W. W. Hansen Experimental Physics Laboratory
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305 - 4085

Gravity Probe B Relativity Mission

GP-B Exceptions to the 'Test It As You Fly It' Philosophy

(Previously Ground vs. On Orbit Test Configurations)

S0622, Rev. A

December 30, 2002

Prepared by:	**Approved by:**
1/8/2003	1/8/2003
Anthony Logan **Date**	**Barry Muhlfelder** **Date**
Approved by:	**Approved by:**
1/9/03	1/9/03
Dorrene Ross **Date**	**Gaylord Green** **Date**
Approved by:	
1-9-2003	
Rich Whelan **Date**	

ITAR Assessment Performed ____________
Tom Langenstein

1/9/03
ITAR Control Req'd? ☐ **Yes** ☒ **No**

Revision History

Rev. A
Date: December 9, 2002

Changes:

1. Title changed: was: Ground vs. On Orbit Test Configurations is: GP-B Exceptions to the 'Test It As You Fly It' Philosophy
2. Added Attachment A, Gyro Test PowerPoint presentation from October 2000 Program Monthly Review Splinter Meeting
3. Incorporated MSFC (Roger Chassay) comments per e-mail dated 1 April 2002 and May 8, 2002.
4. Added section numbers
5. Added section 3.5 Vatterfly Valves and section 5.0 Conclusion.
6. Added Reference section for supporting documentation.

Rev –
Date: January 8, 2002

Original Issue

1.0 GP-B Exceptions to the 'Test It As You Fly It' Philosophy

GROUND vs. ON ORBIT TEST CONFIGURATIONS

The Relativity Experiment, Gravity Probe B, has several subsystem and system configurations that are impractical to operate on Earth in a full mission mode or full mission configuration. In addition, there are high-risk test areas where we choose to only operate on orbit because ground testing in a 1-g environment may cause damage to the fight hardware.

The purpose of this document is to provide full confidence for each of the GP-B exceptions to the "Test It As You Fly It" philosophy that the mission will be successful. This can be established even though the GP-B end-to-end systems tests will not be performed in a flight configuration [i.e., without the flight Gyroscope Suspension System (GSS) suspending all four flight gyroscopes, spinning at full mission rpm as a result of the flight Experiment Control Unit (ECU) commanding the flight Gas Management Assembly (GMA) to provide gas flow through the flight gyroscopes, which is then vented out the flight Vatterfly Valves].

This document defines the GP-B exceptions to the "Test It As You Fly It" philosophy, and provides convincing evidence (via analyses, trade studies, tests using flight equivalent units, engineering memos, briefing charts, etc.) that the GP-B mission will be fully successful, despite the absence of full end-to-end flight systems testing in the mission modes.

Table 1 - Summary of Test vs. On-Orbit Differences

Description	Ground Test Condition	On-orbit Condition	Mitigation
ATC Operations	Only the functionality can be tested by simulating through software the on-orbit inputs to/from the ATC	Nominal on-orbit, the system inputs come from the environment instead of simulation.	ATC simulated on ground. Systems operated on SV in confidence, functional and/or limited tests verifying proper system response.
Vehicle Rotation	No rotation (other than spin balance), Mass trim mechanism functionality tested.	Rotates about roll axis	Roll rate variations verified by analysis. Limited thermal variation testing included in SV Thermal Vacuum test.
Gyro Levitation and High Speed Spinup	2 at a time (goal), 1 at a time if any GSE anomaly is encountered. Spin-up and Spin-down: 1 Gyro Spin-up 170 Hz Flight System 20-90 Hz	Spin-up all 4 Gyros: 80-180 Hz (4,800-10,800 RPM)	Flight gyroscopes levitated in payload. High-speed spinup test performed on one flight gyro. Individual qualification in gyro commissioning process.
Gyro Suspension Level	2 kV	<1 V	Limit gyroscope ground levitation duration.
Vatterfly Valve Performance	Valve exhaust ports are capped and staked	Valve exhaust ports are uncapped on the launch pad/orbit	Spare valves leak tested at on-orbit environmental extremes and flight valves are leak tested at Post-Thermal Vacuum E28.Test

Description	Ground Test Condition	On-orbit Condition	Mitigation
Drag Free Operation	No	Yes	Drag Free simulated on ground.
Gyro Suspension System	DDC (Digital Direct Current) for gyroscope levitation	GSS for science gyroscope levitation	GSS used on ground for interface/sanity check, GSS levitations simulated on ground. GSS technology based on DDC (Digital Direct Current) design. Late gyro test activities validate the integrated GSS & GMA system.
Gyroscope Spinup Gas Delivery System	GSE	GMA	S0701 GMA Risk Mitigation Plan calls for subsystem level testing, ECU testing with GMA simulator, and GMA used for flow test on SV. Late gyro test activities validate the integrated GSS & GMA system.
Thermal Environment	Ground ambient (except for thermal vac test)	On-orbit thermal	On-orbit thermal environment simulated in Thermal vac test
Proton Bombardment	None	SAA, solar flares	Subsystems designed and tested for proton bombardment
Venting To The Vacuum Of Space	Vent to pumps	Vent to space and FEE	Analysis shows ground and on-orbit conditions are equivalent
Magnetic Environment	Earth's DC field (except for AC test)	Earth's field up converted to AC	AC ground test is equivalent to on-orbit condition
Integrated Thruster System Tests	Pressure at thruster exhaust simulated by vacuum pump (exactly similar to on-orbit condition). Gas provided by GSE. Thruster Test running with ACE box.	On-Orbit ambient pressure (~10E-9 torr) at exhaust. Gas provided by Payload Dewar venting. ACE, thruster, and Attitude Control System manages vehicle drag free state.	Thrusters tests on vehicle. Engineering unit thruster was run with vent gas from Flight Payload at superfluid (June 99).

2.0 Detailed Discussion:

The following section is divided into Performance differences and Environmental differences. This discussion is not an exhaustive analysis of the tests that are performed or the on-orbit operations. The reader must have a basic understanding of the Gravity Probe B program and the Payload, Spacecraft, and Space Vehicle designs and test plans.

3.0 Performance

3.1 ATC Operations

Attitude Control, on-orbit, involves maintaining a drag free state at the drag free gyro. The system must also direct the telescope pointing to align with the guide star. The system software and hardware components have been verified to perform as specified via component testing, SV level testing, software verification, and simulation. Maintaining a drag free gyro on the ground is not possible -- this is the driving reason for this experiment being conducted on-orbit.

Mitigation: ATC component testing at SV level, flight control algorithms testing in the Integrated Test Facility (ITF) by simulation.

Flight Risk: Since all aspects of the system are tested directly or simulated, there is low flight risk. The approach for GP-B is consistent with other spacecraft with the precision pointing verifications, such as Hubble Space Telescope (HST) and the Space Infrared Telescope Facility (SIRTF). The drag-free control is unique to GP-B.

3.2 Vehicle Rotation

Parameters that vary on-orbit as a function of vehicle rotation are known and have been accounted for in the analysis of error sources that affect science data. The key areas are thermal and magnetic fluctuations. Thermal fluctuations are modeled, analyzed, and simulated in system level T-V testing. The primary components affected by thermal variations are the forward electronics. The FEE (Forward Equipment Enclosure) protects these components, and was added to the design to minimize the variations. The other key payload systems are unaffected by the external thermal variations because the inside of the Dewar / Probe are tightly controlled (QB temperature, SQUID temperature). Magnetic variations could have an effect on the science data if several critical design features had not been implemented. These features include the lead bag, elimination of all ferrous material in the area surrounding the science instrument, and the Payload Magnetometers.

