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THE GRAVITY-PROBE-B RELATIVITY GYROSCOPE EXPERIMENT: AN UPDATE ON PROGRESS*

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The Gravity-Probe-B Relativity Gyroscope Experiment (GP-B) is a new test of Einstein's General Theory of Relativity based on observations with gyroscopes in Earth orbit. The experiment is being developed under NASA funding by a team of physicists and engineers at Stanford University with aerospace support from Lockheed Missiles and Space Company, Inc. Its primary purpose is to measure with great precision two heretofore untested effects of General Relativity: the geodetic precession of a gyroscope due to its Fermi-Walker transport around a massive central body, and the motional or gravitomagnetic precession of the gyroscope due to rotation of the central body itself. In addition, since the measurements are made with respect to the line of sight to a guide star (Rigel) whose direction relative to the Sun changes over the year, the experiment will provide a new determination of the deflection of starlight by the Sun, and as a bonus, a much improved determination of the distance to Rigel.

The test will use four gyroscopes, a proof mass and a reference telescope all placed in an evacuated, magnetically-shielded cavity inside a long hold-time helium dewar operating at 1.8K. The dewar/instrument package is mounted in a drag-free spacecraft

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moving in a 650 km polar orbit around the Earth. The mission lasts between 12 and 24 months, during which time it should be possible to fix the geodetic coefficient to a part in 10^4, the motional coefficient to 2%, the starlight deflection coefficient to 1% and the distance to Rigel also to 1%. Part of the mission will be devoted to a variety of in-flight calibration tests to ensure the truth of the final scientific results.

To execute the experiment four fundamental issues have to be addressed: (1) the drift performance of the gyroscope, (2) measurement of the gyroscope precession angle, (3) referencing of the gyro readout to the line of sight to the guide star, and (4) referencing of the guide star to inertial space. The four issues yield ten fundamental requirements on the design of the experiment.

The most important element in the current phase of STORE is the development of the First Integrated System Test (FIST), a full scale ground model of the STORE instrument mounted in a laboratory test dewar. Our plan is to complete FIST in 1988, launch the STORE dewar/instrument package in 1991, and launch the Science Mission in 1994.

1. INTRODUCTION

The goal of the experiment is to use a set of gyroscopes in Earth orbit to measure two previously untested effects of General Relativity first investigated in detail by L.I. Schiff[1]: (1) the geodetic precession resulting from the orbital motion of a gyroscope though the curved space-time around the Earth, (2) the motional or, as it is sometimes called, gravitomagnetic precession due to the dragging of the inertial frame by the Earth's rotation. Figure 1 illustrates the directions and magnitudes of the two effects as they occur in a gyroscope following a 650 km polar orbit with the gyro spin axis lying in the plane of the orbit and pointing toward a guide star near the celestial equator. The geodetic precession is in the plane of the orbit and has a predicted value in Einstein's theory of 6.6 arc-s/yr. The motional precession is in the plane of the celestial equator and in the same sense as the Earth's rotation; its predicted value is 0.042 arc-s/yr. Our expectation is to determine both effects to better than 1 marc-s/yr; and this requires having a gyroscope with a free precession (uncompensated) drift-rate below 0.3 marc-s/yr or 10^{-11} deg/hr. Note by way of comparison that the best conventional inertial navigation gyroscopes typically have compensated drift rates (i.e., the rate after modeling out predictable error terms) of around 10^{-5} deg/hr, and uncompensated drift-rates around 10^{-2} deg/hr - nine orders of magnitude higher than our requirement.

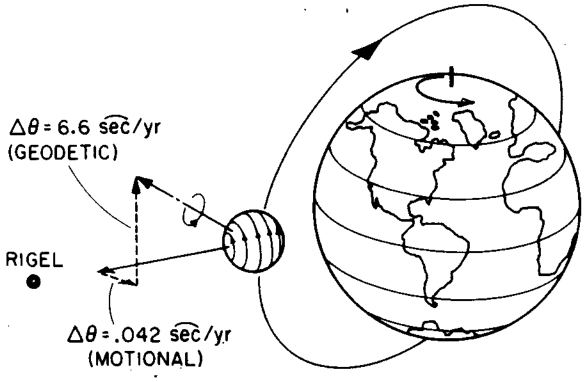

Fig. 1

Relativistic precession rates of gyroscope whose spin vector is parallel to line of sight to guide star and located in orbit plane

The precessions are defined with respect to the framework of the fixed stars, so the experiment uses one or more gyroscopes (in fact four) plus reference telescope pointed at a suitable guide star (Rigel) on or near the celestial equator. In addition, to the two new relativistic measurements, three other relativistic effects will be determined, including the solar deflection of starlight, which has a peak value of 14.4 marc-s/yr. This effect will be calibrated to about 1% and will be an independent check of this effect.

Over the last 25 years during which Stanford has been pursuing this experiment, many articles and technical papers have been published. Some of the more recent articles are listed in the bibliography.

2. GENERAL DESCRIPTION OF THE EXPERIMENT

Figure 2 illustrates the flight dewar/instrument package. Its heart is a quartz block assembly containing four gyroscopes, a drag-free proof mass and the reference telescope. This assembly is mounted in an evacuated chamber inside an ultra-low magnetic field superconducting shield, all enclosed in a superfluid helium dewar of length 118 inch (3.00 m) and diameter 76 inch

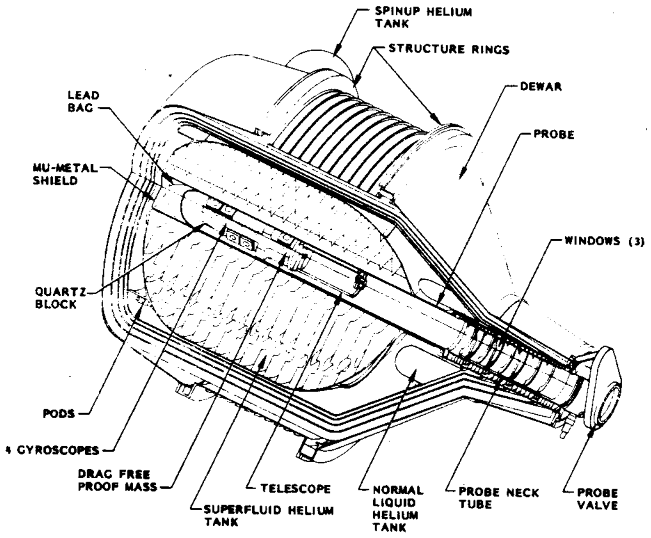

Fig. 2

Gravity-Probe-B flight dewar/instrument package

(1.93 m) designed by R.T. Parmley and others of Lockheed Missiles and Space Company, Inc. The dewar operates at a temperature of 1.8 K and has an expected lifetime of about two years. The dewar/instrument package is assembled with various support equipment to form an autonomous (except for communication) spacecraft which is conceptually illustrated in Fig. 3. An interesting characteristic of the GP-B spacecraft is that the dewar boil-off gas is used by the proportional thrusters to point the spacecraft at the guide star and also to provide drag-free and roll control whose need is explained below. The cylindrically configured solar panels shown in the figure have the important characteristic of keeping the roll disturbances and the aerodynamic drag on the inertially pointed spacecraft low while it orbits the Earth. Such a spacecraft will be used to perform the Gravity-Probe-B Relativity Gyroscope Experiment in what we call the Science Mission to distinguish it from the engineering development efforts.

