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THE GALILEO HIGH GAIN ANTENNA DEPLOYMENT ANOMALY

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ABSTRACT

On April 11, 1991, the Galileo spacecraft executed a sequence that would open the spacecraft's High Gain Antenna. The antenna's launch restraint had been released just after launch, but the antenna was left undeployed to protect it from the heat of the sun. During the deployment sequence, the antenna, which opens like an umbrella, never reached the fully deployed position. The analyses and tests that followed allowed a conclusive determination of the likely failure mechanism and pointed to some strategies to use for recovery of the high gain antenna.

INTRODUCTION

The Galileo spacecraft's mission is to drop a probe (the Huygens Probe) into the atmosphere of Jupiter and then tour the Jovian system for two years, gathering a wealth of data on the system's structure, composition, and environments. The spacecraft was launched from Kennedy Space Center aboard the Space Shuttle on October 18, 1989. Galileo's trajectory carried it toward Venus for a gravity assist on February 10, 1990. The spacecraft then flew by Earth for a second gravity assist on December 8, 1990, and it flew by Earth again on December 8, 1992 for a third gravity assist. The spacecraft is currently on its way toward a December 1995 arrival at Jupiter.

The Galileo spacecraft (Figure 1) is a spin stabilized spacecraft and has three Earth-to-spacecraft communications antennas for commanding and returning spacecraft telemetry. Two of the antennas are low gain and the third is a high gain. One of the low gain antennas was used only during the portion of the mission that the spacecraft was inside Earth's orbit. This antenna, called the Low Gain Antenna-2 (LGA-2), faces the opposite direction of the other two antennas and is deployable and retractable. The remaining two antennas, the High Gain Antenna and the Low Gain Antenna-1, are part of the same assembly and face the same direction. During the portion of the mission that took the spacecraft close

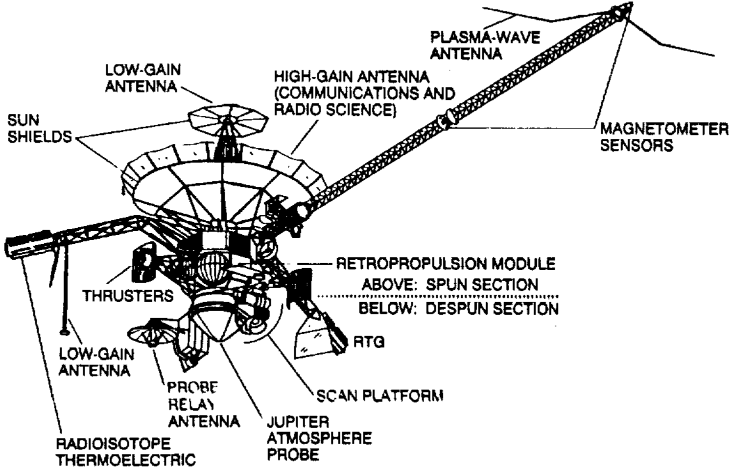

Figure 1.
Galileo Spacecraft Configuration

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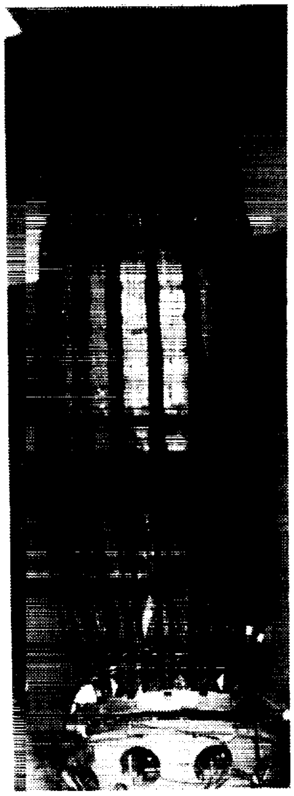


Figure 2.
High Gain Antenna
Stowed Position

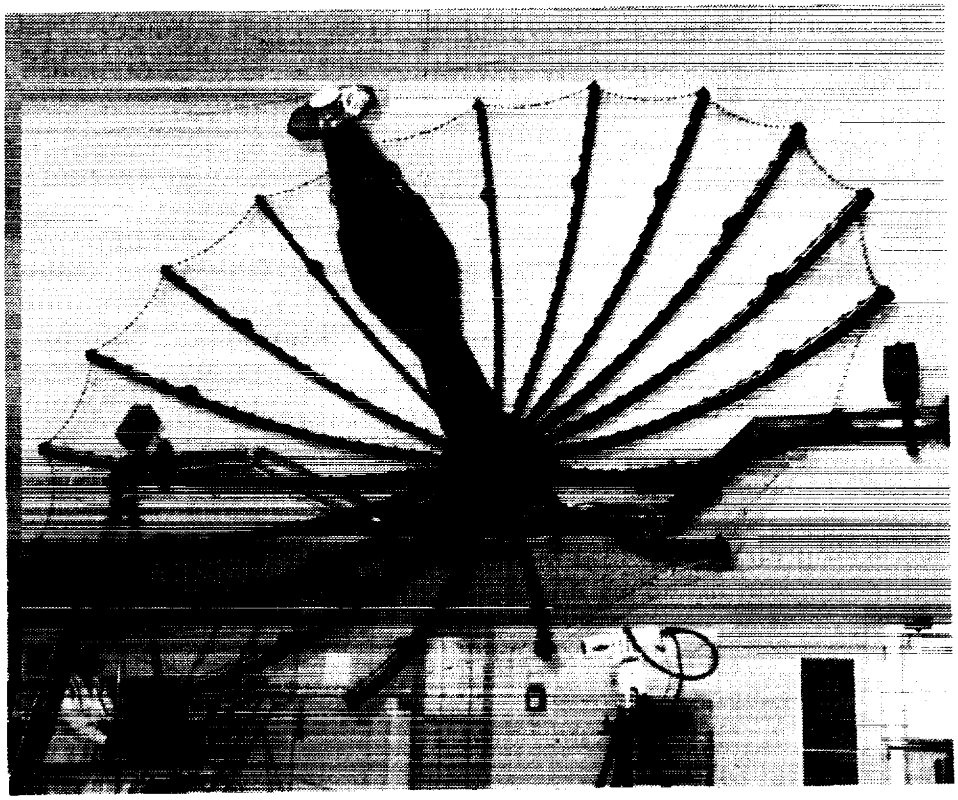


Figure 3.
High Gain Antenna
Deployed Position

to the sun, the High Gain Antenna (HGA) had to be protected from the direct sun. To do this, a sunshade was put on the tip of the antenna structure and the antenna was left in the undeployed position until April 1991 when the sun-to-spacecraft distance was large enough to present no thermal danger to the HGA.