Mitigation: AC magnetic field testing was also included in Payload Verification II to demonstrate that the variations in magnetic field would not affect the critical science hardware.

Flight Risk: Mitigated. Effects of variations on science data have been tested and/ or analyzed sufficiently.

3.3 Gyro Levitation and High Speed Spin-up (80-180 Hz [4,800-10,800 RPM])

See Attachment 1 (page 9) for relevant information on this topic.

<u>Levitation and Spin Up:</u>

This is perhaps the most significant area where differences exist between test and on orbit. One-g levitations are performed to demonstrate end-to-end functionality of the gyro hardware and related systems, but are done so as a balance between verification and risk to the hardware. This risk increases with the increase in rotation rate of the gyroscope. Because of this three of the four flight gyroscopes have not seen the full flight rpm, however, they have shown flight RPM capability.

Mitigation: 1. Each gyro has been successfully levitated and spun up to low spin speeds (20-90 Hz [960-5,400 RPM]). On average the low spin up speed was 67 Hz. Each gyro was deemed acceptable for flight use after extensive commissioning tests. In addition "Late Gyro Test Activities" in E28 mitigate the risk of testing with GSE by validating the functionality of the integrated GSS & GMA systems.

2. A single high-speed gyro spinup (170 Hz [10,200 RPM]) was performed at the payload level to show conclusively that the gyroscopes can achieve the asymptotic spin speed of gyroscope commissioning tests. While not testing all of the Gyros to flight spinup speed adds some risk, the predicted fight speeds have been validated by correlating the gyro asymptotic spin speed function with low-spin speed test results. Overall there is a greater risk of damaging flight hardware (see "Risk of performing test" below) by performing the high-speed gyro spinup on each gyro than the risk of decreased accuracy in science data.

Risk of performing test: The risk is largely due to the voltage levels required to levitate the gyroscopes on the ground (several orders of magnitude greater) then on orbit. The probability of damaging the hardware is increased as the gyros are spun during levitation and increased further as the gyros are spun to high speeds. Arcing can occur. If arcing occurs there are one of two likely results: damage to the Niobium rotor coating or loss of suspension destroying the flight gyroscope.

Flight Risk: Mitigated. Ground testing is far more severe than on orbit operation.

<u>Simultaneous multiple gyroscope levitations:</u>

Levitations of 2 gyros at a time are done when both gyros are performing within specified parameters. In the case of any anomalous indications, each gyro is tested separately to reduce the potential for damage.

Due to the nature of hardware redundancy on the Science Payload, it is very risky to ground test more than 2 gyros at a time (2 gyros are installed 90 degrees offset from the installation of the other 2 and have different support lands orientations).

Mitigation: Gyros are levitated, although not more than two simultaneously. It is not possible to achieve the low voltage parameters of levitation in ground test that are expected on orbit.

Risk of performing test: Testing all four flight gyros simultaneously on the ground would put the payload at great risk of rotor arcing (as discussed in 3.3.1 above), as well as the risk of a particle(s) of contamination jamming the rotor (putting very high stress into the quartz block), while still not providing a flight-like (low voltage) test.

Flight Risk: Mitigated. Potential areas of interaction between gyros during on orbit spin up and operation have been considered in analyses. Gyros can be viewed as independent systems while being operated on orbit. 4 gyros provide system level redundancy.

3.4 Gyro Suspension Level

As discussed in the previous items, the suspension levels are dramatically different between ground (1-g) and on orbit (drag free for one gyro, near drag free for the other three).

Mitigation: Each gyro is levitated on the ground, with specially adapted hardware and software that allows for demonstration of this functionality. Low voltage testing is not possible due to earth's gravitation field.

Flight Risk: Prudent flight verifications have mitigated this to low risk – no flight like test is possible in ground testing. Limited subsystem design verification testing on-orbit is not feasible and would require an additional test satellite.

3.5 Vatterfly Valve Performance

There are four 2.5" vatterfly valves in gyroscope spinup gas vent lines and two 6.0" vatterfly valves in the Probe vent lines. These valves are designed to prevent air from leaking into the SIA (Science Instrument Assembly) on the launch pad and to maintain the ultra-high vacuum in the SIA on-orbit. During ground testing there is an enormous risk to the Payload if the valves were accidentally opened during ground testing or if the valves did not seal properly after testing. Air leaking in to the probe would freeze and form blocks of ice in the vent lines because of the very low temperatures in the Dewar. This would prevent gyroscope spinup. The remedy would cause months of schedule delay in order to warm up the Dewar and thaw the ice block, and then to cool the Dewar back to operating temperatures. To mitigate this risk of contamination the vatterfly valves are capped, back filled with Helium, and staked, so that they are airtight during Payload and Space Vehicle testing (i.e., Modal, Acoustic, Thermal Vacuum, and Spin Balance). This very necessary mitigation also changes the configuration of the Space Vehicle so that it does not exactly match that of the uncapped on-orbit configuration. On-orbit the valves are to maintain the ultra-high vacuum produced after a low temperature bakeout where the SIA and the vacuum of space will be at approximately the same pressure (about 10^-9 torr) and then the SIA will be cooled to produce the ultra-high vacuum (about 10^-11 torr). The primary particle for GP-B orbit in the vacuum of space is atomic oxygen, and at space vacuum pressures does not affect the science. The experiment could be performed on-orbit with the valves open (except for EMI considerations). The ultra-high vacuum ensures that the spin-up helium has been properly vented. While there is no significant risk to the payload if the vatterfly valves leak more than allowed on-orbit, if the valves leak more than allowed on the launch pad or during ascent, then enough air could enter the SIA to cause damage to the experiment. The leak rate of the valves therefore must be verified after environmental testing prior to launch operations at Vandenberg.

Mitigation: The spare vatterfly valves have undergone extensive leak testing at on-orbit environmental extremes (both vibration and temperature) and have successfully shown to meet the required leak rate with margin. In addition all of the flight vatterfly valves mounted on the Space Vehicle are leak tested after Space Vehicle Environmental Testing (i.e., Acoustic and Thermal Vacuum) at E28 to validate that the valves meet the leak rate requirement prior to launch.

Flight Risk: Mitigated – The experiment is unaffected by vacuum level amounts of atomic oxygen leaking into the SIA on-orbit. Vatterfly valves will be capped and leak tested until just before launch.

3.6 Drag Free Operation

At the heart of the need for performing this experiment in Earth orbit, drag free cannot be achieved on the ground.

Mitigation: GSS and ATC algorithm checkout ensures that the control systems are in place to maintain drag free operation.

Flight Risk: Prudent flight verifications have mitigated this to low-risk – no drag free operation is possible in ground testing.

3.7 Gyro Suspension System

DDC (Digital Direct Current) ground test equipment has been developed as the tool for suspension of gyroscopes on the ground and serves as the precursor to the flight Gyroscope Suspension System. The GSS, while retaining functionality for 1-g suspension, are designed for drag free suspension.

Mitigation: GSE testing of gyro suspension uses similar hardware and control algorithms that have been implemented in the flight GSS. GSS electronics have had engineering testing with the payload in Payload Verification II. SV level testing will be performed to show end-to-end-functionality (without suspension at 1-g levels).

Risk of performing tests: There is little design margin and therefore high risk in testing at 1-g gyroscope suspensions using the flight GSS system.

Flight Risk: Prudent flight verifications (GSS bump test at Post-Thermal-Vacuum Test E28) have mitigated this to low-risk – no flight like (low voltage suspension) test is possible in ground testing.

