Space Station Control Moment Gyroscope Lessons Learned

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Abstract

Four 4760 Nms (3510 ft-lbf-s) Double Gimbal Control Moment Gyroscopes (DGCMG) with unlimited gimbal freedom about each axis were adopted by the International Space Station (ISS) Program as the non-propulsive solution for continuous attitude control. These CMGs with a life expectancy of approximately 10 years contain a flywheel spinning at 691 rad/s (6600 rpm) and can produce an output torque of 258 Nm (190 ft-lbf)[1]. One CMG unexpectedly failed after approximately 1.3 years and one developed anomalous behavior after approximately six years. Both units were returned to earth for failure investigation.

This paper describes the Space Station Double Gimbal Control Moment Gyroscope design, on-orbit telemetry signatures and a summary of the results of both failure investigations. The lessons learned from these combined sources have lead to improvements in the design that will provide CMGs with greater reliability to assure the success of the Space Station. These lessons learned and design improvements are not only applicable to CMGs but can be applied to spacecraft mechanisms in general.

Introduction [2]

The International Space Station (ISS) is currently the largest man-made object to ever orbit the Earth and represents one of the greatest engineering and integration efforts the National Aeronautics and Space Administration (NASA) has ever undertaken. The Guidance, Navigation, and Control (GN&C) system is composed of both a US non-propulsive attitude control system and a Russian thruster attitude control system. Nominal operations are conducted under US control using its four Control Moment Gyroscopes (CMGs), shown in Figure 1, with the Russian system providing momentum desaturation through thruster assists. When configured for completely non-propulsive control, the CMGs provide the ISS with the micro-gravity environment that is required for science payloads.

The US GN&C system uses a one-, two-, or three-axis Torque Equilibrium Attitude (TEA) seeking controller to minimize the amount of momentum required to maintain attitude control. Due to thermal issues with external components, several of the assembly stages require a biased attitude to minimize sun exposure to specific surface regions. Analysis of the momentum necessary to maintain the required attitude envelope has shown that the momentum of four CMGs is required for much of the assembly phase.

This paper describes the configuration of the ISS CMGs, their operations, a description of CMG1's "hard" bearing failure after approximately 1.3 years of operation. Included also are the findings for CMG3's "soft failure" that led to its removal from service and the corresponding most probable causes and lessons learned.

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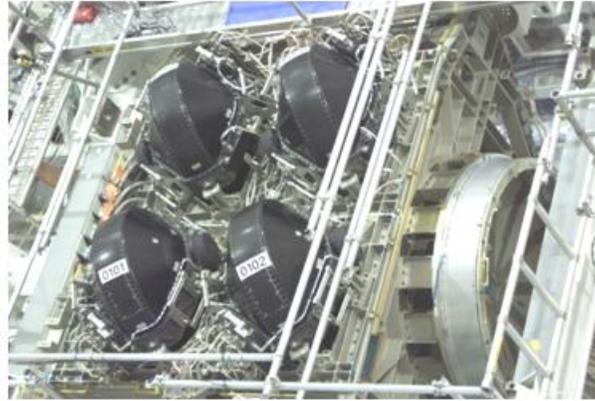
Figure 1. CMGs 1-4 Mounted on Z1 Truss

Space Station Z1/CMG Configuration[2]

The four CMGs operate as momentum storage devices that exchange momentum with the ISS through induced gyroscopic torques. These torques are created by a motor-driven constant-speed momentum flywheel mounted inside two orthogonal gimbals. Both gimbals have torquer motors and position resolvers mounted on the rotational axis and move by use of a gear train system. The momentum flywheel is mounted inside the inner gimbal and is supported by bearings mounted on each side of the flywheel. This configuration is shown in Figure 2. Double Gimbal CMGs were selected for the ISS because of the spherical momentum envelope. The control law is heuristic with no singularities and should the active number of CMGs change, the entire momentum envelope varies in proportion to the initial momentum sphere.[3]
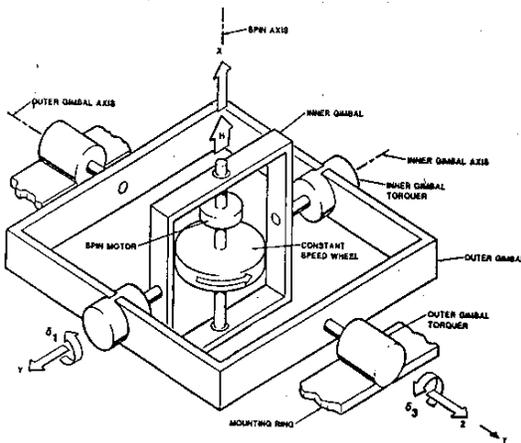
Figure 2. CMG Gimbal and Flywheel Assembly
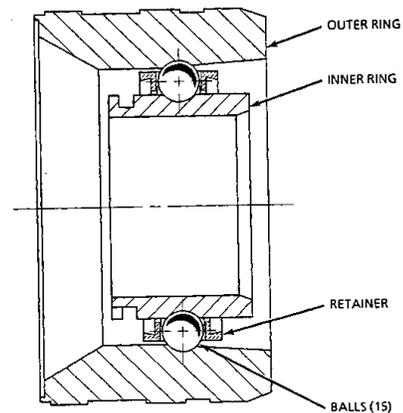
Figure 3. CMG Spin Bearing Assembly

The flywheel is mounted on two spin bearings, one on the Spin Motor (SM) side, and one on the Hall Resolver (HR) side. The Spin Motor is a low torque motor mounted on the spin axis with a control loop to maintain the commanded wheel-speed. The Hall Resolver provides digital wheel-speeds for downlinking via telemetry. The Spin Motor Command Current (SMCC) ranges from 0 to 1.6 Amps and nominally averages 0.37 Amps. The SMCC varies due to viscosity changes in the spin bearing lubricant caused by thermal variations and high gimbal rates that induce radial loads on the spin bearings. The SMCC is used as an indicator of spin bearing health and status.

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An accelerometer is mounted to the inner gimbal of each CMG to monitor flywheel unbalance. The accelerometer signal is filtered to a bandwidth of 20 to 120 Hz to eliminate frequencies/disturbances not associated with the flywheel unbalance frequency.