The Galileo High Gain Antenna is shown in Figure 2 in the stowed position, and Figure 3 shows the antenna in the deployed position. The HGA is deployed and stowed by a mechanism located in the base of the antenna called the Mechanical Drive System (MDS). This system consists of a Dual Drive Actuator[1] (DDA), a 0.5 inch (12.7 mm) diameter, eight threads per inch (0.125 in, 3.175 mm pitch) ballscrew/ballnut assembly, a carrier assembly, 18 pushrods, and 18 ribs. (Figure 4) The ribs have a gold-plated wire mesh connected to them that stretches and forms the reflector surface when the antenna is fully deployed. Figure 5 shows the Mechanical Drive System in the fully deployed position. The lower end of the ballscrew is supported by a bearing housing containing a radial roller bearing and two roller thrust bearings. As the ballscrew is turned by the DDA, the carrier, which is prevented from rotating by the pushrods, moves toward the DDA. This motion results in the pushrods forcing the ribs to rotate about their pivot point and open out like an umbrella. The motion of the ribs pulls the wire mesh out and stretches it tight, creating the reflector surface. The ribs open out until each rib fitting contacts a mechanical stop, preventing any further deployment of the rib. The continued motion of the carrier compresses a spring on each of the pushrods, preloading the ribs against their stops, and

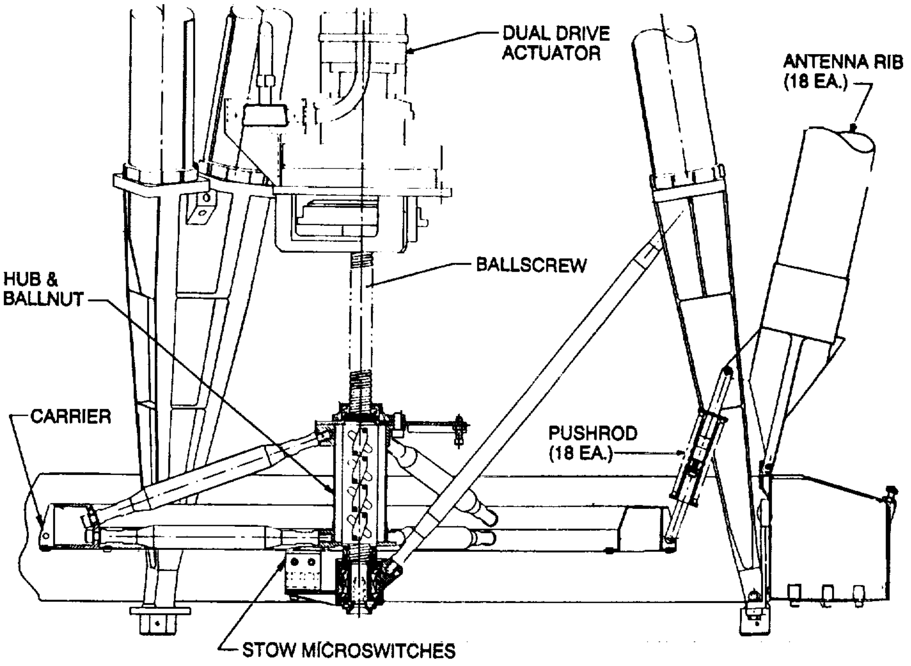


Figure 4.
Galileo High Gain Antenna Mechanical Drive System
(Stowed)

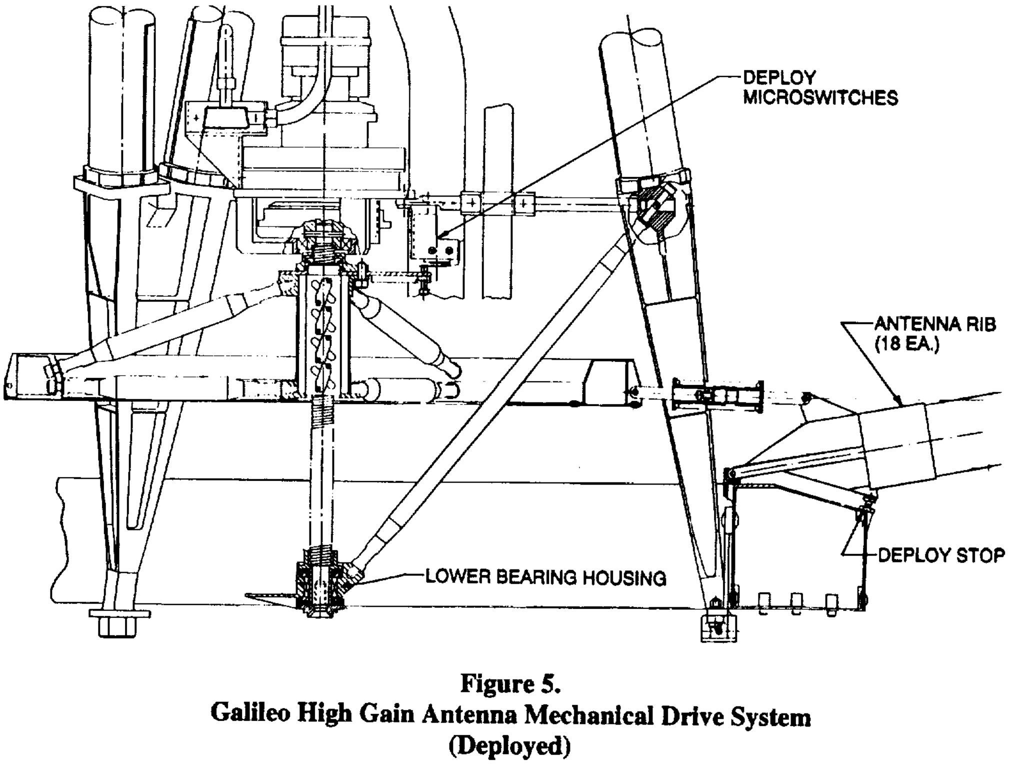


Figure 5.
Galileo High Gain Antenna Mechanical Drive System
(Deployed)

continues until the pushrods pass over center. This maintains a constant preload on the ribs in the deploy direction after the DDA is shut off at the fully deployed position.