3.8 Gyroscope Spinup Gas Delivery System

Ground support equipment is used to spin the gyros during all spin up testing. On orbit, the flight GMA will perform the same functions (gas delivery rate and pressure).

Mitigation: The flight GMA will receive subsystem level testing and be used for integrated interface testing and limited functionality testing on the ground. ECU testing will include GMA simulators, while software is being verified at SV level.

Risk of performing tests: Although there may be little risk in performing an end to end flight like gas flow test on the ground, other system elements cannot be made as flight like to support this (see items above). Flowing gas into the probe creates a substantial logistical/ GSE issue with resources required for pumping on the Probe vacuum space. Benefits of this test are minimal.

Flight Risk: The risks and related mitigations are covered in S0701: GMA Risk Mitigation Plan. The baseline plan to use the GMA for late integrated testing only has been approved by LM, SU, and MSFC.

4.0 Environments:

4.1 Thermal Environment

Consistent with other spacecraft test and verification, the thermal environment for the space vehicle is simulated in a thermal – vacuum chamber. Detailed models have been developed to predict the thermal environment that each component will see on orbit. These components have been separately thermal-vacuum tested.

4.2 Proton Bombardment

In addition to the typical spacecraft design practice to mitigate the effects of proton bombardment (design of exterior surfaces, radiation hardened electronics, etc.), specific payload subsystems were added or modified to deal with the effects of proton bombardment. The effected subsystems include the gyroscope charge control system, mass shielding of the SIA, and magnetic flux slipping in the gyro readout. Simulations and tests were performed which successfully verified system performance given the designs as implemented. There is no plan to verify the response to proton bombardment at the system level.

4.3 Venting to the Vacuum of Space

The vacuum of space can be simulated in test facilities. This difference between a test vacuum and space represents very low programmatic risk. Any risk associated with this difference would be from the basic risk of testing any satellite on the ground. Venting on the ground must be sent to pumps that keep the vent lines in relative vacuum, otherwise they would vent into the vacuum chamber during testing and create an environment that is not flight like for the entire Space Vehicle.

4.5 Magnetic Environment

Like the differences in venting, this difference represents low programmatic risk. The magnetic environment in ground test is constant where the on-orbit environment will vary in field strength and direction depending on the position and ration rate of the Space Vehicle in orbit relative to the Earth. At the 640-km polar orbit for the mission, the Space Vehicle is expected to see a variation in field strength from near zero to about ground test levels. Some EMI testing was done with magnets to verify adequate magnetic attenuation and system stability. Other mitigation activities were covered in the "Vehicle Rotation" section. The Lead Bag that covers the SIA (Science Instrument Assembly) stays at a constant magnetic field and significantly blocks external magnetic fields, which in turn keeps the science experiment in a constant magnetic field. Because the Space Vehicle uses MIL-STD parts, has high level of magnetic attenuation, and by design and testing EMI compliant there is very little programmatic risk with the differences between the ground and the on-orbit magnetic environment.

5.0 Conclusion:

This document summarizes the differences between the GP-B ground testing - "Test It" – configuration and practices with the on-orbit - "Fly It" – experiment configuration. Several of the highlighted differences are unique to GP-B, and several are common to all satellites. To highlight every difference in every test would be an extensive project requiring several months of work and would have little impact to the program at its current stage of integrated space vehicle testing. Even with these differences, the mitigation activities and thorough ground testing of the Space Vehicle support that GP-B will meet the mission criteria for success with successful completion of all ground testing.

References For Further Insight On GB-P Ground Testing

Stanford University Science Documents

1. S0443 Gas Management Assembly TRR (Test Readiness Review)
2. S0446 TRR Two and a Half Inch and Six Inch Vatterfly Valve
3. S0456 Payload Verification Phase "A" Testing TRR
4. S0461 Acoustic Test Segment Test Readiness Review
5. S0485 Aft GSS TRR Package
6. S0486 Forward GSS TRR Package
7. S0497 Post-Acoustic Confidence Tests 95% Subatmospheric Refill & Phases B, C and D of Payload Verification II Testing Test Readiness Review
8. S0506 Mission Operations Demo Test Phase 1, Phase 2, Network and End-to-End Tests TRR
9. S0664 SC and Hardware Acceptance Data Review Plan
10. S0685 GMA Testing of Stanford TRR
11. S0702 Gyroscope Suspension System (GSS) Performance Verification Test TRR Completion Certificate

The Payload and corresponding Subsystem ADPs (e.g., Magnetometer, Gyroscope, Telescope, etc.) contain Drawing Trees, Assembly Drawings, “As-Run” Procedures, and supporting Analyses that detail the ground test configurations and results.

Note: S0664 provides a map to the primary data that comprises the Space Vehicle Acceptance Review, and outlines additional sources for reference.

Lockheed Martin Engineering Memos

1. P480537 Facilities, Transportation, and Modal TRR
2. P480582B Acoustic TRR
3. P480641 Thermal Vacuum TRR
4. P480681 Spin Balance TRR (release date 1/15/2003)

The Spacecraft and corresponding Subsystem ADPs (e.g., Thrusters, Mass Transfer Mechanism, Star Tracker, etc.) contain Drawing Trees, Assembly Drawings, “As-Run” Op Orders, and supporting Analyses that detail the ground test configurations and results.

Attachment A

LATE GYRO TEST – OCT 2000 PMR SPLINTER - V2.PPT
391 KB
Bill Bencze, author

Note:

No Caging per PCB 477

This package was prepared prior to caging system issues lead to PCB 477. PCB 477 removed the caging functionality, removed associated requirements, and altered system level plumbing and the GMA design. The arrow shown has been added to the original presentation material where caging is mentioned. No other modifications have been made.

Gyroscope Testing at the Space Vehicle Level

William Bencze

Agenda

- Summary.
- Baseline Test Plan.
- Possible Additional Testing Options.
- Evaluation of Test Options.
- System-level Risk/Benefit Analysis.
- Recommendations.

Summary

Goal:

Program risk management through appropriate testing.

Issue:

Gyro and caging system not performance tested in ~1 year span from the end of Payload Verification II to launch.

Current Baseline:

1. Gyro performance testing through Payload Verification II.
2. Gyro/system interface testing during Space Vehicle integration.

Gyro verification plan is consistent with the rest of the system verification approach for the payload.

Risk Mitigation:

Add appropriate testing which has a positive risk/benefit tradeoff.
Options:

No Caging per PCB 477

0. Continue with baseline; no gyro performance testing post Payload Verification II
1. **Uncage/recage gyro, flight-level voltage testing with GSS.** ***GP-B Recommendation***
2. Suspend with GSE (DDC system).
3. Suspend and spin with GSE (DDC system) .
4. Suspend/spin with GSS flight units.

