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ABSTRACT

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 apparatus comprises 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 1.8 K. The dewar/instrument package is mounted in a drag-free spacecraft 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.

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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.

Earlier accounts have concentrated on design concepts, error analysis and the development of laboratory hardware. In 1980 NASA completed an independent technology review which concluded that the experiment is feasible and recommended the establishment of a university/aerospace team to proceed with a flight program. This was followed in 1982 by a Phase B study of the experiment, and in 1983 by the definition of a two phase program. The first phase (now known as STORE for Shuttle Test Of the Relativity Experiment) consists in building the dewar/instrument package and performing a 7 day engineering test of it on-board Shuttle. The second phase consists in refurbishing the STORE hardware, interfacing it with a spacecraft and relaunching it via Shuttle as a free-flying Science Mission. In March 1984 the NASA Administrator gave NASA approval for the STORE program, following which in November 1984 Stanford issued a subcontract to Lockheed for development of flight hardware.

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 March 1988, launch the STORE dewar/instrument package in 1991, and launch the Science Mission in 1994.

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1. INTRODUCTION

This and the following paper by G.M. Keiser constitute the fourth account of progress on the Gravity-Probe-B Relativity Gyroscope Experiment (GP-B) given at successive Marcel Grossmann meetings since the series was founded in 1976.

The goal of the experiment has remained fixed throughout this nine year period. It is to apply 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

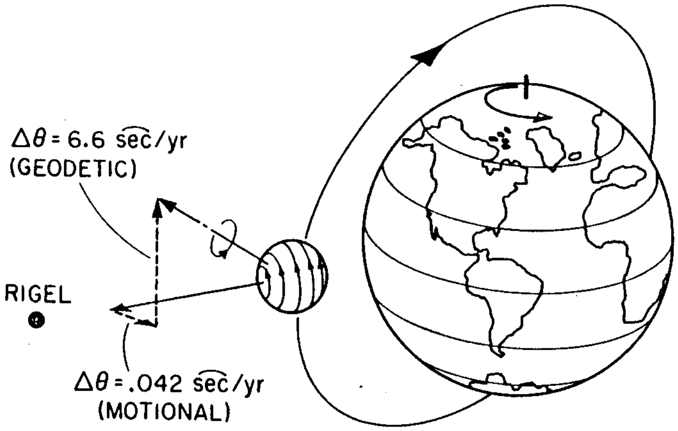

FIGURE 1

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

The precessions are defined with respect to the framework of the fixed stars, so the experiment consists in having one or more gyroscopes (in fact four) plus reference telescope pointed at a suitable guide star on or near the celestial equator. Rigel, the guide star we have chosen, has a right ascension of 5^h14^m and a declination of $8^o15'$ south, which puts the line of sight approximately 30^o from the Sun on the day of closest approach (June 10). In addition to the two main precession terms, three smaller relativistic effects will be observed in the experiment: (3) the geodetic effect from the Sun, which, as was first pointed out by W. de Sitter[2] in 1916, causes a precession of 19.0 marc-s/yr in the plane of the ecliptic, (4) a correction to the geodetic precession due to the Earth's oblateness, discussed by several people and amounting, as J.V. Breakwell[3] has shown, to a reduction (in a polar orbit) of 7 marc-s/yr from the precession calculated for an orbit of the same mean radius about an ideal spherical Earth, and (5) the relativistic deflection of the light from the guide star by the Sun. The influence of starlight deflection in the experiment was first pointed out by R.F. O'Connell and G.L. Surmelian[4]. Its peak value with Rigel as guide star is 14.4 marc-s/yr. Because of the difference in time signature from other effects it can be separated from them in data analysis, and hence, as T.G. Duhamel[5] has shown, the gyroscope experiment will provide an independent check of the Einstein's prediction for starlight deflection good to about 1%, comparable with the existing limit from VLBI measurements on radio stars. Further detail on how the relativistic effects will be separated and calibrated in the flight experiment is provided elsewhere[6].

The papers given at earlier Marcel Grossmann meetings illustrate the range of issues facing us in the development of the experiment. In 1976 C.W.F. Everitt[7] provided a general description of the experiment in the context of a historical and critical survey of experiments on gravitation and relativity from Cavendish in 1798 to modern times. The 1979 paper "Progress on the Relativity Gyroscope Experiment since 1976" by J.T. Anderson, B. Cabrera, C.W.F. Everitt, B.C. Leslie an J.A. Lipa[8] concentrated on a laboratory development of the experiment, especially the development under J.A. Lipa's direction of a working gyroscope with London moment readout contained in a 2×10^{-7} G ultra low magnetic shield. At the 1982 meeting R.A. Van Patten's paper[9] "Flight Suspension for the Relativity Gyro" described the design and simulation of a multilevel electrical suspension system to support the gyroscope under a wide range of operating conditions on Earth and in space, while an unpublished paper by J.T. Anderson described results from the GP-B Phase B study[10] of the flight mission performed jointly between NASA Marshall Space Flight Center and Stanford University during 1981 and 1982. The years since 1982 have been equally productive, as we shall now explain.

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

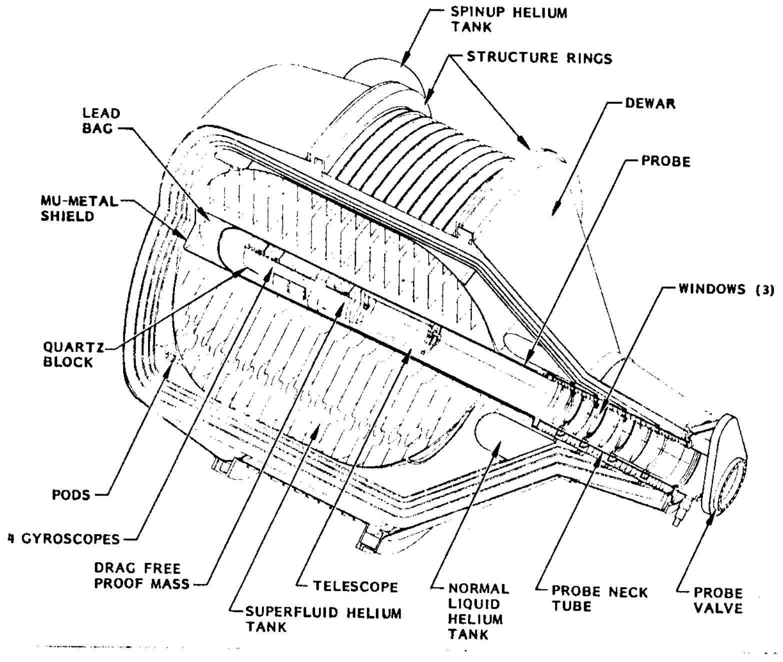

FIGURE 2

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.

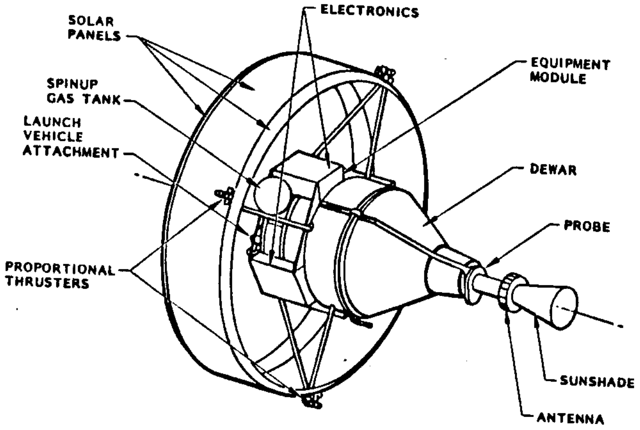

FIGURE 3
Gravity-Probe-B spacecraft concept

2.1. The gyroscope

The principles of the gyroscope have been explained in an earlier paper[11]. 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. Since, however, flux in a superconductor is a conserved quantity, the total flux through the closed circuit formed by the pickup loop and the SQUID input loop must stay constant. The change in flux through the first loop therefore produces a canceling current in the circuit, which in turn produces a flux in the second loop proportional to the readout angle, and this is what the SQUID measures. In general a three axis readout requires three orthogonal loops, but the experiment configuration reduces the requirement to a single loop for each gyroscope.

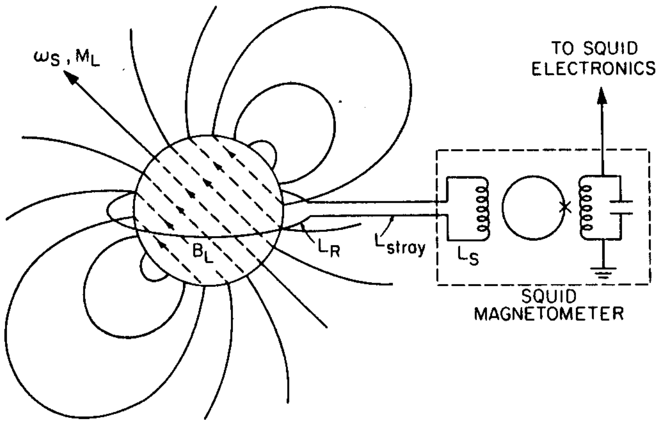

FIGURE 4

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

The London moment readout has four attributes of significance in our experiment: (1) it measures the spin axis directly and thus works even with a perfectly spherical, perfectly homogeneous gyro rotor; (2) it has adequate resolution (1 marc-s in 5 hours with an NBS (National Bureau of Standards) dc SQUID or 80 hours with an BTI (Biomagnetic Technologies, Inc., formerly S.H.E. Corp.) 19 MHz rf SQUID); (3) it is sensitive only in second order to changes in centering of the gyro rotor; and (4) the reaction torque it exerts on the gyroscope is a negligible disturbance in our experiment.

