Systems Engineering for the Gravity Probe-B Program

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Abstract

Current sensors and experiment systems take full advantage of the space environment to obtain extreme precision for scientific measurements. The systems therefore perform to design levels only in space, and can only be tested in the space environment. The sensors and support systems use specially developed technologies and also apply existing technologies in ways that push performance to the natural limits. These requirements place high emphasis on the task of the Systems Engineer to meet the challenges of integrating a broad range of technologies and verifying performance so that residual risk is tolerable at each stage of development and at launch.

Gravity Probe-B (GP-B) is typical of this modern system challenge, as it represents the state of the art in sensors (gyroscopes and readout) and magnetic shielding, and incorporates state-of-the-art requirements for cryogenics, optics, satellite control, atmosphere-drag makeup, electronics, and supporting disciplines. Systems Engineering for GP-B will be called upon for innovative use of simulation and analytical techniques in conjunction with carefully selected development testing. For example, an existing error analysis is being used to develop the technology interactions and to support decisions (tradeoffs) on the configuration of the experiment system. This paper discusses the requirements that the GP-B system must meet, and describes our approach to integrating the technologies developed by Stanford University over the past 22 years with cryogenics and other disciplines developed for spaceflight by the aerospace community.

Introduction

This paper discusses the approaches being taken by Gravity Probe-B Systems Engineering to develop and integrate this highly interactive, high-technology system. The Systems Engineering disciplines and analysis being used to deal with multiple system interactions will be discussed, as well as our response to the challenge of integrating the technologies into an experiment system - a careful plan to move into system-level integration through a series of ground tests and a flight test, on Shuttle, of the experiment package.

Gravity Probe-B is representative of the challenging programs that NASA is undertaking in the third decade of space flight. As technical capability in space has advanced, emphasis for space science has moved toward full use of the space environment as a laboratory for making measurements not possible in any earthbound lab. As the experiment sensor sensitivity increases by orders of magnitude, two trends must occupy the attention of spacecraft Systems Engineers. First, the total spacecraft becomes more an integrated part of the experiment apparatus as the measurements require lower and lower disturbance levels, greater shielding from external environments, long observation periods, and improved pointing performance. Second, the ultimate flight performance requirements are more difficult to demonstrate in ground tests and may, as for GP-B, be impossible to verify unambiguously under full gravitational acceleration, with practical restrictions on optical path lengths, and under ambient earth disturbance levels.

The basic technologies required for GP-B have been developed and demonstrated in the laboratory and in orbit over the past 22 years by, or in cooperation with, Stanford University. Currently, as the last step before building the full satellite system for the Science Mission, Stanford and Lockheed have teamed to perform the Systems Engineering leading to the Science Mission and to develop and demonstrate experiment integration. This program is called STORE (Shuttle Test of the Relativity Experiment).

Discussion

The objective of the Stanford Relativity Gyroscope Experiment (Gravity Probe-B) is to precisely test two aspects of Einstein's general theory. The experiment has been fully described elsewhere, most recently by C. W. F. Everitt.[1]

An overview of the experiment hardware is presented in the paper by Bardas et al.[2]

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Experiment concept

The experiment apparatus consists of four near-perfect gyroscopes and a stellar reference telescope in drag-free orbit around the earth. A current concept for the Gravity Probe-B Science Mission satellite is shown in Figure 1. It is a free-flying, Shuttle-launched, 2-year mission in a 650-km polar orbit. The gyroscopes (in a quartz housing or block) and the telescope are enclosed within a probe inserted into a large liquid helium dewar, as shown in cutaway in Figure 2. Electronics, power, control thrusters, and other supporting subsystems are arranged around the dewar exterior. The telescope axis shown in Figure 1 is in the orbit plane, as is the star it tracks. The satellite rotates (rolls) about the telescope axis at about 36 deg/min to modulate (chop) body-fixed gyro torque offsets and instrument drifts. The satellite is about 4.3 m long and wide and weighs about 1500 kg. It is designed to be compatible with direct injection/retrieval by the Shuttle and also with orbital maneuvering vehicle (OMV) injection from a Shuttle launch.

Systems Engineering for the current phase of the program began with a study of the concept and the experiment performance requirements that had been developed by Stanford. It was immediately clear that requirement derivation and system development planning would have to take special account of performance interactions and also of the new and unique technologies that would be integrated. Much of the analytical and physical system integration can be performed in advance of the full satellite development, resulting in reduced risk for the Science Mission. STORE was therefore allocated the burden of integration demonstration, including ground and flight tests. The relationship of the STORE objectives to the Science Mission and the overall experiment objective is diagrammed in Figure 3. STORE has been assigned the objective of confirming that the science payload, with its inherent challenging technology, can be proven flight ready.

System interactions

The GP-B satellite is essentially an integrated experiment apparatus and therefore the performance of each part of the system is dictated or strongly constrained by the experiment requirements. Magnetic shielding, mass and moment balance, mass distribution, drag-free orbit control, and pointing to the guide star all place interrelated requirements throughout the system. A design decision that affects any part of the system must be made with full cognizance of the interactions with other parts and with system disciplines.

