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GRAVITY PROBE B RELATIVITY MISSION

JUSTIFICATION FOR LAUNCHING WITH GYROSCOPES UNCAGED

S0522 Rev -

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1. Overview

The Gravity Probe B payload includes a caging mechanism which is designed to press the gyroscope rotor against its housing during launch. The goal is to keep the rotor from "rattling" back and forth inside the housing thus protecting it from potential damage due to rotor-housing collisions. This mechanism was included in the design even though there was substantial evidence that it was probably not necessary.[1] The science gyroscope system has been fully qualified to launch in the caged configuration.

This document outlines the justification for launching the gyroscopes in an uncaged configuration. The primary source of this justification is a set of 8 qual-level gyroscope shake tests in an uncaged configuration, all of which indicated that the gyroscope was suitable for use on orbit after the shake. Several of these shakes were performed to levels far in excess of a standard qual-level program. Also, the Payload Acoustic Test was performed with the gyroscopes in an uncaged configuration, so "test it like you fly it" further supports the argument that the gyroscopes should be launched in the uncaged configuration.

[1] See, for example, S0494 Vibration Test of the Gravity Probe B Gyroscope

2. Referenced Documents

The following Stanford GP-B Science Documents have been released and provide information in support of system qualification for launching in the uncaged configuration.

S-doc	Title
S0181	Stress Analysis of a Quartz Gyroscope Housing
S0211	Gyroscope Caging Mechanism Design
S0288A	GP-B Rotor Mass Unbalance and Difference in Moments of Inertia
S0289	GP-B Rotor Shape and Torque Coefficients
S0370	Validation of Rotor Asphericity Requirement 1.4, T003
S0487	RT vs. Cold Gyro Shake Analysis
S0488	Gyro Shake Pass/Fail Criteria
S0492	Justification for Performing Acoustic Test Uncaged
S0494	Vibration Test of the Gravity Probe B Gyroscope (Thesis 10/89)
S0498	Justification for Gyro Shake Test Configuration
S0499	Justification for Gyro Shake Test Levels
S0521	Summary Report of Uncaged GP-B Gyroscope Shake Testing
S0522	Justification for Launching Uncaged
S0525	Effect of Uncaged Launch on Science Data
S0561	Summary of Uncaged GP-B Gyroscope Shake Testing in the Shuttle Test Unit
S0562	Uncaged GP-B Gyro Shake Testing during Retention Hardware Development
S0563	Report on the Shake Test of FQH51 October 17, 2000
S0566	Summary of Preliminary Shake Tests in the Gyroscope Shake Test Facility (February – March 2001)

The following Lockheed Engineering Memoranda have been released and provide information in support of system qualification for launching in the uncaged configuration.

Document #	Title
SMS 214B	Spacecraft Launch and Operational Loads
SMS 233	ARP Pre-MECO Loads Analysis
SMS 260A	Dynamic Loads Model, Coupled Loads Analysis #2
SMS 304	Evaluation of Coupled Loads Analysis Results
SMS 349	Evaluation of PreMECO & MECO Loads Analysis Results
SMS 370	Integrated Payload Acoustic Test Plan
SMS 375	Shocklog Record of Test Gyro Transportation
SMS 377	Pathfinder Environment for Palo Alto to Sunnyvale Transportation

The following documents provide additional information in support of system qualification for launching in the uncaged configuration.

- *Delta II Payload Planners Guide*. This document is in the public domain and can be downloaded electronically at http://www.boeing.com/defense-space/space/delta/delta2/guide/index.html.

- *MDC Letter A3*-Y935-EDAO-98-080 (11 December 1998). This is Boeing's analysis detailing the environment GP-B can expect during MECO. They used Boeing's Finite Element Model of GP-B to generate accelerations at every degree of freedom of the model.

- Data from the Spacecraft Loads and Acoustic Measurement (SLAM) spacecraft, which launched August 25, 1997 on a Delta II to measure the vibration environment. Electronic copies of the data are available at http://analyst.gsfc.nasa.gov/slam. These plots have been supplemented by Matlab files containing the actual measured SLAM data, compliments of the SLAM program, Goddard Space Flight Center, and Marshall Space Flight Center.