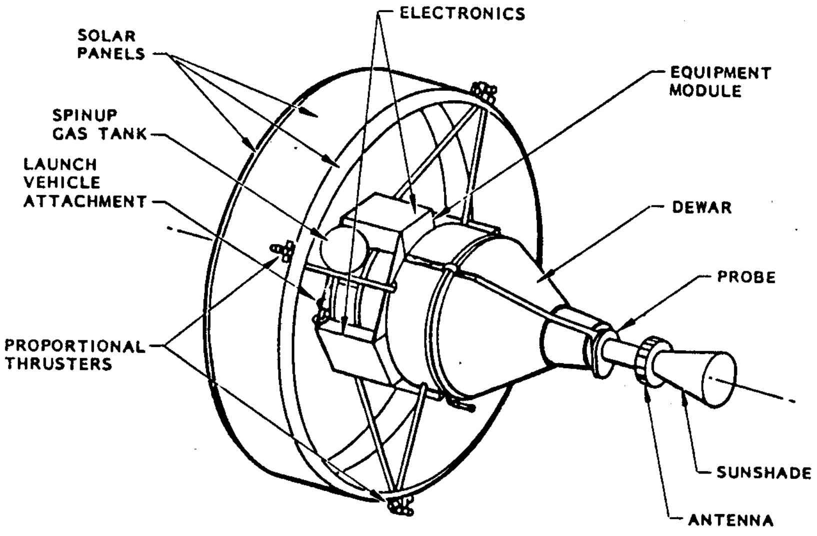

Fig. 3

Gravity-Probe-B spacecraft concept

2.1. The gyroscope

The principles of the gyroscope can be found in the 1978 paper by Everitt[2]. Each gyroscope is a 38 mm diameter fused quartz ball, of extreme sphericity and homogeneity, coated with a thin layer of superconducting niobium. Each is electrically suspended in an evacuated spherical cavity. The gyroscope is spun up to a speed of 170 Hz by means of helium gas jets, after which it is pumped down to a pressure of 10^{-10} torr and allowed to coast freely. The characteristic spin down time at 1.8 K and 10^{-10} torr is about 4000 years. The direction of spin is read out by observations of the London moment in the spinning superconductor.

2.1.1. Gyro readout

According to the London equations of superconductivity a spinning superconductor develops a magnetic moment aligned with its instantaneous spin axis, having in a sphere of radius r the magnitude $M_L = -(mc/e)r^3\omega_s$ G-cm^3, where (mc/e) is the mass/charge ratio of the electron in electromagnetic units and ω_s is the spin rate. For a 38 mm diameter sphere spinning at 170 Hz, M_L is 2×10^{-4} G-cm^3. Figure 4 illustrates the principles of the London moment readout. The ball is surrounded by a superconducting loop coupled via a second loop to the input of a SQUID (Superconducting QUantum Interference Device) magnetometer. If the direction of spin changes, the magnetic flux through the pickup loop will change. In general a three axis readout requires three orthogonal loops, but the experiment configuration reduces the requirement to a single loop for each gyroscope.

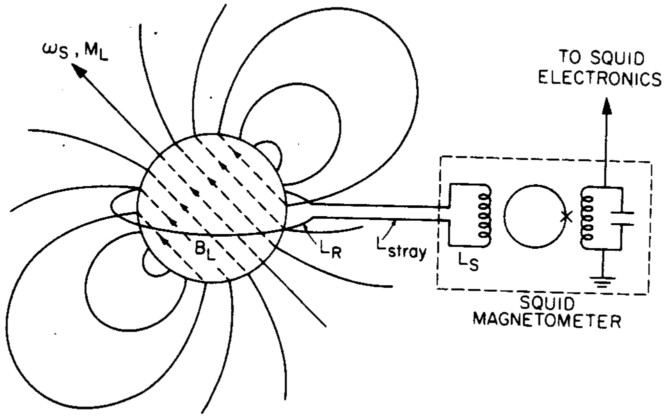

Fig. 4

Schematic of gyro readout using London magnetic moment and superconducting quantum interference device (SQUID)

An important practical consideration is magnetic shielding. The gyroscope has to be operated in a magnetic field that is both low and constant: constant to prevent changes that would couple into the readout and masquerade as a relativity signal, low to limit the amount of flux trapped in the gyro rotor as it cools through its superconducting transition temperature. The requirements are that the trapped flux must not exceed 10^{-7} G and changes in ambient field must not exceed 2×10^{-13} G (nearly thirteen orders of magnitude lower than the Earth's field). We discuss in Section 5.2.4 how these extremes of shielding are achieved.

2.1.2. Gyro Suspension

While the drag-free proof mass reduces the peak acceleration to 10^{-8} g and the average to 10^{-10} g, there is still a requirement to trim out these small effects with a support for the gyro rotors. This suspension is achieved by applying alternating voltages to three mutually perpendicular pairs of saucer-shaped electrodes inside the spherical housing. In the ground-based tests done so far, the rotor electrode gap has typically been 1.8 milliinch (46 m) and the support voltage has been about 1000 V_{rms}. On orbit the required support voltage will be reduced to about 0.1 V_{rms}. The suspension scheme we adopt is similar to one developed by Honeywell Incorporated in the early 1960s, following the pioneering work of A. Nordsieck[3] and others at the University of Illinois.

The novel element in the flight suspension system is a need to adjust the suspension over an extremely wide range, from 1 to 10^{-7} g say, while maintaining support. The approach developed by Van Patten[4] is a microprocessor controlled suspension system in which the bandwidth and control range are simultaneously switched between four modes, each capable of operating over a range of preloads and covering two decades of acceleration.