Examples of GP-B system interactions can be seen by examining the Science Mission experiment requirements. The nine fundamental requirements given in Table 1 have been derived by Stanford[1,3] from the Science Mission objective given in Figure 3. The numerical values for fundamental requirements numbers 1, 2, 3, 6 and 8 are all stated as "less than" or "better than" 1 marcsec/yr, which is the overall experiment measurement accuracy requirement. The error budget process described subsequently allocates specific values to each of the fundamental and lower level requirements so that the combined accuracies will provide the overall measurement accuracy of better than 1 marcsec/yr. Each of the first eight requirements in Table 1 generates interactive requirements on most parts of the system. For example, fundamental requirement 1 places stringent limits on the torques that can be applied to the gyros. Requirements 1 and 2 together require a gyro readout that is sensitive to extremely small precessions and that applies near-zero reaction torque on the rotor, and thus lead to the London moment readout concept. An ultralow magnetic field at the gyros and high attenuation of varying external magnetic fields are required to permit the London moment readout to meet the sensitivity requirement, and also to prevent spurious signals at all frequencies from appearing in the gyro readout in response to requirement number 7. The means for obtaining the ultralow field, and also most of the shielding, is a superconducting shield placed inside a highly permeable shield, both having a high ratio of length to diameter. The earth's field causes torques on the shield which must be considered in the attitude control design to maintain ultralow accelerations on the gyros. Also, the shield length drives the system length, and therefore the total mass distribution, which involves the overall satellite design. The interactions at this level of the system, while complex, are well established;[3] the error budget, which will be discussed later, will be used to determine the interactions down to lower levels of the system.

Special technologies

The Stanford group and others have addressed the very special technologies required for the experiment during 22 years of laboratory testing plus flight demonstration of drag-free orbit control. Major developments include making gyroscope rotors that are spherical to within a few parts in 10^7 using quartz homogeneous to within a few parts in 10^7 and use of superconductor properties (London moment, SQUID magnetometers) to provide submilliarcsecond measurement resolution of the gyro spin axis direction.[4] Other special technologies include use of superconducting shields to achieve a steady state magnetic field at the gyroscopes of 10^{-7} gauss and provision of 13 orders of magnitude shielding against varying (<1 Hz) external magnetic fields.[4] Helium gas spinup of the gyros and low-temperature bakeout to achieve vacuum at the gyros of $<10^{-10}$ torr have been developed for GP-B. We are required to apply state-of-the-art cryogenic technology throughout the design of the apparatus to achieve <2-kelvin temperatures at the gyroscopes and readout devices. Requisite technologies also include an all-quartz telescope having milliarcsecond accuracy,[5] satellite control and atmosphere drag makeup using the cryogen vent gas directed through proportional thrusters, drag-free orbit control, and extremely low-force electrostatic gyroscope support and position control.

Recent developments in materials and concepts have allowed Lockheed to design a high-performance neck tube for the experiment probe and for the corresponding dewar neck tube.[6] Special electrical cables for the electrostatic gyro suspension have been designed. The probe concept will also use magnetic material control developed by Stanford. These technologies must be integrated into the complex probe neck tube shown in Figure 2.

Technology development

Reviewing the progress made in developing the individual technologies, we are able to conclude that the potential "show-stoppers" have been systematically identified and dealt with by test and analysis.[7] Additional component and subassembly-level laboratory tests are proceeding to demonstrate single-gyro performance to the extent possible in ground test and to verify some features of the probe concept. Some questions, however, require that we combine subsystems. For example, investigation of potential intergyro spinup gas interactions requires a multiple-gyro quartz block as a test article. Verification that the gas which leaked into the probe during spinup will be conducted out of the probe to achieve the probe vacuum will require a test article that includes the probe, neck tube, and the quartz block. These and other test and integration objectives can only be met at higher levels of integration. The next major step, therefore, is to combine the critical technologies in the quartz block, probe, dewar, and other interactive subsystems into selected higher levels of system integration.

System performance verification

As stated above, one of the desirable results of STORE is a demonstration that the experiment science payload will meet the Science Mission performance requirements. Analysis shows, however, that the fundamental requirement on the gyroscope drift rate cannot be demonstrated in ground testing. The drifts caused by earth gravity and rotation will completely mask the 10^{-11} arcsec/s goal for nonrelativistic drifts of the gyro. Even for the lowest ambient accelerations that can be provided by the Shuttle ($\sim 10^{-4}$ g), the gyro drift rate will still be as much as six orders of magnitude higher than will be achieved in the disturbance-free environment ($<10^{-10}$ g) of the Science Mission. We have had to conclude that GP-B must depend very heavily on analysis and modeling to extrapolate performance from ground tests of the parameters that can be tested. We will place heavy reliance on systems analysis for performance verification, which we plan to base on the GP-B error budget/analysis.

Error budget

The GP-B error budget will respond to the need for a method of identifying and quantifying system interactions and for analytically verifying the system performance. Another value of the error budget is to analytically interpret the fundamental requirements across the system at all levels to ensure that the design engineers have a totally consistent set of performance requirements from which to work.