Baseline Gyroscope Test Program Performance and Interface Verification

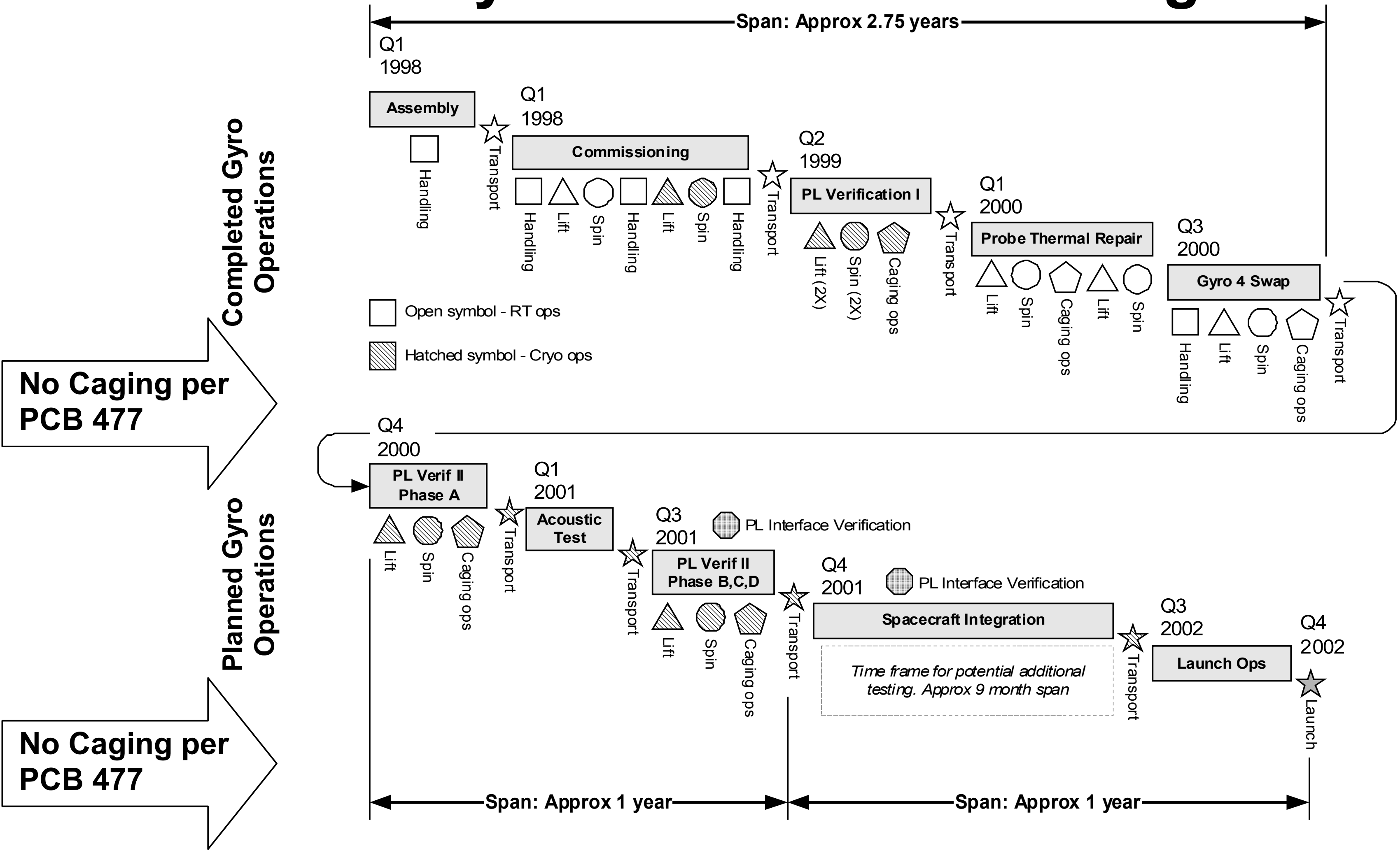
Baseline Gyroscope Test Program

- Performance Testing:
  - Commissioning, Payload Verification I, II levels.
  - Verifies performance of each gyro multiple times during a 3.75 year span.
- Interface Verification:
  - At Space Vehicle level of integration.
  - Verifies that no changes have occurred post Payload Verification II.

Test Item	Where Tested	Conditions
Gyro performance	Commissioning Payload Verification I Probe Repair Gyro 4 swap Payload Verification II	Full performance test. Suspension with GSE Room temp, low temp
Caging system functionality	Payload Verification I Gyro 4 swap Payload Verification II	Full performance test.
GSS	Payload Verification I Payload Verification II SV level	Interface verification; GSS performance tested on GSS Testbed.

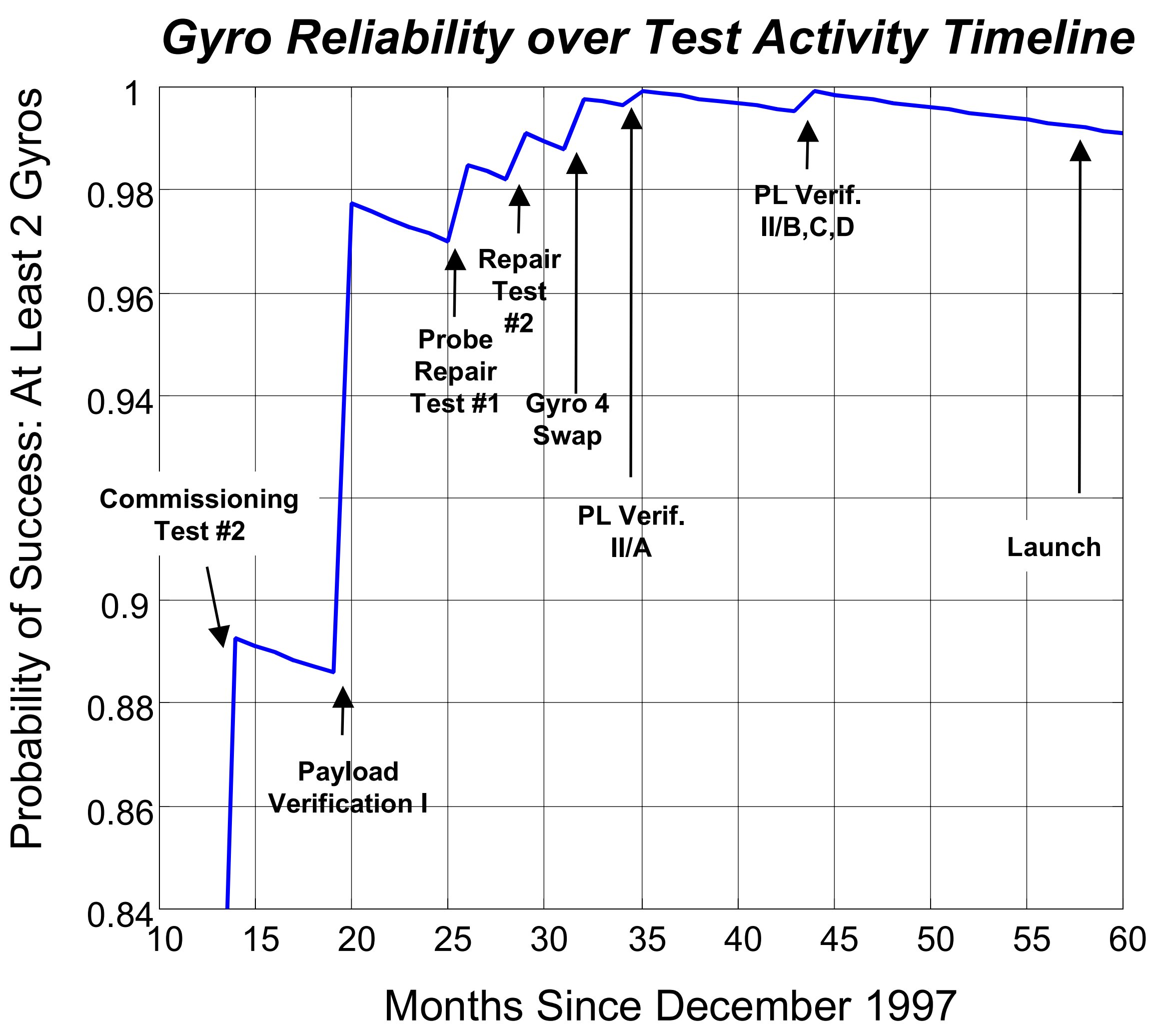
Baseline Gyroscope Test Program Summary

Baseline Gyro Performance Testing Flow



Gyro Test Span: 3.75 years performance testing prior to Spacecraft Integration
Per Gyro: 4 Room Temp Suspensions; 4 Low Temp Suspensions; 5 Caging Tests

Gyro Reliability Improvement with Testing



Gyro Reliability at launch (baseline)

≅ 0.993

Gyro failure rate assumptions:

Months 1-12: 0.25% / month

Months 13-32: 0.15% / month

Months 33+: 0.05% / month

Shows decreasing failure rate with time/experience.