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. Trapped flux, unlike the London moment, is tied to the body of the spinning rotor, and therefore appears in the readout as a 170 Hz alternating signal, modulated at the polhode frequency. If small, this alternating signal does no harm; indeed it is a valuable adjunct to the experiment since it provides a measure of the spin speed and can also be of aid in calibrating the scale factor of the gyroscope, but if the trapped fields are too high they will cause a nonlinear output from the readout amplifiers with unfortunate consequences. 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 μm) 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}. Details of the flight housing design are given in Section 5.1.2 below (see Fig. 7). The principles of the flight suspension system are explained in the paper presented by R.A. Van Patten[9] at the third Marcel Grossmann meeting. In essence two needs have to be fulfilled: one common to all electrically suspended gyroscopes, the other special to our experiment. The common element goes back to Earnshaw's theorem in electrostatics. Since no system of separated static attractive masses is inherently stable, some means has to be provided for measuring the rotor-electrode gap, and applying the measurement in a feedback control loop to keep the ball centered by adjusting the support voltage.

The suspension scheme we adopt is similar to one developed by Honeywell Incorporated in the early 1960s, following the pioneering work of A. Nordsieck[12] and others at the University of Illinois. Two sets of signals at different frequencies are applied to each pair of electrodes: a low frequency support voltage and a higher frequency signal of smaller amplitude for use in a capacitance bridge to measure the displacement. In the laboratory suspension system the support signals have, as already remarked, an amplitude of about 1000 V_{rms}, with an operating frequency of 20 kHz in our original design and 2 kHz in a more recent design. The sensing signal has an amplitude of 1 V_{rms} and a frequency of 1 MHz. In our and similar suspension systems, the control effort is linearized by "preloading" the system, that is a certain nominal support voltage is applied and control authority is obtained by raising the voltage on one electrode and lowering it on the opposite electrode. The preload may be expressed as a voltage level or alternatively as an equivalent acceleration defined as that acceleration which has to be applied parallel to a support axis to just drive the voltage on one electrode to zero.

The novel element in the flight suspension system is a need to adjust the preload over an extremely wide range, from 1 to 10^{-7} g say, without dropping the ball. The approach developed by Van Patten[9] 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 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 latter scale roughly with the square of the support voltages as explained in the accompanying paper by G.M. Keiser. 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

$$\Omega_u \approx \frac{f}{v_s} \frac{\Delta\rho}{\rho} \tag{1}$$

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, $\Delta\rho/\rho$ 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, together with the accompanying investigation of suspension torques by Keiser, 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.

In 1959 G.E. Pugh[13], in a proposal for an orbiting gyroscope experiment conceived independently of Schiff, suggested the principle of drag-free control. His idea was to orbit a single large gyroscope surrounded by a "tender" satellite to shield it from radiation pressure and air drag. The gyroscope would follow an ideal gravitational orbit; the tender would have a set of thrusters in three axes; measurements of the displacement between the two bodies would provide a control signal that could be used in making the tender follow the gyroscope, permanently shielding it from external disturbances. Pugh suggested many other potential applications for drag-free control.

The same idea occurred later but independently to B.O. Lange in 1961. Lange's doctoral dissertation of 1963[14] in the Stanford Guidance and Control program contained the first thorough investigation of the principles and limitations of drag-free control. It was followed by a series of experimental and analytical studies by different people, culminating in the development under D.B. DeBra of the DISCOS (DISturbance COmpensation System) drag-free controller for the U.S. Navy's TRIAD Transit navigation satellite which was launched[15] in July 1972 and operated for about two and one-half years. The DISCOS attained a drag-free performance level of 5×10^{-12} g, limited by the self-gravitational attraction of the spacecraft on the proof mass.

From an early stage in the development of the gyroscope experiment, calculations like that based on Equation (1), which is merely a variant of an argument by Pugh, 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, which is closer to Pugh's idea, 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[16]. 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. The subtraction is done either on-board the spacecraft in the 18 bit data instrumentation loop described in our earlier papers or in a ground-based Kalman filter implemented in a computer[17].

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 either in an automatic gain control circuit in the on-board data instrumentation system or as an input to the ground-based Kalman filter.

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 five 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.

To understand why only one pickup loop is needed for each gyroscope, consider an idealized experiment in which the gyroscope is initially lined up exactly with the line of sight to the guide star. As time evolves the direction of spin will precess away from the line of sight through an angle $\theta = \sqrt{\Omega_G^2+\Omega_M^2}$, where Ω_G and Ω_M are the geodetic and motional precession rates, and ϕ has a phase relation to the orbit plane $\tan^{-1}\phi = \Omega_M/\Omega_G$. As the spacecraft rolls, a pickup loop whose plane includes the roll axis will measure a sinusoidal signal of amplitude θ; and the phase of this sine wave may be determined by adding a roll reference system consisting of conventional rate integrating gyroscopes on the outside of the spacecraft and a transversely mounted telescope (star blipper) to pick up a signal once each revolution from a second bright star (Canopus, say) located approximately 90° away from the guide star. The roll phase has to be determined to about 20 arc-s, which requires care but is feasible.

2.4.3. 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[5]. 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[18] (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[19] and J.V. Breakwell, extended by T.G. Duhamel[5] and by R.A. Van Patten, R. DiEsposti and J.V. Breakwell[17]. 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.

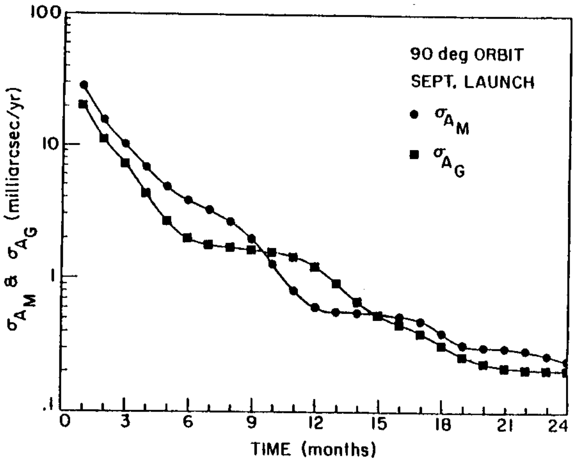

FIGURE 5

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 need for a program of in-flight calibration of the instrument was first strongly emphasized at the time of the Rosendhal review (see Section 4) through discussions with two members of the committee, D. Wilkinson and R. Weiss, though some of the ideas to be reviewed here had previously been incorporated into our thinking without being articulated as a coherent policy. 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?

In the laboratory the physicist customarily assures himself of the soundness of his results through a battery of tests, many of them done while the equipment is being developed. Informally the process may be called getting to know one's apparatus. With Gravity Probe B we have in some degree been through such a process during past years of ground-based gyroscope and telescope testing, and we shall continue it with assembled instruments in the First Integrated System Test and Shuttle test (see Section 5), which are to be performed over the next few years on the ground and aboard Shuttle. The difficulty is, however, that the conditions under which these tests are to be carried out will be very different from those of the final free-flying Science

Mission. The acceleration levels on Shuttle are 10^{-4} to 10^{-5} g rather than the 10^{-10} g of the Science Mission.

Another principle often applied in laboratory experiments is this; that, if one does not know how large a disturbing effect on an apparatus is, one should try making it larger to see how bad it is. The principle has a long history: the remarkable use Cavendish made of it in his experiment of 1798 on the gravitational constant was reviewed in C.W.F. Everitt's paper for the First Marcel Grossmann meeting. Admirable as it is, however, tact is needed if this principle is to be applied to a spacecraft experiment. In the Rosendhal committee discussions, I. Taback strongly emphasized the opposite principle that once a spacecraft is operational the wise manager will intervene only with the most extreme reluctance. Reflection on these two opposed principles, one of engineering, the other of physics, leads us to an in-flight calibration plan embodying 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[20]. Briefly it is based on the application of six verification concepts: redundancy, variation, enhancement, separation, continuity and absolute relationships.

With four gyroscopes, all of which ought to agree in drift rate and readout performance to well below 1 marc-s/yr throughout phase (2) of the experiment, we have redundancy. The agreement, if it exists, argues strongly for the validity of the results, but the argument is greatly strengthened by the fact that redundancy is combined with variation. Each of the four gyroscopes has a different shape and mass distribution; each therefore is subject to different suspension and mass unbalance torques. The expectation from G.M. Keiser's calculations is that the absolute drift rates from these support-dependent torques will be below 0.1 marc-s/yr. But the differences in shape and mass distribution are such that the differences in drift rate will be of the same order as the absolute drift rates; the absolute rates for successive gyroscopes may even be of opposite sign. If therefore the differences are less than 0.1 marc-s/yr, our confidence of having absolute drift rates that meet the requirement may be quite high. Other significant variations are that each of the four gyroscopes is at a different distance from the drag-free proof mass and that two are spinning clockwise and two counterclockwise. These variations, if combined with agreement in performance to 0.1 marc-s/yr, set limits on errors from gravity gradient disturbances, either from the actions of the Earth's field on the gyroscope's quadrupole mass moment or from certain indirect effects coupled in through suspension and mass unbalance torques.