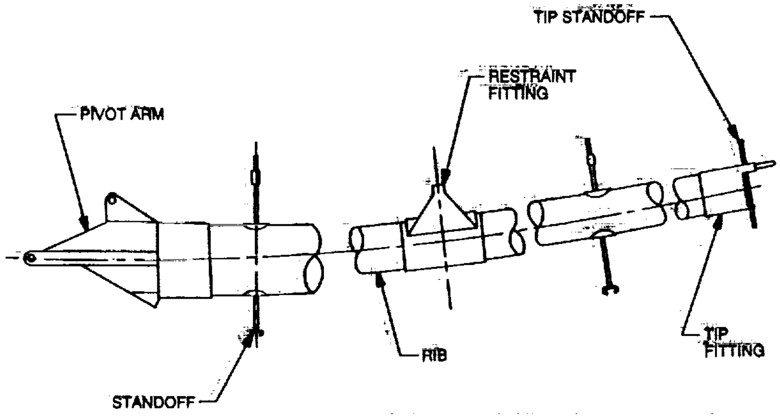


Figure 6.
Rib Assembly

Figure 6 depicts a rib assembly sectioned to show the pertinent components. The ribs are restrained during launch at the restraint fitting by a spoke assembly which is held in place by the Central Release Mechanism (Figure 7). This mechanism is opened by a spring when the retaining shaft, held in place by a Non Explosive Initiator (NEI), is released. After launch, the Central Release Mechanism (CRM) is actuated, releasing all 18 spokes and allowing the MDS to deploy the antenna. For launch, the spoke assemblies are each preloaded to 378 N (85 lb) and this preload is reacted by two pin-socket combinations called the mid-point restraint (inset, Figure 8). Both pins are titanium 6Al-4V with spherical ends that engage the sockets. The pin receptacle design is shown in Figure 9. One receptacle is a cone, the other is a V-groove, they both have included angles of 90 degrees, and they are both made from Inconel 718. The reason for the different receptacle designs was to avoid multiple load paths in case the pins did not have the exact same separation as the receptacles. The two receptacles balance the tension from the spoke preload, the cone locates the rib in the plane of the receptacles, and the V-groove reacts any rotation about the cone receptacle. The tip restraint of the ribs is a pin (shown in Figure 6) in a tuning-fork-like receptacle. This design prevents rotations of the ribs about their mid-point restraints and allows the ribs to move out freely during deployment.

Antenna Transportation History

The antenna was built at the HARRIS Corporation in Melbourne, Florida. The ribs were then stowed with the launch preload of 378 N (85 lb) and shipped by ground transportation to the Jet Propulsion Laboratory (JPL) in California. The shipping method supported the antenna by its flight interface horizontally (cantilevered) in the shipping container. The antenna was tested at JPL and then shipped by ground transport to Kennedy Space Center (KSC) for launch in May 1986. The Challenger disaster prevented Galileo from launching in 1986, and so the spacecraft and antenna were returned to JPL. The flight antenna was again returned to KSC for launch in October 1989.