The Spin Bearings, shown in Figure 3, are single angular-contact ball bearings with modified inner and outer races. There are 15 steel balls mounted in a retainer to maintain consistent ball motion. The spin bearings are lubricated with KG80, a super refined mineral oil, in an active oiler system. Pairs of cartridge heaters mounted near the outer race of each bearing are provided to maintian the lubricant above the pour point temperature and in the range of 15.6^{o}C to 26.7^{o}C (60°F to 80°F) during cold orbital conditions.

Space Station Operational History

ISS Assembly

Assembly of the ISS began in November, 1998, with the first Russian component, the Functional Cargo Block. Since then, the ISS has expanded with the addition of many sections, several of which are of international origin. Major components include Node 1 (a connector module), the Russian Service Module, the Z1 Truss, the US Laboratory Module, a Canadian robotic arm, the Integrated Truss Structure with eleven segments, four sets of solar arrays, Node 2, the European Space Agency Columbus module, and the Japanese Experiment Module. Node 3 will be added in early 2010. Russian components were transported via their own launch vehicles. All other components were carried into orbit using the US Shuttle Transportation System (STS). The ISS has been permanently inhabited by international crews since October, 2000.

Figure 4. International Space Station, Present Configuration

To date, the ISS has flown in three different orbital attitudes:
- *X Body Axis on the Velocity Vector (±XVV),* also referred to as Local Vertical, Local Horizontal (LVLH). The ISS design is optimized for this attitude for microgravity, altitude re-boosts, and vehicle dockings, hence this is the primary flight attitude. Normally the +XVV attitude is flown, but during docked Space Shuttle missions, the attitude is changed to –XVV to allow for the Space Shuttle to not be in the forward velocity direction to avoid the potential for micro-meteorite debris.
- *X-Principle Axis Perpendicular to the Orbit Plane (±X-POP)* was utilized during early Space Station construction since full solar array capability was not achieved until Flight 12A. During certain solar beta angles, ISS would be maneuvered to this attitude to allow the existing solar arrays to point more directly to the sun.
- *Y Body Axis on the Velocity Vector (± YVV)* is a similar but alternate attitude from the ±XVV attitude. During YVV, the Space Station is rotated 90 degrees from the typical ±XVV attitude. This attitude was

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useful during early construction when full solar array capability was unavailable, but due to other constraints, it was not desirable to operate at the higher temperature X-POP attitude.

Since assembly Flight 12A in September 2006, the ±YVV and ±X-POP attitudes are no longer used, although in future unique situations, they may be used as contingency attitudes.

GN&C Operational CMG Usage
Prior to CMG activation, the ISS attitude control was accomplished using thrusters. Thrusters are now used as a backup for CMG control, for large attitude maneuvers, or for translational control.

Nominal quiescent operations are handled by the CMGs using a concept known as momentum management. A Momentum Manager controller is designed to perform via the following two methods: (1) seeking the TEA by finding the attitude having the lowest momentum, and (2) maintaining a particular attitude by expending the appropriate amount of momentum to bias that attitude. Usually, controllers combine a TEA-seeker in one ISS body axis (pitch) with an attitude bias for the other two axes (yaw and roll).

GN&C software maintains a given attitude by commanding the CMG inner and outer gimbals to specific locations. This positions the individual momentum contributions from the CMG flywheel spin axes to provide a total momentum vector for vehicle control. External torque disturbances on the vehicle can be countered by moving the vector as appropriate.

If a disturbance torque imparts a momentum that is greater than the total combined control momentum, the CMGs 'saturate', having expended all available momentum to counter the disturbance. The controller commands thruster firings to 'desaturate' the CMGs, or unload the momentum to a specified value. The CMG gimbals are then re-positioned to attain a lower total momentum. A CMG desaturation happens quickly, and may result in rates of gimbal rotation that are substantially higher than those needed for quiescent operations having low or non-existent disturbance torques. The CMG desaturation function can be disabled, and attitude control is then handed completely over to the thrusters in the case of CMG momentum saturation.

CMG Operational History

The original four CMGs were launched on the Z-1 Truss, Mission STS-92, ISS Flight 3A, on October 11, 2000. They remained dormant and unpowered for a few months until being activated on February 12, 2001 during Space Station Flight 5A. On June 8, 2002, CMG1 developed a problem and failed resulting in 3 operational CMGs. Operations using a 3-CMG control configuration was required until a spare replaced the failed CMG1 on August 1, 2005 during Space Shuttle Flight LF-1. The ISS then continued to operate under 4-CMG control until CMG3 exhibited signs of distress. The initial CMG1 Failure Root Cause Investigation together with the CMG3 experience led to the development of on-orbit monitoring criteria intended to identify problems and prevent a hard failure. An additional benefit of implementing these criteria was to preserve the hardware for re-use and subsequent forensic analysis. On October 10, 2006 CMG3 was shut down because the unbalance sensor had reached the shut-down criterion. It was then taken out of service but remained on the Z1 Truss with the Electrical Assembly (EA) and heaters enabled, until it was removed on August 13, 2007. A 3-CMG control configuration was again implemented for attitude control. During CMG3's non-operational time period, various diagnostic tests were performed to support the joint L-3 S&N, Boeing, and NASA decision to remove and replace CMG3. This "soft failed" CMG was replaced by another ground spare on August 12, 2007 during Space Shuttle Flight 13A-1 and the ISS was restored to a 4-CMG control system.

The CMG1 investigation identified high gimbal rates as a contributor to the failure. During the earlier stages of ISS assembly, CMG gimbal angular velocity was restricted by CMG firmware to a maximum rate of 0.054 rad/s (3.1 deg/s). Following the two CMG failures, GN&C engineers limited all CMG gimbal

rates to 0.014 rad/s (0.8 deg/s) within the GN&C software. Acceleration was originally restricted only by the CMG firmware was similarly limited to 0.0007 rad/s^2 (0.04 deg/s^2) by the GN&C software. These limits were imposed with intent to potentially benefit CMG health, but still allow satisfactory vehicle attitude control.