We are fortunate that Stanford has already done quite a complete end-to-end error analysis.[8,9] This analysis is the basis for rapid development of an error budget for the system. The current GP-B error budget work has begun with the construction of an "error tree." A small segment of the error tree is shown in Figure 4. The tree is inverted, with the overall experiment performance requirements at the top. The tree then branches downward from each top-level requirement into all of the concept features that contribute directly to meeting the requirement. The maximum allowable tolerance or error for each top-level requirement is then apportioned to the contributors as a root-sum-square. These values (the requirements) will be shown in the lower left-hand space under the name of the parameter or design feature. The lower right-hand space is reserved for the actual measurement or prediction of the performance, so the two values can be compared directly. As indicated in Figure 4, each of the nine fundamental Science Mission requirements from Table 1 are identified in the tree, although not all are shown in the Figure 4 sample.

The goal of the error budget is to apportion the major experiment requirements, such as the total gyro nonrelativistic drift and the drift measurement accuracy, to all of the system characteristics that contribute to meeting the requirement. Apportionment is facilitated by using the tree structure. For example, the gyro rotor roundness requirement has been set in parallel with the interacting requirement on accelerations of the satellite. As can be seen in Figure 4, the top-level requirements have been apportioned so that the experiment performance meets the 1 marcsec/yr overall requirement. Fundamental requirements numbers 1, 3 and 6 are each currently allocated 0.3 marcsec/yr, and number 9, the error in proper motion of the guide star, is allocated 0.5 marcsec/yr. The rest of the fundamental requirements are treated in a similar fashion throughout the tree.

For GP-B, the tree structure is extremely useful to delineate and track the rich interactions in the system. Where a design feature appears in several areas of the budget, we can identify the driving requirement and also the less stringent requirements on that feature which will become drivers if the original driving requirement is relaxed. As tradeoffs become necessary, the error budget is the primary tool for determining where performance margins can be traded to compensate for a shortfall in any area. A fallout of the error analysis procedure is that it provides good traceability on the flowdown of quantified requirements. The most critical requirements are easily discerned, and these are the primary subjects for analytical derivation if not already performed. Stanford and Lockheed are currently working on several areas that were not completely covered in the original error analysis. The paper by Van Patten, Di Esposti, and Breakwell[10] describes development of a simulation tool that will enable us to establish characteristics and error budgets for the telescope/gyro scale factor matching and the end-to-end data reduction. In determining the gyroscope precession, the gyroscope readout signals must be subtracted from the telescope readout signals with an accuracy of better than 0.3 marcsec/yr. Mismatches between the gyro and telescope scale factors could combine with errors in the pointing control to give rise to errors in the signal subtraction, and thus in the gyro precession measurements. In order to match the scale factors of the readouts, an oscillatory "dither" motion is introduced into the satellite pointing. The gains applied to the readouts can then be adjusted so that the dither motion results in the same angle measurements from the gyros and the telescope so the readout subtraction is accurate. The simulation will permit selection of an optimum dither angle.

For the STORE phase of the program, the error budget is also being used to determine which requirements can be fully or partially verified in the ground and Shuttle tests. As the verification plan for GP-B is developed, the error budget, and the analyses that support it, will be the primary tool for deciding whether verification is to be accomplished by test or analysis, and what degree of analysis is required. For GP-B, the error analysis itself will serve as analytical verification for many requirements.

Error budgets are a commonly used design tool, but for GP-B, with its highly integrated system and experiment performance levels that cannot be verified on the ground, the error budget takes on crucial importance.

Satellite concept development

For STORE integration development to be fully applicable to the Science Mission, we have to establish the relationship of the development equipment to the eventual Science Mission hardware without performing a full detailed design of the satellite. We therefore evaluated several satellite concepts such as the one shown in Figure 1, to assure ourselves that we had a reference to set requirements against. We knew that most of the early system development would center on the experiment hardware and the probe and dewar. We therefore made the satellite concept modular, with the equipment that is needed only for the satellite mission modular around a central experiment module consisting of the quartz block/telescope, probe, dewar, and spinup subsystem. Figure 1 shows that the flight electronics, power subsystem, control thrusters and sensors, structural interfaces, communications, and sunshade are external to the experiment module. Most of these items are mounted on a girth ring structure attached to a main structural ring in the dewar. Except for the gyro suspension and readout functions of the electronics, these components and subsystems are within current capabilities and do not contain critical integration issues that should be addressed in STORE. The future satellite equipment is assigned performance, size, power, and mass performance requirements with margins sufficient to permit later development and integration of the external equipment with the experiment module without changing the experiment equipment.

Experiment module concept

Many of the configuration choices for the GP-B experiment hardware, such as the probe concept, had been made by Stanford and others during Phase A and B studies. The current concept for the experiment module is not too different from the earlier concepts.[11,12]

However, development of advanced cryogenic techniques over the past several years, coupled with improved satellite control understanding and availability of new materials, have enabled us to improve performance margins while simplifying the system.