2.2. Earth orbit with drag-free control

Operation in space and the use of a low voltage suspension system are two of the keys to a successful relativity experiment. On Earth the performance of electrically suspended gyroscopes is limited mainly by support torques, and the uncompensated drift rate is, as already remarked, some nine orders of magnitude higher than the 10^{-11} deg/hr needed. These support torques are of two kinds: a mass unbalance term from inhomogeneity of the gyro rotor and terms arising from the action of the support voltages on the out-of-roundness of the rotor. The mass unbalance torque is $Mf\delta r$, where M is the mass of the rotor, δr is the time averaged distance between its center of mass and center of geometry for the spinning rotor (δr is along the spin axis), and f the component of acceleration transverse to the spin axis. Writing the gyro drift rate Ω_u in terms of the maximum variation $\Delta\rho/\rho$ in rotor density we get

$$\Omega_u \approx \frac{f}{v_s}\frac{\Delta\rho}{\rho} \qquad (1)$$

where v_s is the peripheral velocity of the ball (20 m/s for a 38 mm diameter ball spinning at 170 Hz). Now the total uncertainty in drift from all sources should be less than 0.3 marc-s/yr (10^{-11} deg/hr or 5×10^{-17} rad/s). Let us specify that the drift rate from any individual term such as mass unbalance be less than 0.1 marc-s/yr. Then for a ground-based gyroscope ($f=g=9.8$ m/s^2), disregarding the averaging that would come from working at the equator, would have to be below 10^{-16}. For an orbital experiment it would have to be less than 3×10^{-7} if the residual average transverse acceleration f were 10^{-10} g, and less than 3×10^{-9} if f were 10^{-8} g.

This simple calculation, at once establishes the desirability not only of doing the experiment in a spacecraft but of doing it in a spacecraft having some means of reducing the small acceleration from air drag and solar radiation pressure. For whereas $\Delta\rho/\rho$ in even the most carefully selected materials is at best a few times 10^{-7}, the acceleration acting on a spacecraft of typical area/mass ratio at an altitude of 650 km are of order 5×10^{-8} g, and while the acceleration will tend to average around an orbit, it is unlikely by itself to average to 10^{-10} g.

From an early stage in the development of the gyroscope experiment, calculations like that based on Equation (1),convinced us of the necessity for applying drag-free control in the experiment and using the helium boiloff gas as the source of thrust. Two approaches are possible. One is to have a nonspinning drag-free proof mass independent of the gyroscopes. This is the approach we have generally favored on the grounds that it separates drag-free control from gyroscope suspension; it is assumed in the quartz block design illustrated in Fig. 2 and in Fig. 9 below. The alternative is to modify the gyro suspension system to serve also as a drag-free accelerometer. This has a number of attractions, not least among them the redundancy that comes from being able to switch from one gyroscope to another. Crucial to its success must be the ability in emergency to switch from the drag-free mode to a normal support mode, a process which would seem to be feasible with only modest changes in the design of the multilevel suspension system. The choice between the two approaches is still open.

2.3. The telescope

The telescope is a folded Schmidt Cassegrainian system of physical length 14 inch (0.36 m) focal length 150 inch (3.81 m) and aperture 5.6 inch (0.14 m), fabricated entirely of fused quartz and held together by optical contacting. Details of its design and expected performance, and of the development and testing of a preliminary laboratory version of it are given elsewhere[5].

Its output is expected to be linear to 0.1 marc-s over a range from ±40 to ±70 marc-s depending on the design approach. With Rigel as the guide star, its resolution will be about 1 marc-s in 1 sec of observation time, a result which should be compared with the 1 marc-s in 5 hours for the gyro readout using a dc SQUID.

2.4. Overall instrument operation

The gyroscopes are arranged, as Fig. 1 shows, with their spin axes lying in the plane of the orbit, two spinning clockwise and two counterclockwise. Their precessions are measured in two axes with respect to a guide star whose line of sight also lies in the plane of the orbit. Of necessity relativity data is taken only when the star is in view. During that time the spacecraft pointing system is referred to the telescope; during the remainder of the orbit when the star is occulted the pointing system is referred to the gyroscopes. Since the telescope readout is much quieter than the gyro readouts the pointing will be far more precise when referred to the telescope, but even so the spacecraft cannot be pointed at the star with the 0.3 marc-s precision required for the relativity data. Our goal instead must be to point within the ±40 to ±70 marc-s linear range of the telescope and then subtract the telescope signals from the gyroscope signals.

2.4.1. Scale factor matching

A valid subtraction is only possible if the scale factors of the telescope and gyro readouts are matched. Otherwise a pointing error may combine with the scaling error to produce a null offset that masquerades as a relativity signal. In general the scale factors, being only approximately known and variable over the year, will not be matched. To remove the error we inject a low frequency dither signal into the pointing controller in order to make the spacecraft and hence the gyro/telescope package swing back and forth across the line of sight to the star with amplitude about 20 marc-s and period about 1 min. If the scale factors are matched the dither signal will vanish from the subtracted output, but if they are not matched a 1 min period signal will appear, whose amplitude and phase indicate the necessary correction to be applied.

2.4.2. Spacecraft roll

The spacecraft is rolled about the line of sight to the star with a period of about 10 min. The roll fulfills four functions: (1) it helps average out certain torques (for example gas torques) that would otherwise cause excessive gyro drift; (2) it removes errors due to any long term drifts in the null points of the gyro and telescope readouts as seen in spacecraft coordinates; (3) it allows both relativity effects to be measured in each gyroscope with each having only a single pickup loop; (4) it reduces to an acceptable level an otherwise catastrophic limitation on the gyro readout from 1/f noise in the SQUID magnetometer; and (5) it shifts the gyro/telescope structure stability requirement from dc to roll frequency.

2.4.3 Spacecraft control

The GP-B spacecraft requires both translational and attitude controls that are unusual in the degree of precision required. The translational control system makes use of the outgassing of helium through small reaction control thrusters to regulate specific forces to less than 10-8g. These thrusters were developed and tested at Stanford; they are also used for the attitude control (pointing) system. It was originally thought that the satellite would require both a coarse (outer-loop) and fine (inner-loop) control system. This was driven by the need to stay within the linear range of the telescope which is 40 to 70 marc-s. After futher examination by Parsons, Schaecter and Vassar it was found that the stiffer dewar mounting designed by LMSC allowed a tighter control. Using fairly conservative estimates of telescope noise and torque disturbances, rms pointing accuracies of better than 55 marc-s were expected. The errors and sources are:

Telescope noise (3 sigma)....	17.5
Steady aero torques..........	0.04
Unsteady aero torques........	5.9
Magnetic and gravity grad....	0.04
Dither (intentional).........	30.0

Total	53.4 marc-s

Included in the control system design is an integrator which removes most of the effect of steady state aerodynamic torque.