CMG3 showed short periods of elevated accelerometer activity between the CMG1 failure and the CMG3 soft-failure. Concern over these signatures resulted in the implementation of several operational limitations intended to lower the gimbal angular rates of motion that were believed to be triggering the disturbances. The limitations included significant restrictions on attitude control methods that required nominal CMG momentum desaturations, limited values for the gimbal rotation rates used to manually positioning the CMGs (especially CMG3), and temporary cessation of use of the X-POP flight attitude. X-POP in particular was found to impart cyclical gimbal rates at an order of magnitude greater than the LVLH flight attitudes for quiescent operations

On-Orbit Failure Description and Signature[2]

<u>CMG1 "Hard" Spin Bearing Failure</u>
At the end of May 2002; the ISS was in a high solar beta X-POP period. The ISS attitude was transitioned from X-POP to LVLH on June 7th, several hours prior to shuttle docking. In order to accomplish this re-orientation and docking, large gimbal rates within design requirements were imparted to the CMG due to desaturations. Approximately 6 hours after the docking at ~23:00 on GMT Day 158, 2002, CMG1's Spin Motor Command Current (SMCC), the indicator of the combined bearing torques, started increasing over a 14-minute period. This increase in SMCC was later concluded to be the start of the failure. The increase in SMCC was caused by an increase in the Hall Resolver side bearing torque. This was confirmed by the increase in bearing temperature that indicated the Hall Resolver side bearing may be in distress. During the course of the next 15 hours, CMG1 showed signs of good and bad bearing performance, with the ultimate failure occurring at 14:57 on GMT Day 159, 2002. Several hours after docking, the flight control team noted a flag that indicated the accelerometer on CMG1 had measured 0.5 Gs. The rise in SMCC and associated Hall Resolver temperature was repeated twice during the next 16 hours. Then, following a 30-minute period with no ground communication, telemetry showed that the CMG1 SMCC was at its maximum value, 1.6 Amps, and the wheel-speed was decreasing. After several seconds of maximum current and wheel-speed reduction, Fault Detection and Isolation software declared the CMG failed and automatically shut down the Spin Motor. Normal shut down would result in the flywheel speed decelerating to 0 rad/s in approximately 12 hours. However, during this event, the flywheel stopped 72 minutes after Spin Motor shutdown because of the bearing failed condition. During this run-down period, the Hall Resolver bearing temperature exceeded the maximum telemetry value of 93$^°$C (199.4$^°$F) while the Spin Motor bearing temperature reached only ~30$^°$C (86$^°$F), indicating major distress in the Hall Resolver bearing. Data was retrieved from the on-board data recorders to fill in the missing telemetry for analysis purposes. The timeline of events is given with SMCC and spin bearing temperatures shown in Figure 5, Figure 6 and Figure 7. The CMG1 was later returned to L-3 for disassembly and formal failure investigation.
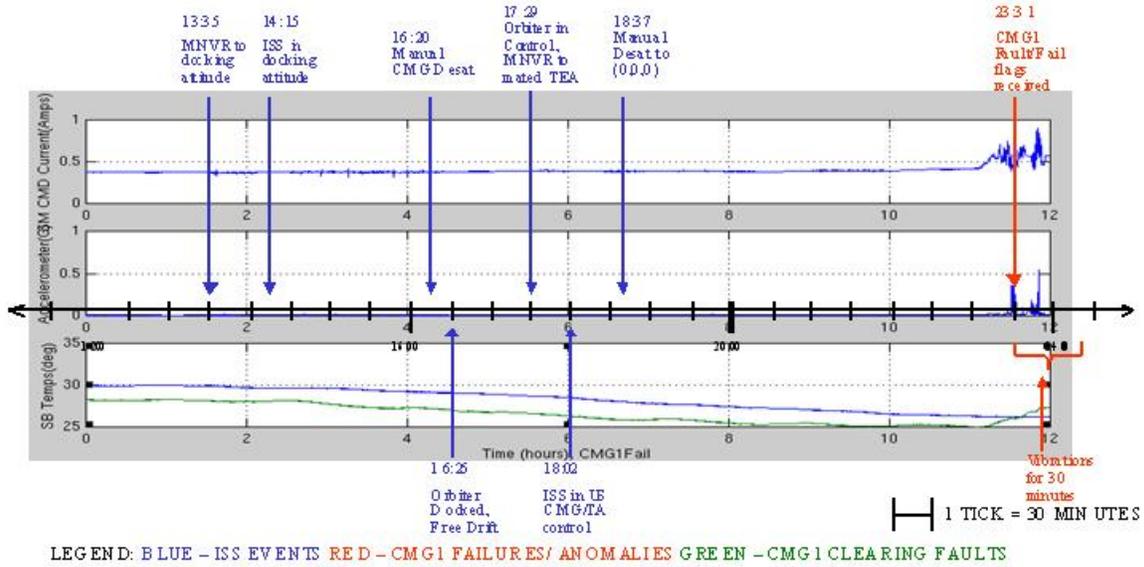
Figure 5. First Indication of Anomalous Behavior GMT 158/2002/12:00-24:00
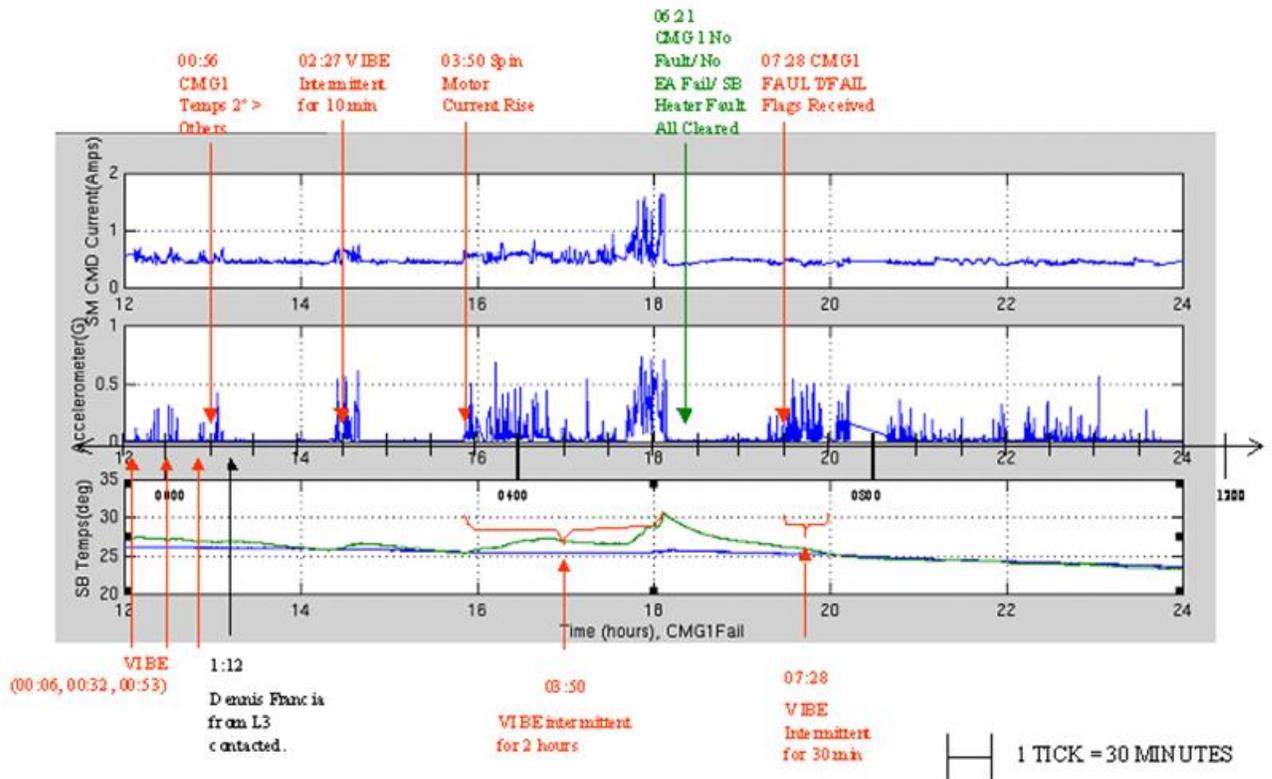
Figure 6. Erratic Behavior after Anomaly GMT 159/2002/00:00-12:00