Enhancement means deliberately increasing disturbing effects of unknown size. To be effective as a diagnostic tool it should be combined with separation, that is, the most useful enhancements are those that discriminate between disturbances of different origin. Cavendish, in the instance already referred to, set a limit on the disturbance to his apparatus from the unknown magnetic moments of his source masses by temporarily substituting bar magnets in their place. For Gravity Probe B, recognizing with Dr. Taback the undesirability of interfering with the apparatus during the period when relativity data is being gathered, we restrict our enhancements to phases (1) and (3) of the mission, the periods of initialization and post-experiment calibration.

Two of the most potent enhancements are connected with the requirement for low-g operations of the gyroscope. Our claim is that the experiment can only be performed by operating at 10^{-10} g and having a low voltage gyro suspension system. One test to apply during the post-experiment calibration phase, therefore, is deliberately to introduce a bias of say 10^{-7} g into the drag-free controller for a limited period. The effect will be to enhance by three orders of magnitude the drift-rates from mass unbalance and odd-harmonic suspension torques, producing in 8 hours a gyro drift equal to the total from these sources in a year under normal operating conditions. Similarly but separately one may raise the suspension preload accelerations from their normal operating level of 10^{-7} to 10^{-4} g. The effect will be a three orders of magnitude enhancement of the initial preload term in the even harmonic suspension torques.

Somewhat more complex are the effects of spacecraft roll. Our claim is that roll is a powerful aid in averaging torques on the gyro rotor from residual gas, magnetic fields, the initial preload term and electric charge on the rotor. A temporary cessation of roll will enhance these terms; to effect a complete separation further successive enhancements of other parameters such as the preload, the magnetic field level and the charge on the rotor would then be needed. Recognizing also that spacecraft roll plays another important part in the experiment by averaging out null drifts in the gyro and telescope readouts, one would then alternate periods of rolling and not rolling to complete this aspect of the diagnosis.

An interesting enhancement of another kind is provided without effort during initialization. In so far as the torques on the gyro rotor are constant in time and independent of the spin speed they will act on it even when it is not spinning. Consider the effect in phase (1) of the experiment of a disturbing torque which in phase (2) produces a drift rate of 0.1 marc-s/yr. Assume for simplicity that the rotor when first levitated has zero angular velocity, though usually it will have received a small torque impulse on initial suspension and be slowly tumbling. The torque will cause an angular acceleration; after one day the rotor will have turned through 13 arc-s, and after two days through 52 arc-s. The trapped magnetic flux in the rotor allows this to be detected; with a 10^{-7} g field level and a dc SQUID the rotation angle can be resolved to 0.8 arc-s in a day. Depending therefore on how much time we set aside for diagnostics during initialization, there is a possibility of learning a good deal about gyro performance even before the experiment begins.

<u>Continuity</u> refers to calibrating effects automatically present in the experiment when the relativity data is being gathered during phase (2). To be useful such effects need to be repetitive, distinguishable from other terms, large enough to be seen but small enough not to upset the measurement. One example, already discussed, is the application of the starlight aberration signals to calibrate the gyro scale factor. Another, discussed below in Section 3.1, is the possibility in a slightly off-polar orbit of exploiting the quadratic contribution to gyro precession in the north-south plane to calibrate mass-unbalance and suspension torques. The latter idea, though intriguing, needs to be entertained with caution. Other <u>continuities</u>, discussed elsewhere[20], are a diagnostic of gyro suspension performance from cyclic gravity gradient accelerations, a diagnostic of certain gyro torques from observation of the rotor polhoding by means of trapped flux signals, and a possible diagnostic of readout performance from small cyclic effects of the Earth's magnetic field.

Our last mode of in-flight calibration, <u>absolute relationships</u>, is among the most interesting. There are two prime examples. The first is from the ability of the experiment to determine to 1% the relativistic deflection of starlight by the Sun. This result may be viewed in two ways, as an independent measurement of a known effect or as a calibration check on the experiment. Suppose that, against expectation, the measurement of the geodetic precession, suitably cross-checked through all of our other in-flight calibration procedures, were to disagree with the prediction of general relativity. The weight to be attached to that result would be much greater if the starlight deflection measurement, in confirmation of the radar-ranging and VLBI measurements, did agree with relativity. Our second <u>absolute</u>

relationship occurs in the separation of the motional and geodetic precessions of the gyroscope through the measurement of roll phase. The roll phase is determined, as already explained, with the aid of external rate integrating gyroscopes and the star blipper. But in addition to the relativity signals there exists a second set of signals lying in specific and known planes with respect to the celestial sphere: the annual and orbital aberrations of starlight. By verifying that the aberrations lie in their expected planes we will obtain a partial verification of this aspect of the data reduction process.

3. THE TEN FUNDAMENTAL REQUIREMENTS

A measurement of the geodetic and motional precessions of a gyroscope involves four distinct issues: (1) gyro drift performance, (2) gyro readout performance, (3) referencing of the measured gyro precession 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 an intermediary structure such as the quartz block of our experiment. Suggestions along these lines were made by G.E. Pugh[13] in his original proposal, and later independently by D.H. Frisch and J.F. Kasper[21], each of whom adumbrated schemes for mounting the telescope on the gyroscopic object, thus making do with a single readout system instead of separate gyro and telescope readouts. Ingenious as these ideas are, they and any obvious variants on them have serious shortcomings. They require the use of a single large spinning object as the test body, and thus lose the advantage in redundancy and cross-check that comes from making simultaneous measurements with four nearly but not quite identical gyroscopes. They sacrifice the even more critical advantage of having a gyro rotor that is as close as possible to being ideally spherical and homogeneous. For these and other more technical reasons we favor the less direct approach of separating the telescope measurement from the gyroscope measurements.

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[22] 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.	Stable gyro/telescope structure	Alignment between telescope axis and pickup loop plane stable to < 0.1 marc-s over roll period
4.	Telescope precision	< 0.1 marc-s precision over its chosen dynamic range (see Section 2.3)
5.	Telescope/spacecraft pointing control system	Telescope kept on line of sight to guide star within chosen dynamic range of telescope
6.	Method of subtracting gyro and telescope readout signals	Subtraction accurate to < 0.1 marc-s
7.	Method to eliminate null drifts from gyro and telescope readouts	Eliminate to < 0.1 marc-s
8.	Method of separating precession terms in north-south and east-west planes	Separate to < 0.1 marc-s accuracy
9.	Absolute scale factor calibration	Calibrate to < 1 part in 10^4
10.	Known proper motion of guide star	< 0.3 marc-s/yr in right ascension and declination

3.1. First issue: gyro 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 we consider the idea of modeling out torques to be exceedingly dangerous - the pathway of illusion. The experimental physicist needs to be perpetually on guard against adjusting his model until it yields the hoped for result, after which the motive for further investigation fades from his mind. Having four gyroscopes, all of which ought to agree to within 0.3 marc-s/yr without modeling, is one of several safeguards we insist on to prevent self-deception.

The partial qualification to the statement that all extraneous disturbances on the gyroscope must be kept below 0.3 marc-s/yr relates to torques arising from two independent effects of the Earth's gravitational gradient. As is explained elsewhere[6] a very basic geometrical argument shows that, in an orbit that is nearly but not quite polar, the gravity gradient terms may cause a small precession in the north-south direction developing quadratically with time but do not cause any precession in the east-west direction. They therefore affect the measurement of the geodetic precession, from which they can be separated by the difference in their time signatures, but have no influence on the measurement of the motional precession. A consequence of allowing such terms to appear in the north-south plane is that they provide a continuous in-flight calibration of a large class of suspension and mass unbalance torques, from which a limit can be set on the error these torques will cause in the motional measurement. To decide whether to eliminate these effects by staying in an exactly polar orbit or to exploit them by moving slightly away from a polar orbit remains an interesting question. A decision to go to a slightly off-polar orbit, even though giving only a modest departure from the notion of making all drift terms less than 0.3 marc-s/yr, should be treated with great caution.

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 and in the accompanying paper by G.M. Keiser. 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[23]. One way of following out its implications is to develop a theme stated by W.M. Fairbank[24] 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, but are large if one were to attempt to measure the relativity effects with a He^3 nuclear gyroscope and SQUID readout; the reaction of the measuring current on the polarized nuclei would be a severe problem because the gyromagnetic ratio for He^3 nuclei is 10^9 greater than for the spinning superconducting sphere of our experiment. The issue with spinup is that whereas the gyroscope must be free of extraneous torques in normal operation, during spinup 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 as explained in the accompanying paper by Keiser; 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. The issue can be expressed through a variant of the torque switching formula just given. Let Γ_r be the residual drag torque and τ_d be the characteristic spin down time which is, as remarked earlier, about 4000 years (1.2×10^{11} s). The maximum allowable asymmetry is $\Gamma_r / \Gamma_s < \Omega_o \tau_d$ or 6×10^{-6}. In a non-rolling housing the inherent asymmetries could be as high as 5%. Rolling the spacecraft averages the effect of such asymmetries by four to five orders of magnitude, making Γ_r / Γ_s at most 2×10^{-6} and the residual drift rate from this source less than 0.1 marc-s/yr.