3. Background

3.1 The Gyroscope

Figure 1 is a drawing of the GP-B gyroscope. The gyroscope rotor is a quartz or Silicon sphere with a Niobium coating sputtered on it (all rotors currently in the science mission probe have a quartz substrate). The rotor resides within the spherical inner cavity of a quartz housing. Three pairs of orthogonal electrodes are sputtered onto the housing so that the rotor can be electrostatically levitated. Helium gas flows through a spinup channel to spin the rotor to its full operational speed of approximately 100 Hz. One of the housing halves (designated the Readout or R-Half) has a pickup loop on the parting plane that is used to detect the rotor's spin axis during the science mission. The other half of the housing, which contains the spinup channel, is designated the S-Half.

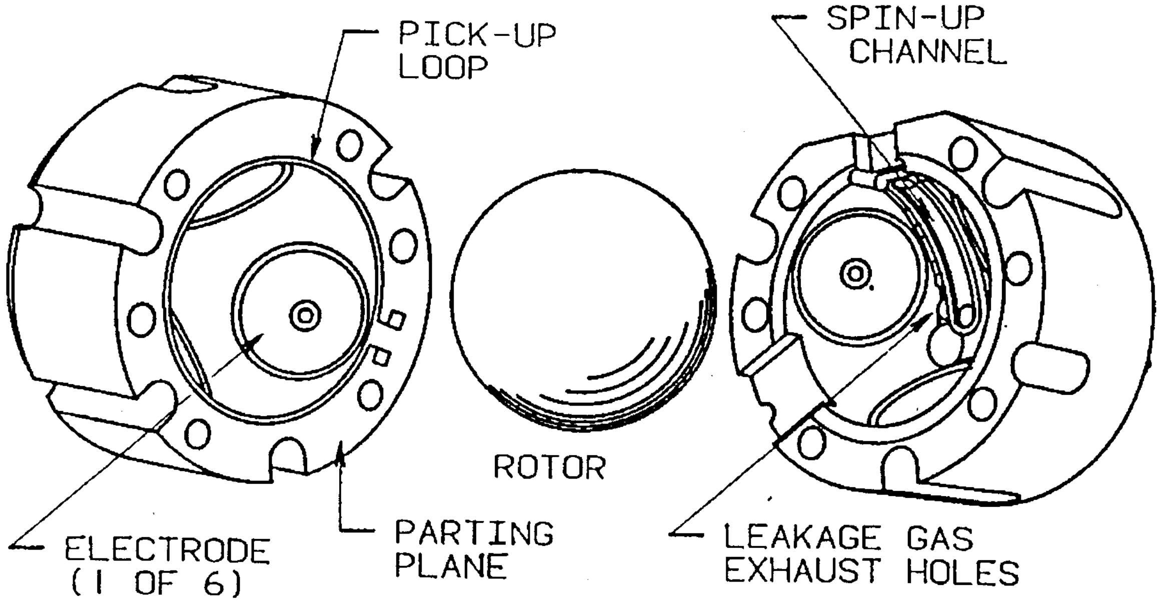

Figure 1: The GP-B Gyroscope

In the nominal flight configuration a cylindrical caging rod enters the cavity through a hole in the R-Half of the housing and presses the rotor against the S-Half, firmly caging it for launch. This rod is actuated via a bellows that is pressurized with Helium gas. However, there are significant problems with the Helium supply lines that feed this caging actuation system for three of the four gyroscopes in the GP-B Payload. This leaves the sphere free to move in response to launch accelerations. Note that the rotor-housing clearance is very small, so that the rotor can move at most 39 μm (1.5 milli-inches) from one side of the housing to the other. Although this tiny space allows very little differential velocity to build up between the rotor and its housing, there is still a question as to whether it is possible that the gyroscope housing or rotor coatings could nevertheless become damaged due to rotor-housing impacts.

The Gravity Probe B gyroscopes have been fully qualified to launch in the caged configuration. This document establishes their suitability for launching in an uncaged configuration.

3.2 The Payload

Although one gyroscope is sufficient to perform the relativity measurement, the GP-B design contains four gyroscope assemblies for redundancy. These gyroscopes are mated to a quartz index plate / spacer assembly, which is in turn mated to a quartz block (shown in Figure 2). Bonded to the quartz block is a telescope that points towards the guide star, which provides the inertial reference for GP-B.

When levitated and spinning, the superconducting gyroscope creates a magnetic field called the London Moment, which is aligned with the spin axis. Therefore measuring the direction of the London Moment is equivalent to measuring the direction of the gyroscope's spin axis. This is accomplished using ultra-sensitive superconducting magnetometers called SQUIDs (Superconducting Quantum Interference Devices).