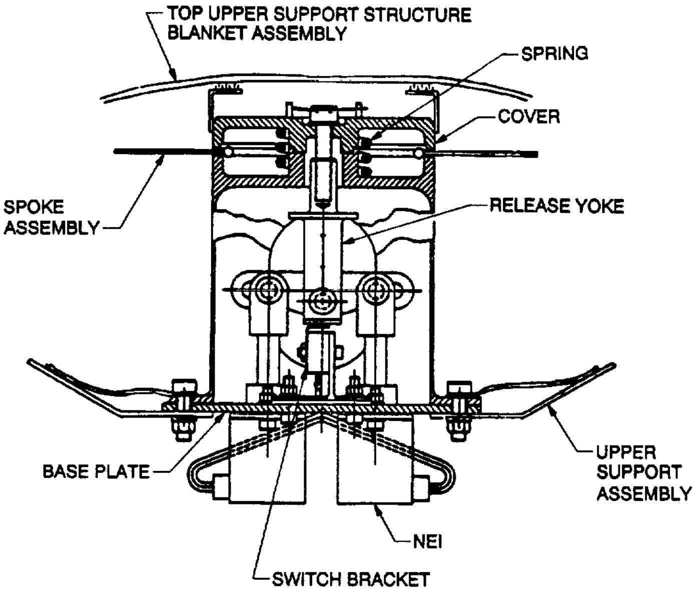


Figure 7.
Central Release Mechanism

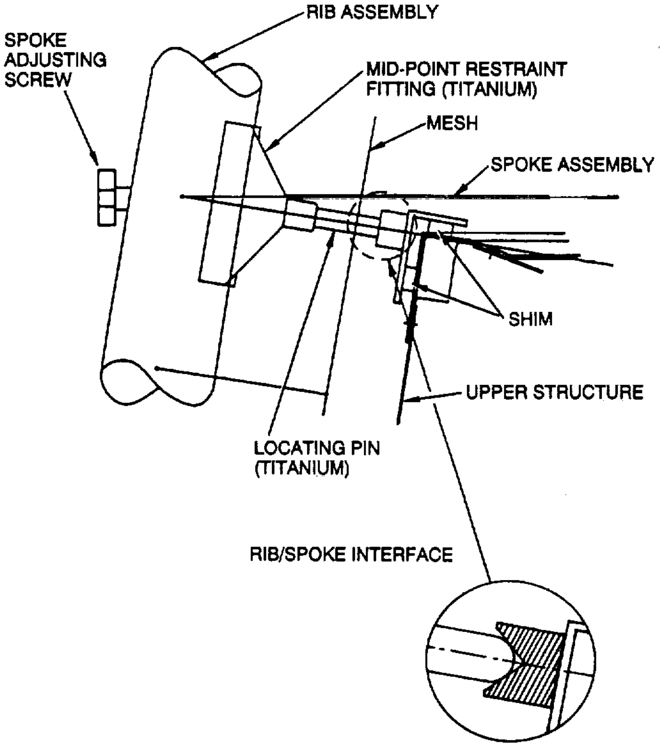


Figure 8.
Rib/Spoke Interface

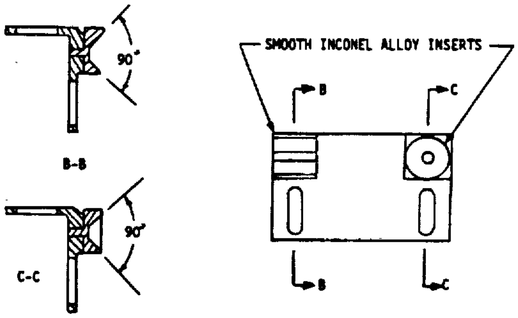


Figure 9.
Receptacle Design

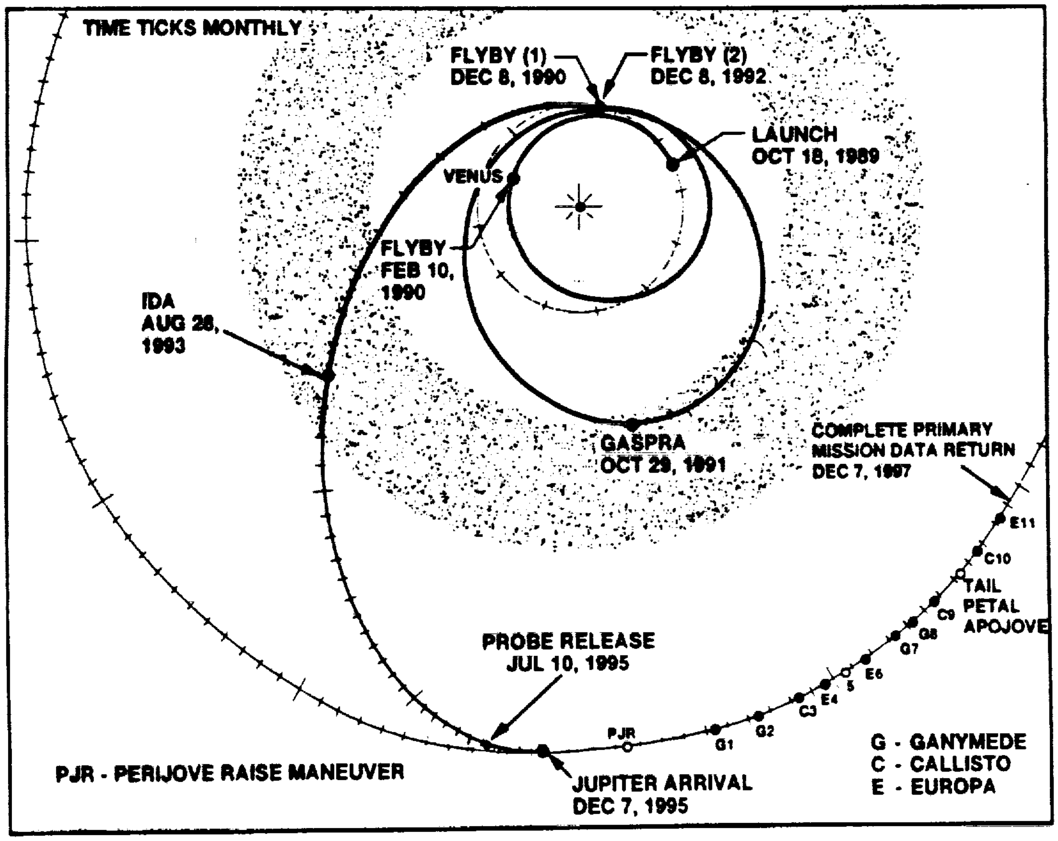


Figure 10.
Galileo Mission Timeline

Galileo Flight History and the Deployment Anomaly

The Galileo mission timeline is shown in Figure 10. The spacecraft was launched on October 18, 1989 and during the launch sequence, the Central Release Mechanism on the HGA was actuated. Telemetry from the spacecraft indicated that the CRM had released properly. The antenna was left in the stowed position so it would not be damaged by the intense sunlight during the early portion of the mission when Galileo would be at sun relative distances of less than one astronomical unit. The spacecraft reached Venus for a gravity assist on February 10, 1990 and then swung around for another gravity assist at Earth on December 8, 1990. This put Galileo on a trajectory that would bring it around for a third and final gravity assist at Earth on December 8, 1992. By April 1991 the spacecraft had reached a point in its mission where it would no longer be thermally risky to deploy the HGA. On April 11, 1991 Galileo executed a sequence to open the High Gain Antenna. The sequence energized the HGA deployment motors (both motors on the Dual Drive Actuator) for eight minutes. A nominal deployment time would have been about 165 seconds with both motors on the DDA operating properly. The deployment time, if one motor/gear train had failed, would have been about 330 seconds. When the antenna reached the fully deployed position, a set of redundant microswitches would have shut down power to the drive motors. The sequence was set to operate the motors for eight minutes to protect the motors from

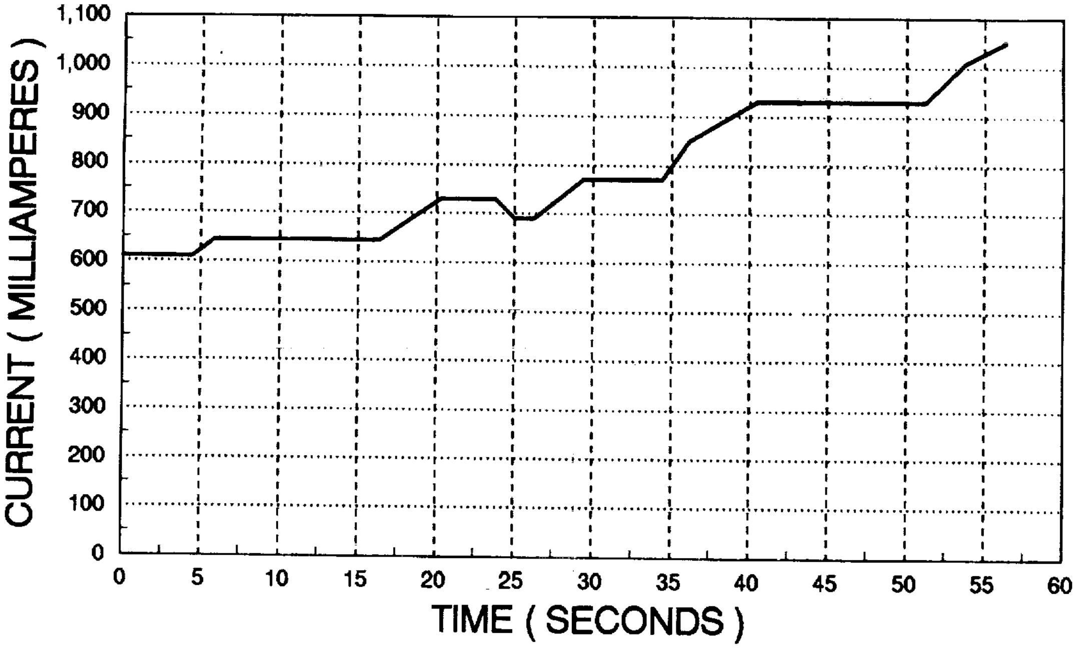


Figure 11.
Motor Current Telemetry
(Start : 19:51:23 spacecraft time)

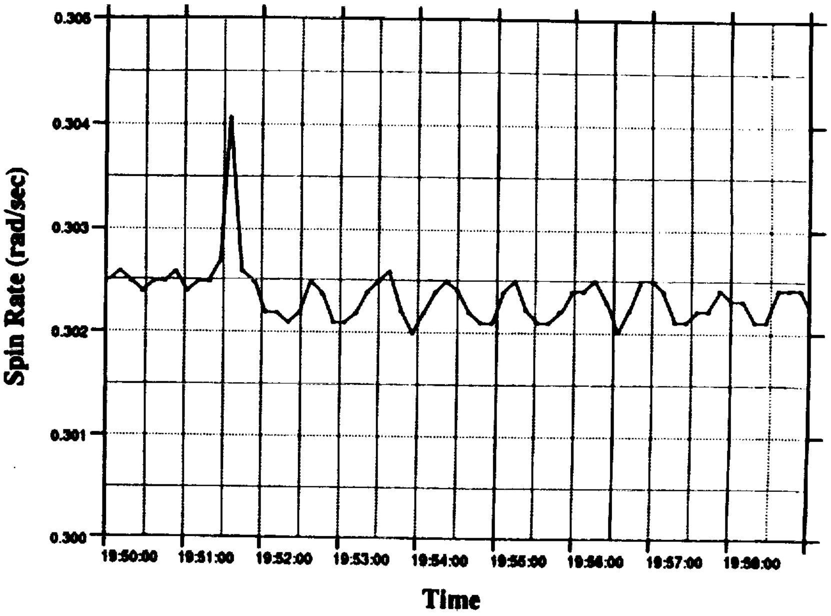


Figure 12.
Spin Detector Telemetry

overheating (if stalled) and to allow enough time for a single motor operating at cold temperature to fully deploy the antenna. The motor current telemetry received from the spacecraft is shown in Figure 11. The current drawn by the motors started higher than expected and continued to rise until it leveled off 56 seconds after initiation.