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 performance

Requirement	Design Solution
2. < 0.1 marc-s precision at suitable bandwidth over ±50 arc-s range	SQUID readout plus roll chopping
7. Elimination of gyro null drifts	Spacecraft roll with gyro spin axes aligned along roll axis
8. Separation of precession terms in north-south and east-west planes	Roll plus precision roll reference system
9. Absolute scale factor calibration	Annual aberration, orbital aberration, 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. The option of supplementing the calibration signals from aberration with non-absolute calibration signals from trapped flux in the rotor has been investigated by T.G. Duhamel[5].

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 (4), (5) and (6) on the designs of the telescope, the pointing system and the data instrumentation system were discussed earlier. The relationship between requirement (3) for a stable telescope/quartz block assembly and requirement (7) 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. Stable gyro/telescope structure	Fused quartz structure at low temperature
4. Telescope with < 0.1 marc-s precision over chosen dynamic range	Optically contacted telescope with roof prism dividers
5. Pointing control system capable of keeping telescope on line of sight within dynamic range	Use of helium boiloff gas with proportional thrusters
6. 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
7. Elimination of null drifts in telescope readout	Spacecraft roll

3.4. Remarks on the effectiveness of spacecraft roll

We have stated that rolling the spacecraft helps in (1) averaging gyro drift errors, (2) removing effects of null shifts in the gyro and telescope readouts, (3) reducing the limitation on gyro readout from 1/f noise in the

SQUID, (4) allowing both relativity effects to be measured with one pickup loop, and (5) shifting the gyro/telescope structure stability requirement from dc to roll frequency. But powerful as roll is, it is not a panacea. The limits to what it can do must also be examined.

Consider the averaging of gyro drift errors. If the gyro spin axis were exactly parallel to and on the roll axis and if the roll rate were exactly uniform, then a large class of torques would be perfectly averaged. But not all. Take the mass-unbalance torque. The average lateral acceleration on the gyroscope must, as already stated, be kept below 10^{-10} g. In a non-rolling spacecraft the limit on drag-free performance is set by the self-gravitational attraction of the spacecraft on the proof mass, which for DISCOS was 5×10^{-12} g. With roll the self-gravitation might be expected to rotate with the spacecraft, making any component transverse to the gyro spin axis average to zero; our criterion on rotor homogeneity, worked out from the 10^{-10} g limit, would seem to be quite unnecessarily conservative. Reality is otherwise. The dewar contains liquid helium which, being subject to the tidal attraction of the Earth, will tend to bias the self-gravitational acceleration towards the center of the Earth. The gyroscopes, being not exactly at the center of mass of the spacecraft, are subject to gravity gradient accelerations of which only some components average around the orbit. Let ℓ be the distance of the gyroscope from the center of mass and R be the radius of the orbit. Then in particular if the line of sight to the guide star is inclined at a small angle θ to the orbit plane, a steady acceleration $f_g = g\ell\theta/R$ will act on the gyroscope toward the orbit plane. With an ℓ of 200 mm, f_g is $3\times10^{-8}\theta$ g; it will exceed 10^{-10} g if θ exceeds 0.2°. The precession that f_g gives rise to is in the orbit plane; it can be handled in other ways; but roll does not reduce it.

Consider next what happens if the roll rate ω is not uniform. Assume the gyroscope is at a distance r radially from the roll axis; r in the absence of an active mass-trimming system will be approximately 2 mm. The gyroscope will experience a centrifugal acceleration $f_c = \omega^2 r$, of order 2×10^{-8} g, varying over the roll period. Both ω and r will vary: ω from the nonuniformity in roll rate, r from warping of the spacecraft structure as it turns in the sunlight. Assume for simplicity sinusoidal variations of amplitude $\delta\omega$ and δr, not necessarily in phase. The bias acceleration δa will be $f_c\sqrt{4(\delta\omega/\omega)^2 + (\delta r/r)^2}$. To stay below 10^{-10} g, $\delta\omega/\omega$ must be less than 2×10^{-3} and $\delta r/r$ less than 4×10^{-3}, that is 8 μm. A tighter constraint on $\delta\omega/\omega$ is a 5×10^{-5} requirement coming from the need to roll average the gas torques (see Section 3.1). Roll averaging for both the gas torques and certain of the suspension torques is also limited by the slight (10-20 arc-s) misalignment between the gyro spin axis and the roll axis.

Another source of error is the heating and cooling of electronics boxes as the spacecraft turns in the sunlight. This will affect both the gyro suspension system and the gyro and telescope readout systems. Any temperature dependence of the centering of the rotor in its housing produces an inertially fixed bias in the suspension torques, as discussed in the accompanying paper by Keiser, setting a limit of ±1.3°C on the allowable temperature swing over a roll cycle (based on the measured temperature sensitivity of our laboratory suspension system). Passive temperature control is sufficient to keep the variation within that range. Similar considerations apply for the gyro and telescope readouts. Long term null drifts rotate with the spacecraft and do not have significant contributions when referenced back to inertial precession, but temperature dependent null shifts can have significant inertially fixed biases, varying over the year, which may simulate a relativity signal or by their annual and orbital variations degrade the aberration measurements. These too set limits on the allowable temperature swings over a roll cycle.

Electronic disturbances of another kind, investigated by C.M. Marcus[25], are shifts in the gyro readout as the SQUID electronics rotate with the spacecraft in the Earth's magnetic field. Small offsets occur at rates singly and doubly periodic with the roll rate; they can be reduced to acceptable levels by magnetic shields of simple design.

Having considered the extent to which spacecraft roll fulfills requirement (7) let us examine requirement (3) on the stability of the telescope/quartz block assembly. If the assembly warps, the relative position of the gyro and telescope readout nulls will shift. Can such a shift masquerade as a relativity signal? Once again it depends whether the effect is a long term drift tied to spacecraft coordinates, or whether it has an inertially fixed component. The causes of warping are several: (1) elastic distortion due either to external accelerations or changes in the stress applied to the quartz block assembly by its mounting flange, (2) creep, (3) the relaxation of intrinsic stresses in the quartz block assembly through the delayed elastic effect, and (4) thermal distortion. Creep, the delayed elastic effect and changes in the stress from the mounting flange are all long term processes which will be very effectively averaged by roll. External accelerations may have inertially fixed components but the effects they produce are far too small to be of concern. The one real issue is thermal distortion.

A temperature gradient $\vec{\nabla}T$ across an element $\vec{\delta\ell}$ of material of expansion coefficient α will distort it through an angle $\vec{\delta\theta} = \alpha\vec{\nabla}T \times \vec{\delta\ell}$. Applied to the telescope this means that a transverse heat flux warps the structure, tilting the secondary mirror and producing lateral displacements of it and the image dividers. Both effects shift the null point of the telescope; warping of the quartz block also shifts the null points of the gyroscopes with respect to the telescope and each other. The distortion is lessened if the telescope/quartz block assembly is surrounded, as indeed it is, with a sheath of aluminum or other high thermal conductivity material. To keep the distortion below 0.1 marc-s the transverse heat load on the telescope must not exceed a value $\dot{Q}_{max}$ proportional to $\alpha(kw+k'w')$, where α is the expansion coefficient of fused quartz and k, k' and w, w' are the respective thermal conductivities and wall thicknesses of the telescope and aluminum sheath. The quantities α, k and k' are all functions of temperature. Table 5 gives numerical values of $\dot{Q}_{max}$ at different temperatures for the telescope shown in Fig. 9 below, taking the wall thicknesses of the telescope and aluminum sheath as 10 mm and 3 mm, respectively.

TABLE 5

Maximum allowable transverse heat load on the telescope at different operating temperatures

aluminum sheath	1.8 K	77 K	300 K
without	0.05 mW	0.0001 mW	0.0008 mW
with	11 mW	0.03 mW	0.06 mW

Consider a telescope at ambient spacecraft temperature, sideways on to the Sun. The total heat load from solar radiation over the projected area of the telescope is 80 W. The load can be reduced by thermal insulation, and its effect is further attenuated by the rolling of the spacecraft, but even so there will be a distinct tendency of the telescope to "hotdog" away from the Sun - or to be more exact in some direction in inertial space whose phase with respect to the ecliptic will depend on time of year, spacecraft roll rate and the thermal time constant of the insulation. From Table 5 one finds that in order to keep the inertially fixed bias below 0.1 marc-s with a telescope at ambient spacecraft temperature, the heat load would have to be attenuated by a factor of 1.4×10^{6} for a telescope with an aluminum sheath and 10^{8} for one without a sheath. Such requirements verge on the preposterous and point to the advantages of our operating the telescope at cryogenic temperatures.

The case is quite otherwise with a telescope at 1.8 K. For sources of heat external to the dewar the allowable transverse heat load is the 11 mW given in

Table 5 for the sheathed telescope. The total load down the dewar neck is 45 mW, most of it symmetrically disposed and shorted out at the top of the helium well. The only direct load on the telescope is 0.6 mW of radiation from the last gold-coated window; it too is symmetrically disposed. A conservative estimate would put the transverse heat load across the sheathed telescope from external sources below 0.1 mW, more than a factor of 100 below our requirement. The largest load from internal sources is about 2 mW from the temperature controllers for the SQUID magnetometers. If these were attached directly to the telescope/quartz block assembly they might cause trouble; being on the probe support structure they have no ill effect.