Source: Sam Pullen, GP-B

Test Standards:

- The gyroscope test program (ca 1995) has been developed to ensure the GP-B gyroscopes meet mission requirements.
  - Gyroscope requirements are verified via gyroscope commissioning and post-installation qualification testing. (Payload Verification I, II).

- The GP-B test program is consistent with:
  - NASA-STD-7002 for payload-level testing.
    - » To a large extent possible, GP-B adheres to the "*test it like you fly it*" philosophy.
    - » Not all hardware can be tested in this way; adjustments must be made on a case by case basis.
    - » Test plan tailored around hardware constraints.
  - MIL-STD-1540 for S/V level testing.

"*Test it like you fly it*" - Gyro Issues

- To the greatest extent possible, GP-B's test program tests the flight hardware in the same way that we plan to use it on orbit - *Test it like you fly it.*
- The suspension of GP-B gyroscopes can not be fundamentally tested in this way.
  - To do test faithfully, we would need a 0.1g environment.
  - Any suspension tests performed on a gyroscope on the ground is an <u>extreme over-test</u> of the device.
    - » This type of suspension is required, however, for gyroscope development, gyroscope functional, and cleanliness verification.
    - » Test program endeavors to minimize the exposure of the gyros to these extreme test conditions.
  - Verification of proper operation of this system is done by a synthesis of:
    1. Hardware tests (GSS Box ATP + GSE suspensions of the flight gyroscopes)
    2. In-the-loop simulations (GSS Testbed).
    3. Analysis using proven control system techniques.

❶ Performance verification of this system is directly analogous to a spacecraft attitude control system; it cannot be directly tested on the ground.

1g Suspension and Gyro Overstress

- During testing, field emission is primary cause of gyro damage.
  - Can generate gyroscope charging and arcing in 1g.
  - Primary cause of gyroscope de-levitation in ground testing.
  - Not an issue on orbit (see chart below).
- These tests are required on the ground to verify gyro function.
  - Risk to gyroscopes proportional to net 1g test time.
  - Baseline test plan is designed to minimize these suspension risks.

	Max Force Required	Max Voltage at E'trode	E Field (rotor centered)	Field Emission (normalized)
Science Mode	6.4×10^{-9} N (10^{-7} g)	0.26 V	8.1×10^{3} V/m	$10^{-46,000}$
Spin-up Mode	1.9×10^{-3} N (0.03 g)	108 V	3.4×10^{6} V/m	1
One-g Levitation	6.4×10^{-2} N (1 g)	980 V	1.9×10^{7} V/m	10^{99}
Best demonstrated breakdown limit, sputtered coatings:			~ 5×10^{7} V/m	-

The Completion of Performance Testing

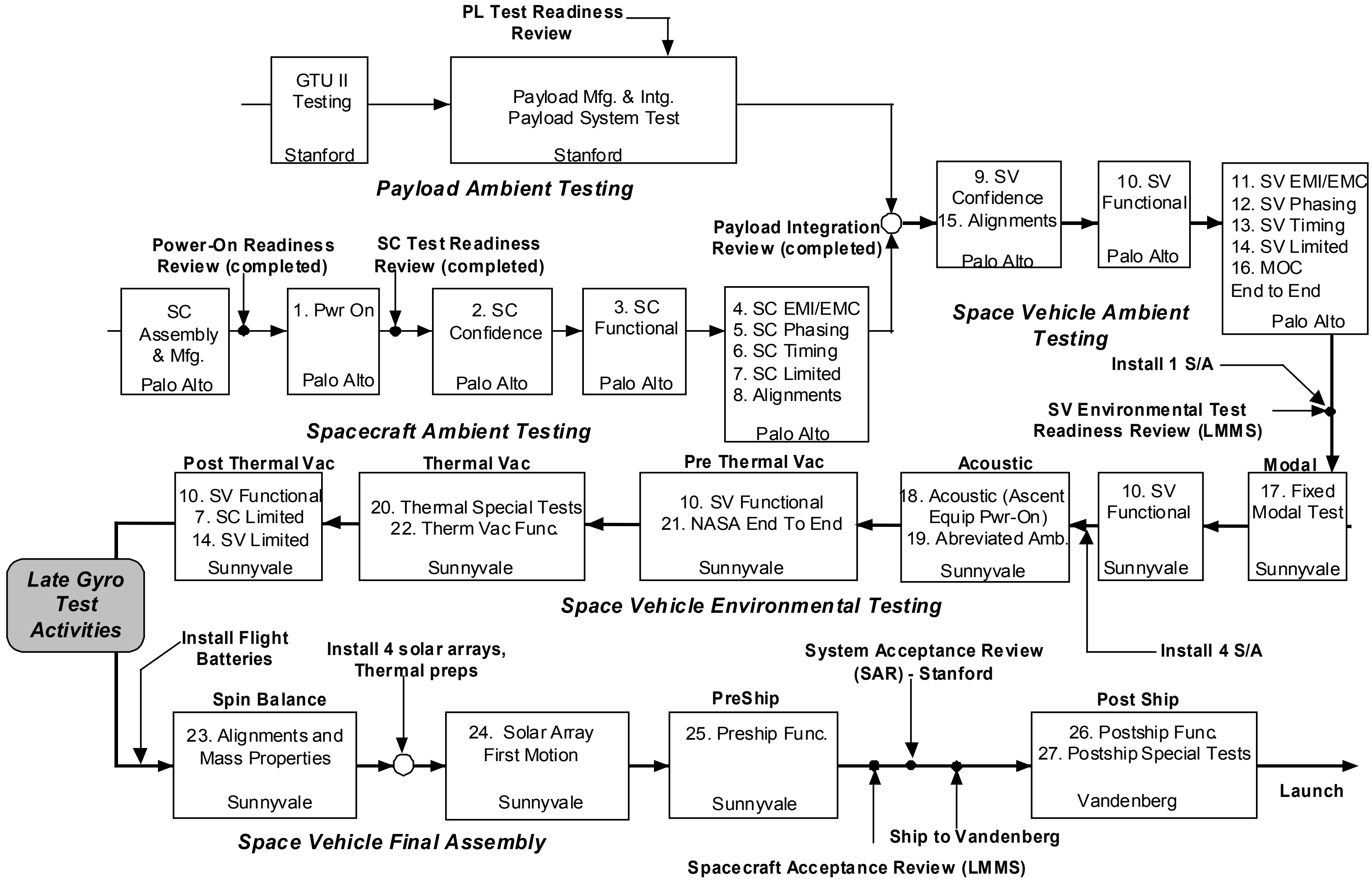
- At the end of Payload Verification II:
  - Gyros shown to have good performance after almost 4 years of handling and testing at room temp and cryogenic temperatures.
  - Gyros have survived the perils of 1g suspension, acoustic test at Probe/dewar level, gyro replacement, probe repair.
  - Gyros that fail performance testing can be replaced with minimal Payload disassembly (e.g. Gyro 4).
  - Performance testing is complete.
- Post Payload Verification II:
  - Interfaces to gyroscopes are verified in caged position via Payload Electronics boxes.
    - » Verify that nothing has changed after each of the major Space Vehicle test segments.
    - » Test philosophy for gyroscopes is consistent for all payload systems.
    - » Gyroscopes do not see any new environments or stresses during Space Vehicle integration.
      - Already undergone an acoustic test at the probe/dewar level.
      - Thermal/Vacuum test has no effect on cryogenic gyroscopes.