The other telemetry significant to the anomaly received from Galileo during the HGA deploy attempt are a spike in the Spin Detector output (Figure 12), a reduction in the output of the Sun Gate at certain clock angles (Figure 13), a decrease in the spin rate, and an increase in the wobble of the spacecraft. The Spin Detector is a very sensitive accelerometer mounted on the spinning portion of the spacecraft. This sensor is used to detect the spin rate of the spacecraft. At eight seconds after the start of the deployment, a sudden acceleration occurred and produced the Spin Detector output spike shown in Figure 12. Figure 13 shows the output of the Sun Gate after the deploy attempt. The Sun Gate is a detector that is used to protect the spacecraft from exceeding an angle of 15 degrees between the sun and Galileo's long axis. This was necessary to protect the Galileo during the portion of the mission when it was close to the sun. During the HGA deploy attempt, the Sun Gate output dropped at a spacecraft clock angle of 265 degrees. The clock angle is an angular position measurement on the spacecraft with the origin at the rotational center of Galileo and in a plane perpendicular to the HGA long axis. Also, the decrease in spin rate was not enough for a fully deployed antenna (due to the increase in the antenna's moment of inertia) and the reason for the increase in wobble was not initially understood.

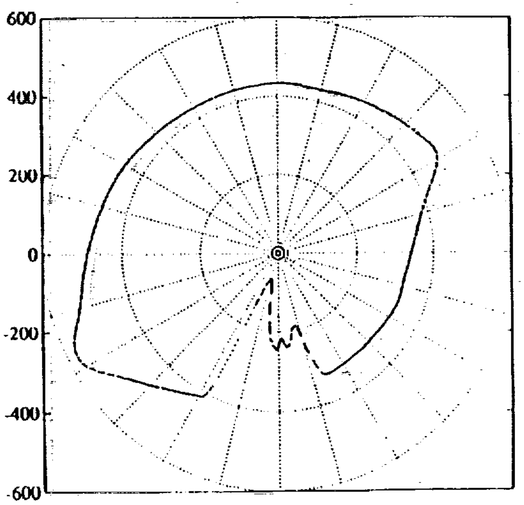


Figure 13.
Sun Gate Output vs. Clock Angle

DATA ANALYSIS

The first conclusion that can be drawn from the Sun Gate data is that the output was reduced by the shadow of an antenna rib. Analysis of the Sun Gate's location with respect to the antenna shows that only one rib can shadow the Sun Gate and that this rib can only shadow it at deployment angles of 34 to 43 degrees given the spacecraft-to-sun angle at the time of the deploy attempt (5.39 degrees). Analysis of the amount of obscuration of the Sun Gate indicated that the one rib that can shadow the Sun Gate was deployed about 35 degrees from its stowed position.

The motor current telemetry indicated that the motors stalled at 56 seconds after initiation. The telemetry was then used to determine how far the ballscrew in the Mechanical Drive System had rotated from the stowed position. The motors on the DDA are brushless dc motors. The DDA, therefore, has the speed-torque-current relationship shown in Figure 14.

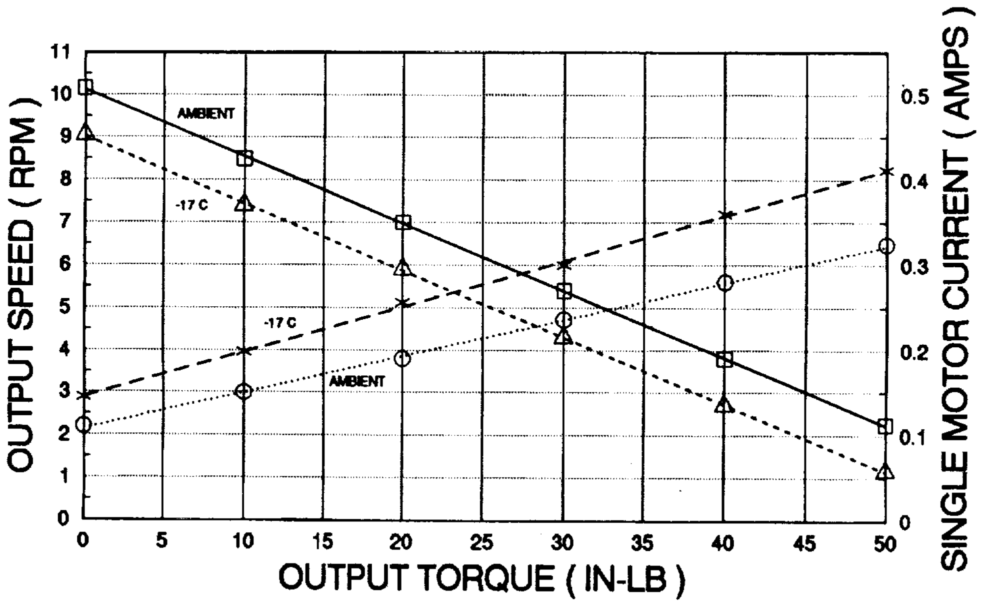
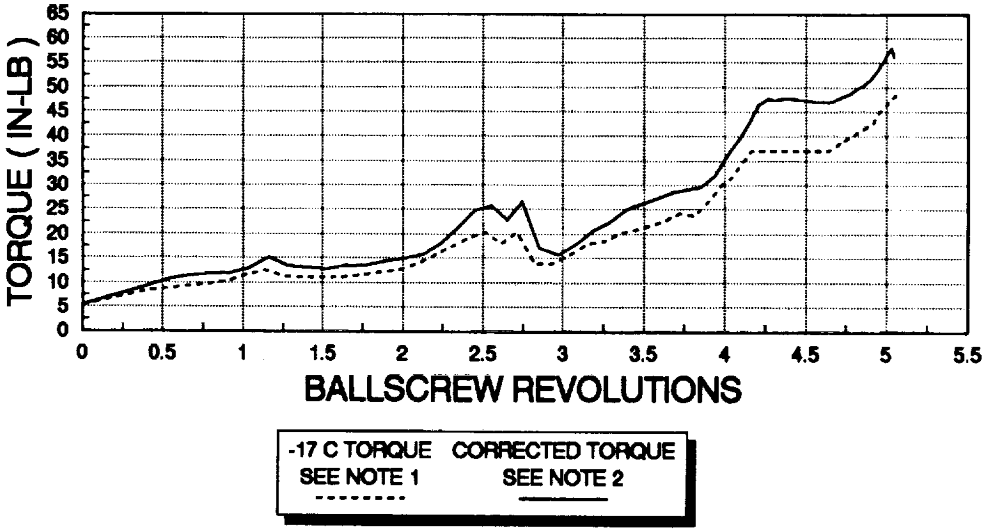