We set out to examine the system in the light of the new techniques available, and to concentrate on resolving conceptual issues that affected both STORE and the Science Mission. The first of these issues was found as we began to develop the interface between the quartz block and the probe. For several years, the GP-B concept included fine pointing control actuators between the quartz block and the probe to overcome the lack of bandwidth of the external control system for maintaining the pointing reference of the telescope.[3] The limitation on control authority was due in part to another of the interactions within the concept: thrust for control and drag makeup is obtained using the dewar helium gas boiloff, which is necessarily limited to a low rate to meet the lifetime requirement. We had to design cryogenic actuators or find an alternative so we could design a probe that would be the same for the STORE and the Science Mission. We were able to eliminate the inner actuators altogether, partly as a result of dewar design advances. The GP-B dewar uses 12 passive orbital disconnect struts (PODS), which were developed under NASA funding,[13] to support the helium tank within the dewar as indicated in Figure 2. These devices provide a much higher stiffness to thermal conductivity ratio than is achievable with nondisconnect cryogen tank supports. Using PODS, we found that the lifetime could be maintained while the structural compliance between the probe, containing the gyros and telescope, and the outer shell, where the control thrusters will be located, was much greater (stiffer) than had been assumed in the original studies that indicated the need for inner pointing actuators. Stanford authorized a special study of the satellite control which determined that the high stiffness of the new dewar (first mode greater than 20 Hz) will provide sufficient outer control authority relative to the sensors mounted within the dewar and therefore permit elimination of the inner actuators. Several optimal control approaches were tried, and it was found that standard control techniques would provide adequate margin. The decision to eliminate the inner actuators resulted in a much simpler system concept with good performance margins.

Several other configuration changes from the Phase B concepts are discussed in a paper by R. T. Parmley.[6] From the view of Systems Engineering, the main result of these changes is that they contribute to improving the margins available for the satellite system, and therefore permit us to move forward confidently on the portions of the system design covered by STORE.

STORE integration test evaluation

The first requirement for determining the configuration of STORE systems was to decide how much of the Science Mission technology should be included in the systems tests. We reviewed the tests that had already been done, and the component and assembly-level tests that were planned. We determined that most of the critical experiment technologies have been, or will be, tested to the extent possible on earth at low levels of integration. This leaves, as the most critical need, testing at successively higher levels of integration where the new technologies are brought together in an operating system. Higher levels of integration will disclose the last round of tradeoffs between potentially conflicting requirements and design solutions.

We developed a somewhat subjective methodology for evaluating the potential payoff of various development test hardware configurations, both toward our integration goal and also in terms of direct heritage for the Science Mission. The Science Mission system was broken down into smaller entities that could be considered independently. Included were 12 flight and ground subsystems and assemblies, prelaunch Shuttle integration and operations, flight operations, and data reduction and analysis. Each of these was scored relative to the others based on its integration complexity, which was equated to its content of "new" or special technologies plus the number of interactions with other parts of the system. Scoring was normalized so the Science Mission system total equals 1. The resulting integration complexity scores are shown in Figure 5. A high complexity score indicates a high value for including the subsystem or discipline in the development tests. Not surprisingly, the quartz block containing the gyros, with the telescope, was ranked as having the highest integration complexity, since it includes many of the special technologies and its requirements interact with the entire system.

The next step was to compare potential experiment module test configurations on the basis of integration demonstration value versus relative cost. Ground and flight tests were considered separately. Several configurations were considered, using full and partial complements of gyros, complete and partial neck tubes, and various dewar configurations up to and including the full flight dewar. For each of the subsystems or areas defined in Figure 5, we assessed the fraction of the Science Mission counterpart that would be included in the test configuration. This fraction (test content divided by Science Mission content) was multiplied by the corresponding complexity factor to arrive at a test value. The values for all areas included in the test were then added to obtain a total relative level of Science Mission integration verification that would accrue from the test. The results are shown in Figure 6, with test value plotted against relative cost factors.

We found that tests below the system level (not shown in Figure 6) had low integration value. For example, the value of integrating the quartz block by itself was reduced from Figure 5 because the interactions with the rest of the system could not be demonstrated. Based on this procedure, we selected a test of the integrated system using a nonflight dewar as having a high value to the program. The nonflight dewar permitted the test to be conducted early in the program, thus greatly enhancing its true value beyond what our analysis showed and reducing cost. This is the "first integrated systems test" (FIST) shown on Figure 6. The test article configuration includes a full quartz block with two operating gyros and with the suspension and readout electronics. In selecting this configuration, our evaluation confirmed an earlier evaluation by Stanford that most of the outstanding quartz block integration goals can be achieved by initially testing two gyros. The probe for this test will contain all the features that will be required for the Science Mission probe. The probe neck tube will provide a high fidelity development test article for determining the spinup gas inlet cooling efficiency and the conductance for spinup leakage gas out of the gyro cavities. The latter investigation, in particular, benefits from high fidelity of both the quartz block and the probe to validate the complex thermal/gas flow analytical models. The development dewar will accept the superconducting lead bag and the high magnetic permeability shield to demonstrate achievement of the full extent of the ultralow magnetic environment around the gyros. To perform the FIST, we will develop the facilities and integration procedures, and will perform the system design, necessary to develop and demonstrate more than 25 percent of the remaining technical accomplishment for GP-B, at a very low cost. This system development test has the additional benefit of being the first step in the phased buildup of the system ground test capability for both STORE and the Science Mission, with the expectation that the final ground test capability will demonstrate fully a third of the integrated system, as noted on Figure 6.