Thus requirement (3) for a stable telescope/quartz block assembly is met, and only met, by operating the instrument at low temperature. The low temperature cryogenic solution does not require our invoking spacecraft roll. Here is one more illustration of the advantage of operating "near zero".

3.5. 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[26] (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. Nevertheless it or any other FK4 star would seem at first glance a poor choice for our purpose since measurements confined to a group of stars within our galaxy hardly seem capable of providing information about the rotation of the galaxy. Surprisingly that is not the case; the FK4 data does yield numbers for the two principal constants of galactic rotation. It does so because the measurements are referred to the ecliptic plane which lies at an angle of 60° to the plane of our galaxy. The solar system acts in effect as a torque free gyroscope against which the collective motion of the FK4 stars is defined. J.T. Anderson and C.W.F. Everitt[27] 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[28] and H.A. Hill[29], 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 incoporated in the determination of the motional and geodetic coefficients.

4. DEVELOPMENT OF THE PROGRAM BETWEEN 1980 AND 1985

Up to the year 1980 work on the gyroscope experiment had been concentrated mainly on broad design concepts, a fairly detailed error analysis and the development of laboratory hardware. A Mission Definition Study[30] performed for NASA by Ball Brothers Research Corporation (now Ball Aerospace Systems Division) in 1971 gave some indication of the shape of the flight mission and had independent historical importance in that it provided Ball with the impetus to develop an experimental superfluid helium dewar which in turn led to the successful flight dewar for the IRAS (InfraRed Astronomy Satellite)[31]. Other mission related studies included two smaller NASA funded studies performed by Ball Aerospace in 1973 and 1976, and a Phase A study[32] done in-house at NASA Marshall Space Flight Center in 1979. Much more was required, however, before a realistic flight program could be defined.

In 1980 the Space Science Board of the National Research Council approved a "Strategy for Space Research in Gravitational Physics in the 1980s"[33] making the Gravity Probe B Relativity Gyroscope Experiment the "centerpiece of our strategy".[34] In July of the same year NASA conducted a very thorough technology review of the experiment by a group of fifteen independent physicists and engineers under the chairmanship of J. Rosendhal, concluding that "the remarkable technical accomplishments of the dedicated Stanford experiment team give us confidence that when they are combined with a strong engineering team in a flight development program this difficult experiment can be done"[35].

In December 1980, following these reports, NASA commenced a Phase B Study[10] of the Gravity Probe B program, done in-house at NASA Marshall Space Flight Center with Stanford support and completed in July 1982. The Study addressed for the first time many important issues of engineering development but resulted in a far too expensive a program ($200M to $300M in FY1982 dollars), with three factors in particular inflating the cost: a great uncertainty about the performance to be expected from superfluid helium dewars in space, the complexity of the integration problems as we then saw them, and a large initial estimate of the power needed to run the experiment (557 W). Doubts about the dewar originated in ground test data from the IRAS dewar, just then becoming available, which suggested to some reviewers that its on-orbit lifetime might only be four to six months rather than the twelve months originally hoped for. For GP-B a dewar lifetime of twelve months or longer is almost essential. This together with the integration problems seemed to dictate having a very large cigar-shaped dewar, 162 inch (4.11 m) long; the power requirement dictated the use of large articulated solar arrays. The result was a huge, complex, unwieldy spacecraft, weighing 5534 lb (2512 kg), which posed in turn awkward problems for Shuttle launch into an orbit even as low as 550 km. Since historically there is a well established correlation between program costs and the size and complexity of a spacecraft, there was no escaping the $200M to $300M price estimate arrived at from detailed cost studies. Somehow a smaller, simpler spacecraft/instrument combination had to be devised.

Soon after IRAS was launched in January 1983, it became evident that the dewar was performing far better than had been feared. The final demonstrated on-orbit lifetime of 300 days[36] was gratifyingly close to predictions from an earlier thermal model and, more to our point, it was within striking distance of the 12 to 14 month lifetime desired for GP-B. We decided to investigate whether the instrument could be redesigned to fit within either the IRAS dewar or the slightly elongated version of it being developed for COBE[37] (COsmic Background Explorer). Besides the generic advantage of a smaller spacecraft, such a plan would yield a lower, more credible dewar cost. The $11M price tag for the IRAS dewar (including substantial development costs) compared favorably with the $35M estimate for the Phase B dewar.

To take proper advantage of the smaller dewar/instrument package, the power for the experiment also had to be greatly reduced; otherwise solar array considerations would dominate the spacecraft design. We decided on a design goal of 125 W for the total instrument and spacecraft power.

In March 1983 Stanford and a group from Ball Aerospace Systems Division, headed by J. Chodil, jointly conducted a short feasibility study of an instrument to fit within a slightly modified COBE dewar, the modifications being to add a neck tube and reduce the inner diameter of the dewar well.

Preliminary thermal analysis indicated a dewar lifetime in excess of one year. The central issue in laying out the modified instrument was to work out an adequate system of magnetic shields for the gyroscopes, especially with respect to ac shielding. An investigation, due mainly to J.M. Lockhart, led to the design concepts described below in Section 5.2.4. Our final conclusion, reported in a Stanford University document "Account of the Restructuring of the Gravity Probe B Flight Program"[38] (October 1983) was that use of a modified COBE dewar would yield a spacecraft of weight 3200 lb, power 143.2 W (close to our design goal), and that program costs of $134M in FY1984 dollars (equivalent to $120M in FY1982 dollars) were reasonable. This figure brought us within sight of an acceptable program.

Another 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"[35]. 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

In this section we discuss the development of a gyroscope which meets the first fundamental requirement: a gyroscope 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 ($< 3\times10^{-7}$) 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. The density homogeneity of fused quartz can be determined as a function of position by measuring its optical index of refraction since variations in density ($\delta\rho/\rho$) are proportional to variations in optical index of refraction ($\delta\eta$): $\delta\rho/\rho = 2.27\,\delta\eta$ (ref. 39). Thus the density homogeneity requirement is equivalent to a requirement that the index of refraction difference across the rotor not exceed $1.3\text{x}10^{-7}$. Optical grades of natural fused quartz with a maximum optical index of refraction variation of less than $1.5\text{x}10^{-6}$ 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 $8\text{x}10^{-7}$ and an expected variation of about $4\text{x}10^{-7}$. We have purchased a number of cubic blanks of this material including interferograms for all three directions. Not all of this material is expected to meet the homogeneity requirement. However it is close, and thus after careful measurement it should be possible to select and verify material of suitable homogeneity.

G. Edgar and M.A. Player at the University of Aberdeen, Scotland, are developing an apparatus[40] with the capability of measuring variations in the index of refraction to $\sim 2\text{x}10^{-8}$ over a 5 cm length (18% of the GP-B requirement). The design of this instrument, which is based on earlier work at Aberdeen[41], utilizes a laser interferometer with a resolution of $1\text{x}10^{-3}\lambda$ and a liquid bath which has an index of refraction approximately matching that of fused quartz. A fused quartz cubic sample, whose faces are optically flat and parallel, is placed within the liquid bath in the path of the laser interferometer sensing beam (about 2 mm in diameter) which makes both a forward and, after reflection, a reverse pass through the quartz sample. To make measurements of the index variation, the sample is moved in the liquid in a raster pattern through the beam, and the interferometer records variations of the optical path length. The matched liquid serves to make the measurement insensitive to variations in the dimensions of the fused quartz. The greatest challenge in constructing such an apparatus is maintaining the liquid bath and quartz at a very constant and uniform temperature (approximately 1 mK).

If a set of measurements of index variations is made perpendicularly through one face of a cube, the resulting variations will be those for a set of rods perpendicular to the face of the cube. The capability of the apparatus may be extended to provide tomographic data on the index variations by measuring through all three faces at both perpendicular and inclined angles[42]. Such data allow a better estimate to be made of the quartz rotor mass unbalance.

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[43] 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 1.0 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[44]. 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[45] 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.

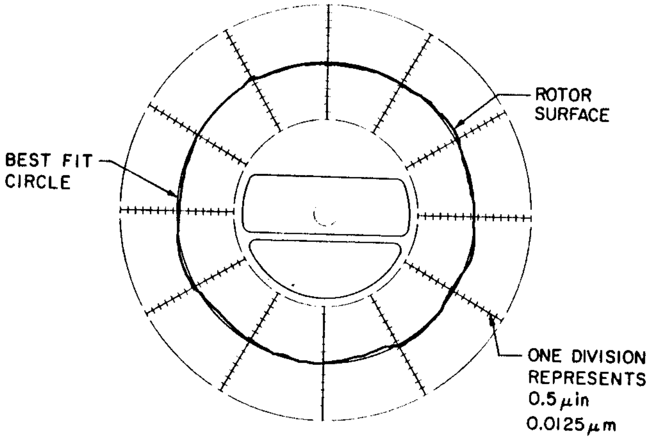

FIGURE 6

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.