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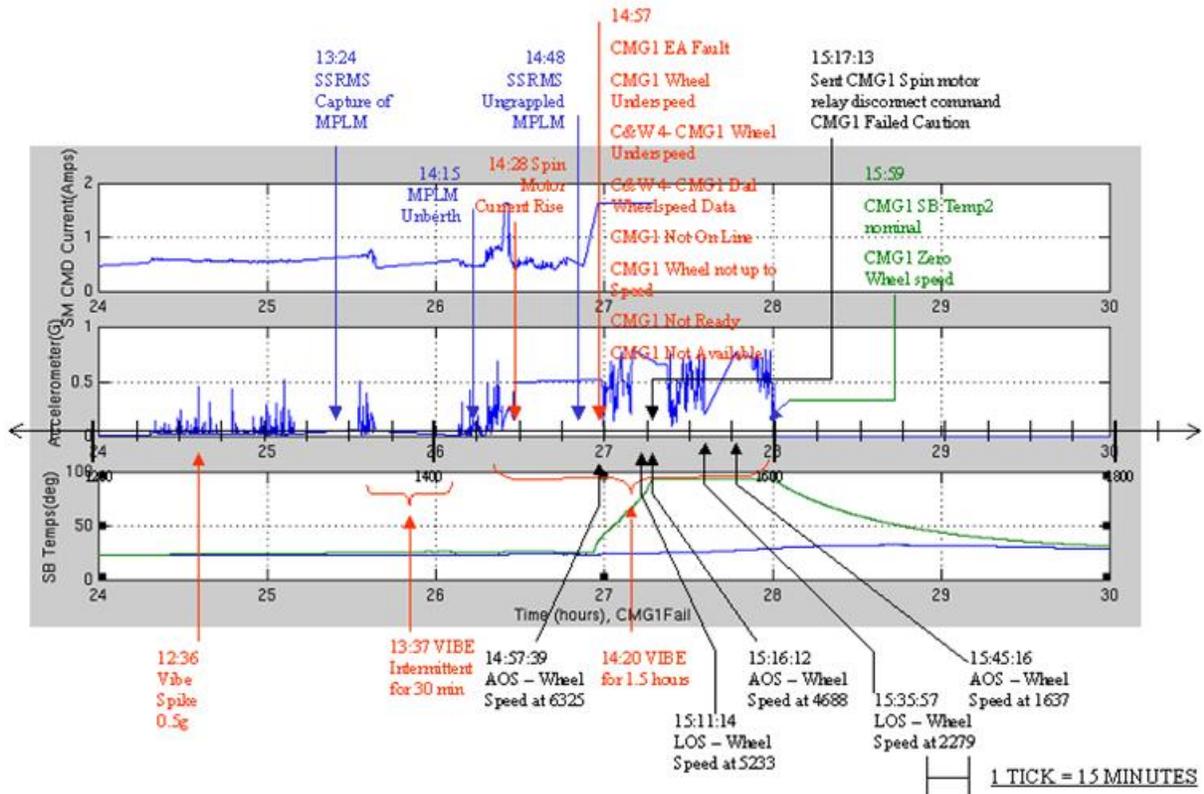
Figure 7. Hard Failure and Shutdown GMT 159/2002/12:00-18:00