The content of the Shuttle test was examined and traded off in the same way as the ground tests, but the cost basis was higher because of the more stringent rules that will be applied to the development and integration. Assessments for three alternate configurations are shown in Figure 6. The simplest configuration, identified as "A," would be an on-orbit functional test of the quartz block assembly in a minimum size dewar with no neck tube. The test value is only slightly greater than for the ground test, with a large share of the value resulting from inclusion of the flight environments. Configuration B would place the quartz block in a full-size probe in a "boilerplate" dewar, and shows a large gain in value for a small increase in relative cost. The cost increase is due in part to the increase in size to essentially full size necessitated by a full probe. The value gain includes consideration for being able to make some gyro performance measurements, but several important issues, such as a true test of the dewar and probe dynamics, are not addressed. Configuration C introduces the full-size flight dewar so that the full experiment module is ground and flight tested. This approach verifies more than 60 percent of the Science Mission integration requirements, including operations, and also has a major cost benefit for the total program since the dewar and probe will be reusable for the Science Mission. If we normalize Figure 6 to remove Shuttle integration and flight operations so the ground and flight tests are on an equal, hardware-only basis, the full experiment module will satisfy about 2/3 of the flight hardware integration requirements. The relative cost is slightly higher than for Configuration B due to the increased performance analysis and design.

We chose to develop the full experiment module shown in Figure 2 for the Shuttle test. This is the most cost-effective approach, and closes out nearly all of the crucial Science Mission integration questions. Some of the tests not covered by the Shuttle test can be done in ground test. The telescope, for example, will be ground tested independently of the Shuttle test.[5] The cost effectiveness is enhanced because about 70 percent of the hardware and software developed for the Shuttle test will be carried directly over to the Science Mission. The Shuttle test will be a relatively small step away from the full Science Mission experiment apparatus.

GP-B Shuttle test description

Figure 7 shows the configuration of the Shuttle test, with the experiment module mounted on a typical Spacelab pallet (which could be an MDM or EMP/STEP). The Shuttle test experiment module is the same as shown in Figure 2 for the Science Mission. The girth ring equipment module structure of the satellite concept (Figure 1) has been retained to house the Shuttle test electronics and the spinup subsystem that is part of the experiment module. The Shuttle test electronics perform most of the same functions as the Science

Mission electronics. The girth ring provides all launch load paths to the dewar outer shell so that the dewar design can be identical to the Science Mission concept.

Requirement development

Now that we have determined the configurations of the major system development test hardware, it is necessary to make sure that the relationships of Science Mission requirements to the requirements for each of the development systems are known.

As a first step in determining the requirements that systems engineering would provide, we devised the systems hierarchy shown in Figure 8. The top level of the hierarchy is set by the experiment and program requirements which are immediately allocated to the systems that are specifically part of the Gravity Probe-B program. (See Figure 3.) At the next level down in the hierarchy, the specific systems requirements appear for the Science Mission, Shuttle Test system, ground test systems (including the first integrated system test), and facilities. Below the systems level, related functions for the Science Mission were grouped into subsystems. Bottom-up derivation of requirements from the gyroscopes and their readouts necessitates expanding the performance requirements down to the assembly level for the quartz block. We therefore expanded the experiment probe subsystem into the next lower level, which includes the quartz block, telescope, probe, and sunshade assemblies. The experiment module parts are outlined by a dashed line on Figure 8.

Returning to the systems level of the hierarchy, the dashed lines leading from the Shuttle test system and ground test systems to the subsystem level indicate our intent to maintain corresponding Science Mission functions for the Shuttle test equipment and also for the several ground test systems. Using this overlay approach, we can make sure that Science Mission requirements are carried over wherever possible as requirements are derived for each of the systems and subsystems. Where differences must be permitted, the effect on the validity of flight or ground test is assessed. We will set up a requirements traceability system on a microcomputer to track requirements flowdown and the relationships between systems. We will treat each major systems ground test for which major new hardware is created as a complete hardware/software system to ensure that relationships to the Science Mission are understood. We will write performance requirements documents as necessary for each system.

Conclusion

The result of several months of work by a coordinated Stanford University/Lockheed team is a systems integration approach for the GP-B STORE program. The approach meets the challenge of ensuring applicability of development hardware/software to the future, very highly integrated, Science Mission program, and also ensures analytical verification of performance that cannot be measured on earth. Most important, the physical integration is being addressed early in the program in a consistent step-wise approach, including a flight test on the Shuttle.

