GRAVITY PROBE B: *II. HARDWARE DEVELOPMENT; PROGRESS TOWARDS THE FLIGHT INSTRUMENT*

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ABSTRACT

The Gravity Probe B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes in Earth orbit. For a 650 km polar orbit the two effects predicted by the theory, known as the geodetic and frame-dragging precessions, are orthogonal with calculated rates of 6.6 arc-s/yr and 0.042 arc-s/yr respectively. The goal of the experiment is to measure the geodetic effect to better than 0.01% and the frame-dragging effect to better than 1%. This paper summarizes progress towards development of the GP-B flight instrument, focusing primarily on the accomplishments of the last three years. It describes the First Integrated Systems Test (FIST), successfully completed in 1990, of a partially prototypical version of the flight instrument. Future integrated systems tests leading to the Science Mission are also outlined. These will consist of a series of ground tests on more prototypical instruments, as well as the development and flight of a Shuttle Test Unit (STU) which will test aspects of the gyro system performance in a low acceleration environment.

1. Introduction

The development of the Stanford Relativity Gyroscope Experiment has proceeded since 1964 following a proposal by L.I. Schiff[1] for a new test of the General Theory of Relativity. The *geodetic* and *frame-dragging* precession rates, 6.6 arc-s/yr and 0.042 arc-s/yr respectively, will be measured with respect to the line-of-sight to a suitable guide star (Rigel), corrected for the star's proper motion and the difference between its apparent and actual positions (see also discussion and figures by Everitt[2] in these proceedings). By fabricating the gyroscope to exacting standards, and by careful control of its environment, an absolute drift rate (due to all known non-relativistic disturbance torques) of ≤ 0.3 milliarc-s/yr is achievable. Combining this with a similar error expected in the readout-chain yields a total measurement error in the relativistic drift rate (excluding proper motion of the guide star) of ≤ 0.43 milliarc-s/yr. In fact, the error is expected to be lower than this and thus the primary experiment objective, that of measuring the geodetic effect to ≤ 0.01% and the frame-dragging effect to ≤ 1%, seems achievable with margin. Other experiment objectives and a comprehensive discussion of other aspects of GP-B are described in a number of papers.[3,4,5] Figure 1 is a picture of a disassembled gyroscope showing the quartz housing, with its spin-up channel and electrodes, and a niobium coated

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quartz rotor. Details of recent gyroscope performance testing are described in an accompanying paper by Xiao[6] in the proceedings of this conference.

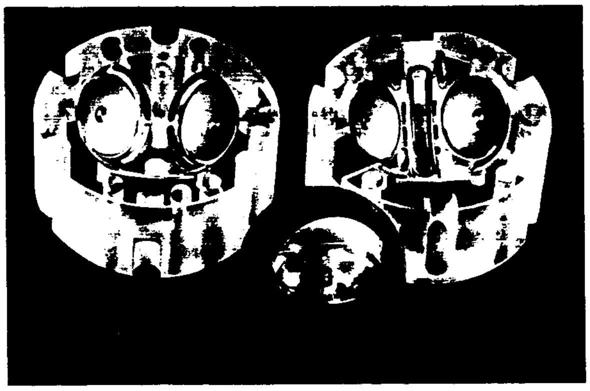

Figure 1. Photograph of a disassembled GP-B gyroscope. Shown is the quartz housing with coated electrodes (four of the six visible due to the camera angle) and coated spin-up channel. The readout loop was not yet fabricated onto this gyroscope's housing. Also shown is the niobium coated quartz rotor. See text for dimensions and details.

The GP-B program presently consists of three main parts: (a) development of the Science Mission payload via the fabrication of a series of ground test prototypes, each a major increment closer to the flight unit, (b) development of a flight payload, consisting of a non-cryogenic two-gyroscope system, to be tested on the NASA Shuttle in the mid-1990s, and (c) spacecraft studies for the Science Mission by aerospace contractors. Lockheed Research and Development Division is teamed with Stanford for parts (a) & (b), the subjects of this paper. After over thirty-five years of development, the program will culminate with the launch of the Science Mission satellite towards the end of the 1990s.

2. Science Mission Payload Development

2.1. Description of the Experiment

The GP-B Experiment Payload (Fig. 2) consists of a superfluid (2200 *l*) helium dewar[7] within which a high-vacuum probe is installed containing the Science Instrument Assembly (SIA) made up of a Quartz Block Assembly (QBA) optically contacted to a quartz Cassegrainian telescope[8] (Fig. 3). The QBA consists of four gyroscopes and a drag-free proof-mass sensor mounted in a precision machined fused-quartz block. The SIA is maintained at a stable temperature of ~2 K which provides stability of the precision alignment necessary between the gyroscopes and the telescope. Each gyroscope consists of a niobium coated 38 mm diameter fused quartz sphere (rotor), spherical to better than 50 nm, electrostatically suspended within a precision fused-quartz housing. The gyroscope is spun up to ~170 Hz, with its spin vector parallel to the line-of-sight to Rigel, by means of a helium gas jet. It is then evacuated to a pressure of $\leq 10^{-11}$ torr which, in conjunction with the averaging effect of rolling the spacecraft about the line-of-sight to the guide star, sufficiently minimizes torques due to differential gas damping. The proof-mass sensor controls thrusters which compensate for the effects of residual drag on the spacecraft,[9] and achieves an average acceleration at the gyroscopes of $\leq 10^{-11}$ g. As a result the *Newtonian* precession rate, due to all disturbance torques, is reduced to an acceptable level. Readout of gyroscope precession is accomplished by detecting changes in the direction of the London magnetic dipole moment which is co-aligned with the spin