In addition to these control systems, a roll controller will take the output of roll-rate gyros and a star blipper to control rotation about the line of sight to the reference star. This will insure that the Geodetic and Motional effects can be accurately separated into their respective planes. It is likely, as well that some type of active mass-center and/or inertia tensor control may be required. These have been studied at Stanford, but an explanation is beyond the scope of this paper.

2.4.4. Data reduction

In practice the data reduction process is more complex than this simple picture would suggest. There are, as already noted, additional relativistic terms from the motion of the Earth around the Sun and the variation through the year of the apparent position of the guide star due to the deflection of starlight by the Sun. Besides these there are the much larger variations in star position arising from aberration: the annual term of ±20.384 arc-s in the ecliptic plane due to the Earth's motion around the Sun, and a term in the plane of the spacecraft orbit, of amplitude approximately ±5 arc-s with a period of approximately 100 min, due to the spacecraft's motion around the Earth. Neither annual nor orbital aberrations are exact sine waves. The latter is modified by the Earth's oblateness and any eccentricity in the orbit; the former is modified by the eccentricity of the Earth's orbit around the Sun, by the perturbations of the Earth-Sun barycenter caused by the motions of the Moon and of Jupiter, and by the necessity to apply a small correction to the standard aberration formula from an effect of special relativity[6]. Finally with Rigel as a guide star there is the additional complication of parallax, which produces an annual variation in the ecliptic plane, 90° out of phase with the annual aberration, with an amplitude that is about ±4 marc-s but is not known to nearer than 30%.

At first sight these aberration and other secondary signals would seem to be a nuisance and a grave complication to the experiment. They do impose the requirement for an increase in linear range of the gyro readout from the ±10 arc-s set by relativity alone to about ±50 arc-s. That is easily achieved, however, and on closer examination the aberration signals are seen to be in reality essential to the experiment. The aberrations, depending as they do only on the ratios of orbital velocities to the velocity of light, are very exactly known. The annual aberration can be computed at each point in the orbit from JPL ephemerides data to 0.07 marc-s. The orbital aberration can be computed to 2×10^{-4} marc-s with a GPS[7] (Global Position System) receiver mounted on-board the spacecraft. The two signals taken together provide a continuous, precise and absolute calibration of the scale factor of the gyroscope, and hence of the relativity signals.

Data reduction is by a Kalman filter covariance analysis developed by R. Vassar[8] and J.V. Breakwell, extended by T.G. Duhamel[6] and by R.A. Van Patten, R. DiEsposti and J.V. Breakwell[9]. Included in the analysis have been studies of the effects of orbit inclination and launch date, of long and short term variations in gyro scale factor and spacecraft roll rate, of interruptions in data both with and without a step change in gyro orientation, and of the process of matching the gyro and telescope scale factors. Figure 5, due to Vassar, shows the evolution in time of the uncertainties σ_{A_M} and σ_{A_G} in measuring the motional and geodetic precessions for an experiment using a BTI 19 MHz SQUID magnetometer in a polar orbiting spacecraft with a September launch date. After one year the resolution is

0.61 marc-s/yr for the motional coefficient and 1.25 marc-s/yr for the geodetic coefficient. These limits are reduced approximately by a factor of 4 if the BTI 19 MHz SQUID is replaced by the NBS dc SQUID.

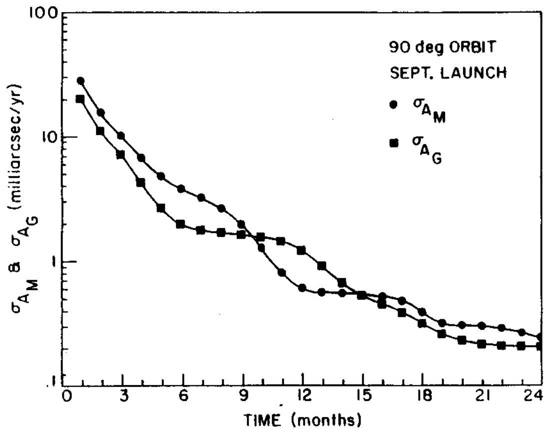

Fig. 5

Effect of Science Mission duration on errors in geodetic and motional precession rates

The peculiar shape of the curves in Fig. 5 requires comment. At first glance one would expect σ_{A_M} and σ_{A_G} to improve with time as $t^{-3/2}$ since the signal increases with t and the readout noise decrease as $t^{-1/2}$. In reality the SQUID noise enters not only in the measurement of the readout angle but also in establishing the gyro scale factor and even the roll phase angle. The six month periodic effect seen in the curves is a rectification of the annual aberration signal interacting with SQUID noise and scale factor fluctuations in the total process of calibrating the scale factors and measuring the readout angle. The final precision depends on launch date owing to the differences in phase of the annual aberrations, with March and September being the best launch months.

An unexpected by-product of the experiment, also first analyzed by Vassar, is to yield an improved measurement of the parallax from, and hence of the distance to, Rigel. With a gyro readout based on an NBS dc SQUID, the uncertainty in distance should be reduced from its present value of 30% to 1%. In the long view it would seem possible to extend the measurements to other nearby stars, especially Cepheid variables in our galaxy, and thus contribute towards an improvement in the distance scale of the universe.

2.5. In-flight calibration of the experiment

An experiment as refined as this, with gyroscopes whose drift-rates have to be many orders of magnitude below those of existing gyroscopes, demands the most rigorous checking before its results are accepted. The essence of the in-flight calibration process may be stated thus: granted that the goal of the experiment is to make the effects of all sources of disturbance or measurement error sufficiently small so the final overall error in the result is less than 1 marc-s/yr, what checks can we perform to assure ourselves and the scientific community that the error contributions are indeed that small?

Our in-flight calibration plan embodies different strategies in three distinct phases of the experiment: (1) the period of initialization (one to two weeks), (2) the period of gathering relativity data (a year or more), and (3) a special additional period of post-experiment calibration tests (about two months). A more extended discussion of this calibration plan, as applied to the gyroscopes, is given elsewhere[10]. Briefly it is based on the application of six verification concepts: <u>redundancy</u>, <u>variation</u>, <u>enhancement</u>, <u>separation</u>, <u>continuity</u> and <u>absolute relationships</u>.

3. THE TEN FUNDAMENTAL REQUIREMENTS

A measurement of the geodetic and motional precessions of a gyroscope involves four distinct issues: (1) gyro Newtonian drift performance, (2) gyro readout relative to the quartz block structure, (3) referencing of the quartz block to the guide star, and (4) knowledge of the proper motion of the guide star with respect to the inertial frame provided by the rest of the universe. All have to be addressed if the experiment is to be a success.

In principle the second and third issues could be reduced to one by devising a method of measuring the angle between the spin axis and the line of sight to the guide star directly rather than through the intermediary structure of the quartz block.