The Quartz Block Assembly (including gyroscopes), the SQUID magnetometers, and miscellaneous supporting hardware together comprise the Science Instrument Assembly (SIA). The SIA is mounted in a cryogenic probe that is evacuated and then inserted in a dewar filled with superfluid liquid Helium to create the integrated GP-B payload. Thus the GP-B gyroscopes operate in a cryogenic vacuum environment.

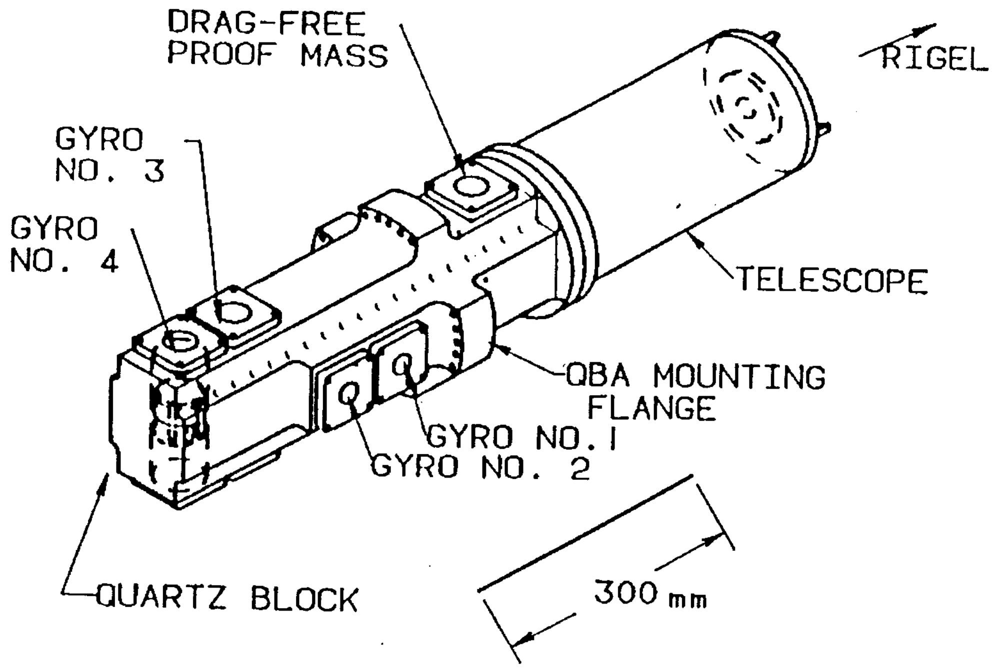

Figure 2: The Quartz Block Assembly

3.3 The Gyroscope Caging Lands

The gyroscope housing contains approximately 40 rotor support lands that serve as "bumpers" to protect the sensitive housing coatings from rotor impacts. GP-B drawings 23167 and 23168 detail the location of all support lands on the gyroscope housing. Physically, these support lands are arcs of metallic coating which are sputtered around the electrodes and spinup channel so as to keep them from being damaged by an impacting rotor. They consist of a Titanium-Copper-Titanium trilayer with an average thickness of 550 microinches. The two Titanium layers are very thin (only 25 microinches each) so that overall the support land responds to stress and impact forces like a thin piece of copper. Figure 3 is a drawing of the R-Half of the gyroscope housing with 1 of the 21 support lands on that half specifically pointed out for reference. Note that the hole in the center of the housing in Figure 3 is where the caging rod enters the housing.

Three of the support lands on the S-Half of the housing happen to be in a location where the rotor touches them when it is fully caged. These are called the caging support lands. However, physically there is no difference between the caging support lands and the multitude of other rotor support lands in the housing. Inspection of drawings 23167 and 23168 indicates that all lands are identical in composition and height.

When launching a gyroscope uncaged, the rotor will sit in one of the two positions indicated in S0499. This means that the rotor will be resting against a different set of support lands than those that were designated for caging. During the ascent to orbit, the quasistatic component of the acceleration will press the rotor against these lands, providing an effective caging force for the rotor. Since the quasistatic component of the acceleration is only about 8% of the nominal caging force and the rotor is being pressed against support lands of identical composition to the caging lands, it is clear that launching in this configuration holds no problem from a quasistatic point of view. This is examined in more detail in S0499. The primary concern involves what happens when the dynamic component of the housing acceleration overcomes the quasistatic component so that rotor-housing impacts occur.