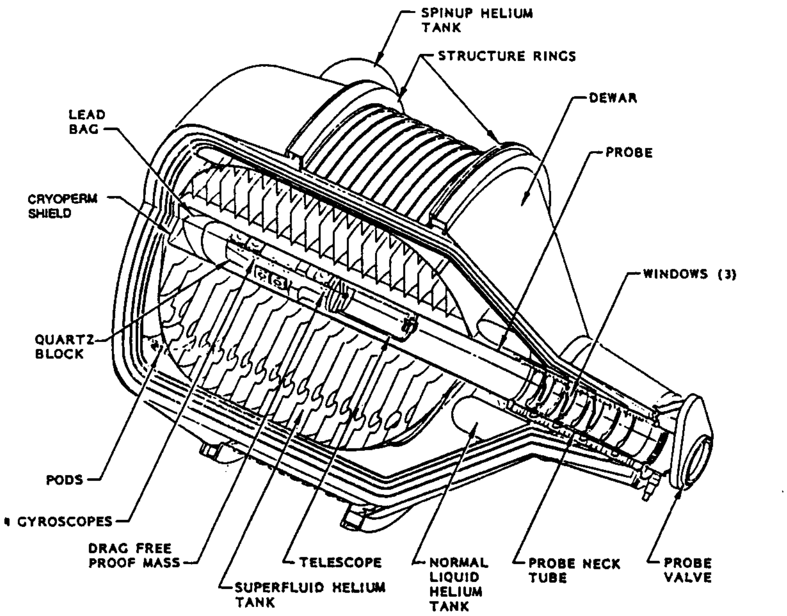

Figure 2. The GP-B Science Mission payload illustrating its major components.

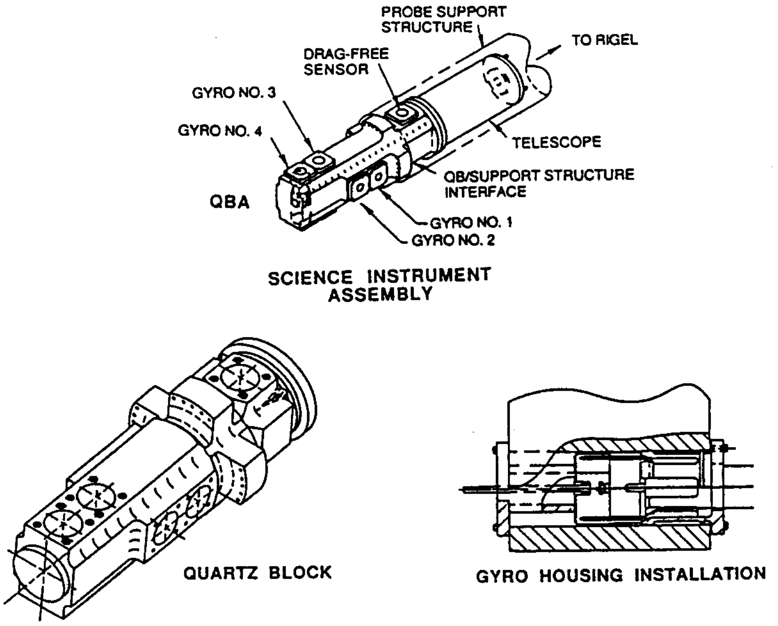

Figure 3. The Science Instrument Assembly (SIA) consists of four gyroscopes and a drag-free sensor integrated into the Quartz Block Assembly (QBA) which is optically contacted to the quartz telescope.

vector of the gyroscope. It results because the surface of the spinning rotor has a superconducting coating (~ 2.5 μm Nb, $T_c = 9.2$ K). As the London moment changes direction, the magnetic flux passing through a superconducting pickup loop which surrounds the rotor changes and is detected by a Superconducting QUantum Interference Device (SQUID) magnetometer.[10,11] The gyroscope and its readout are protected from the disturbance of external magnetic fields by a shielding system consisting of a ferromagnetic shield, a superconducting lead bag, and a local superconducting shield.[10] To ensure an acceptably low trapped magnetic flux in the rotor coating, the dc field at the gyroscope is required to be $\leq 2\times10^{-7}$ G. To prevent the Earth's magnetic field from masquerading as a drift signal, the shielding factor for time varying fields must be $\geq 10^{13}$.