Applied to our experiment, the four fundamental issues yield ten fundamental requirements that must be met to obtain satisfactory relativity data. These requirements, summarized in Table 1, have been accounted for in a preliminary error budget[11] for the GP-B experiment as described in Section 2. It is instructive to see how the fundamental requirements are tied back to the fundamental issues and are met in the experiment.

Table 1

THE TEN FUNDAMENTAL REQUIREMENTS

Nature of Requirement	Measure of Requirement
1. Gyro drift rate from non-relativistic disturbances	$<10^{-11}$ deg/hr (~0.3 marc-s/yr)
2. Gyro readout precision	<0.1 marc-s precision over ± 50 arc-s dynamic range
3. Method to eliminate null drifts from gyro & telescope readouts	Eliminate to <0.1 marc-s
4. Method of separating precession terms in north-south and east-west planes	Separate to <0.1 marc-s accuracy
5. Absolute scale factor calibration	Calibrate to <1 part in 10^4
6. Stable gyro-telescope structure	Alignment between telescope axis and pickup loop plane stable to <0.1 marc-s over roll period
7. Telescope precesion	<0.1 marc-s precision over its chosen dynamic range (See Section 2.3)
8. Telescope/spacecraft pointing control sytem	Telescope kept on line of sight to guide star within chosen dynamic range of telescope
9. Method of subtracting gyro and telescope readout signals	Subtraction accurate to <0.1 marc-s
10. Known proper motion of guide star	<0.3 marc-s/yr in right ascension and declination

3.1 First issue: gyro Newtonian drift performance

The first requirement is simply a restatement of the first issue in its more stringent form. That is to say, given the desire to measure a relativistic precession to better than 1 marc-s/yr one may in principle follow two alternative paths. The more conservative is to demand that all extraneous disturbances be kept below 0.3 marc-s/yr. The less conservative is merely to demand that they be parametrically modelable to 0.3 marc-s/yr. With one partial qualification intend to follow the more conservative path.

The disturbances acting on the gyroscope may be divided into two categories: support dependent and support independent. The support-dependent effects include mass unbalance and suspension torques as discussed above. Examples of support-independent effects are torques from the action of a magnetic field on the London moment, differential damping torques from residual gas in the gyro housing, the gravity gradient torque from the action of the Earth's gravitational field on any quadrupole mass moment in the gyro rotor, and electric torques due either to an electric dipole moment on the rotor or to the interaction between static charge on the rotor with induced charges on the electrodes.

A detailed analysis of the gyro drift rate from nonrelativistic disturbances is given elsewhere[12]. One way of following out its implications is to develop a theme stated by W.M. Fairbank[13] in a paper of 1982 entitled "Near Zero: a New Frontier of Physics". A significant class of physics experiments, including the gyroscope experiment, depend for their execution on simultaneously making a large number of disturbing effects very small. Cryogenic techniques often prove helpful in achieving the necessary extreme of isolation, so our first near zero is, as stated in Table 2, to operate at ~1.8 K, close to the absolute zero of temperature. In addition there are six other near zeros: three (asphericity, inhomogeneity and electric dipole moment) characterizing the gyro rotor and three (residual acceleration, residual pressure and residual magnetic field) characterizing its environment. The constraints on electric dipole moment and magnetic field are inherently complementary: a gyroscope with magnetic readout has to have a rotor with a magnetic dipole moment and must therefore operate in extremely low magnetic field, a gyroscope with an electrical suspension system has to operate in the presence of electric field and must therefore have a rotor with extremely low electric dipole moment.

Table 2
THE SEVEN NEAR ZEROS

Type of Zero	Value
1. Temperature	1.8 K
2. Rotor asphericity	<0.8 microinch p-v
3. Rotor inhomogeneities	$<3\times10^{-7} (\Delta\rho/\rho)$
4. Rotor electric dipole moment	$<10^{-10}$ e.s.u.
5. Residual acceleration	$<10^{-10}$ g
6. Residual pressure	$<10^{-10}$ torr
7. Residual magnetic field	$<10^{-7}$ G

Ideal isolation is compromised, at levels far above quantum mechanical limits but within the requirements of the experiment, by two operational considerations. The gyroscope has to be read out and it has to be spun up. The readout system exerts torques of two kinds on the gyro rotor: one from the reaction of the measuring current on the London moment, the other from the dissipation of alternating currents induced in the readout by rotating trapped flux. In the present gyroscope both are negligible. The issue with spinup is that, whereas the gyroscope must be free of extraneous torques in normal operation, during spin up a large torque has to be applied to it. Let Γ_s be the spinup torque and Γ_r the residual of that torque transverse to the spin axis after the spinup operation is over. Then if Ω_0 is the desired drift rate (0.1 marc-s/yr) and τ_s the spinup time, then $\Gamma_r/\Gamma_s < \Omega_0\tau_s$, which with a spinup time of 2000 s means having a torque switching ratio of 3×10^{-14}. A gas spinup system is one of the very few that can provide such a large switching ratio.

One additional requirement beyond the seven near zeros proves to be essential in achieving a drift performance of 0.3 marc-s/yr: spacecraft roll. The roll averages some of the electrical suspension terms. It averages the torque on the London moment from the transverse component of magnetic field trapped in the lead bag; finally and most importantly, it averages the gas torques. Even at a pressure of 10^{-10} torr the residual gas in the cavity exerts a significant drag torque on the rotor, and if the drag has any asymmetry within the housing it will cause the spin axis to precess.

3.2. Second issue: gyro readout performance

To measure the gyro spin direction much more is involved than the fine resolution of the SQUID; four of our ten requirements enter the process. These are set out in Table 3 with a statement of how they are met in the experiment.

Table 3

THE FOUR REQUIREMENTS FOR GYRO READOUT RELATIVE TO THE QUARTZ BLOCK

Requirement	Design Solution
2. <0.1 marc-s precesion at suitable bandwidth over 50 arc/s range	SQUID readout plus roll chopping
3. Elimination of null gyro drifts	Spacecraft roll with gyro spin axes aligned along roll axis
4. Separation of precession terms in north-south and east-west planes	Roll plus precision roll reference system
5. Absolute scale factor calibration	Annual aberration, orbital abberation, trapped flux in gyro rotor (optional)

Spacecraft roll, it will be noted, enters the Table three times: in obtaining the resolution, in eliminating null drifts and in extracting the two relativity terms from the data. In particular, as remarked above, roll is the crucial factor enabling us to extract both terms with a single pickup loop through the rotation of that loop around the gyroscope. This point is even more significant than it appears. In practice only one pickup loop on any gyroscope can be made to yield full sensitivity. Without spacecraft roll each gyroscope would only be able to measure one of the two relativity effects.