Additional Gyroscope Tests
Options and Tradeoffs

Motivation for Post PL Verification II Testing

- Risks to Gyroscopes:
  - Space Vehicle integration and testing may cause previously unidentified contamination to migrate into the gyro cavities.
    - » Passed 3.75 years of extensive testing without contamination.
    - » Risk is further mitigated by having 4 redundant gyroscopes.
  - Caging system not operated in the ~1 year span between Payload Verification II and launch. Question: Will it operate as required after this period?
    - » Off-line testing possible.
- Mitigation Options:
  - Given these concerns, some additional gyroscope performance tests may be run to completely or partially mitigate these risks.
  - Best time to run these tests is after SV acoustic and SV thermal/vac testing.

Location of Gyro Tests in SV Test Flow



Source: LMMS IT-02 Rev D

Additional Testing of Gyros: Selection Criteria

Candidate post Payload Verification II performance tests shall be evaluated against the following criteria:

1. Test to realistic flight levels using realistic flight configuration.*Test it like you fly it.*
2. Avoid tests with potential for overloading/inadvertent damage.
3. Risk abatement from successful test must be greater than added risks.
4. Program schedule and budget impacts to implement mitigation option. *(not included in risk/benefit tradeoff)*

Options for Additional Gyro Tests - Summary

No Caging per PCB 477

- Test Options:
  0. Current Baseline.
  1. Gyro uncaging/GSS voltage testing.
     » Long term gyro caging test in separate facility also possible.
  2. Gyro suspension with GSE.
     A. Direct connect to Probe-C.
     B. Via splice into GSS cabling.
  3. Gyro suspension and spin with GSE.
  4. Gyro suspension/spin with GSS.
- Advantages and disadvantages for each option examined against the 4 selection criteria.
- Prototype schedule of activities for each of the test options shown.

0. Baseline Test

- Description:
  - Verify that nothing has changed in measured gyroscope parameters (position, etc) since the end of Payload Verification II.
  - Done as part of the SV level functional test.
  - Verifies GSS interfaces, bridge, and amplifier functionality.

- SV Operations:
  - No special (additional) operations are required for this test.

0. Baseline Test Plan Tradeoff Matrix

	Advantages	Disadvantages
Flight config	• Flight configuration of GSS, SRE, ECU. • Uses flight interfaces, algorithms.	
Potential for damage	• No potential for damage	
Risk Retirement		• Does not retire any additional risk (caging, contamination)
Program impacts	• No impacts to baseline effort or schedule	

1. Gyroscope Uncaging/GSS Voltage Test

No Caging per PCB 477

- Description:
  - Use the flight GSS to observe the motion of the gyroscope when it is uncaged and recaged.
  - Demonstrates the functionality of the caging system and connectivity of the GSS to the gyroscope.
  - Apply on-orbit spinup level voltage kicks to the gyro to induce it to roll around the bottom of the housing.
    - » Useful test; is an established part of DDC suspension pre-levitation procedure.
    - » Demonstrates connectivity of LV and HV amplifiers to the gyroscope.
    - » Exposes gyroscope and probe to maximum on-orbit voltages from the flight GSS.

No Caging per PCB 477

- SV Operations:
  - Required reorientation of SV to re-cage gyroscopes.
  - No flight interfaces need be broken for this test.

1. Uncaging/GSS Voltage Test Tradeoff Matrix

	Advantages	Disadvantages
Flight Config	• Flight configuration of GSS, SRE, ECU. • Uses flight interfaces, algorithms. • <u>Exposes probe and gyro to maximum on-orbit voltages.</u>	
Potential for damage	• Little to no potential for damage to gyros.	• <u>Additional handling of the space vehicle</u>
Risk Retirement	• <u>Verifies that gyro is free to move when uncaged.</u> • <u>Verifies proper connectivity of the GSS, SRE, parts of the ECU.</u> • <u>End-to-end test of caging system.</u> • <u>Spinup voltage test in flight configuration.</u>	• <u>Does not fuly verify that the gyro is free from particulate or cryo contamination (gross contamination only)</u>
Program impacts	• <u>Does not require any HW development</u>	• <u>Small impact to schedule</u>

(Deltas from previous test scenario are <u>underlined</u>)

1. Gyroscope Uncaging Test Span

Step	Operation	Est duration (days)	Running duration
1	Attach GSE	2	2
2	Uncage gyroscope; watch motion	1	3
3	Orient SV for caging gyros 1, 2	1 ✷	4
4	Cage gyros 1, 2.	1	5
5	Orient SV for caging gyros 3,4	1 ✷	6
6	Cage gyros 3,4	1	7
7	Prep for next activity	3	10
8	Margin (30%)	3	13

Estimated time needed for test: 13 days on critical path

✷ *Duration is a preliminary estimate*

2. GSE-based Lift Test

No Caging per PCB 477

- Description:
  - Uses DDC suspension to suspend gyros in probe.
  - Use the flight GSS to observe the motion of the gyroscope when it is uncaged and recaged; end-to-end test of caging system.
  - Interface requirements:
    - » Option 2A: Direct connect to top hat
      - Disassemble FEE, Disconnect other systems; Disconnect GSS.
      - Suspend with DDC.
      - Reconnect GSS, Reconnect other systems; Replace FEE.
    - » Option 2B: Tee-into GSS suspension cables.
      - Requires development of new splitter device, with integral switch (40 units).
      - Requires new ground test cable harness (1 per GSS) routed to edge of FEE.
      - Unknown impact to signal integrity between GSS and Tophat.

No Caging per PCB 477

- SV Operations:
  - Required reorientation of SV to re-cage gyroscopes.
  - Extensive FEE disassembly required for Option 2A.

2. GSE-based Lift Tradeoff Matrix

	Advantages	Disadvantages
Flight Config	• Gyro uncaging/recaging can be observed by the GSS. • <u>Option 2B: flight-like configuration</u>	• <u>Option 2A: breaks flight configuration of GSS, FEE (penalty test req'd)</u> • <u>Option 2B requires new flight hardware to be developed</u>
Potential for damage		• <u>Potential for gyroscope damage, greater than Payload Verification II testing.</u> • <u>Unknown vibration, EMI environment.</u>
Risk Retirement	• Verifies that gyro is free to move when uncaged. • <u>Verifies that gyro suspends and pendulates freely.</u>	• <u>Option 2A: Does not verify the proper connectivity of the flight GSS while suspended.</u> • <u>Does not verify gyroscope spin performance</u>
Program impacts		• <u>Option 2A requires extensive disassembly and reassembly of FEE and cabling; large schedule hit.</u> • <u>Option 2B requires development of new flight hardware; significant system architecture change. Current manpower levels insufficient to do the job.</u>

No Caging per PCB 477

(Deltas from previous test scenario are <u>underlined</u>)