CMG3 "Soft" Failure

CMG3 operated continuously at 691 rad/s (6600 rpm) from its activation on February 12, 2001 until the unbalance sensor level reached the criteria (0.2 g) for removal from the active steering law on Day 272, September 29, 2006. This occurred as the CMGs were being pre-positioned for Momentum Management startup in the XVV flight attitude. CMG3 was kept out of the steering law pending further analysis. Several times the unbalance sensor levels reached 0.2 g while the CMG was operational but not used to actively control the ISS. On Day 283, October 10, 2006, the unit was shut down because the unbalance sensor reached the shut down criteria of 0.4 g. Figure 8 shows the performance signatures and events that preceeded the shut down of CMG3. CMG3 was returned to L-3 Communications Corporation Space & Navigation (L-3 S&N) on March 11, 2008 for disassembly and a failure investigation.
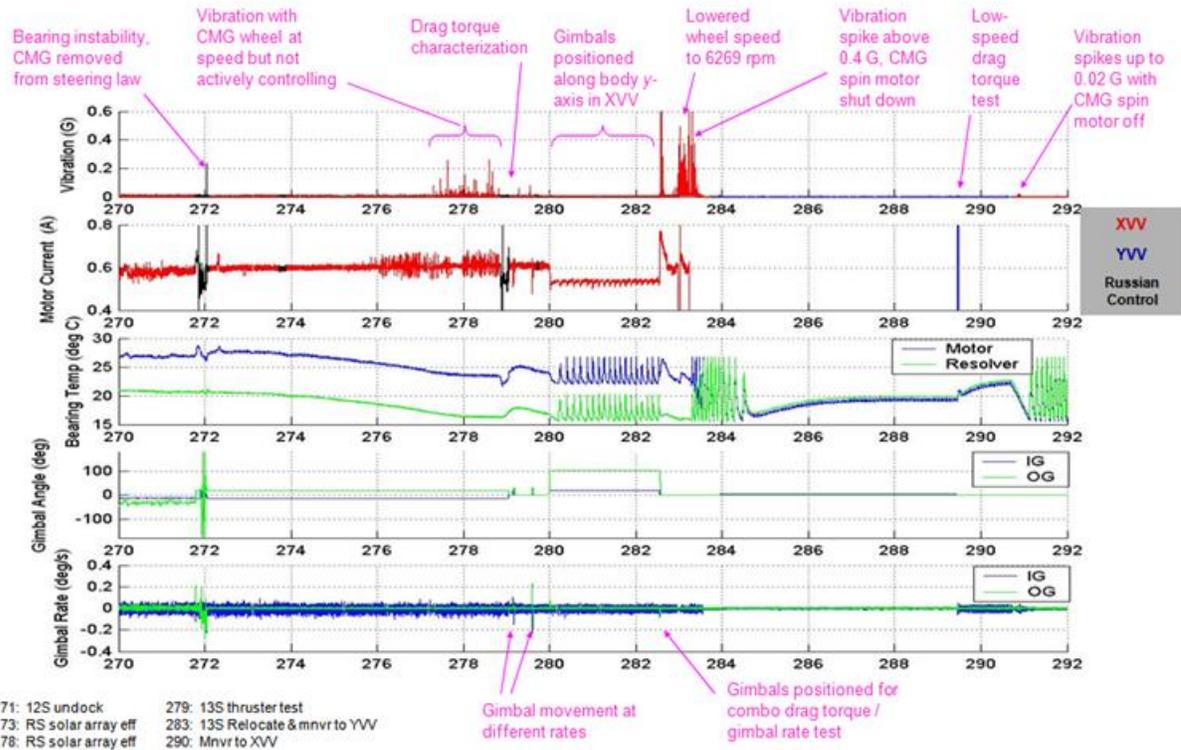
Figure 8. CMG3 Time Line to Shutdown

Forensic Findings

CMG1 Forensic Findings

The failure investigation confirmed that the HR spin bearing of CMG1 suffered a failure after 1.3 years of operation. This spin bearing was severely damaged and the rings were seperated. Exposure to high temperature was clearly evident. Verification testing of the active oiler system flowrate could not be performed due to the extensive damage from high temperature. The inner raceway contained a significant amount of smeared metal. A secondary raceway was generated when some of the balls were driven from the manufactured raceway and became wedged between the outer race land and inner race land on the load side of the inner race. Two balls were fused together with severe skidding damage at both the inner and outer race contact locations. The remaining 13 balls were of various size and shape. The inner race was seized to the flywheel shaft and required the machining of two axial slots for removal from the flywheel shaft. The outer raceway also contained smeared metal and was stuck in the bearing housing steel sleeve. The outer race was seized in the bearing cartridge steel sleeve and was also machined out using a similar technique. No damage was done to bore of the steel sleeve during the outer race removal process. The retainer was almost completely destroyed, with only two significant pieces remaining, showing that the cage appeared to split circumferentially down the center line. The two major fragments remaining each had portions of several ball pockets. A smaller segment containing several pads on which the cage is guided by the inner race land was also recovered. There was no obvious evidence that the cage had experienced unusual wear either within the ball pockets or at the pad-land interface.

The SM bearing survived the 72-minute deceleration period. Radial and axial control of the spinning mass was unconstrained by the failed bearing and the spinning flywheel coned about the SM bearing. However, radial constraint is provided by sequential gaps between the rotating mass and the stationary parts, i.e.,

the stator support labyrinth seal/flywheel shaft air gap. These features allow for a controlled fail safe deceleration.

The SM side bearing (non-failed side) was in good condition. Adequate lubrication was noted in the ball race contact zone and at the retainer pad and inner race land interface. The balls were bright with some wear tracks that are considered consistent with operation time. Except for one uneven wear track on the outer race, the wear tracks on both races are considered nominal for the operational time. A ring of degraded lubricant was noted on the inner race land, which is abnormal for the accumulated operating time. The retainer was not damaged and did not contain any evidence of unstable operation or distress. Inspection verified the location of the SM bearing wear tracks were consistent with CMG1's lifetime load conditions. Additionally, testing of the active oiler system verified that the lubricant flow was consistent with the presence of fresh oil in the bearing.

As the investigation continued, the evidence supported that a compromised bearing preload led to the failure. The following findings are evidence that the spin bearing preload system was compromised:

1. Some "fretting" type marks were observed on the steel sleeve of the SM bearing cartridge steel sleeve. The fretting marks were 180 degrees apart from the area on inboard section to the area on the outboard section, an indication of bore misalignemnt. If these conditions occurred before the failure, either during on earth acceptance testing or during operation, this misalignment would have affected the preload system. In addition, a particular mark coined a "galled fret" was observed on the CMG1 HR steel sleeve. This galled fret may have specifically been the one that prevented the outer race to slide properly which would compromise preload and initiate ball skidding.
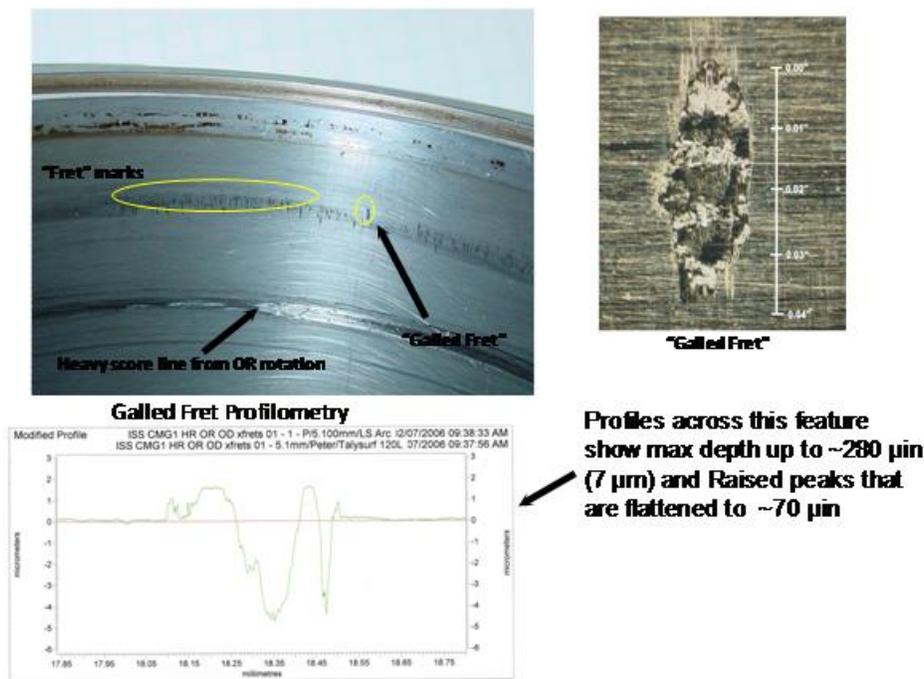
Figure 9. HR Side Bearing Housing Steel Sleeve