The fourth requirement, absolute scale factor calibration, has already been discussed.

3.3. Third issue: Referencing of the measured gyroscope precession to the guide star

Five of the ten requirements enter the process of referencing the gyro signal to the guide star. These are set out in Table 4, again with a statement of how they are met in our experiment. The interconnected requirements (7), (8) and (9) on the designs of the telescope, the pointing system and the data instrumentation system were discussed earlier. The relationship between requirement (6) for a stable telescope/quartz block assembly and requirement (3') for a method of eliminating null drifts must now be discussed in the context of a review of the significance of spacecraft roll.

Table 4

THE FIVE REQUIREMENTS FOR REFERENCING THE GYRO SIGNAL TO THE GUIDE STAR

Requirement	Design Solution
3'. Elimination of null drifts in telescope readout	Spacecraft roll
6. Stable gyro/telescope structure	Fused quartz structure at low temperature
7. Telescope with <0.1 marc-s precesion over chosen dynamic range	Optically contacted telescope with roof prism dividers
8. Pointing control system capable of keeping telescope on line of sight within dynamic range	Use of helium boiloff gas with proportional thrusters
9. Method of subtracting gyro and telescope signals to <0.1 marc-s precision	On-board science data instrumentation system or ground-based Kalman filters, dither of pointing system for scale factor calibration

3.4. Fourth issue: motion of the guide star with respect to inertial space

Ideally the guide star should be bright, close to the celestial equator, and have a proper motion with respect to distant astrophysical objects that is small or at least very exactly known. Brightness and small proper motion are competing requirements; a bright star means one located within our galaxy, and therefore rotating with the galaxy as well as having appreciable angular velocity with respect to the other stars in it.

The best existing astrometric framework is the FK4 catalog[14] (Fourth Fundamental Catalogue) based on accumulated observations on 1535 stars within our galaxy. Rigel has relatively small and well known proper motion with respect to the other FK4 stars. J.T. Anderson and C.W.F. Everitt[15] in a lengthy document conclude that the current best numbers for the uncertainty in absolute proper motion of Rigel are 0.9 marc-s/yr in declination and 1.7 marc-s/yr in right ascension. These are the largest known sources of error in determining the two relativistic gyroscope precessions.

Three avenues exist for reducing the uncertainties. HIPPARCOS, the European Space Agency's orbiting astrometry telescope, scheduled for launch in 1988, should fix the angular distances between pairs of stars to within 1 to 2 marc-s, eventually yielding submarc-s/yr determinations of individual proper motions. The Hubble Space Telescope should also provide good astrometric data. Finally there is the possibility, independently suggested to us by R.H. Dicke[16] and H.A. Hill[17], of devising a special ground based apparatus, specifically to measure the proper motion of Rigel with respect to one or more distant quasars in the same region of the heavens. Since knowledge of the proper motion of Rigel is not embedded in either the design or operation of the GP-B spacecraft (other than the fact that it is small and constant), any improvement in the value of its proper motion, whether obtained before or after the Science Mission, can be incorporated in the determination of the motional and geodetic coefficients.

4. RECENT DEVELOPMENTS

An important element in shaping a satisfactory flight program is to find an intelligent means of controlling risk. The gyroscope experiment unites many new technologies. To make the transition from a laboratory research effort to a properly engineered flight experiment requires clear thought not only on the technology but also about the organizational process that will in the words of the Rosendhal report combine "the Stanford experiment team...with a strong engineering team in a flight program"[18]. During 1983 and early 1984 we held many discussions with NASA personnel and others which led ultimately to the conception of a two phase flight program, the first phase (now named STORE for Shuttle Test Of the Relativity Experiment) to consist of building the flight instrument and dewar and performing a 7 day engineering test of it on Shuttle, and the second phase to consist of refurbishing the flight-tested instrument, interfacing it with the spacecraft and proceeding with a free-flying Science Mission. The two phase approach has many advantages. It concentrates early effort on the instrument; it forces an early integration of the Stanford and aerospace teams; it allows the principal technology problems to be solved by a dedicated instrument team without carrying the large "marching army" costs of a spacecraft team; and by providing a rehearsal of the experiment under the working conditions of Shuttle, it reduces the risk of surprise in the Science Mission. In March 1984 the NASA Administrator gave a go-ahead for STORE.

In August 1984, with approval from NASA Marshall Space Flight Center, Stanford University issued a request for proposals for a subcontract to industry to provide aerospace support for the STORE program. After receiving proposals and conducting a full Source Evaluation Board procedure, Stanford announced on November 2, 1984 the selection of Lockheed Missiles and Space Company, Inc. as its subcontractor. On November 19, 1984 a joint Stanford/Lockheed proposal was submitted to NASA Marshall

Space Flight Center and on March 5, 1985 NASA issued a contract commencing the first phase of STORE.

5. THE SHUTTLE TEST OF THE RELATIVITY EXPERIMENT (STORE)

The purpose of STORE program is to provide engineering heritage and confidence for the GP-B Science Mission by carrying out the remaining detailed scientific and engineering developments; and the design, integration and operation of a full size GP-B instrument incorporating several state-of-the-art technologies. Three aspects of this program are discussed below: gyroscope development, the First Integrated System Test (FIST) and the Shuttle test of the full size GP-B instrument.

5.1. Gyroscope development

The gyroscope must satisfy the first fundamental requirement: having a drift rate from nonrelativistic disturbances below 10^{-11} deg/hr. Nearly all of the technical concepts needed to make a gyroscope with this low drift rate have been individually investigated and demonstrated in the laboratory at or near their required level of performance. What remains is to improve the engineering design and reliability of the gyro components and to put them together into an assembled and tested gyroscope which can be integrated with the GP-B instrument. Many of the concepts involve working at the state of the art, both in the manufacturing of hardware and in the related measurement science. A number of the gyroscope requirements given below are the result of preliminary error allocations given in the error tree. As more engineering data are collected, the individual requirements, including those for the gyroscope, will be adjusted slightly to reflect the relative difficulty in achieving them.

5.1.1 Gyro rotor

The gyro rotor is made from very homogeneous fused quartz which is lapped and polished into a 1.5 inch (38 mm) diameter sphere of extreme sphericity. The fused quartz rotor is coated with a very uniform thin layer of superconductor, which must be resistant to damage from possible arcing when the rotor is electrically suspended. The requirements on rotor sphericity (<0.8 microinch (20 nm) peak to valley) and density homogeneity (<3x10-7) are given above in Table 2. The uniformity requirement for the superconducting layer depends on the material used; for niobium, the layer must be uniform to 0.3 microinch (7.5 nm) peak to valley or less. All three of these requirements are based on worst case assumptions regarding the spatial distribution of the relevant quantity. Therefore, if measurements are made of these quantities as a function of position, a more precise determination of their effect on gyro drift can be made. Generally, this process should make the above requirements less severe.