Figure 14.
Dual Drive Actuator Performance



NOTE 1 : DERIVED TORQUE AT DDA CONSTANT TEMP.
NOTE 2 : DERIVED TORQUE CORRECTED FOR MOTOR INTERNAL SELF-HEATING

Figure 15.
Torque vs. Ballscrew Revolutions
for the High Gain Antenna Deployment Anomaly

This allows the expression of speed as a function of current. Utilizing this relationship, the current telemetry from the spacecraft, and integrating over time allowed the determination of the ballscrew position as a function of time. Taking into account the granularity of the current telemetry, converting the current telemetry to torque, and plotting this as a function of ballscrew revolutions resulted in the curve shown in Figure 15. The data indicates that the ballscrew rotated just over five turns. (A full deployment requires 25 rotations of the ballscrew.) Converting the five rotations to carrier movement and then to rib rotation indicates that the ribs could not have deployed to an angle greater than 11 degrees, which is inconsistent with the Sun Gate data. The way the ribs are connected to the carrier allows for an asymmetric deployment of the ribs if one or more ribs are restrained by something. After several tests on the spare antenna, it was determined that the most likely configuration of the antenna was three ribs restrained at their stowed position. This would allow the opposite rib (over the Sun Gate) to deploy to the position indicated by the Sun Gate data. Also, the number of ballscrew revolutions and the torque required to deploy the antenna under these conditions is consistent with the current telemetry. Figure 16 is a photograph of the spare antenna in the three restrained rib configuration. This asymmetrical configuration is also consistent with the amount of reduction in the spin rate and the increase in wobble.

The Spin Detector spike occurred at a time in the deployment that coincided with an increase in torque for the DDA. The initial thinking that the spike was due to the release of some other restrained ribs was not consistent with the increase in torque required from the drive system.

After the shape of the antenna was determined, the design was dissected to find what could possibly be holding the ribs in the stowed position. Four possibilities survived this analysis. They were:

1. The tip shade (sunshade mounted on the tip of the antenna to protect it during the early part of the flight) snagged in the wire mesh.
2. Restraint of the Mechanical Drive System (MDS).
3. Retention of the rib tips in their tuning-fork-like sockets.
4. Retention of the ribs at the mid-point restraint due to friction, cold welding, or adhesion.

Tests performed on the spare antenna to snag the tip shade were totally unsuccessful. No configuration of tangling the tip shade in the wire mesh could be found that would restrain the ribs at the stowed position. All attempts resulted in significant rotation of the restrained ribs from the stowed position, allowing a much greater number of ballscrew revolutions before stalling the Dual Drive than indicated by the current telemetry.

Restraint of the MDS was eliminated due to the order in which testing and assembly occurred at Kennedy Space Center. The area around the MDS was closed and no longer

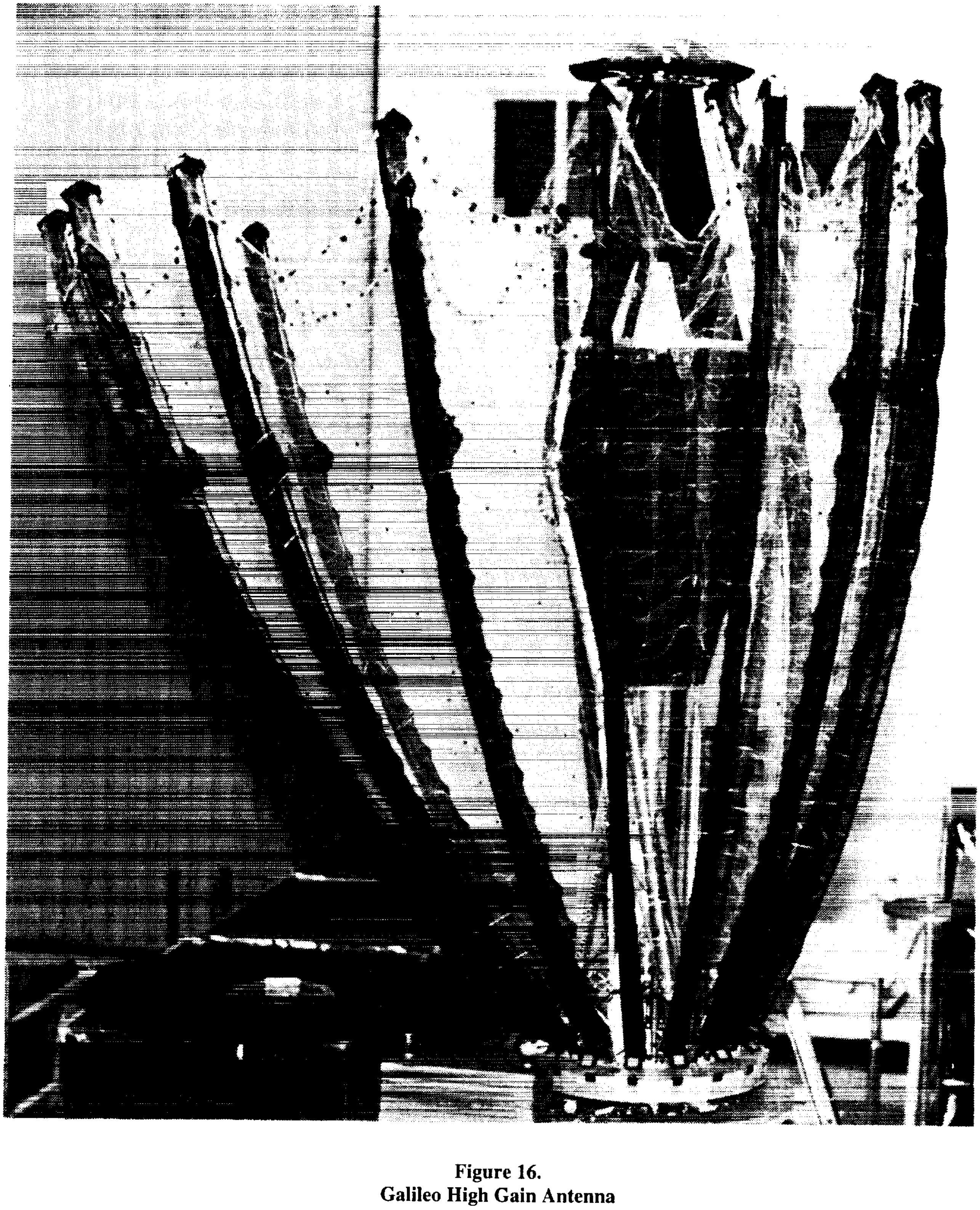


Figure 16.
Galileo High Gain Antenna
Asymmetric Deployment Configuration

accessible prior to several deploy tests of the flight antenna. Also, this area was not accessible during installation of the antenna on the spacecraft.