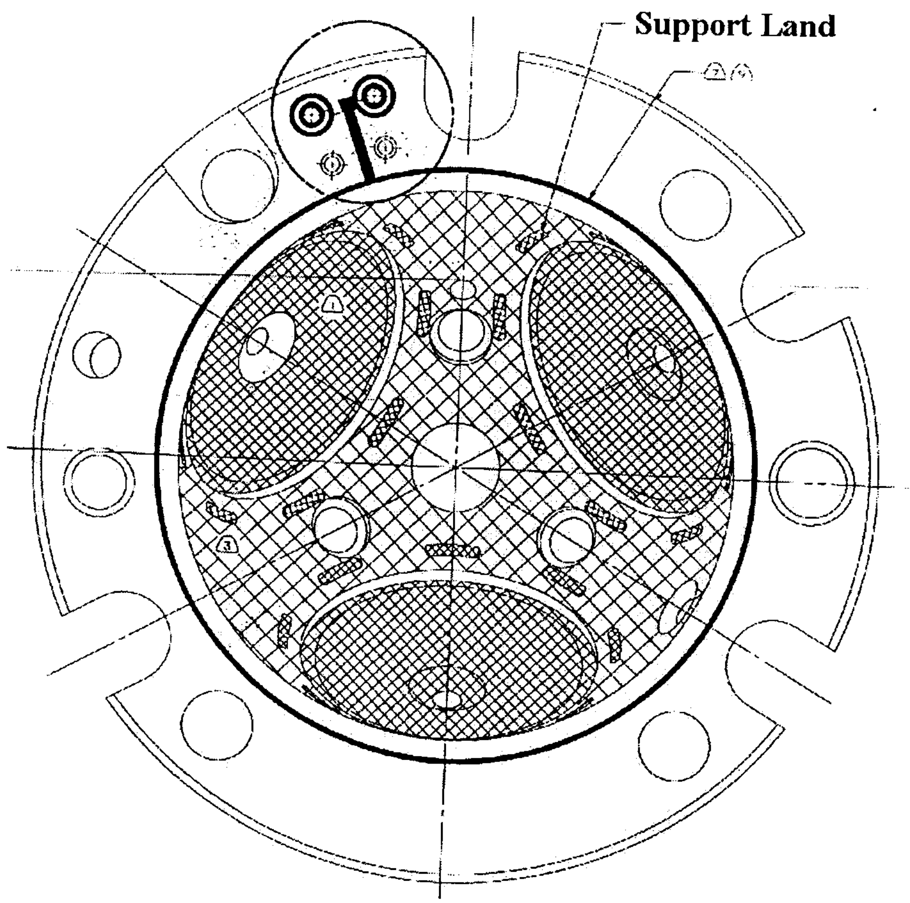

Figure 3: Rotor Support Lands (R-Half Shown)

3. The Change in System Configuration

Launching uncaged entails three changes to the system configuration:

(a) The caging lines are evacuated instead of pressurized.

(b) The tip of the caging assembly (which in nominal operation is pressed against the rotor's surface) is retracted from the inner cavity of the gyroscope housing.

(c) The rotor is constrained only by the boundaries of the housing inner cavity and is free to "rattle" in response to launch vibrations.

Of these three differences, only the last holds any tenable damage or failure mechanism for the experiment, however all three shall be addressed in this document.

4. Potential Failure Modes and Damage Mechanisms

This section and the next section summarize the results of S0499 Justification for Gyroscope Shake Test Levels. In a few cases, the scope is broadened somewhat past the S0499 discussion to include all system-level aspects of launching in the uncaged configuration.

4.1 The Caging Line (including caging line plug + leak)

As stated above, when launching uncaged the caging line is evacuated instead of being pressurized. From this fact alone, there is really no credible failure mode. The tube was designed to fly with over 10 atmospheres pressure of Helium gas in the line, so the pressure delta across the line is decreased substantially when flying in the uncaged configuration. This effectively increases the margin of safety for the line by approximately a factor of 10.

There are also several anomalies in the current construction of the caging lines, associated with several caging-related Discrepancy Reports (DR's). Each will be discussed briefly to assess whether it can be associated with some reasonable failure or damage mode for the system.