The most suitable technique for applying the niobium layer to the rotor is sputter coating developed at Stanford for rotors by J.A. Lipa[46] following earlier work by J. Seeman of Honeywell Inc. To obtain a uniform coating the rotor has to be rotated either continuously or intermittently to different orientations under the sputtering gun. The rotors produced at Stanford satisfied the early needs of the program. P. Peters[47] at MSFC has extended the technology to produce a rotor manipulator which typically gives uniformities of 3% peak to valley. Independently, J. Siebert[48] of the Ball Aerospace Systems Division developed a sputter coating process with which he produced a 20 microinch (500 nm) niobium coated rotor that was successfully suspended at Stanford. Once these two capabilities (3% uniformity and thin, robust coatings) have been combined, one may expect a rotor with a 20 microinch (500 nm) thick coating, uniform to about 0.6 microinch (15 nm) peak to valley, which can be suspended. This possible 0.6 microinch uniformity is twice the requirement as stated above; the discrepancy is mitigated however by a combination of the worst case nature of the 0.3 microinch requirement which is based on a linear variation in thickness across the rotor and of the local nature of much of the thickness variation of actual coatings which is due to the sputtering profile and geometrical considerations. More precise estimates of the torque disturbance from actual coatings (not tied to the 0.3 microinch requirement) can be made using the data coming from the measurement technique briefly described below.

At Stanford we are continuing to develop the sputter coating technology[49]. The superconducting transition temperature of niobium has been investigated as a function of sputtering parameters, and it is found to be 8.8-9.2 K for satisfactory ranges of both sputtering rate and substrate temperature. The adhesion of niobium to fused quartz has also been investigated. The basic adhesion strength is found to be excellent (about 7×10^3 psi); in fact, often the underlying quartz fails in test rather than the bond between the niobium and quartz. The technology of producing uniform layers is also being further investigated. A rotor manipulator has been designed and constructed which, using two independent rotational motions, can roll the rotor about any horizontal axis. This manipulator allows the rotor to be moved to any orientation under computer control. With it the rotor can be moved to discrete positions for sputter coating as is done at MSFC (for example, the angles associated with the 20 faces and 12 vertices of an icosahedron) or can be continuously moved during sputtering with a specific or quasi-random motion. Preliminary coatings have uniformities adequate for our current needs, but the apparatus still requires mechanical improvements.

The coating thickness and uniformity are measured by means of a Betascope TC-2000 manufactured by Twin City International, Inc. Electrons from a radioactive beta-ray source impinge onto the surface of the rotor coating. They penetrate the niobium film and some of them backscatter from both the quartz rotor and from within the niobium film. These backscattered electrons are counted by a Geiger-Mueller tube. The Betascope is calibrated for a particular coating material and substrate (in this case niobium and quartz) by taking measurements on a set of standards following which the actual coated rotor is measured at many points on its surface. At present, instrument drift and rotor positioning errors limit measurement accuracy to 1% for film thicknesses greater than 30 microinch. This is sufficient for measurements on rotor coatings now being used. We expect to improve the uniformity measurement of coatings by reducing the effects of systematic errors. One method under consideration will combine the results of Betascope® thickness uniformity measurements with Talyrond® roundness measurements.

5.1.2. Gyro housing

In the last year we have undertaken a major redesign of the gyro housing[50]. 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. These three functions result in many design requirements, one of which is discussed below. 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.

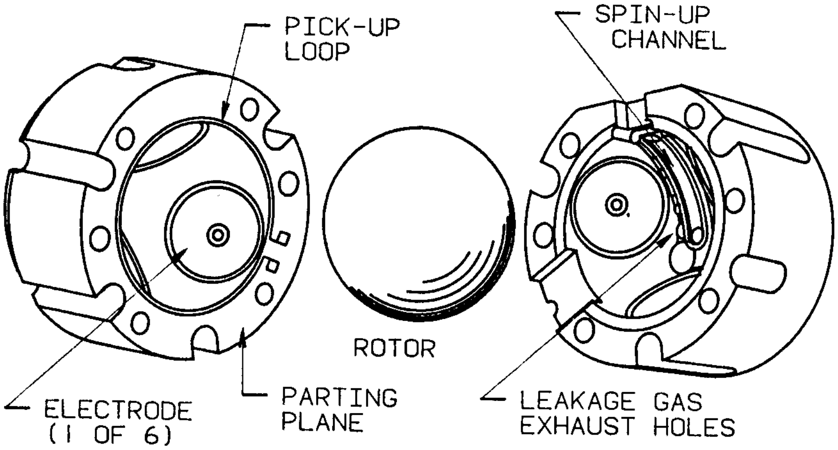

FIGURE 7

Exploded view of gyro housing and rotor

The most critical requirement on the quartz housings is that the inner surfaces of the electrodes lie on a spherical surface to within 5 microinch (125 nm) of the best fit sphere (10 microinch peak to valley). This requirement follows from the need to keep the gyro drift rate due to secondary suspension torques below 0.1 marc-s/yr (see accompanying paper by G.M. Keiser). The 10 microinch requirement yields two challenges: machining the fused quartz housing to provide a very accurate spherical electrode substrate and maintaining the sphericity during the subsequent coating of the 100 to 200 microinch thick electrodes. The machining operation is the more difficult of these two tasks. The machining requirement has been nearly met in the past by hand lapping. We are now investigating a superior approach by a method known as tumble-lapping. Initially the two housing halves are machined to form hemispheres spherical to about 1 milliinch. The two halves are then paired and held in alignment with tapered dowel pins in matched tapered holes. A lapping tool and grinding compound are placed inside the paired housing halves which are then clamped and held in alignment with the dowel pins. The housing is tumbled in a quasi-random way to produce an accurate spherical surface. Seven sets of housing halves are being prepared for tumble lapping experiments at Stanford which will commence in the middle of 1986. We expect the tumble-lap approach to meet the 10 microinch requirement.

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"[8] which provides a test region at low temperature (4.2 K) and ultra low magnetic field ($2x10^{-7}$ 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 $5x10^{-7}$ 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. Roll also permits study of the accuracy of initial alignment of the gyroscope from spinup. A final feature of the facility is that the air-bearing turntable can be gimballed to follow the precession of the gyroscope, offering the possibility of further improving the characterization of gyro performance. The inside of the probe containing the gyroscope is nearly all metal. This should allow the gyroscope to be operated at 10^{-10} torr.

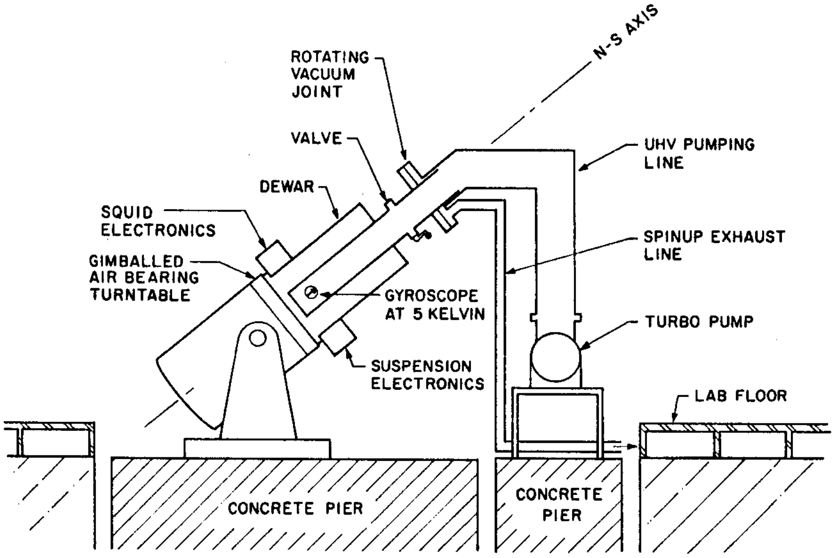

FIGURE 8

Schematic of new gyro test facility

The first phase of construction and testing of the new facility, including all features except roll and gimballing, has just been completed. We are now making preparations to test a gyroscope which consists of a niobium coated quartz rotor in an alumina ceramic housing. The precession and polhoding of the gyroscope will be observed by measuring with three orthogonal pickup loops, the signals due to the magnetic field trapped in the spinning rotor. With this information, we will be able place upper limits on the rotor mass unbalance and the ratios of its principal moments of inertia. In addition to this data, many other types of useful engineering information will be collected. Roll capability will be added in the second phase of the construction this 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 those of greatest design, integration and operation challenge.

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 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.

5.2.1. Quartz block assembly (QBA)

The quartz block holds the gyroscopes, drag-free proof mass and telescope in precise alignment. It is made from a single block of fused quartz as are the telescope, gyroscopes and drag-free proof mass so that there is very little differential thermal contraction among these components. Figure 9 is an isometric view of the quartz block assembly with a telescope attached. As shown in the figure, gyroscopes 1 & 2 are perpendicular to gyroscopes 3 & 4;

this allows the first pair of gyroscopes to be referenced to one plane of the telescope and the second pair of gyroscopes to the second plane (provides some level of redundancy). The quartz block assembly is attached to a support structure built into the MGP at a single, planar surface on the quartz block (labeled QBA mounting flange in the figure) to minimize bending between the QBA and telescope structure. Minimizing bending due to mechanical stress and thermal expansion is extremely important since, as discussed above in Section 3.4, any bending which roll averages mimics a gyro precession. The drag-free proof mass (labeled drag-free sensor in Fig. 9) and telescope are located on the upper side of the QBA mounting flange so the center of mass is near this flange. FIST will use a quartz block designed to accept four gyroscopes, a drag-free proof mass and a telescope, but of these only gyroscopes 1 & 2 will be installed.