2. GSE-based Lift Test Spans

No Caging per PCB 477

Step	Operation	Direct-connect to Top Hat (Option 2A)		T-connect to GSS Cables (Option 2B)	
		Est duration (days)	Running duration	Est duration (days)	Running duration
1	Attach GSE	2	2	2	2
2	Uncage gyroscope; watch motion	1	3	1	3
3	Remove FEE; attach DDC cables	11 ✥	14	0	3
4	Orient SV for suspension of gyros 1,2	1 ✸	15	1	4
5	Suspend gyro 1	1	16	1	5
6	Suspend gyro 2	1	17	1	6
7	Cage gyros 1, 2	1	18	1	7
8	Orient SV for suspension of gyros 3,4	1 ✸	19	1	8
9	Suspend gyro 3	1	20	1	9
10	Suspend gyro 4	1	21	1	10
11	Cage gyros 3,4	1	22	1	11
12	Reinstall FEE	21 ✥	43	0	11
13	Penalty tests	10	53	0	11
14	Prep for next activity	3	56	3	14
15	Margin (30%)	17	73	4	18

Only critical path schedule shown; does not include significant efforts required before these tests can be run

✸ *Duration is a preliminary estimate;* ✥ Updated 28 Oct 00

3. Suspend/Spin with GSE Test

No Caging per PCB 477

- Description:
  - Uses DDC suspension to suspend gyros in probe.
  - Spun up via GMA system/ECU to ~0.5 Hz.
  - Use the flight GSS to observe the motion of the gyroscope when it is uncaged and recaged; end-to-end test of caging system.
  - Interface requirements:
    - » Option 3A: Direct connect to top hat (see previous).
    - » Option 3B: Tee-into GSS suspension cables. (see previous).
    - » Significant external pumping equipment required for spinup gas.
- SV Operations:
  - Required reorientation of SV to re-cage gyroscopes.
  - GMA may require recharging when test is complete.
  - Extensive FEE disassembly required for Suspension Option 3A.
  - Attachment of external pumping apparatus needed for spinup gas.

3. Suspend/Spin with GSE Tradeoff Matrix

No Caging per PCB 477

No Caging per PCB 477

	Advantages	Disadvantages
Flight config	• Gyro uncaging/recaging can be observed by the GSS. • Option 3B: Flight-like configuration	• Option 3A: breaks flight configuration of GSS, FEE (penalty test req'd) • Requires external pumping equipment. • GSE requires recharging.
Potential for damage		• Potential for gyroscope damage, significantly greater than Payload Verification II testing. • Unknown vibration, EMI environment. • Additional chances for contamination of system via external pumping system.
Risk Retirement	• Verifies that gyro is free to move when uncaged. • Verifies that gyro suspends and spins freely.	• Option 3A: Does not verify the proper connectivity of the flight GSS while suspended.
Program impacts		• Option 2A requires extensive disassembly and reassembly of FEE; large schedule hit. • Option 2B requires development of new flight hardware. Current manpower levels insufficient to do the job. • Portable pumping system needs to be developed for off-site spinups.

3. GSE Lift + Spin: Test Span

No Caging per PCB 477

Step	Operation	Direct-connect to Top Hat (Option 3A)		T-connect to GSS Cables (Option 3B)	
		Est duration (days)	Running duration	Est duration (days)	Running duration
1	Attach GSE	2	2	2	2
2	Uncage gyroscope; watch motion	1	3	1	3
3	Remove FEE; attach DDC cables + pumps	11 ❖	14	5	8
4	Orient SV for suspension of gyros 1,2	1 ✸	15	1	9
5	Suspend gyro 1	1	16	1	10
6	Spin gyro 1	2	18	2	12
7	Suspend gyro 2	1	19	1	13
8	Spin gyro 2	2	21	2	15
9	cage gyros 1,2	1	22	1	16
10	Orient SV for suspension of gyros 3,4	1 ✸	23	1	17
11	Suspend gyro 3	1	24	1	18
12	Spin gyro 3	2	26	2	20
13	Suspend gyro 4	1	27	1	21
14	Spin gyro 4	2	29	2	23
15	cage gyros 3,4	1	30	1	24
16	Reinstall FEE; remove pumps.	21 ❖	51	5	29
17	Penalty tests	10	61	10	39
18	Prep for next activity	3	64	3	42
19	Margin (30%)	19	83	13	55

Only critical path schedule shown; does not include significant efforts required before these tests can be run

✸ *Duration is a preliminary estimate;* ❖ Updated 28 Oct 00

4. Suspension/spin with GSS Test

No Caging per PCB 477

- Description:
  - Uses GSS suspension to suspend gyros in probe.
  - Spun up via GMA system/ECU to ~0.5 Hz.
  - End-to-end test of caging system.
  - 100% Flight cabling.
  - Interface requirements:
    - » GSS requires significant testing to gain confidence in its operation on the probe with flight gyroscopes.
    - » Boost computer plugs into test port on aft GSS box. (required for better suspension performance).
    - » Requires some GSE hardware development.
    - » Additional external pumping equipment required for spinup gas.

No Caging per PCB 477

- SV Operations:
  - Required reorientation of SV to re-cage gyroscopes.
  - GMA may require recharging when test is complete.
  - Attachment of external pumping apparatus needed for spinup gas.

4. Lift/spin with GSS Test Tradeoff Matrix

	Advantages	Disadvantages
Flight config	• Flight configuration of GSS, SRE, ECU.	• Significant additional pumping capacity is needed to evacuate spinup gas. (spin option) • May require reconditioning of GMA system post-caging and post-spin.
Potential for damage		• Potential for gyroscope damage, significantly greater than Payload Verification II testing. • Possibility of damaging GSS, SQUIDs as well. • Suspension arcing may require the gyros to be flux flushed.
Risk Retirement	• Verifies that gyro is free to move when uncaged. • Verifies that gyro spins freely. • Verifies proper connectivity of GSS, parts of ECU, SRE.	
Program impacts		• Portable pumping system needs to be developed for off-site spinups (spin option) • Significant effort req'd to gain and develop GSE to confidence in GSS for suspensions in Probe C.

No Caging per PCB 477

4. GSS Lift/spin Test Span

No Caging per PCB 477

Step	Operation	Est duration (days)	Running duration
1	Attach GSE	2	2
2	Uncage gyroscope; watch motion	1	3
3	Install pumps	5	8
4	Orient SV for suspension of gyros 1,2	1 ✸	9
5	Suspend gyro 1	2	11
6	Suspend gyro 2	2	13
7	Cage gyros 1,2	1	14
8	Orient SV for suspension of gyros 3,4	1 ✸	15
9	Suspend gyro 3	2	17
10	Suspend gyro 4	2	19
11	Cage gyros 3,4	1	20
12	Remove pumps	5	25
13	Penalty tests	10	35
14	Prep for next activity	3	38
15	Margin (30%)	11	49

Only critical path schedule shown; does not include significant efforts required before these tests can be run

✸ *Duration is a preliminary estimate*

Test Options against Evaluation Criteria

No Caging per PCB 477

Test Option	Risk Abatement Ranking	Changes from Flight Configuration Ranking	Potential for damage Ranking	Schedule Impacts Ranking	Resource Impacts Ranking	Aggregate Score
1. Uncage/GSS voltage	3	1	1	2	1	8
0. Baseline	4	1	1	1	1	8
2B. Lift with GSE	2	3	2	3	3	13
4. Lift, spin with GSS	1	2	4	4	4	15
3B. Lift, spin with GSE	1	4	3	5	3	16
2A. Lift with GSE	2	5	2	6	2	17
3A. Lift, spin with GSE	1	6	3	7	2	19

Schedule/resource impacts not used in risk/benefit tradeoff

Interpretation of this table:

- **Each column ranks the relative merit of each test option for that column, 1 = "best". This is purely an ordered list from best to worst.**
- **Aggregate Score is the sum of the individual rankings with no weighting for absolute resource impacts or risk levels.**

Test Options against Risk/Benefit Tradeoff

No Caging per PCB 477

Test Option	Mission Benefits		Mission Risks			Benefit - Risk
	Risk Abatement Ranking	Estimate of Mission Risk Retired	Flight Config Changes Ranking	Potential for damage Ranking	Estimate of Additional Mission Risk	
1. Uncage only	3	0.25 %	1	1	0.10 %	+ 0.15%
0. Baseline	4	0	1	1	0	0
2B. Lift with GSE	2	0.35%	3	2	2.0 %	- 1.65%
3B. Lift, spin with GSE	1	0.40%	4	3	2.5 %	- 2.10%
2A. Lift with GSE	2	0.35%	5	2	4.0 %	- 3.65%
3A. Lift, spin with GSE	1	0.40%	6	3	5.0 %	- 4.60%
4. Lift, spin with GSS	1	0.40%	2	4	8.0 %	- 7.60%

Relative rankings of test options carried over from previous chart for reference.