References

1. Everitt, C. W. F., The Stanford Relativity Gyroscope Experiment (A): History and Overview, Stanford University, Contract NAS 8-36125, in Near Zero: New Frontiers of Physics, editors B. S. Deaver, C. W. F. Everitt, J. Fairbank, P. Michelson, (W. H. Freeman, in press).
2. Bardas, D, Cheung, W. S., Hacker, R., G. M. Keiser, J. P. Turneaure (Stanford), J. M. Lockhart (Stanford/San Francisco State), Hardware Development for Gravity Probe-B, SPIE Paper 619-04, Jan 23, 1986.
3. Report on a Program to Develop a Gyro Test of General Relativity in a Satellite and Associated Control Technology, Coordinated by C. W. F. Everitt, NASA Grant 05-020-019, USAF Contract F36615-67-C1245, NASA Contract NAS8-32355, Stanford University, June, 1980.
4. Lockhart, J. M., SQUID Readout and Ultra-Low Magnetic Fields for GP-B, Stanford/San Francisco State, SPIE Paper 619-16, Jan 24, 1986.
5. Everitt, C. W. F., (Stanford), D. E. Davidson (Davidson Optical Instrument Design), R. A. Van Patten (Stanford), Cryogenic Star Tracking Telescope for Gravity Probe-B, SPIE Paper 619-19, Jan 23, 1986.
6. Parmley, R. T., (Lockheed), Gravity Probe-B Dewar/Probe Concept, SPIE Paper 619-13, Jan 23, 1986.
7. An Assessment of the Technological Status of the Stanford Gyrorelativity Experiment, Committee Report chaired by J. Rosendhal, NASA Headquarters, Sep 1980.
8. Vassar, R. H., Error Analysis for the Stanford Relativity Gyroscope Experiment, Stanford University SUDAAR 532, 1982.
9. Duhamel, T. H., Contributions to the Error Analysis in the Relativity Gyroscope Experiment, Stanford University SUDAAR 540, Apr 1984.

10. Van Patten, R. A., R. Di Esposti, J. V. Breakwell, (Stanford), Ultrahigh Resolution Science Data Extraction for the Gravity Probe-B Gyro and Telescope, SPIE Paper 619-17, Jan 24, 1986.

11. Gravity Probe-B Phase B Final Report, George C. Marshall Space Flight Center, Huntsville, Alabama, Feb 1983.

12. Account of the Restructuring of the GP-B Relativity Gyroscope Program, C. W. F. Everitt, editor, Stanford University, Sep 1983.

13. Parmley, R. T., W. C. Henninger, S. A. Katz, I. Spradley, Test and Evaluate Passive Orbital Disconnect Struts (PODS-III), NASA Contractor Report 177368, Contract NAS2-11946, Aug 1985.