2.2 Key Technologies and Requirements

Table 1 summarizes the key GP-B technologies necessary for the Science Mission. Most have already been demonstrated in experiments with individual components during the last fifteen years, and integrated systems tests of full-sized, partially prototypical hardware have recently begun (section 2.3). Component development facilities include those for rotor polishing and metrology, gyroscope housing and rotor coating, readout loop fabrication, SQUID development and test, suspension system development, ultralow field testing, as well as room temperature and cryogenic gyroscope testing. Table 2 lists key GP-B gyroscope fabrication and readout requirements, and achievements to date. Most requirements have been met, or are expected to be met soon. Several facilities have been recently constructed, e.g., those for high spin speed testing and telescope development. At the present time, the GP-B program has a total of over 500 m^2 of clean rooms dedicated to component fabrication and integrated systems assembly and testing.

Table 1. Key GP-B technologies.

1. ELECTROSTATICALLY SUSPENDED GYROS USING GAS SPIN-UP SYSTEM
    - *Precision quartz housings, rotors, and thin film coatings*
2. GYROS IN NEAR-ZERO AVERAGE ACCELERATION ($\leq 10^{-11}$ g);
    - *Satellite controlled by proportional thrusters to follow "proof mass"*
3. ULTRAHIGH VACUUM ($< 10^{-11}$ torr); DIFFERENTIAL DAMPING NEGLIGIBLE
    - *Low temperature "bake" at ~ 7 K; incorporate cryopump into probe*
4. "AVERAGING OUT" OF RESIDUAL TORQUES ON THE GYRO
    - *Satellite rolled with ~ 10 minute period around line of sight to star*
5. ULTRASTABLE MECHANICAL ENVIRONMENT (GYROS, QBA, TELESCOPE)
    - *All quartz construction at ~ 2 K within superfluid helium dewar*
6. LONDON MOMENT READOUT OF GYRO PRECESSION USING DC SQUIDS;
    - *~ 5 hr integration time to achieve 1 milliarc-s resolution*
7. SUPERCONDUCTING MAGNETIC SHIELDING OF GYROS AND READOUT
    - *Lead bag surrounding probe plus local Nb shields around each gyro*
8. INTEGRATION OF WARM PROBE INTO CRYOGENIC DEWAR
    - *Thermal/mechanical coupling via indium coated links at heat exchangers*

Table 2. Gyroscope fabrication and readout requirements, and achievements.
(Bold type indicates requirement met as of September, 1991)

Item	Requirement	Achieved	Comments
Rotor mass unbalance (rotor and its coating)	≤ 50 nm	**< 50 nm**	displacement from center of mass to geometrical center
Rotor coating (Nb) T_c	≥ 8 K	**> 9 K**	London moment, 8 K spin up
Rotor asphericity	≤ 50 nm p–v	**≤ 25 nm p–v**	peak-to-valley difference
Electrode substrate sphericity	≤ 250 nm p–v	**≤ 200 nm p–v**	tumble lapping operation
Electrode coating uniformity	≤ 350 nm p–v	≤ 500 nm p–v	improve the sputter masks
Charging (at 10^{-11} g)	≤ 50 pC (≤ 0.1 V)	**≤ 50 pC**	charge meas; UV discharging
Pressure at gyroscope	$\leq 10^{-11}$ torr	$\sim 4\times10^{-11}$ torr	measured in dedicated test
Rotor spin speed at 2 K	170 (+10/-30) Hz	172 Hz @ 293 K 62 Hz @ 8 K	incorporating modifications (nozzle) to spin-up channel
SQUID sensitivity (1.7 mHz)	$\leq 5\times10^{-29}$ J/Hz	**$\sim 5\times10^{-29}$ J/Hz**	measured in dedicated test
dc magnetic field at gyro	$\leq 2\times10^{-7}$ G	**$\sim 9\times10^{-8}$ G**	20 cm bag; low field facility
ac magnetic shielding factor	$\geq 1\times10^{13}$	$> 7\times10^{12}$	FIST magnetometer data plus *expected* rotor self shielding

2.3 Integrated Systems Tests

2.3.1 The First Integrated Systems Test (FIST)

Since 1985, the program has used an incremental prototyping philosophy for hardware development. This approach minimizes paper studies in favor of fabrication and testing of full-size SIA, probe and dewar systems. The first such hardware was used for FIST which was conducted during 1990. The FIST hardware (Fig. 4) consists of an SIA, a probe and a dewar which are each more or less prototypical of their respective Science Mission (SM) counterparts. Specifically: (i) The SIA consists of a QBA which is essentially SM prototypical but it does not have a telescope optically contacted to it. It contains two gyroscopes, in positions 1 and 2, and a magnetometer in position 3, while the proof mass and 4th gyroscope positions are empty. (ii) The probe, known as Probe-A, has a full-size SM-prototypical neck tube and heat exchanger system, internal SIA support structure, vacuum shell, and "top hat" containing the feedthroughs servicing the gyroscopes, SQUIDs and instrumentation. It was designed to support operation of only two gyroscopes and a magnetometer, with cabling to support up to three rf SQUIDs and one dc SQUID. It has no cryopump nor any support for telescope readout, and is not specifically designed to withstand launch load conditions, although the latter was considered a goal during the design phase. Extra instrumentation was incorporated into the probe for diagnostic purposes. (iii) The dewar, called the Engineering Development Dewar (EDD), is SM-prototypical with regard to its interfaces with the probe at the heat exchanger connections in the neck and the main thermal-mechanical lock-down at the ~2 K heat exchanger (HEX-0). It also has a SM-prototypical vacuum well designed to maintain an expanded superconducting lead bag. To keep costs down it was fabricated by a commercial dewar manufacturer with non-flight plumbing components, a two-week-hold main tank (instead of ≥ 1.5 year), and a structure that can not withstand launch loads.