Note: See next slide for notes on the interpretation of these data.

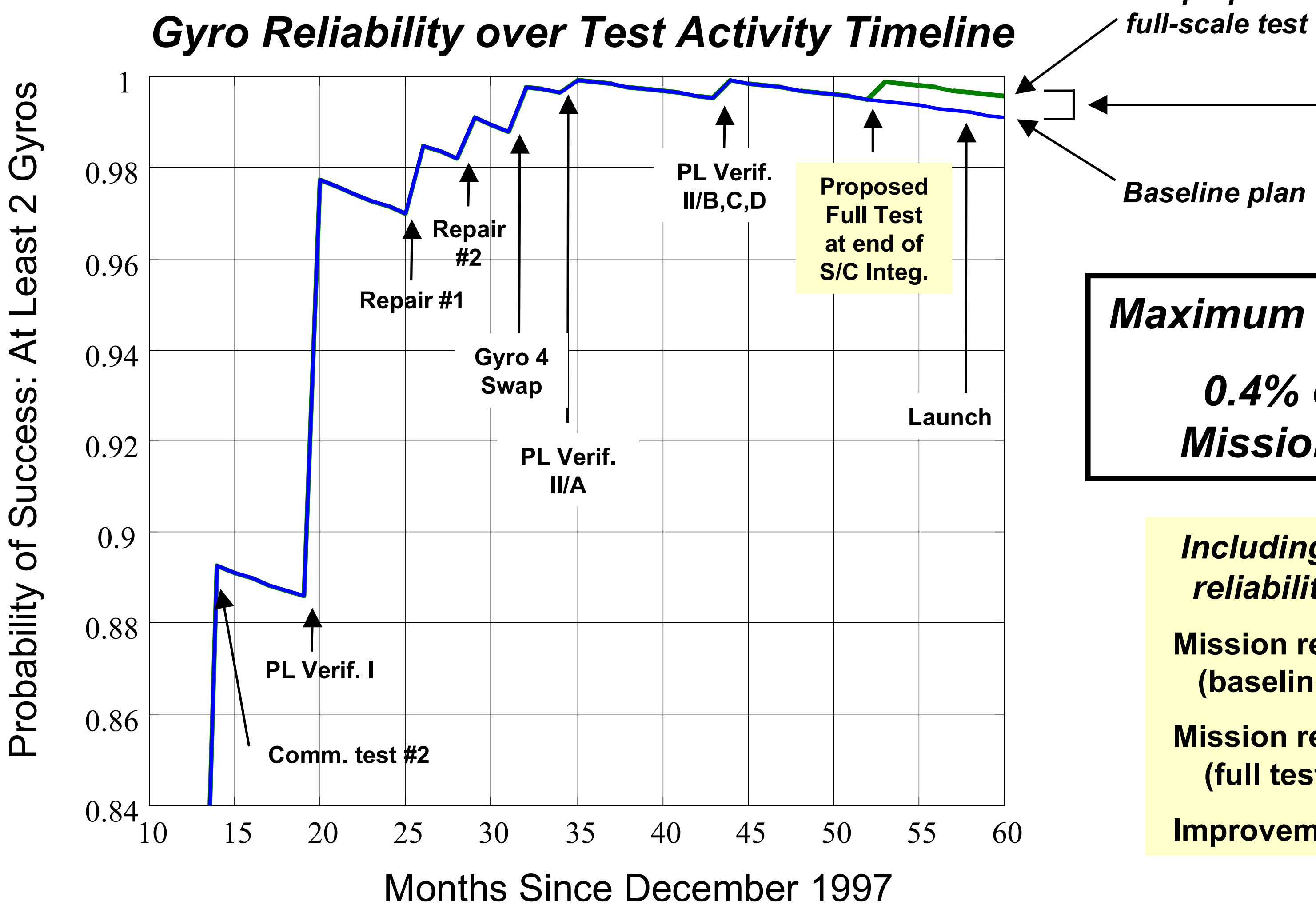
Risk/Benefit Comparison (continued)

- Notes on "Estimate of Mission Risk Retired" column:
  - Based on model of evolution of gyro reliability during the GP-B test program.
  - Best case risk mitigation 0.4% from additional gyro testing.
  - Suspension-only (2A, 2B) tests seen to be slightly inferior to suspension + spin tests (3A, 3B, 4).
  - The uncaging/on-orbit voltage test (1) retires about half the risk of the most perceptive tests (3A, 3B).

No Caging per PCB 477

- Notes on "Estimate of Additional Mission Risk" column:
  - Risk numbers shown are initial estimates.
  - Refinements are being generated based on FMECA-like analyses; currently in work.

Mission Risk Retirement by Late Gyro Test



Maximum risk retired:

0.4% of overall Mission Success

Including non-gyro reliability ≅ 0.964:

Mission rel. at launch (baseline) ≅ 0.957

Mission rel. at launch (full test) ≅ 0.961

Improvement ≅ 0.004

Source: Sam Pullen, GP-B

Test Option Evaluation - Summary

No Caging per PCB 477

- **Test 1 - Gyro uncaging/GSS spinup voltage test:**
  - Carries the only positive benefit on overall mission risk.
  - Requires moderate amount of work to implement and run.
  - Minimal effect on overall schedule.
  - Can be implemented with existing resources.
- **Tests 2B and 3B- GSE lift, spin with GSS cable splice box:**
  - Realizes the full benefit of late gyro testing, but with added risk to gyros, hardware.
  - Requires development of new flight hardware; 1 man-year effort.
  - Uses known GSE.
  - Can be tested in PL Verification II.
- **Tests 2A and 3A - GSE lift, spin by removing FEE**
  - Large schedule cost. SV post-test configuration extensively altered.
- **Tests 4 - GSS lift and/or Spin**
  - 1-2 man year required to qualify GSS for 1g suspension; not part of current plan.

Recommendations

Recommendation

No Caging per PCB 477

❶ Implement Uncaging/GSS voltage tests - Test Option 1

Benefits:

1. Net improvement in overall probability of mission success.
2. Test is run in flight configuration with 100% flight hardware.
3. 100% end-to-end test of the caging system.
4. Verifies proper GSS connectivity to probe.
5. Gyro, GSS, and probe is exposed to maximum on-orbit suspension voltages.
6. Partially verifies freedom from particulate and cryo contamination.

Costs:

1. Small addition to critical path schedule, 13 days estimated.
2. Procedure development; can be absorbed into current manpower plan.
3. Very low risk to gyroscopes, probe, GSS, SQUIDs