Density homogeneity. The rotor is made from optical quality fused quartz which can be obtained with very great homogeneity. Optical grades of natural fused quartz with a maximum optical index of refraction variation of less than 1.5×10^{-6} over a 7 cm diameter are readily available. At our request, Heraeus-Amersil Inc. has developed an improved method for processing natural quartz into fused quartz with a not-to-exceed index variation of 8×10^{-7} and an expected variation of about 4×10^{-7}.

Rotor sphericity. The quartz material for the rotors is ground into an approximate sphere which is then lapped and polished to achieve the required sphericity. The lapping and polishing machines, which were developed by W. Angele[19] at the NASA Marshall Space Flight Center (MSFC), are of similar design and each uses four spring loaded lapping or polishing cups in a tetrahedral arrangement with three of the cups symmetrically supporting the rotor from below and one pressing down on it from above. While a slurry containing the lapping or polishing compound and water is continuously directed onto the rotor, the lapping or polishing cups are synchronously driven at a constant angular velocity and periodically change their relative rotational directions. Based on previous experience, MSFC has recently redesigned and built a new set of lapping and polishing machines which provide for better alignment of the lapping elements and for a number of other improvements. W.J. Reed of MSFC is now producing polished rotors with maximum peak-to-valley variations from sphericity of 0.7 microinch (25 nm) for a set of three mutually orthogonal great circles.

The measurement of the rotor sphericity is itself a challenge. It is accomplished with a Talyrond® (a product of Rank Taylor Hobson, England) which utilizes a stylus mounted on a very high quality spindle. Although the spindle for this type of machine has an out-of-roundness of about 1 microinch (25 nm), it is constant over long times (at least months). Thus the spindle out-of-roundness can be removed allowing roundness measurements to be made at the 0.1 microinch (2.5 nm) level[20]. An example of a roundness measurement made on a great circle for a recently polished rotor (S/N 85-10) is shown in Fig. 6. The peak-to-valley deviation of the data in this figure relative to the best fit circle is 0.7 microinch. This roundness measurement technique has been extended at Stanford[21] to the sphericity measurement of gyro rotors with the results being displayed as contour maps. We are currently instrumenting our Talyrond® at Stanford so that, after making measurements around 20 great circles which intersect at a common pole, the sphericity data can be quickly transformed into the coefficients of spherical harmonics using a computer connected to the Talyrond®. These coefficients are used to make a more accurate determination of the support dependent torques discussed in the accompanying paper by G.M. Keiser.

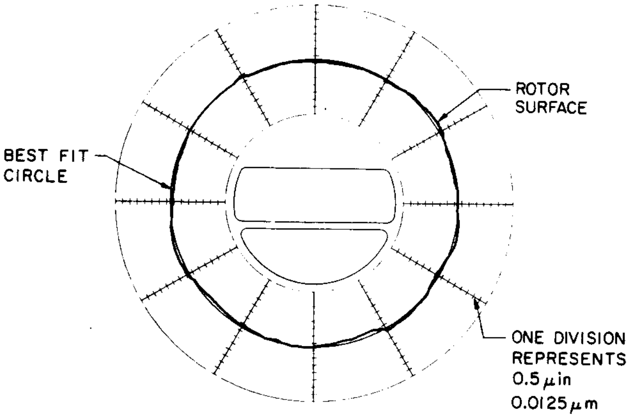

Fig. 6

Roundness measurement in one plane for rotor S/N 85-10
Rotor and data supplied by Marshall Space Flight Center

Rotor coating uniformity. The quartz rotor is coated with niobium so that when it is spinning at low temperature it produces the London moment for the gyro readout. The niobium, in both its superconducting and normal states, also serves as an equipotential surface for electrical suspension of the gyro rotor. Applying this niobium layer to the quartz rotor is one of our greatest technical challenges: there is a conflict between the 0.3 microinch uniformity requirement which favors a thinner layer and the requirement that the coating be resistant to damage from possible electrical arcing which favors a thicker layer.
P. Peter[22] at MSFC has extended the technology to produce a rotor manipulator which typically gives uniformities of 3% peak to valley.

5.1.2. Gyro housing

In the last year we have undertaken a major redesign of the gyro housing[23] The items providing the three principal functions of the housing are (1) six electrodes for electrical suspension of the rotor, (2) a spinup channel and related details for gyro spinup to 170 Hz, and (3) a surface on which the London moment pickup loop can be accurately placed relative to the rotor, telescope axis and star blipper. Figure 7 is an exploded view of the gyro housing and rotor showing the location of the above mentioned items. The housing is made from fused quartz to match the thermal expansion of the rotor, quartz block and telescope. Fused quartz housings, for use in gyro development, are currently being machined by the Speedring Division of the Rexham Corporation.

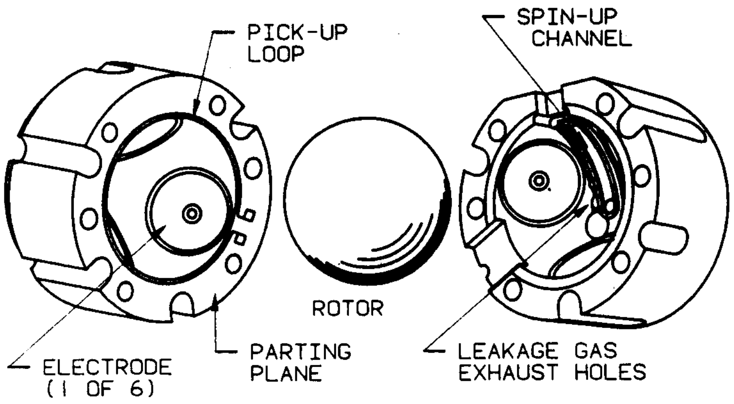

Fig. 7

Exploded view of gyro housing and rotor

5.1.3 Gyro testing

Ground testing of gyroscopes has taken place at both room and low temperature. Gyroscopes have been tested for more than 10,000 hours in the "Low Temperature Gyro Test Facility"[24] which provides a test region at low temperature (4.2 K) and ultra low magnetic field (2×10^{-7} G). The applications of lead bag expansion to achieve ultra low magnetic fields, of helium gas spinup, and of London moment readout have all been demonstrated in this facility. The facility does have limitations: the orientation of the gyro housing is fixed in the laboratory making characterization of gyro performance difficult, and the materials used for construction of the low temperature probe prevent the attainment of pressures below 5×10^{-7} torr.