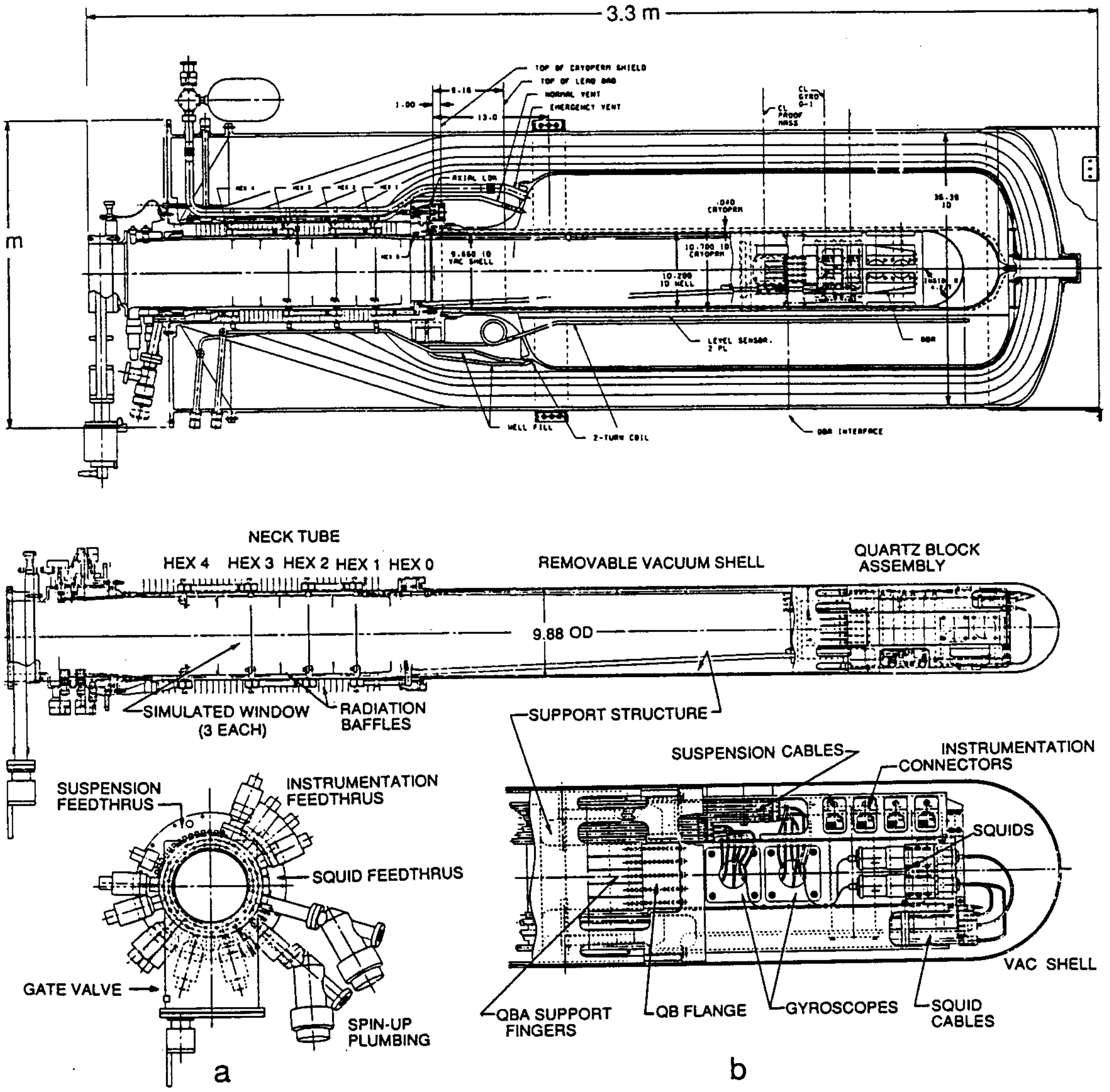

Figure 4. FIST instrument hardware. The top drawing shows the final package with the probe integrated into the EDD. In the lower drawing the probe is shown separately for greater clarity and includes views of [a] the "top hat" with its feedthroughs and gate valve, and [b] a blow-up of the SIA (QBA) region.