2. Some scoring (record grooving) on both the Spin Motor and Hall Resolver side preload nuts has been observed. This condition inhibited the spring action to react properly during the load and release cycle during axial motion of the flywheel. Preload was reduced to cause ball skid.

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Figure 10. Pre-Load "Record Grooving"

3. Assembly evaluations also identified a built in misalignment caused by the inner gimbal covers distorting the inner gimbal structure and altering the precision bearing bore alignment. This bore misalignment exacerbated the wear observed on the steel sleeves of the Bearing Housings.

CMG3 Forensic Findings

The most notable observation was the excellent condition of both Inner Gimbal spin bearings. In general, the HR side spin bearing was in good condition. An abundant amount of lubrication was noted in the ball race contact zone and at the retainer pad and inner race land interface. The balls were bright with some wear tracks, i.e., frosted bands, composed of repeated dents most likely caused by hard particles embedded in the raceway. The inner race was not significantly worn. It contained glazed bands but not beyond the original surface finish. The retainer was not damaged. It contained very light deposits around the ball pocket. Some amount of de-wetting was noted on the inner and outer raceways, but not on the balls. Gas Chromatography/Mass Spectroscopy (GC/MS) analysis of the lubricant by The Aerospace Corporation showed good correlation to unused KG80 oil. However, long chain fatty acids and plasticizers contaminats were identified. The burnishing and slight deposition of the darkened lubricant, more on the fore and aft portions of the pocket than on the sides. indicates this bearing may have operated with periods of mild retainer instability. The failure investigation team consensus is that this bearing was in good shape with wear commensurate with its 5.8-year life and *not* a contributor to the observed anomalous accelerometer signature.

Initial visual observation classified the SM side bearing in comparatively worse condition than the HR side bearing but still acceptable. An abundance of lubrication was noted in the ball race contact zone and at the retainer pad and inner race land interface. The balls were bright, with wear tracks and the oil was beaded as droplets (evidence of dewetting). Some wear tracks are composed of metallic wear debris and some grooves due to mild surface distress. Some patches of the balls are rich in sulfur. Other bands are composed of repeated dents most likely caused by hard particles embedded in the raceway. The inner race contained a significant wear track and glazed bands due to mild surface distress. The retainer was not damaged. Deposition of darkened lubricant was observed on the fore and aft portions of the pockets. Only two of the inboard and outboard quadrants contained minor accumulations of slightly degraded lubricant. The Aerospace Corporation GC/MS Analysis of the lubricant showed good correlation to unused KG80 oil however "contaminants" like long chain hydrocarbons, long chain fatty acids and plasticizers were more predominant in this bearing. The failure investigation team consensus is that this bearing is in worse condition than the HR bearing, but still acceptable, it contained more wear but still commensurate with its 5.8-year life. It had higher concentrations of contaminants and more areas of de-wetting, including the balls. It is believed that this wear was accumulated over the life of the unit and not

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just in its last days of operation. Additionally, testing of the active oiler systems verified that the lubricant flow was consistent with the presence of fresh oil in the both bearings.

Evidence to further support the CMG1 failure conclusions and provide support that the bearing preload was reduced to cause the unbalance monitor to reach the "take action criteria" for the CMG3 soft failure are:
1. Similar "fretting" type marks were observed on the steel sleeve of the bearing cartridge steel sleeves (Figure 11). The fretting marks were near 180 degrees apart from the area on inboard section to the area on the outboard section, an indication of bearing bore misalignment. If these conditions occurred before the failure, either during on earth acceptance testing or during operation, this misalignment would have affected the preload system.

Figure 11. Typical Cartridge Fretting

2. Some scoring (record grooving) on both the Spin Motor and Hall Resolver side preload nuts has been observed (Figure 12). This condition inhibited the spring action to react properly during the load and release cycle during axial motion of the flywheel. Preload was reduced to cause low preload and ball skid.
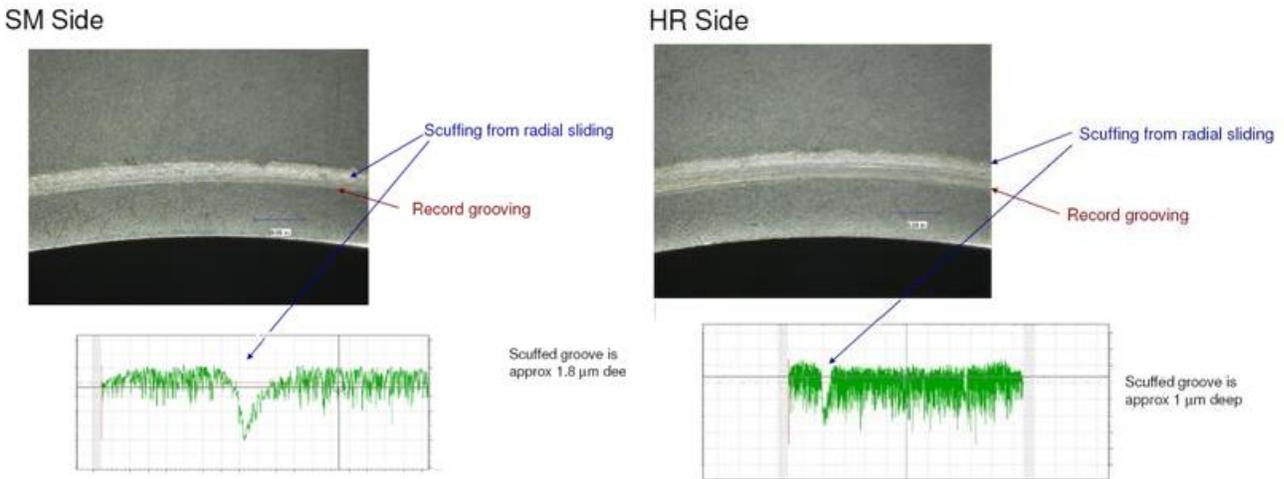
Figure 12. Typical Preload Nut Record Grooving

3. Assembly evaluations also identified a built in misalignment caused by the inner gimbal covers distorting the inner gimbal structure and altering the precision bearing bore alignment. This bore misalignment exacerbated the wear observed on the steel sleeves of the Bearing Housings. Similar distortation characteristics to the CMG1 covers were confirmed on CMG3.