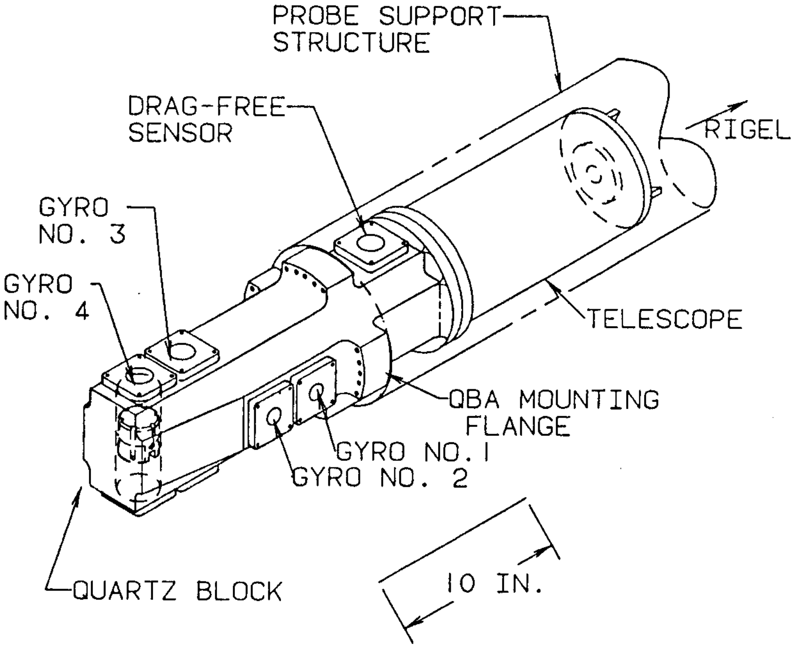

FIGURE 9

Drawing of quartz block assembly and telescope

The gyroscopes must be demountable from the quartz block in the event that they are damaged during installation or fail during test. This requirement is a severe one when taken in conjunction with the very stringent requirements on the alignment (±5 arc-s) of the gyro pickup loop with respect to the telescope axis and its stability (±0.1 marc-s during roll averaging). This demountability and alignment are achieved with the hardware shown in Fig. 10. The initial alignment is accomplished by having optically flat and parallel surfaces on the index plate, spacer and gyro housing halves, two optically flat and perpendicular surfaces on the quartz block and an optically flat mounting flange on the telescope. The gyroscope is held by springs against the spacer and is located by the housing retainer which acts as a collet between the gyro housing and the circular hole in the quartz block. In all there are five interfaces between the telescope mounting flange and the gyro pickup loop, three of which are optically contacted. Each interface is to be manufactured to a 1 arc-s precision and measured to a level of 1 arc-s or less. This should produce an absolute alignment and stability which meets the above requirements.

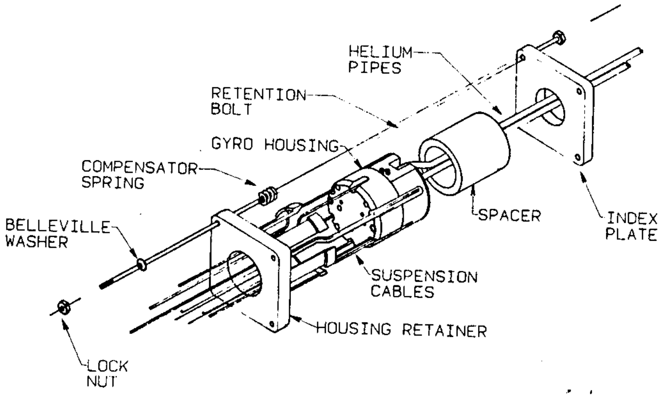

FIGURE 10

Exploded view of gyroscope with retention hardware

The quartz block assembly and telescope must be capable of withstanding, without damage, the Shuttle launch loads which have been estimated to be approximated by 15 g quasistatic loads in any direction. This requirement accounts for a number of features of the quartz block assembly: the center of mass located near the mounting flange, the cruciform shape and the thickness of the mounting flange. Fused quartz is a brittle material which fails most easily under tension. Although fused quartz can have tensile strengths up to 7×10^3 psi, it also has a great deal of variability downward due to local stress and other material conditions. For this reason a very conservative maximum stress level of 750 psi is allowed in the quartz block / telescope assembly during Shuttle launch loads. The stress in this assembly has been analyzed by the finite element method. The analysis gives a frequency of about 790 Hz for the lowest frequency mode when the assembly is not supported, which justifies the quasistatic assumption since no significant loads on the QBA are expected above 200 Hz due to launch vibrations. The preliminary finite element analysis indicates that the maximum stress, which is in the QBA flange region, should not exceed the 750 psi requirement. The analysis is being extended to include effects of thermal loads, the preload in the bolts and the presence of the QBA support structure.

5.2.2. Multi-gyro probe (MGP)

The multi-gyro probe has many functions: it provides a vacuum container in which the QBA is mounted at low temperature, it acts as a conduit for the many services needed by the QBA from outside the dewar, it provides a means of inserting and removing the QBA into the dewar while filled with liquid helium, and when inserted it provides thermal connection to the liquid helium to keep the QBA and other components at low temperature. The services needed by the QBA from outside the dewar are many: electrical cables (a total of more than 100 conductors) for gyro suspension, SQUID readout, heater power, and thermometry; fluid lines for spinup gas supply and exhaust; a vacuum line for pumping the helium gas that leaks out of the spinup channels; optical light pipes for the telescope readout; and very importantly, an optical window through which the telescope sights the guide star. Note that, although room will be reserved in the MGP for the window and light pipes, these components will not be included in FIST. Since the MGP is intended to be prototypical not only of the service functions but also of the Science Mission thermal design, all these services have to be provided without adding excessive parasitic heat loads. With the current Science Mission dewar design the average parasitic heat load reaching the liquid helium to achieve a two year lifetime cannot exceed 74 mW, less than that of typical laboratory test dewars.

The GP-B dewar design contains a substantial departure from the IRAS and COBE designs. In both IRAS and COBE the instruments are assembled into the low temperature regions of their dewars while warm, whereas the GP-B instrument has to be mounted in a vacuum tight probe which is inserted into the dewar while it is cold. The multi-gyro probe design, although simplified from earlier concepts, is nonetheless a substantial challenge. This is why designing a full size probe, prototypical of the Science Mission probe, is an essential element of FIST.

The multi-gyro probe is too complex to be adequately described by a single drawing, although some aspects of it are indicated in Fig. 2 of this paper. The probe has an overall length of 112 inch (2.84 m) and a nominal diameter of 10 inch (0.25 m), and it has three regions along its length: the lowest, which is nearly isothermal at about 1.8 K, is 70 inch long; the middle (called the probe neck), which has a temperature gradient between 1.8 K and room temperature, is 28 inch long; and the highest, which is at room temperature and includes a large vacuum valve, is 14 inch long. The probe size is governed by a number of issues including magnetic shielding, telescope aperture, vacuum conduction for spinup leakage gas, room for all the various conduits mentioned above, and dewar lifetime. The probe is inserted into a dewar well which has a 1.8 K cavity and a neck region both of about the same length as the corresponding probe regions. We discuss here two major probe issues and their design resolution. Other aspects of the probe and dewar are discussed in a recent paper by R.T. Parmley, J. Goodman, M. Regelbrugge and S. Yuan[51].

The first major issue is how does one build a probe that has adequate structural integrity, can be inserted and removed from the dewar well, and has a very low thermal conduction to the liquid helium. A major source of thermal conduction down the probe neck is through the large, approximately 10 inch diameter, cylindrical tube which provides the vacuum enclosure for most of the conduits and for vacuum conduction. The initial Lockheed concept was to make most of the tube's length from an E-glass/epoxy composite which has a low ratio of thermal conduction to Young's modulus, with possibly a graphite/epoxy composite section at the low temperature end. This tube needs adequate strength to prevent structural damage before and during installation into the dewar when it is under an external pressure load of one atmosphere and also during Shuttle launch conditions. To provide adequately high strength and low thermal conduction, a folded neck tube structure composed of three coaxial tubes was designed increasing the effective length for thermal conduction without reducing structural strength. Recently, Lockheed has been investigating another more promising material, a γ-alumina/epoxy composite. Although there is as yet relatively little engineering experience with this material, it has a lower ratio of thermal conduction to Young's modulus. A neck tube has been designed using this material which meets the strength and thermal requirements using a single tube rather than the three for the folded design. A single tube significantly reduces the complexity of the probe design. A development tube of this material has been made and will be shortly under test.

The second major issue is the attachment of the MGP to the dewar. After the probe is inserted into the dewar well it must be attached both mechanically and thermally at several remote locations: at the low temperature attachment point for the probe at the top of the 1.8 K region of the dewar well and at four heat stations which couple the probe to the helium dewar boil-off heat exchangers. The low temperature attachment point also serves as the primary mechanical connection between the quartz block assembly and the liquid helium container which, for the Science Mission, is in turn connected to the the spacecraft structure through passive orbital disconnect struts[52], developed by Lockheed. After investigating a design based on bolts and expansion rings, Lockheed has designed a twist lock mechanism: the probe is inserted into the dewar well and then twisted 18^{o} with all attachments being locked into place. Although this design requires tight manufacturing tolerances and careful attention to friction, it greatly simplifies integration as well as improving other features of probe and dewar design.