The main goals of FIST were: (1) verification of integrability of all subsystems, (2) verification of facilities and GSE, (3) verification of cryogenic operations at LHe I and

LHe II temperatures, (4) verification of gyroscope spin-up and readout performance in a fully integrated system, (5) parametric gyroscope spin-up studies, (6) measurement of ac shielding factors, (7) verification of probe and dewar performance–thermal, gas flow, vacuum properties. The results are summarized in Table 3. Taber *et al.*[12] present a comprehensive description of FIST and a detailed discussion of results achieved.

One aspect of SM-prototypicality was postponed until operation of Ground Test Unit–0 (see Section 2.3.2) due to an earlier discovery of a helium leak in the neck/well region of the dewar. Cryogenic lead bag expansion operations (which achieve the ultra-low dc magnetic field) and the subsequent insertion of the probe require that the dewar well be kept full of LHe to preserve the superconducting state of the lead bag ($T_c = 7.2$ K). However, under these conditions the helium leak would seriously compromise the guard vacuum of the dewar. Therefore the integration method used for FIST was to insert the probe into the dewar first, and then cool down the entire assembly once vacuum was established in the well. A lead bag was installed into the well, at room temperature prior to probe insertion, because it still contributes to the ac magnetic shielding factor. Gyroscope readout in FIST was accomplished by observing the signal from the magnetic flux (~1 mG, provided by the dewar's Cryoperm ferromagnetic shield) trapped in the rotor.

Table 3. Major Results from FIST (1990).

INTEGRATION OF QUARTZ BLOCK ASSEMBLY (QB):
- *Completely successful; demonstrated SM gyroscope alignment to QB*

INTEGRATION OF QBA INTO PROBE:
- *Proceeded smoothly; facility and GSE worked well; gyro functional on first attempt*

INTEGRATION OF PROBE INTO DEWAR:
- *First attempt successful; facility & equipment performed well (warm probe insertion)*

CRYOGENIC PERFORMANCE:
- *Performance of probe & dewar and thermal-mechanical interfaces met requirements*

GAS/VACUUM PERFORMANCE:
- *Probe leakage-gas conductance met spin-up requirement (gyro pressure* $\leq 5\times10^{-4}$ *torr)*
- *Bake-outs to ~ 7 K achieved only* 4×10^{-9} *torr (instead of* $\leq 10^{-11}$ *torr)*
  - *Cryopump to be included in future probes*

CRYOGENIC GYRO OPERATION:
- *Had trouble-free operation of two gyros for > 500 hr*
- *13 successful spin-up cycles for both gyros to ~ 5 Hz*
- *Gyro#1 spun to ~ 50 Hz with ~ 7 K gas during 2 K dewar operations*
  - *Provided data for check of updated spin-up model*

GYRO READOUT PERFORMANCE:
- *SQUID reliability and stability*
  - *2 rf & 1 dc SQUID(s) operated well; 1 rf squid failure on cool-down*
    - *More reliable dc SQUID is now base-lined for Science Mission*
  - *No SQUID flux jumps during gyro operations; verifies EMI shielding system*
- *Trapped flux readout; London moment readout planned for Ground Test Unit-0*
  - *Improvement in trapped flux uniformity by flux flushing (bake to ~ 10 K)*
- *Readout signal to noise of rf SQUID consistent with expectation (SM configuration)*

MAGNETIC SHIELDING FACTOR:
- *Infer ac shielding factor >* 2×10^{11} *without rotor; consistent with SM requirements*

The facilities and ground support equipment (GSE) that were constructed for FIST will be used, with appropriate modifications, for integration and testing of future hardware including the Science Mission payload. In particular these include: (a) the ultra-clean (Class 10) QBA and probe integration facility and its GSE including cleaning equipment, precision manipulators and alignment measuring instrumentation, and (b) the Integrated Systems Test facility and its GSE including vacuum pumping systems (one with a pumping speed for He of ~3000 *l*/s), data acquisition systems, and He airlock for probe to dewar integration. All integrations proceeded very smoothly as a result of trial runs with mock QBAs and probes. Figure 5 shows the major steps in the integration of the QBA and probe while those for probe to dewar integration and FIST operations are shown in Figure 6.