CMG1 and CMG3 Most Probable Causes

After a thorough review of the forensic findings and the on-orbit telemetry the failure investigation teams concluded the most probable causes for the CMG1 bearing failure and CMG3 excessive unbalance were:

- Fretting/galling at the bearing Outside Diameter (OD)/Steel Sleeve interface inhibited free motion of bearing preload mechanism, this reduced bearing preload to a threshold level to initiate ball skid which ultimately caused failure.
- Scoring (record grooving) on the Spin Motor and Hall Resolver side preload nuts adversely affected the bearing preload and bore alignment also contributing to a compromised preload that initiated ball skid.
- Bearing misalignment introduced by the inner gimbal covers exacerbates the wear conditions at the preload nut and sleeve interfaces.
- Additionally, research conducted during the CMG Root Cause Investigations showed that the adverse mechanical conditions described above were exacerbated by spin bearing radial loads induced by highest allowable gimbal rates. Operational limits were put in place to control both gimbal angular velocity and acceleration to restrict the amount of radial loading imparted to the bearings.

Design Improvements

The failure investigation, consisting of test, disassembly, evaluation and analysis of CMG1 and CMG3, identified the wear characteristics at the bearing outer race/bearing housing steel sleeve interface, scoring of the preload and inner gimbal cover induced gimbal distortion. These conditions adversely lower the bearing preload to the point where ball skid can occur. This can cause a bearing failure as in CMG1,

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or increase vibration to the "take action" criteria as observed during CMG3 on-orbit operations. These observations led to the following redesigns;

1. Change the sleeve material to a harder dissimilar metal than the bearing outer race to prevent fretting and galling
2. Add Rheolube grease to the bearing/steel sleeve interface to improve long term lubrication, reduce wear/galling/fretting, and improve sliding
3. Change the preload nut material from A286 to harder 52100 to prevent wear/record grooving
4. Add flats to the Belleville preload spring to reduce contact stresses and prevent wear/record grooving of the preload nut
5. Improve the inner gimbal cover/inner gimbal interface to reduce gimbal distortion and maintain bearing bore alignment
6. Improve the cleaning process of bearing housing sleeves to minimize/eliminate hard particles that may have contributed to the repetitive marks in the bearing raceway and that may have lodged between the outer race and steel sleeve resulting in locked outer races

The design improvements identified from these investigations were successfully demonstrated in a re-design verification test program and have been implemented in the rebuild of CMG1 and CMG3 to minimize the most probable failure mechanisms and increase the life of the spare CMGs. These CMGs will be stored on the Space Station as "ready to use" spares.

Conclusions

Determining the cause for failure was the primary focus of the investigation teams. The same teams were utilized to develop modifications to eliminate the design susceptibilities. From these two CMG failures, valuable engineering and programmatic lessons learned surfaced to improve future space programs. The lessons learned from these failures are:

1. Sliding fits should be properly designed and lubricated to minimize wear and galling/fretting over the life the device. This can be accomplished through proper selection of materials at the interface. In general, the use of dissimilar metals at sliding interfaces will reduce the likelihood of galling/fretting. Galling/fretting/wear tests should be performed in the design phase to optimize the sliding fit interface.
2. Ensure all structure distortions are totally analyzed in the design phase. Do not underestimate the importance of thermal-stress analysis.
3. Ensure a cleaning validation and verification process are present for the parts in the critical sliding fit applications. Sliding fits can deteriorate quickly if hard particulate residue remains at critical fits from manufacturing operations.
4. As part of the qualification program a disassembly evaluation should be planned. The Space Station CMG program did not include a disassembly of the qualification unit; acceptance was based on performance after environmental exposures. A disassembly and evaluation of the qualification unit may have identified these susceptibilities at the sliding interfaces.
5. New designs based on heritage are a good starting point; however, incorporation of present day technology should not be discouraged. A thorough risk analysis should be performed before a deviation from a heritage design is accepted. Evaluation tests using "design of experiments" must be performed in the development phase to demonstrate the innovative configuration provides a low risk improvement over heritage.

The ISS, an orbiting laboratory, is providing a learning opportunity not only for the planned scientific experiments but also for spacecraft design and operation within the International Aerospace Community. The lessons learned from the CMG failures are only a few of the many that have been identified during the assembly and operational phases of the ISS.