1. There is a leak from the Gyro 3/4 circuit into the vacuum can. The line was evacuated of all Helium gas, and any air that leaked into the line has been turned into ice by the cryogenic temperatures. Therefore this is a leak between two vacuum regions, and it therefore has no impact on the system.

2. There is an ice plug in the Gyro 3/4 circuit that is obstructing the line. This opens up the question as to whether the ice could warm up at some point in the mission, either creating enough pressure to cage the gyroscope or leaking gas into the vacuum can through the leak described above and thereby introducing unwanted torques during the science mission. This would be a concern, except that tests indicate that the location of the ice plug is deep inside the dewar, at a location where the nominal operating temperature is less than 10 Kelvin. There are two redundant caging paths to the circuit which are united at the 10 Kelvin location. These lines were shown to be clear by flowing gas down through one path and observing it flow back up the other, localizing the plug to somewhere below the union and therefore colder than 10 Kelvin. This temperature will not change in any appreciable way until well after all the Helium in the dewar has evaporated away. Therefore there is no chance the plug will warm up within the lifetime of the mission, and it is not associated with any credible failure mode.

3. The Gyro 2 caging circuit has a substantial leak into the well (note that there is no ice clog in the Gyro 2 circuit). Since both caging line and well are evacuated, there is no credible failure mode associated with this.

The conclusion of this investigation is that there is no credible failure mode associated with the change in configuration to the caging line (from pressurized to 10 atmospheres to evacuated). The system went through the Payload Acoustic Test in this configuration with no ill effects.

4.2 The Caging Actuator Assembly

The caging tip is retracted when launching in the uncaged configuration. This leaves the metallic tip (which is less than ¼ inch in diameter and approximately 3/8 inch long) unconstrained. Its suitability to launch in this configuration has been shown by qualification testing, which will be addressed in future sections.

4.3 The Gyroscopes

The only substantial concern is related to whether or not caging is necessary to protect the gyroscope. There are three potential damage mechanisms for an uncaged rotor that must be addressed through qualification testing.

1. The quartz could fracture on either the housing or the sphere.

2. As the sphere scrapes against the rotor support lands, the top of the lands could create either a scratch or an indentation in the rotor coating. If the defect is bad enough, it could interfere with 1-g levitation. Enough defects could potentially interfere with the achievement of science-level performance from the rotor.

3. As the sphere scrapes against the rotor support lands, portions of the rotor support lands could rub off on the sphere, possibly interfering with one-g levitation. If enough material gets transferred, then it could potentially interfere with the science-level performance of the rotor.

The probability of any of these damage mechanisms occurring in flight (as discussed in more detail in S0499) depends on (1) the number of rotor-housing impacts, and (2) the momentum of the impacts. Because of the nonlinear nature of the gyroscope dynamics during an uncaged launch, it is not immediately obvious how to establish the details of a test program that will ensure the qualification gyroscope is subjected to the proper number and intensity of collisions. For this reason, it was necessary to create a detailed simulation that models rotor-housing collisions. This work was conducted in detail in S0499 in order to determine quantitative criteria for establishing whether a test was to a suitable qual-level environment.

Future sections will summarize the results of numerous gyroscope shake tests to at least qualification levels (and often substantially above qualification levels) which have proven that none of these damage mechanisms will occur when launching a gyroscope in the uncaged configuration.

5. Analysis Summary

As detailed in Section 2, there have been 18 Stanford S-documents released containing analysis or reports related to launching in the uncaged configuration. The results of three of the most important documents will be summarized here.

5.1 S0499 Justification for Shake Test Levels

The primary analysis document related to this question is S0499 "Justification for Shake Test Levels". This document performed the following:

1. Examined gyroscope damage mechanisms and established a set of quantitative criteria for evaluating the severity of a test environment with respect to launch.

2. Performed an in-depth analysis of all phases of the ascent to orbit, ground transportation, and ground testing to establish in a quantitative manner the environment to which the flight gyroscopes will be exposed.

3. Analyzed various ground testing environments to establish their effect on the gyroscope and compared those quantitatively to what the flight gyroscopes will see. This allowed the establishment of a set of criteria which a qualification environment should meet.