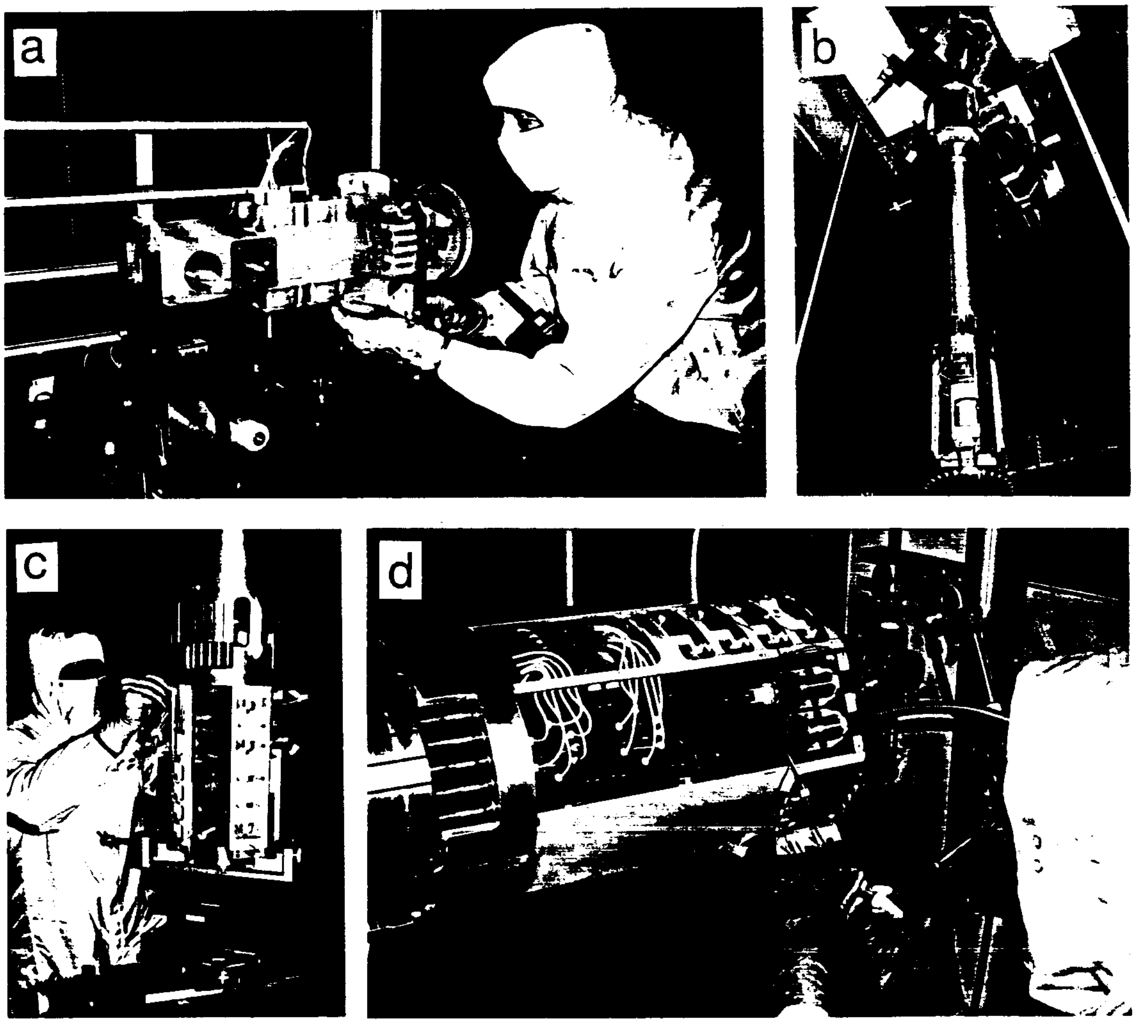

Figure 5. (a) Integration of QBA (Gyro 2 partially installed). QB is held in rotatable fixture facilitating cleaning, gyro installation, and alignment verification. (b) Probe on its manipulator lifted out of vacuum can in 5.5 m high Class 10 clean room. (c) Integration of QBA with probe showing installation of bolts which fasten QB flange to probe support structure. (d) SIA region of probe at final integration stage during attachment of readout cables to SQUIDs (right). Gyro suspension cables visible (top).