5.2.3. Engineering development dewar (EDD)

As mentioned at the beginning of this section on FIST, the engineering development dewar will be made prototypical only at its interfaces with the multi-gyro probe and the magnetic shielding subsystem. The reason for this decision is the relatively strong engineering heritage from the IRAS and COBE programs. Lockheed has also proceeded with an independent development program to build a space qualified helium dewar which refines a number of the important technologies for GP-B and other programs. Because of this strong heritage for space helium dewars, the EDD design emphasizes the development of the full-sized, prototypical interfaces to the MGP and magnetic shielding subsystem which are unique to GP-B. The rest of the EDD will be made using standard methods for building laboratory helium dewars.

An important aspect of the EDD to MGP interface is that both the low temperature and neck regions between the probe and the dewar well are kept under a common high vacuum during normal gyro operation. This high vacuum condition yields a design with thermal conduction to the probe and expanded lead bag provided through mechanical connections to the dewar. An objective of FIST is to verify that these connections provide adequate thermal conduction as predicted by analysis. This approach with the common high vacuum will allow integration procedures of much less complexity than would have been possible in some of our earlier designs.

The region between the probe and dewar well is not always operated under vacuum. The first low temperature operation is the expansion of superconducting lead bags to produce the ultra low magnetic field. During this operation, the dewar is at 4.2 K where the vapor pressure of liquid helium is one atmosphere and the low temperature portion of the dewar well is filled with liquid helium. This allows the lead bags to be expanded using the existing technology developed at Stanford (see Section 5.2.4). The probe is also inserted into the dewar when it is at 4.2 K and the dewar well filled with liquid helium, again allowing the use of established probe insertion procedures[8]. After the probe is inserted and locked into place, the region between it and dewar well is evacuated; the thermal conduction is then through mechanical connections, while the high vacuum in the neck region prevents heat transfer by helium gas that would otherwise produce a large parasitic heat load. For the Shuttle test and Science Mission, helium exchange gas could be inserted into this region to provide additional thermal conduction at low temperature during Shuttle launch accepting temporarily a larger heat load until on orbit.

5.2.4. Magnetic shielding subsystem

The magnetic shielding is achieved using several elements in the dewar, quartz block and gyroscope. The two magnetic shielding requirements are discussed in Section 2.1.1: the magnetic shielding must attenuate the ambient magnetic field so that (1) the residual dc magnetic field at the gyro rotor does not exceed 1×10^{-7} G and (2) the ac magnetic field at the gyroscope does not exceed 2×10^{-13} G. Since the ambient field in orbit is about 1 G, the second requirement is equivalent to a shielding attenuation factor of 2×10^{-13}. Not only must adequate magnetic shielding be provided, but the materials in the dewar, probe and quartz block assembly must be chosen to not contribute excessive magnetic field due to remanence or thermoelectric currents. This requires control of materials in the design and in the manufacturing processes. A major objective of FIST is to verify that these magnetic requirements can be achieved in a full size instrument system.

J.M. Lockhart[53] has recently discussed the subject of magnetic shielding in detail. In reviewing the shielding concept it is useful to refer to Table 6 which contains a list of the shielding elements and the allocation of ac field attenuation and dc residual field among them. The two outermost shielding layers are used to meet the dc residual magnetic field requirement and to provide a portion of the total required ac shielding. The first layer of shielding uses a conventional high permeability ferromagnetic shield; we expect to use Cryoperm® (a product of Vacuumschmelze GMBH) which is designed to have its best shielding properties at low temperature and can thus be located in the liquid helium dewar around the low temperature portion of the dewar well. This shield is a simple cylinder closed at its lower end and open at its upper end. It is expected to provide a dc residual magnetic field of about 30 mG. Inside the ferromagnetic shield a series of superconducting lead bags are expanded so that the final lead bag yields a residual dc field of 8×10^{-8} G or less, which more than meets the dc residual field requirement. The lead bag is also closed at its lower end and open at its upper end.

TABLE 6

Attenuation of dc and ac magnetic fields

Element	DC Residual Field	AC Shielding Factor
Ferromagnetic shield	3×10^{-2}	5×10^{-2}
Lead bag	8×10^{-8}	4×10^{-7}
Local shield		
depth	-	1×10^{-2}
symmetry	-	3×10^{-2}
Rotor self-shielding	-	1×10^{-1}
Ground plane/counterloop	-	$1\text{-}3\times10^{-1}$
TOTAL	8×10^{-8}	$6\text{-}18\times10^{-14}$
REQUIREMENT	1×10^{-7}	2×10^{-13}

The ferromagnetic shield and the superconducting lead bag are designed to yield ac shielding attenuation factors of 5×10^{-2} and 4×10^{-7}, respectively. To reach these attenuation factors, the ferromagnetic shield extends about one diameter beyond the open end of the lead bag, and the lead bag has a length of 60 inch (152 cm) and a diameter of 10 inch (25 cm). The balance of the ac attenuation is provided by the remaining elements which are located in the quartz block and gyroscope. A local superconducting shield is made of a thin film of niobium placed on the surface of a circular cylinder with a diameter of 2.375 inch (60 mm) and a length of 6.375 inch (162 mm) bored in the quartz block. Each gyroscope is positioned at the center of its local shield with its pickup loop coaxial with this shield (see hidden lines for gyro no. 4 in Fig. 9). This arrangement produces ac shielding due to the depth of the gyroscope in the shield (1×10^{-2}) and to the symmetry of the shield and gyroscope (3×10^{-2}). The superconducting gyro rotor also serves to shield the pickup loop against external fields by an amount depending on the average distance between the rotor and pickup loop. The current design is expected to yield an attenuation factor of 1×10^{-1}. Additional shielding from external fields is achieved by a combination of a superconducting ground plane under the pickup loop and of a single counterwound loop which is placed further from the gyroscope rotor than the main portion of the pickup loop. This combination, which is discussed in more detail by Lockhart[53], is expected to yield an attenuation factor of from $1\text{-}3\times10^{-1}$ depending on the some design tradeoffs yet to be made.

Of the shielding elements, the superconducting lead bag yields the greatest engineering challenges. This technology, originally developed for GP-B by B. Cabrera[54], involves a cyclic process in which several folded superconducting lead bags are sequentially expanded. A folded lead bag is slowly cooled through its superconducting transition temperature in a glass cooling tube with the cooling rate controlled by helium exchange gas. When the folded lead bag becomes superconducting, it traps the ambient magnetic field. The lead bag is then expanded with a plunger with the result that the magnetic field inside the bag is decreased because the trapped flux is now distributed over a greatly increased volume. The process is repeated after placing a second folded lead bag inside the expanded lead bag. Although this expansion process can be repeated many times, the residual field is eventually limited by trapped flux produced by thermoelectric currents in the lead bag.

This lead bag technology has recently gone through a significant engineering advance under the direction of Lockhart[53] with the participation of personnel from Lockheed which has the responsibility of providing the superconducting lead bag for FIST. The manufacturing methods for producing the folded lead bags (particularly the seam welding and folding of the bags) and the various equipment to support the expansion process have been improved. To demonstrate these improvements a series of lead bags were expanded in the existing "Low Temperature Gyro Test Facility" dewar culminating in the expansion of an 8 inch (0.20 m) diameter by 44 inch (1.12 m) long lead bag, which is close to the size needed for the Science Mission and FIST (10 inch diameter by 60 inch long).

Figure 11, which is a plot of the residual magnetic field as a function of the number of expansions, illustrates the success of this lead bag development effort. All but the last lead bag have a 4 inch diameter after expansion. The smaller diameter bags are advantageous for two reasons: they reduce the leakage at the open end of the lead bag and are easier to manufacture and handle. An initial residual field of 3 mG is provided by a ferromagnetic shield. As can be observed in the figure, a dc residual field of 8×10^{-8} G is achieved after five expansions if one ignores expansion 1A. The only abnormal behavior during the entire expansion process was due to failure of the helium recovery system. The helium recovery system is unnecessary for the lead bag expansion process and can be disconnected in future expansion work. The remaining lead bag development tasks for FIST are to extend this technology to the modest 25% larger size needed for the Science Mission and to design a means to keep the lead bag below its superconducting transition temperature when the dewar well is under vacuum.

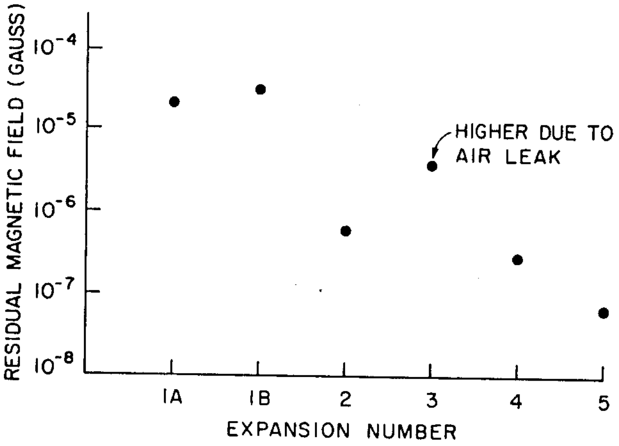

FIGURE 11

Residual magnetic field in superconducting lead bag as a function of expansion number

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 gyro 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 the next Marcel Grossmann meeting, we expact to report the initial test results coming from this full size instrument, as well as reporting advances in gyroscope development and in the design of the flight instrument for the on-board Shuttle test.

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