-dragging effects. The GP-B Relativity Mission distinguishes between these theories.

An in-depth view of the experimental implementation for the GP-B Relativity Mission is shown in Figure 2. The experiment is configured so that the pointing direction of each of the four gyroscopes will be compared to the position of a reference star. A telescope is used to track the position of the star, thus providing a nearly fixed pointing direction. A quartz block provides a stable and a precision platform for both the telescope and the gyroscopes. This platform allows comparisons to be made between the pointing direction of the telescope and the pointing direction of each of the gyroscopes. A readout system for each gyroscope measures the angle subtended by the spin axis (pointing direction) of each gyroscope and the telescope's optical axis. Any changes in this angle, those due to relativistic effects for example, will be reflected in the output of the gyroscope readout system. Since the telescope tracks the guide star, the gyroscope's pointing direction can be compared to the star's position.

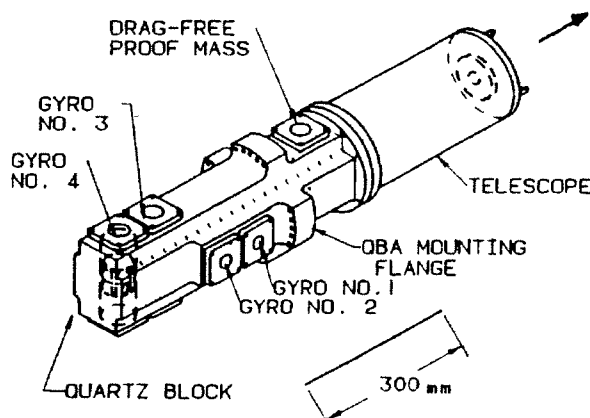


Fig. 2 Quartz block assembly with four gyroscopes, drag-free proof mass and telescope (with arrow pointed toward the guide star). The entire assembly is located within a dewar and is cooled to 2 K which facilitates the gyroscope readout system and helps to stabilize the assembly mechanically.

The entire quartz block assembly is located within a spacecraft which rotates about the telescope's optical axis once every several minutes. As a result, each of the four gyroscopes provides similar information. Although the signals from gyroscopes #1 and #2 will be phase shifted by  $90^\circ$  with respect to gyroscopes #3 and #4, the rotation phase can be determined with a spacecraft star blipper (mounted orthogonally to the optical axis of the telescope) and through data analysis.

Four main types of error sources must be understood and controlled in this experiment. These error sources are gyroscope drift induced by Newtonian torques, gyroscope readout noise, telescope/spacecraft pointing error and the proper motion of the guide star. Following this paper, which gives an overview of the experiment and the associated error sources, there is a set of four papers which discuss some of the specific technologies and related issues in greater detail. Those papers cover the gyroscope, the telescope, the guide star, and a supplemental gyroscope readout system.

## 2. The Gyroscope

The overall drift rate of the gyroscopes due to Newtonian torques must be maintained at less than 0.1 marcsec per year. We minimize gyroscopic torques by controlling the mass properties and geometry of the gyroscopes and by minimizing the force applied to the gyroscope. In order to understand gyroscopic torques, it is necessary to give a physical description of the gyroscope. The gyroscope consists of a spherical rotor encased within a housing. The rotor has a metallic surface coating which allows it to be electrostatically levitated with respect to the housing. Once levitated, the rotor is spun by passing helium gas along the surface of the rotor through a channel which is located in the gyroscope housing. To achieve the 0.1 marcsec per year drift rate, the rotor must be fabricated from material with a mass density homogeneity of better than 2 parts per million, the rotor must be polished to be spherical to better than 3 parts per million peak-to-valley, the rotor's coating must be applied uniformly to give a mass unbalance of better than 50 nm and the rotor must be spun to a frequency of approximately 130 Hz.

The mass properties and geometry of the gyroscope as given above require that the average acceleration transverse to the spin axis of the rotor be kept below  $1 \times 10^{-12}$  g. We achieve this by allowing a test mass (one of the gyroscopes) located inside of the spacecraft to freely orbit the Earth. A servo system causes the spacecraft to follow the path of the test mass thereby minimizing gyroscope accelerations due to the Earth's residual atmosphere, solar wind effects and small particles which impinge upon the spacecraft.

## 3. The Gyroscope Readout System

A schematic view of the GP-B Relativity Mission gyroscope readout system is shown in Figure 3. The heart of the system is based upon the London Magnetic Moment<sup>4</sup> whereby a spinning superconductor develops a magnetic moment which is co-aligned with its spin axis. A shift in the orientation of the spin axis (due for example to relativistic effects) will cause a corresponding change in the direction of the London Moment. These changes induce a current to flow in a closely coupled pickup loop. This

current signal is delivered to the input of a dc SQUID which converts that signal to a voltage at the SQUID output.

In order to use the readout system as described above, it is critical to provide adequate magnetic shielding of two types. First, we must attenuate the ac magnetic field which reaches the pickup loop. This signal is generated as the pickup loop passes through the Earth's dc magnetic field. We must also minimize the dc magnetic field which is trapped in the rotor. We want the trapped field signal to be less than 1% of the London Moment signal ( $10^{-4}$  G). A multi-layered, ferromagnetic and superconductive shield system is incorporated into the apparatus which provides both ac and dc magnetic shielding.