Acknowledgements
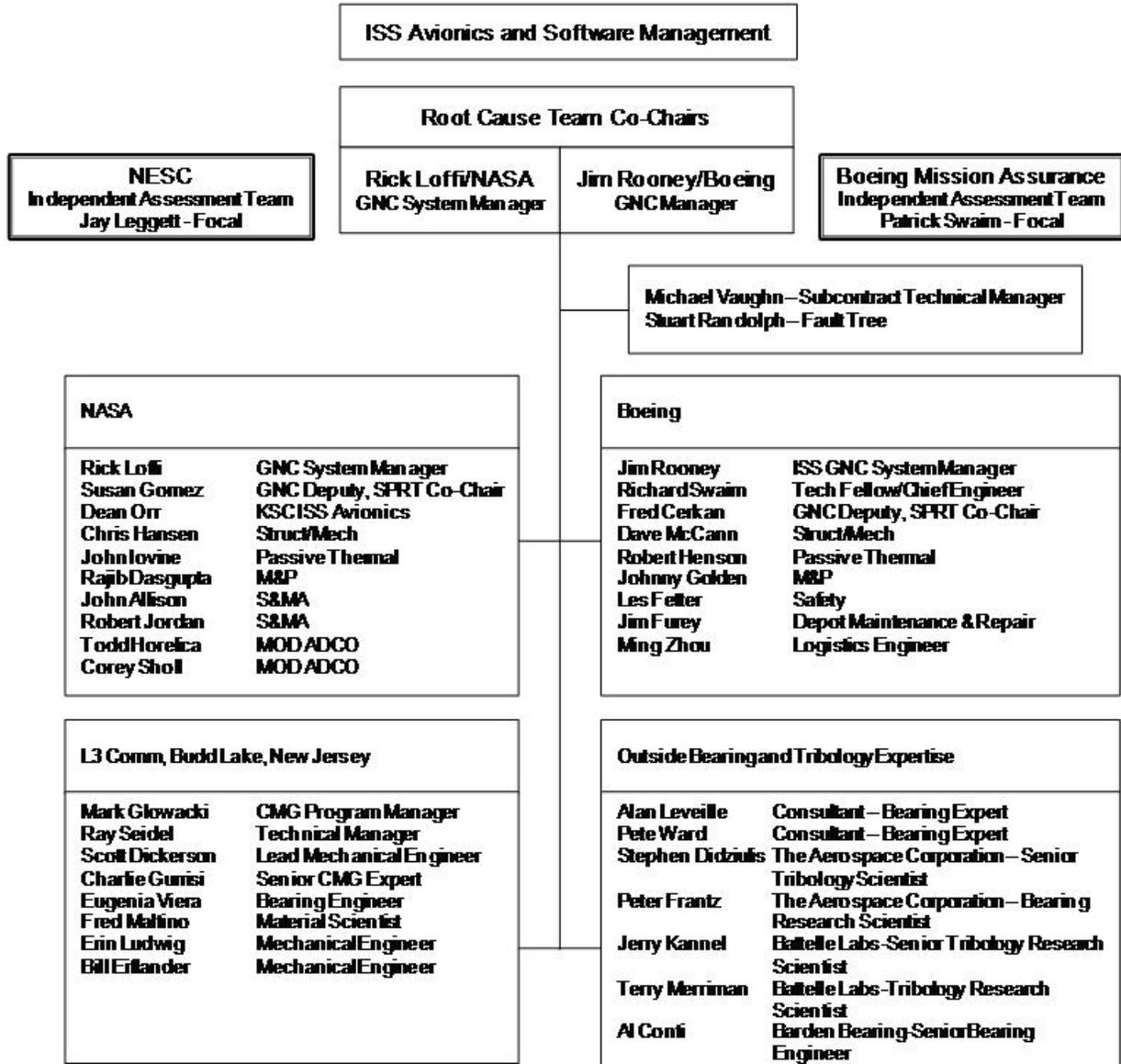
CMG1 Failure Investigation Team

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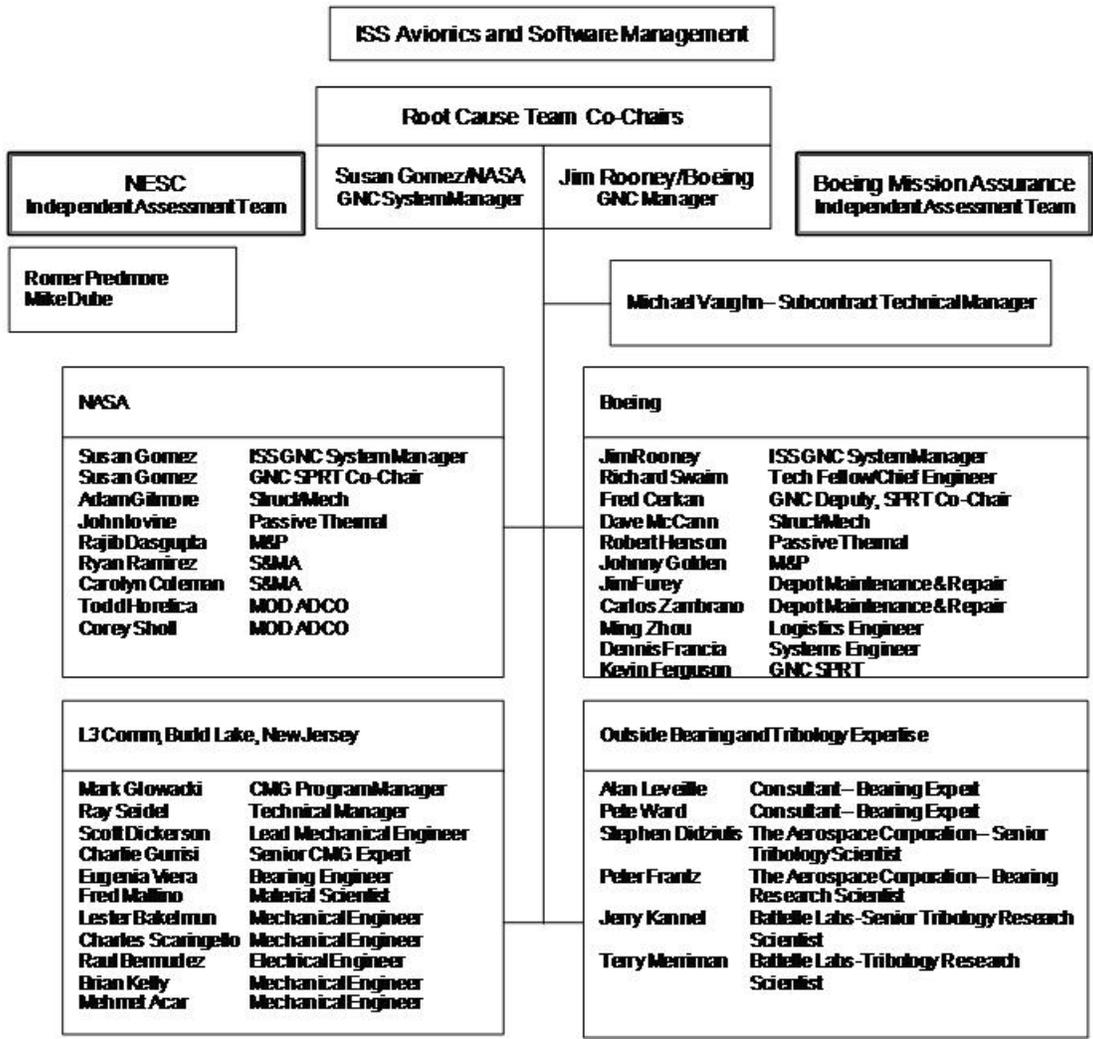
CMG3 Failure Investigation Team

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