To correct these deficiencies, a new low temperature gyro test facility has been designed and constructed. Some of its essential features are shown in Fig. 8. The low temperature probe and dewar are built so that they can be tipped at any angle from vertical to horizontal. This allows the axes of the dewar and the gyroscope to be jointly aligned with the Earth's polar axis. The polar orientation initially separates the precession of the gyroscope from the apparent precession due to the Earth's rotation. The apparatus is mounted on an air-bearing turntable which can roll the dewar and gyro housing about the dewar axis. The roll, which can vary over a large range of periods of one minute or greater, assists in measuring the gyro precession and averages certain suspension torques in a similar manner to the Science Mission.

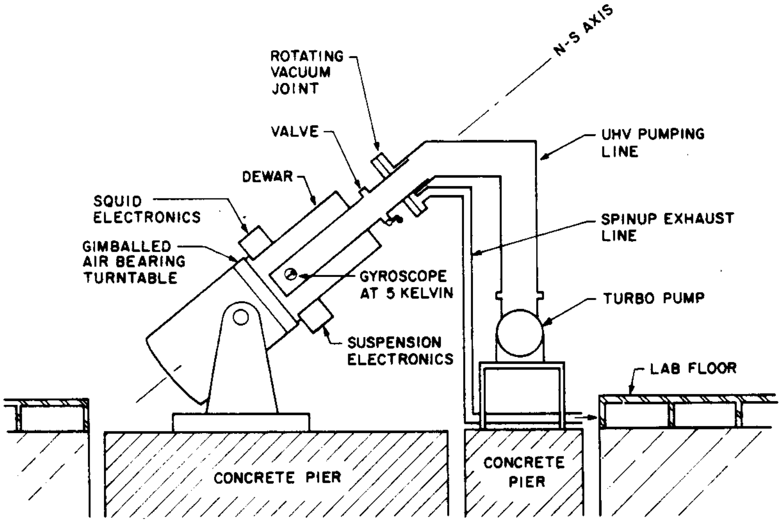

Fig. 8

Schematic of new gyro test facility

5.2. First Integrated System Test (FIST)

In the previous section we have described one specific, although centrally important, component of GP-B hardware which requires state-of-the-art manufacturing and measurement technology. There is however another very important aspect of the GP-B instrument; namely, the building of an integrated system to address system issues: a design which incorporates an appropriate allocation of an error budget among the subsystems, material selection and control, manufacturing methods, assembly and integration procedures, Shuttle launch loads, operational procedures, and data handling and reduction. The First Integrated System Test (FIST) is a ground test engineering unit which attacks a number of these issues, particularly the greatest design, integration and operation challenges.

FIST includes the following major subsystems which are discussed below: a quartz block assembly (QBA) which contains the gyroscopes and a place for mounting a telescope, a low temperature multi-gyro probe (MGP) in which the QBA is placed, an engineering development dewar (EDD) in which the MGP is installed, and a magnetic shielding subsystem which is located both in the QBA and EDD. In general these items are being designed to be full size and prototypical, to the extent reasonable, of the GP-B Science Mission. The engineering development dewar is being built to be prototypical only at its interfaces with the MGP and the magnetic shielding subsystem. FIST also includes laboratory hardware to support the testing, such as electronics, a data acquisition and analysis system, and various other support equipment. The FIST effort will also include integration facilities which will serve during FIST for study of integration procedures to be used for the Shuttle test and Science Mission hardware: for example, the clean room and other integration equipment for assembling the QBA into the MGP. With this equipment, we will study the integration procedures, which must prevent contamination from reaching the gyroscopes. It is expected that only small modifications will make this integration

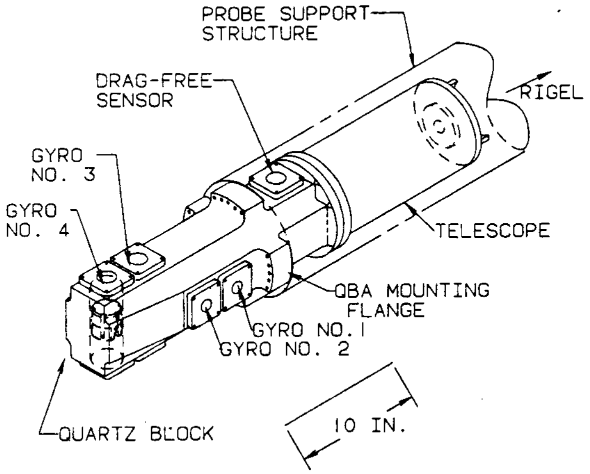

Figure 9

Drawing of quartz block assembly and telescope facility suitable for flight hardware integration. We are now at the design stage of FIST and expect to start testing the fully integrated FIST hardware in March 1988.

5.3 Shuttle test and its relation to Science Mission

The design, manufacture, integration and test of the full size, prototypical hardware for the First Integrated System Test will provide the engineering heritage to proceed rapidly and with confidence to the Shuttle test. The hardware for the Shuttle test, which must be designed, built and qualified to the rigorous demands of safety and launch and landing loads, includes the reflyable instrument shown in Fig. 2 of this paper plus the support needed to operate it. When in orbit as a captured payload on-board Shuttle, the instrument will go through an operational rehearsal for the Science Mission. The sequence of operations over about a 7 day period are as follows: electrical suspension of the gyroscope rotor including testing of the multi-level suspension system, gyro spinup while the Shuttle is rolling about an inertially fixed axis parallel to the gyro axis, and observation of the gyro precessions for several days (about once per day the Shuttle will perform the roll maneuver for about 2 hr to simulate the Science Mission). Although the telescope is included in the instrument it is not currently feasible to test it using the Shuttle as a platform, and thus it will be separately characterized in pre- and post-flight ground experiments. We expect the Shuttle test to take place in 1991.

The completion of the Shuttle test, which includes the central portion of the Science Mission hardware, and the related integration and operation experience, should provide a firm foundation for the final effort toward the Science Mission. The reflyable Shuttle test instrument will be refurbished and recalibrated, and the high reliability electronics needed for the instrument will be built and tested. The various spacecraft functions such as solar panels; drag-free, attitude and roll control; and telemetry will be wrapped around the central instrument to complete the Gravity Probe B spacecraft for launch in 1994.

6. CONCLUSION

In this paper an account is given of the current state of the Gravity Probe B Relativity Gyroscope Experiment and of its emergence from a laboratory development program to a flight program. In the current phase of the program, called the Shuttle Test of the Relativity Experiment, we are concentrating our efforts on a ground-based engineering test of a full size, prototypical instrument, the First Integrated System Test. At a later meeting, we expect to report the initial test results coming from this full size instrument, as well as reporting advances in gyroscope development and the design of the flight instrument for the on-board Shuttle test.

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