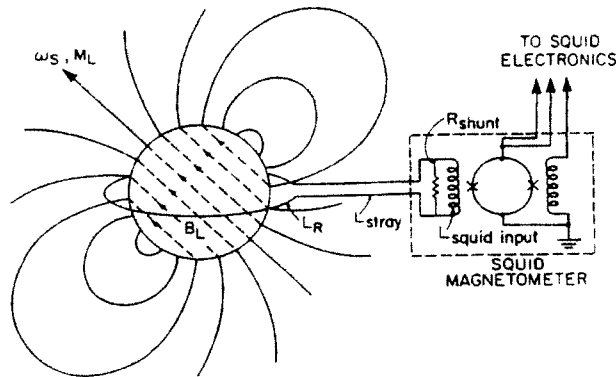


Fig. 3 London moment readout system with London magnetic field of  $B_L$ , pickup loop inductance  $L_R$ , and SQUID input coil inductance  $L_{\text{SQUID input}}$ .

#### 4. The Telescope Pointing System

The purpose of the telescope pointing system is to keep the spacecraft pointed toward a distant fixed star. The heart of the system is a folded Schmidt Cassegrainian telescope, shown in Figure 2. It has a 14-cm diameter main mirror and has a focal length of 3 m. A beam divider splits the star's image and thus allows a two-axis readout. Each axis of light is split again using roof prisms thus providing a differential type of measurement. These four light beams are detected by photodiodes and amplified by cryogenic preamplifiers. This configuration gives a signal proportional to the deviation of the telescope's optical axis from the centroid of the star. This telescope readout signal is then used as the input to a closed loop feedback spacecraft attitude control system which locks the telescope onto the star. Helium boiloff gas flowing through proportional thrusters provides the required spacecraft control authority.

## 5. Test Results

Many different types of tests have been performed which verify that we can achieve the overall mission goal of a 0.1 marcsec/yr measurement. These tests include extensive experimentation on each of the critical subsystems as well as a series of tests of the integrated instrument.

The gyroscope has been tested for more than 70,000 hours of operation, which is the equivalent of eight years of continuous operation. We have measured spin-down rates and precession rates of our gyroscope. Spin-down tests have been performed by comparing the performance of two gyroscopes. These measurements confirm the expected amount of dissipative damping. The resulting torques are consistent with an on-orbit drift rate to better than 0.1 marcsec/year. Separate measurements of the precession rate of gyroscopes in ground-based, cryogenic testing indicate an expected on orbit precession rate of less than 0.1 marcsec/year. Both of these types of measurements confirm the gyroscope's geometry and mass properties. Additional gyroscope performance tests demonstrate the capability to achieve a gyroscope spin speed of at least 130 Hz.

The readout system has also been tested extensively in ground-based tests. Two classes of tests have been performed. First, tests of the isolated readout system have verified the flight requirements. Specifically, the noise performance of isolated dc SQUIDs have given a noise performance (referred to a flight gyroscope configuration) of 135 marcsec/ $\sqrt{\text{Hz}}$ . This performance is consistent with a 0.1 marcsec/yr measurement capability. The second type of readout system test has verified the operation of the readout system with an active gyroscope, however because of the high gyroscope precession rate in a 1 g environment, the low frequency noise of the readout system is masked by the slewing London Moment signal. The white noise of the readout system, however is unchanged by the presence of the gyroscope, and furthermore, the London Moment amplitude has been verified to approximately 1%. These tests confirm that the complete readout system works as expected.

In addition to the London Moment signal, there exists a second type of magnetic signal that is due to the magnetic field trapped in the rotor. If this signal is larger than approximately 1  $\mu\text{G}$ , it may cause excessive nonlinearities in the readout system. We have found that for our rotors, the rotors trap a dc magnetic field which is approximately equal to the ambient magnetic field. A multi-layered set of shields has allowed us to achieve trapped magnetic fields as low as  $2 \times 10^{-7} \text{ G}$ .

An apparatus has been built that allows rigorous end-to-end testing of the telescope system including a light source to simulate the guide star, a cooled telescope

and its associated readout electronics. The noise of the telescope system comes from two main sources: photon counting noise and electronics readout noise. The photon counting noise is the larger of these two noise sources. This photon counting noise depends on the choice of the star, but for all of the stars under consideration it is less than  $10 \text{ marcsec}/\sqrt{\text{Hz}}$ . Since the overall noise performance of the telescope is approximately 10 times smaller than other experimental error sources, the telescope system performance does not significantly increase the overall GP-B Relativity Mission measurement uncertainty.

Finally, we have completed two large integrated systems tests and plan on doing three more. Ultimately these tests will verify the entire experiment payload. Thus far, the most complete test included two gyroscopes and four SQUIDs operating in an ambient magnetic field of better than  $1 \mu\text{G}$ . The main results from that test were that we successfully operated both gyroscopes and all the SQUIDs and that the trapped field in a single gyroscope was measured to be  $4 \mu\text{G}$ . In our next test, we will operate four gyroscopes with six SQUIDs. We have made some changes to the hardware which should reduce the magnetic field trapped in the gyroscopes to less than  $1 \mu\text{G}$ .

## 6. Plans For The Future

There are several significant pieces of hardware that must be completed prior to the 1999 launch. The flight dewar is currently under construction and should be completed in 1996. This dewar will hold 2200 liters of liquid helium to allow for at least 16.5 months of cryogenic operation on orbit. The flight probe is also under construction and should be completed in 1997. This probe is very similar to the existing probe (and in fact the existing probe is a backup to the flight probe). The spacecraft will be available towards the end of 1998. At that point, it will be possible to fully integrate the experiment for system checkout and delivery to the Vandenberg Air Force Base for integration into the launch vehicle.

## 7. References

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