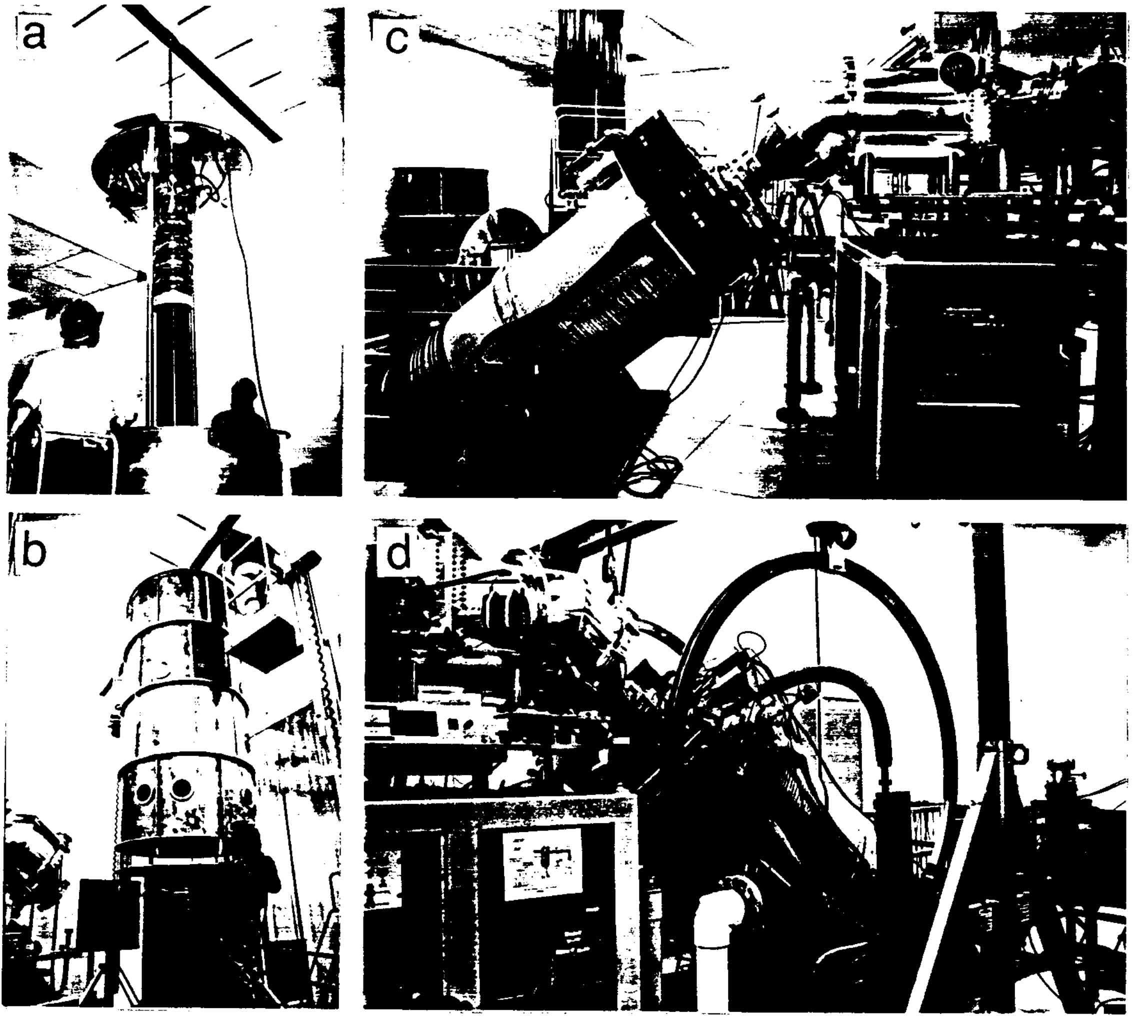

Figure 6. (a) Lowering probe into the airlock in the ~7.3 m. high Integrated Systems Tests facility. (b) Lowering airlock with probe onto dewar. (c) Dewar tilted parallel to Earth's spin axis (to minimize gyro drift due to Earth rotation) and coupled to vacuum pumps. Black boxes are suspension electronics. (d) FIST set-up during measurement of ac shielding factor. Coils of large electro-magnet straddle dewar.

2.3.2 Future Ground-based Integrated Systems Tests

In keeping with the philosophy of incremental prototyping, a series of integrated systems tests have been planned from the present until the testing of the Science Mission payload. Within the constraints of time and budget, a program has been mapped out which takes the largest possible component development step early enough so that any problems that arise can be dealt with prior to the fabrication of its subsequent counterpart. Accordingly, six major ground-based integrated systems tests have been defined, up to and including integration and test of the Science Mission payload. One of these tests, FIST, has already been completed. Figure 7 charts the approximate schedule for these major systems tests, as well as that for the Shuttle Test Unit which is the subject of the next section. Probe-B is now in the final design stage and will be a close prototype of the SM probe. It will support operation of four gyroscopes together with charge control and caging mechanisms (to constrain the rotor during launch), a full complement of dc SQUIDs, a telescope and its readout system, and a proof mass. Analysis will determine whether the probe will survive the launch environment. Probes-C and -D are planned to be full flight-worthy units. Probe-C will undergo extensive ground testing and will be available as a backup to Probe-D, which will be integrated with the SM dewar to form the main part of the SM payload. Following the Engineering Development Dewar (EDD), the next generation dewar using many flight components (hence the name FliComp dewar) will provide valuable prototyping and test experience with Probes-B and -C. It will have most of the characteristics of its Science Mission counterpart but with a much smaller superfluid LHe tank, and no LHe guard tank. Full testing of the integrated probe-dewar system in various attitudes will be possible (to allow spin-up and caging of all the gyroscopes), and the feasibility of performing vibration or modal tests of the system is being studied.

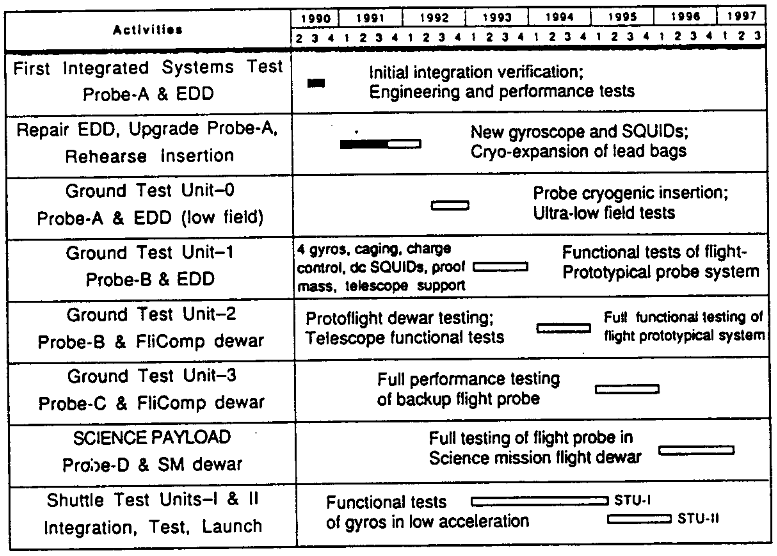

Figure 7. Schedule (as of September 1991) for Integrated Systems Tests through launch of Science Mission. EDD is the Engineering Development Dewar; SM dewar is the Science Mission dewar; FliComp dewar is the flight component dewar (400 *l tank*) which utilizes mostly flight components.