Table 1. Fundamental GP-B requirements

(1) GYROSCOPES WITH < 1 msec/yr DRIFT

(2) GYRO READOUT RESOLUTION BETTER THAN 1 msec OVER ~ 100 sec

(3) STAR TRACKER TELESCOPE ACCURATE TO < 1 msec OVER ~ 50 msec

(4) INTEGRATED GYRO HOUSING TELESCOPE STRUCTURE STABLE < 1 msec/yr

(5) POINTING WITHIN TELESCOPE LINEAR RANGE

(6) DATA HANDLING ACCURACY BETTER THAN 1 msec/yr WITH SCALE FACTOR MATCHING

(7) ELIMINATION OF LONG-TERM DRIFTS FROM GYRO AND TELESCOPE READOUTS

(8) CALIBRATION BETTER THAN 1 msec

(9) KNOWN PROPER MOTION OF REFERENCE STAR

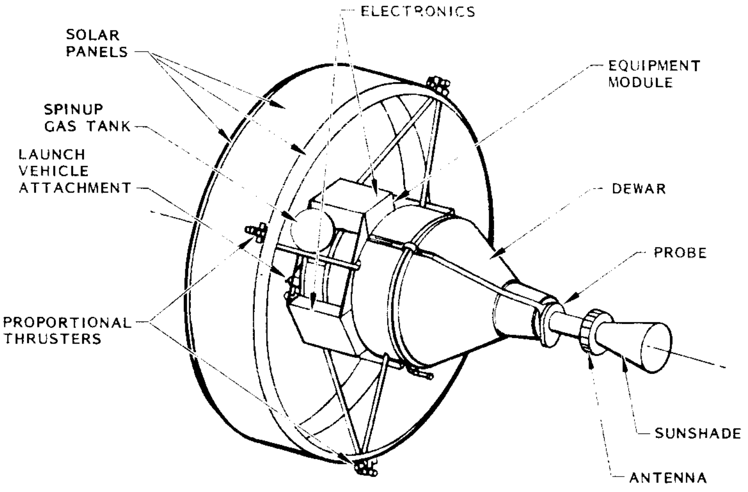

Figure 1. Gravity Probe-B Science Mission satellite concept