One important result of this analysis is that rotor-housing impact velocities during transportation, ground test, and launch are fundamentally small. The maximum impact velocity expected during launch is 4.3 cm/s (0.14 ft/s). The reason why this velocity is so tiny is that the rotor-housing separation is so small, and the rotor only has 0.04 mm of space to accelerate across. This is the single most important factor in understanding the gyroscope's robustness to launching in the uncaged configuration: the rotor can never move fast enough to create damage.

5.2 S0525 Effect of Uncaged Launch on Science Data

This document did an in-depth analysis of a post-shake rotor and established that it still met science mission requirements. The rotor (from Qual Test #8 of the next section) was shook to levels far in excess of the minimum qualification level (i.e. an extreme over-test). Note that it was necessary to shake to these extreme levels in order to produce any features on the rotor that could be observed even with a microscope. Rotors shook to simple qual levels (e.g. Qual Tests #6 and #7) showed no observable effect on the rotor due to the shake. Therefore S0525 shows that even when the rotor is shaken to levels so extreme that microscopic imperfections in the coating become observable (levels in excess of even a qual environment), that there is no appreciable impact on science data.

5.3 S0487 RT vs. Cold Shake Analysis

This document examines the properties of the materials in the gyroscope to ascertain the relevance of room-temperature shake test data. The conclusion is that there is no large change in the important mechanical properties. In fact the materials in the gyroscope were specifically chosen so this would true so that various properties measured at room temperature (such as shape) would be valid at low temperature. The primary mechanical structure is quartz, which is one of the most stable materials known from 2 K to room temperature.

The conclusion is that shake tests performed at room temperature are valid for assessing the performance of a gyroscope at low temperature. Note that any uncertainty in this fact is more than bounded by the extreme over-test conditions of the room-temperature shakes reported in the next section.

6. Summary of Qualification Tests

A total of nine sets of shake tests of flight-like gyroscopes have been conducted. The table on the next page summarizes these and provides a pointer to the S-Document which contains a complete report. Tests 1-4 were on engineering unit gyroscopes. The primary materials and dimensions of these gyroscopes are the same as the final flight design. There are only trivial differences relating to the size and location of a few miscellaneous holes in the housing. Rotor dimensions are to flight specification.

Tests 5-9 were completed with gyroscopes that were manufactured as part of the flight batch and met all flight requirements. However, for the gyroscopes in tests 5-8 the readout loop did not superconduct (the loop was damaged by an ESD event prior to being chosen for the shake test). This loop is remote from the inside of the gyroscope housing cavity, and there is absolutely no way an impacting rotor inside the housing could affect this loop in any fashion whatsoever.

Test 9 was the flight acoustic test on the actual flight gyroscopes. Note that after this test all low-temperature sensitive properties were verified for the gyroscopes. This includes the functionality of the pickup loop and all superconducting-related phenomena such as trapped flux.

During the completion of these tests, (1-8), the gyroscopes were exposed to environments that were much more severe than a standard qualification test. Sequence #2, for example, had 103,918 times high-velocity impacts, whereas during launch only 3 are expected (and only 11,768 total). Even under these extreme conditions, the gyroscopes still survived the test_ meeting on-orbit requirements. These tests covered a variety of housings and rotors. This shows the gyroscope can survive launching uncaged with abundant margin.

Refer to the specific S-Documents referenced in the following page for a more complete description of each test.

SUMMARY OF UNCAGED GYROSCOPE SHAKE TESTS

#	Description	Date	Sdoc	Qz/Si	# of Impacts	Max Velocity	Number > 4 cm/s	Severity	I/P	Comment
--	LAUNCH	--	S0499	Quartz	11,768	4.3 cm/s	3	Flight	--	For comparison purposes
1	Haurani Thesis	10/89	S0494	Quartz	--	--	--	Qual	I	Impacts not estimated, but tests consisted of lateral + vertical sinusoidal shakes from 20-100 Hz and 1.4 – 4.25 g p-0.
2	Retention Hardware Shakes	05/92	S0562	Quartz	236,787	10.6 cm/s	103,918	Qual ++	I,P	Mini Quartz Block (Flight-like)
3	STU Shake #1	04/93	S0561	Quartz	42,273	8.8 cm/s	18,092	Qual +	I	Integrated space vehicle
4	STU Shake #2	08/94	S0561	Quartz	25,119	5.3 cm/s	2,028	Qual +	I,P	Integrated space vehicle
5	Shake of FQH51	10/00	S0563	Quartz	102,245	12.0 cm/s	32,714	Qual ++	I	Flight-design gyro
6	Shake #1 in Integrated Gyro Shake Facility	01/01	S0566	Quartz	12,576	6.8 cm/s	2,365	Qual	I	Flight-design gyro
7	Shake #2 in Integrated Gyro Shake Facility	01/01	S0566	Quartz	12,576	6.8 cm/s	2,365	Qual	I	Flight-design gyro
8	Shake #3 in Integrated Gyro Shake Facility	02/01	S0521	Silicon	39,422	6.8 cm/s	11,756	Qual +	I,P	Flight-design gyro
9	FLIGHT Gyros in Acoustic Test	03/01	S0499	Quartz	6,118	3.8 cm/s	0	Flight -	I,P	