2.3.3 *The Shuttle Test Unit (STU)*

Since 1985, the GP-B program has had a flight test designated on the NASA Shuttle. Originally, the plan was to take the full Science Mission payload (Fig. 2) aloft, in the orbiter cargo bay, for a few days of engineering and functional tests. After subsequent integration of the payload with its spacecraft, it was to be re-launched on the Shuttle and delivered into its polar orbit. With the shut-down of the Vandenberg Shuttle launch facility in California, the required polar orbit became unattainable with the Shuttle, and the SM satellite is now planned for launch on a Delta II rocket. However, important tests will still be performed on the Shuttle in the mid-1990s. Shown in Figure 8, the newly defined Shuttle Test Unit (STU) will consist of the STU Vacuum Assembly (SVA) "probe", containing a scaled down quartz block with two operational gyroscopes, together with caging and spin-up gas management assemblies (GMAs) and a complement of suspension and control electronics. These will be mounted on two plates which attach to the top and side of the Microgravity Program Experiment Support Structure (MPESS). Insulation and heaters will control the thermal environment of STU to approximately room temperature. Two flights of essentially the same payload are presently planned for 1995 and 1996.

The purpose of the STU missions are to verify (in a low-acceleration environment): (i) gyroscope suspension system performance, (ii) gyroscope spin-up methodology, (iii) high vacuum gyroscope spin-down performance, (iv) prototype data acquisition performance and (v) physical integrity of the quartz block assembly through the various space mission environments. The basic mission operations time-line will consist of: (a) uncaging and suspension of the two gyroscopes, (b) spin up of both gyroscopes to ~50 Hz in mission 1 (~170 Hz in mission 2) for ~2 hr, (c) spin down of both gyroscopes to ~ 1 Hz and pump out to high vacuum, (d) collection of gyroscope spin data for 5 to 10 days, including measurement of the response to shuttle-induced accelerations and (e) final spin down, de-suspension and caging for the return trip to Earth.

Many key GP-B team members are working on both STU and the Science Mission payload development. This provides a number of benefits including: (1) simplification of the design and fabrication process resulting from the adaptation of equivalent parts of existing probe technology, (2) natural cross-fertilization of solutions to technical problems-in-common, and (3) valuable flight program experience for the Science Mission team.

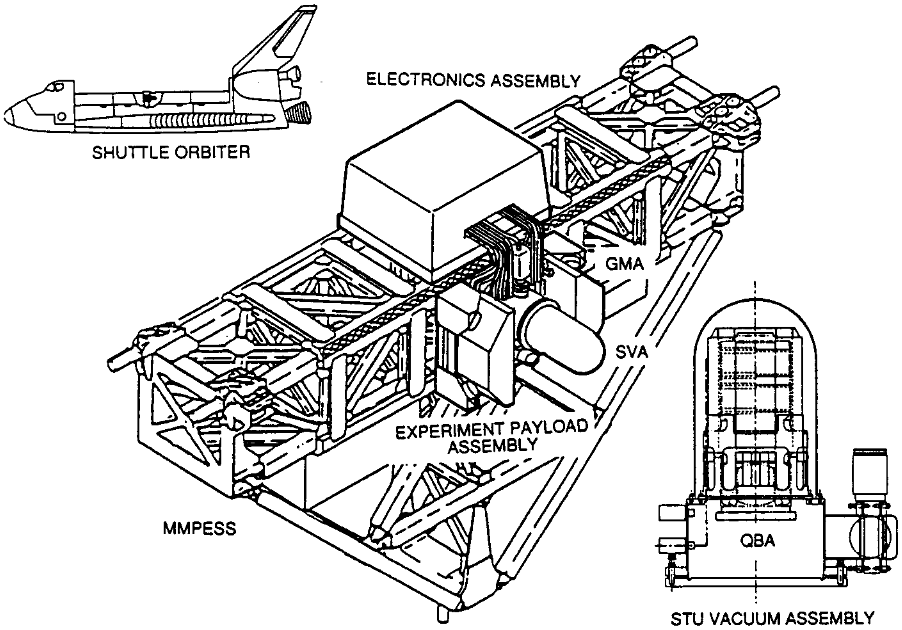

Figure 8. The Shuttle Test Unit mounted on the MPESS. This experiment will test non-cryogenic gyroscopes in low-acceleration and provides valuable experience applicable to the GP-B Science Mission.

3. Conclusion

A prototypical instrument was successfully tested in FIST. Other ground tests and the STU tests are planned, with the launch of the SM satellite by the end of the century.

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