Retention of the rib tips in their tuning-fork sockets was very unlikely due to the prelaunch testing that had been performed. The tuning forks would have to have been damaged after the final deployment test or in flight. A failure of this type would also cause a slower increase in the torque required from the DDA (due to the stiffness of the ribs) during the deploy attempt than was indicated by the current telemetry. This left as the first choice of failure the mid-point restraint pins and sockets. If friction was responsible for restraining the pins, it would require a coefficient of friction greater than one.

The next mystery was how the MDS and the structure were able to carry the load generated by the stalled motors. The Dual Drive stall torque output during the deploy attempt was about 6.33 N-m (56 in-lb). A test was performed on a mock-up of the MDS to determine how it would respond to the odd loading condition created by the antenna. The test fixture shown in Figure 17 was used to apply moment, axial, and shear loads to the "carrier plate" individually and in combination. The results of these tests showed that shear and axial loads do not significantly affect the efficiency of a ballscrew. Moment loads, however, result in very significant losses in a ballscrew/ballnut assembly. The graphs in Figure 18 show that the application of a moment of 339 N-m (3000 in-lb) to a ballnut results in torque losses of 4.18 N-m (37 in-lb), or more than half of the available torque from the DDA. This large amount of torque loss is due to jamming of the balls in the ballnut and sliding contact of the ballscrew with the ballnut body. Also, it was found that further losses occurred at the lower bearing housing (see Figure 5), due to the sliding contact of the ballscrew with the stationary outer housing. The needle roller bearing in the lower housing is not capable of supporting a large moment load, allowing the ballscrew to rotate relative to the housing and come in contact with it. The result of these torque losses was that very little torque was available to move the ribs against their restraints.

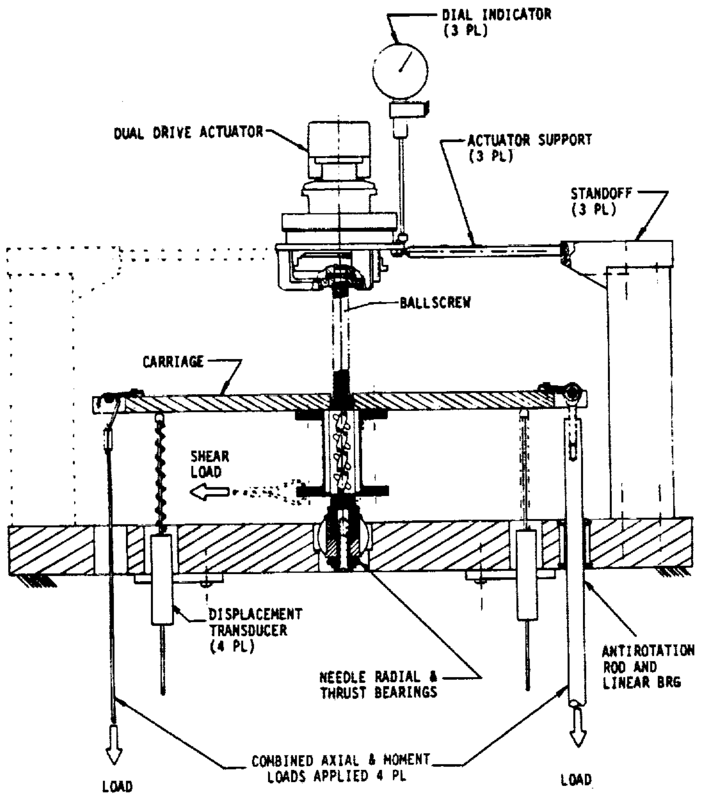


Figure 17.
Mechanical Drive System
Loading Fixture

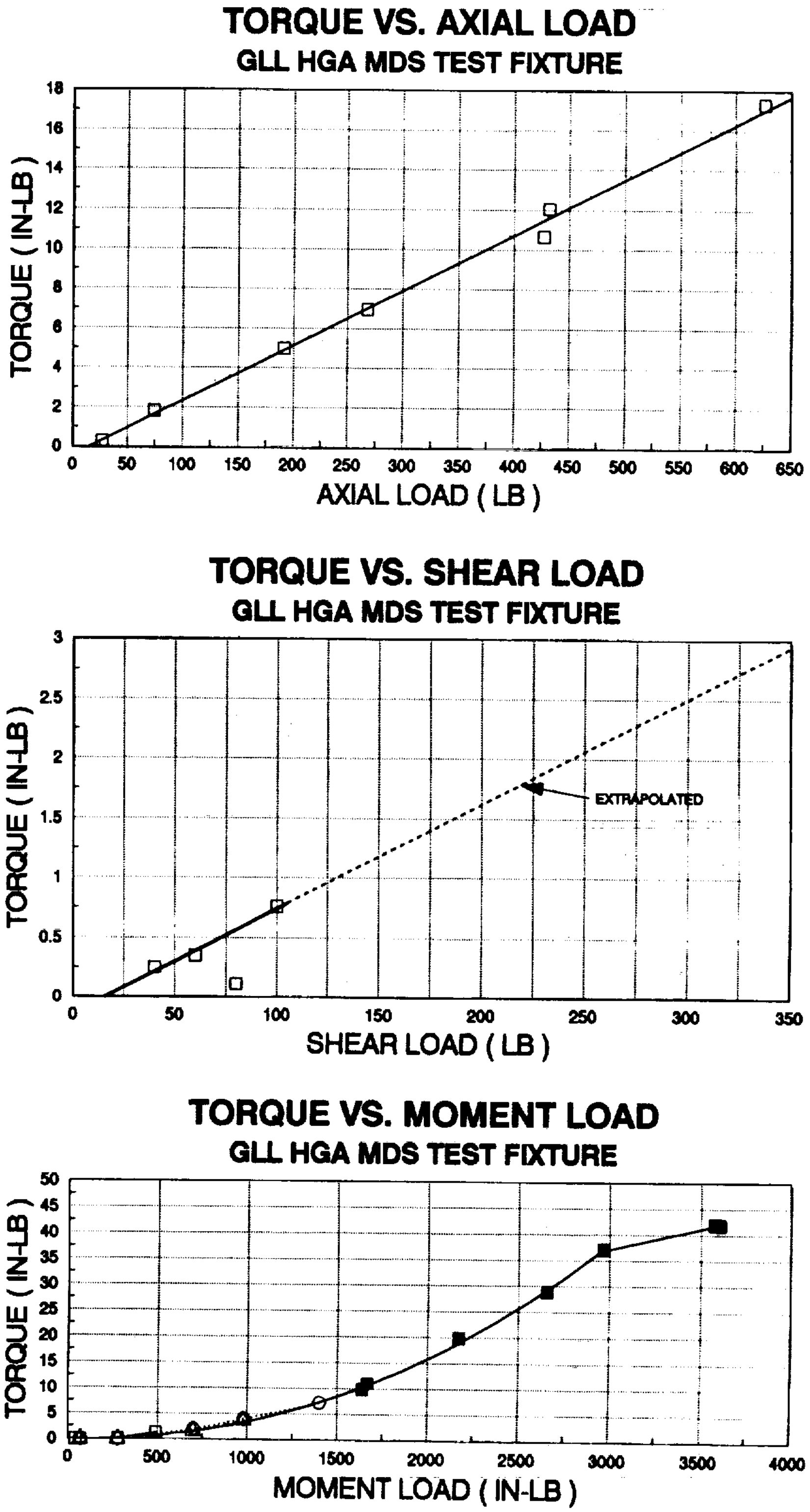


Figure 18.
Mechanical Drive System
Test Fixture Results
(Torque required to turn ballscrew with the specified loads applied)