7. Risk Assessment for Launching Uncaged

7.1 The Caging Line

Based on the discussion in Section 4, the caging line flying unpressurized contributes no incremental risk to the program. Note that it does remove the potential of not being able to *uncage* on orbit. Therefore launching in an uncaged configuration eliminates risks due to GMA caging valve failures or the caging line becoming clogged after the final cage.

7.2 The Caging Actuator Assembly

Tests 6-9 in the qualification test plan were conducted with flight-like caging assemblies in the uncaged configuration. Therefore those qualification tests are appropriate to assess the ability of the caging actuator assembly to fly unpressurized. In all cases, there was no damage to the caging actuator assembly. Therefore this contributes no incremental risk to the program.

7.3 The Gyroscope

Based on the abundance of qualification test data, there is no indication that on-orbit performance of the gyroscope will be influenced in any way if launching in an uncaged configuration. In fact, tests 6 and 7 (which were to normal qual level) indicated no indication whatsoever in post-shake inspection that the gyroscope had been shook. When the test was escalated to "torture test" levels (e.g. Tests 2, 5, and 8), then there was some microscopic indentations on the rotor coating from the rotor impacts on the support lands. However, these microscopic indentations do not interfere in any way with the on-orbit performance of the gyroscope (as evidenced in S0525), and they were only observed in cases where the rotor was exposed to literally tens of thousands of times more high-velocity impacts than the flight gyroscopes will actually see. Therefore the result of the qualification test program is that gyroscopes incur no additional risk due to launching in the uncaged configuration.

7.4 Low-Temperature Considerations

Most of the gyroscope shake tests occurred at room temperature, whereas the flight gyroscopes will launch at low temperature. S0487 indicates that based on only minor changes in materials properties of the particular materials in the gyroscope, a room temperature test is an appropriate indication of flight gyro launch survivability. Furthermore, the four gyroscopes in the payload survived the Payload Acoustic Test in a cryogenic environment. Although this test was not to full launch levels, the maximum impact velocity of 3.8 cm/s was 88% the 4.3 cm/s maximum expected launch impact velocity. Therefore this was still a very significant test, and gives high confidence that gyroscopes can launch uncaged in a cryogenic environment. Finally, the huge levels of margin with which the room-temperature shakes were conducted easily bounds any uncertainty in the change in materials properties at low temperature.

7.5 Gyroscope Charging

The qualification testing program determined that gyroscopes had a greater tendency to charge in one-g levitation after a shake test. This is due to the microscopic indentations on the rotor coating which can occur at the highest impact velocities. S0513 analyzes this effect in detail, and concludes that due to the low voltages required for on-orbit levitation, gyroscope charging will be attenuated by a factor of 10^{20} on orbit, far past the point of being completely negligible. Gyroscope charging is only a ground testing issue, based on the very high voltages needed to keep a rotor levitated in one-g.

8. Conclusions

Based on the 9 separate tests, which were conducted to determine whether gyroscopes could be launched in an uncaged configuration, it is proven that this will not incur additional risk to the program. The fundamental reason for this is that the rotor-housing spacing is so small (0.04 mm) that the rotor can not build up any appreciable velocity relative to the housing.

Launching in an uncaged configuration does eliminate some significant program risks. For instance, it removes the risk that uncaging on orbit will be unsuccessful due to the failure of a GMA valve or the caging line becoming clogged after the gyroscope is caged.

Finally, since the Payload Acoustic Test was performed with the gyroscopes uncaged, the "test it like you fly it" philosophy further strengthens the arguments that the GP-B gyroscopes should be launched in the uncaged configuration.

Based on all these reasons, it is concluded that the GP-B gyroscopes should be launched uncaged.