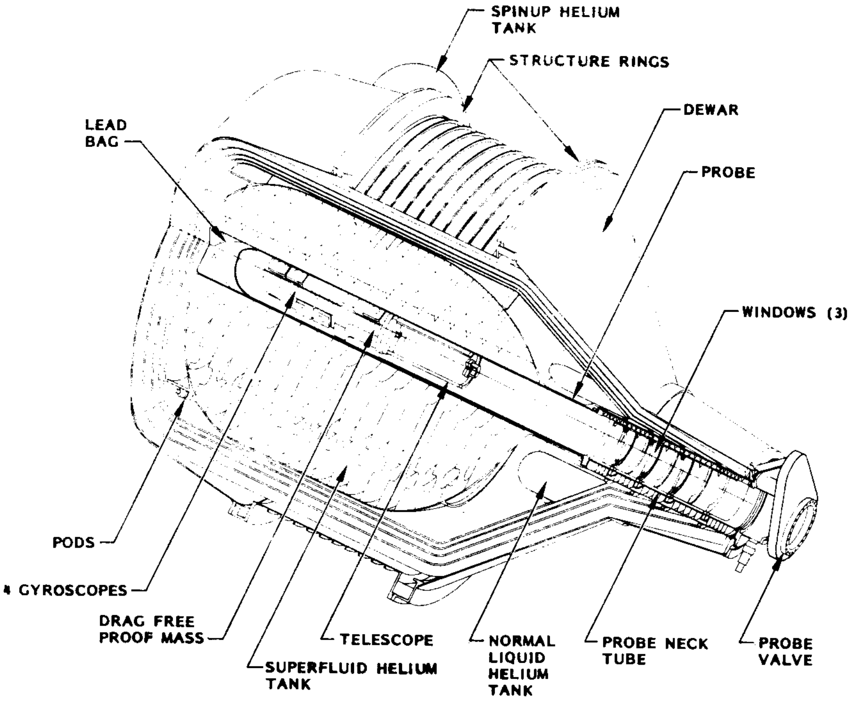

Figure 2. Cutaway of experiment module

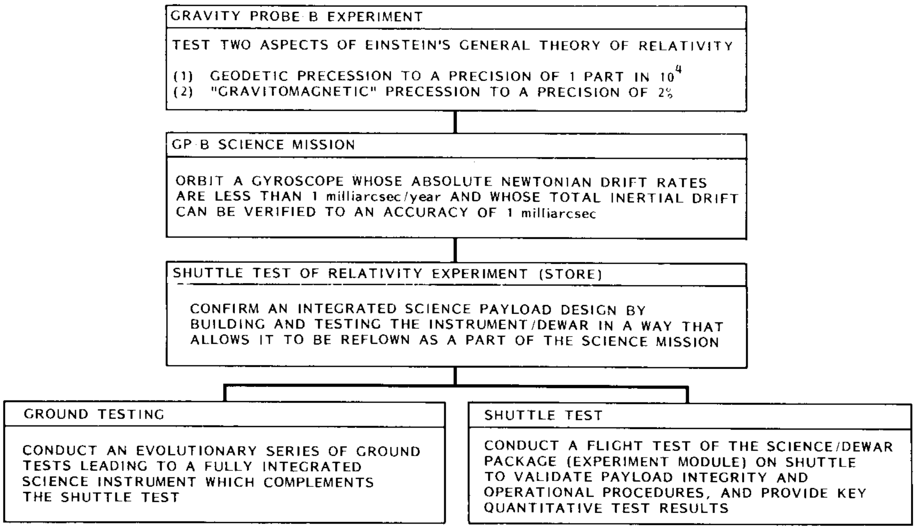

Figure 3. GP-B Program requirements

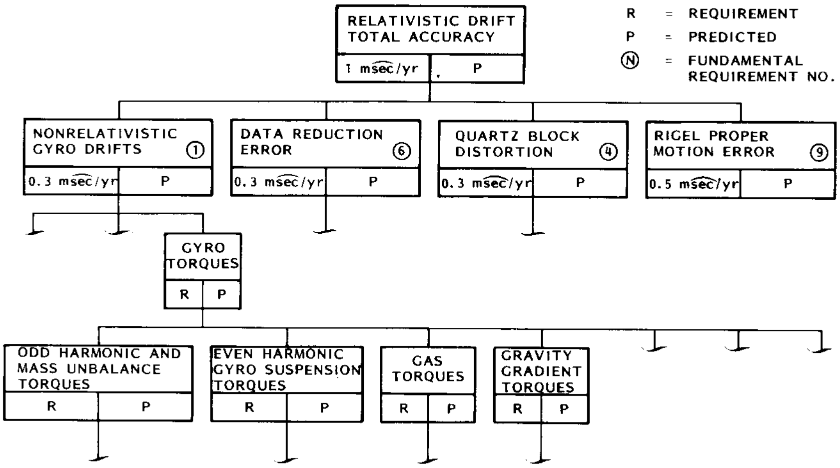

Figure 4. Sample of GP-B error tree

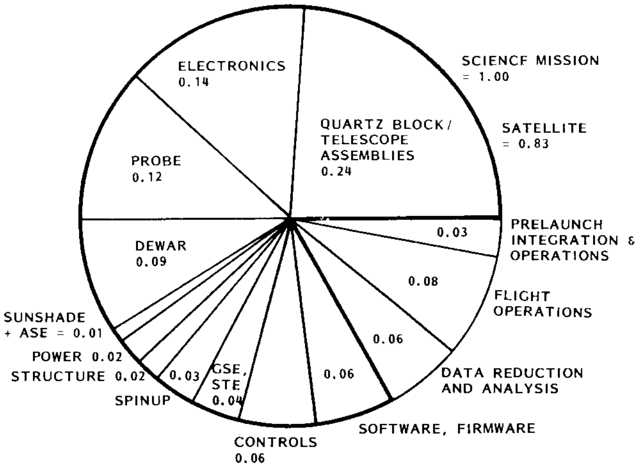

Figure 5. Science Mission relative integration complexity

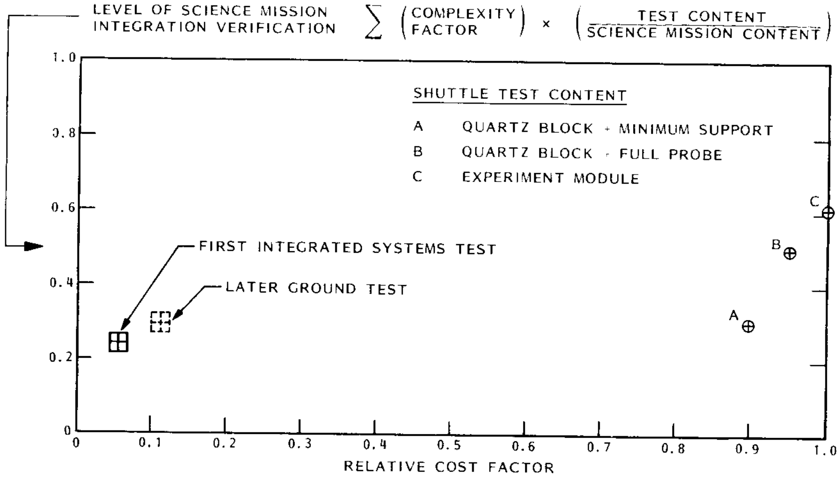

Figure 6. System integration test value assessment

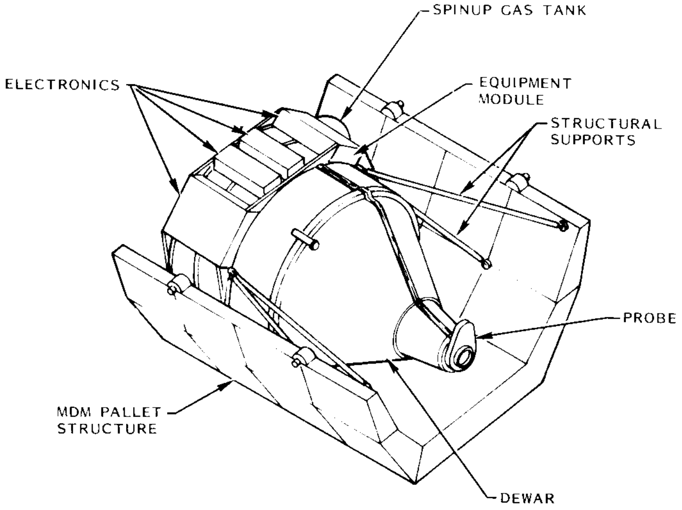

Figure 7. Shuttle test experiment module on pallet

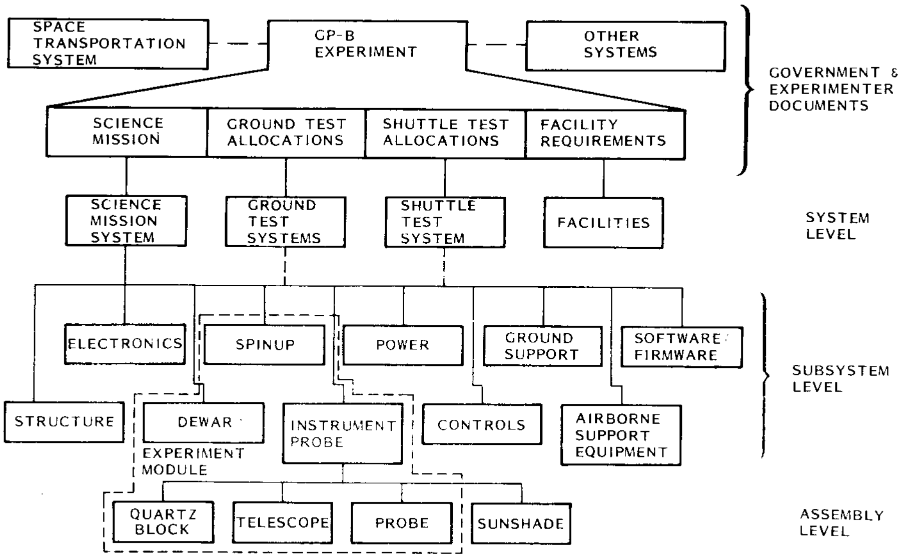

Figure 8. GP-B Program systems hierarchy