RECOVERY TECHNIQUES AND ATTEMPTS

The first suggestion made to get the antenna open was to restow it and try the deployment again. The Dual Drive Actuator, although capable of bi-directional operation, was not wired on the spacecraft to stow the antenna. This operation required human assistance to roll the wire mesh in order to prevent the mesh from snagging on itself or other portions of the antenna. Also, it was later learned through ground testing on the spare antenna that the lower bearing housing torque losses increase every time the antenna is stowed and redeployed, resulting in less and less DDA torque available to overcome the rib restraint. This increase in torque losses is due to the rotating steel ballscrew galling the stationary aluminum housing. The galling changes the surface finish of the aluminum so much that the torque required to turn the ballscrew increases. The testing showed that after just five deploy and stow cycles, the amount that the ballscrew could be rotated from the stow position was less than half the original amount of five revolutions.

The first attempt at breaking loose the antenna was to rotate the spacecraft away from the sun and then toward the sun. The thermal expansion and contraction of the antenna structure would be much greater than the expansion of the ribs and would cause a significant change in the forces at the mid-point restraints. A computer analysis of the pin-socket joints indicated that after several (4 to 6) thermal cycles of the antenna, the pins might come out of the sockets due to infinitesimal sliding each time the forces changed from the temperature cycle. This analysis assumed friction was holding the pins in the sockets. After seven thermal turns, there was no indication that the rib pins were "walking" out of their sockets.

The next recovery technique used was to swing the LGA-2 and impart a shock to the spacecraft structure. The LGA-2 swings 145 degrees at about five RPM and then hits a hard stop. The Low Gain Antenna-2 mast is approximately 2 meters long with the low gain antenna mounted on the end. The moment of inertia of this assembly is very large and imparts a significant impulse to the spacecraft structure. The LGA-2 was swung six times with no results.

The final recovery technique tried to date was to pulse the HGA Dual Drive motors at 1.25 and 1.875 Hertz. It was found during testing that the Dual Drive Actuator has a mode of oscillation that is due to the coupling of the motor armature inertia and the gearbox stiffness. The result of this mode is that the DDA can produce a pulsing torque at the output shaft that is forty percent greater than the stall torque value. When the pulsing was performed on a DDA in the spare High Gain Antenna, the antenna also responded at the same frequencies. The combination of the DDA and the antenna was able to turn the ballscrew another 1.5 revolutions beyond the stall point. This significantly increased the force on the mid-point restraint pins to a pullout force of 18 N (4 lb) and a shear force of 213 N (48 lb). These forces were high enough to elastically deform the ribs and pull them out of the bottom of the tuning-fork receptacles if they had been restrained there. The forces applied to the ribs on the Galileo spacecraft, after completion of the DDA pulsing, conclusively eliminate the tip fittings as a possible source of restraint. The ribs are therefore restrained at the mid-point restraints.

PIN AND SOCKET ANALYSIS

Several pin and socket pairs were removed from the spare HGA for evaluation and testing.[2] The spare HGA had been through a significant amount of vibration testing, which causes relative motion between the pins and sockets. The sockets were made of Inconel 718 with a surface finish of 0.2 microns RMS (8 micro inch RMS). The pins were made from titanium 6Al-4V and were finished with the Tiodize type II and the Tiolube 460 processes. These processes consist of putting an anodize coating on the titanium and following this with a molybdenum disulfide coating for dry lubrication.

A conical socket and its associated pin are shown in Figure 19. The contact area on the conical receptacle shows a transfer of some drylube from the pin, which was expected. The surface shows no indications of damage of any kind. The surface of the pin also shows no damage. There is a barely visible ring on the spherical surface where the pin made line contact with its receptacle. The Hertzian contact stresses on this surface were well within the operating capability of the pin and its surface coatings.

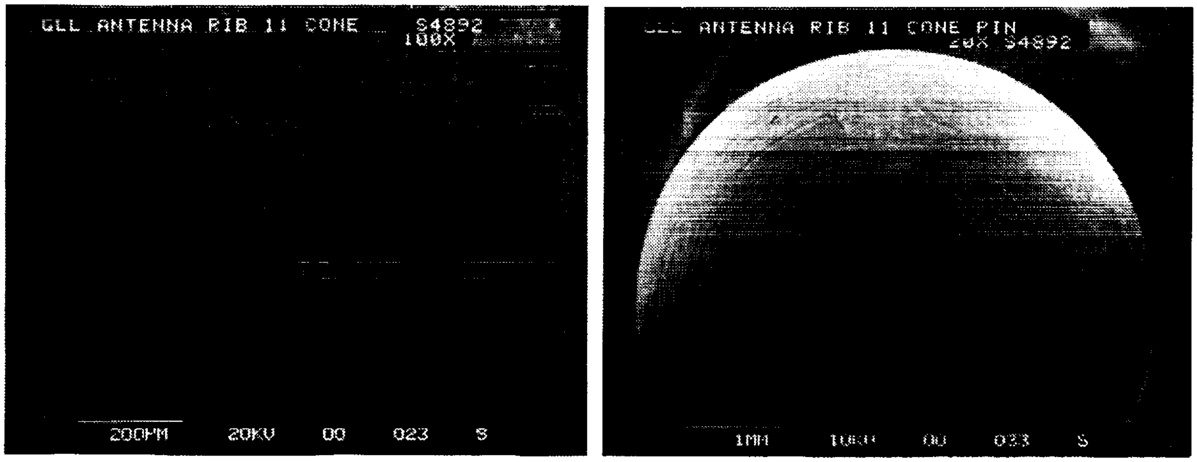


Figure 19.
Cone Socket and Pin

A V-groove socket and its mating pin are shown in Figure 20. These are from the same rib as the cone and pin shown in Figure 19. The surface of the pin is plastically deformed to a flat spot, as shown by the arrow. Although X-ray diffraction scans of the surface show the presence of MoS2 on the contact area, scans of some other pins from other ribs showed no presence of MoS2 on their contact patches. This indicates that the deformation of the surface destroyed the Tiolube and Tiodize coatings. The contact stresses actually exceeded the capability of the pin coatings by about five times. A higher magnification of the upper spot on the V-groove receptacle in Figure 20 is shown in Figure 21. The surface has been

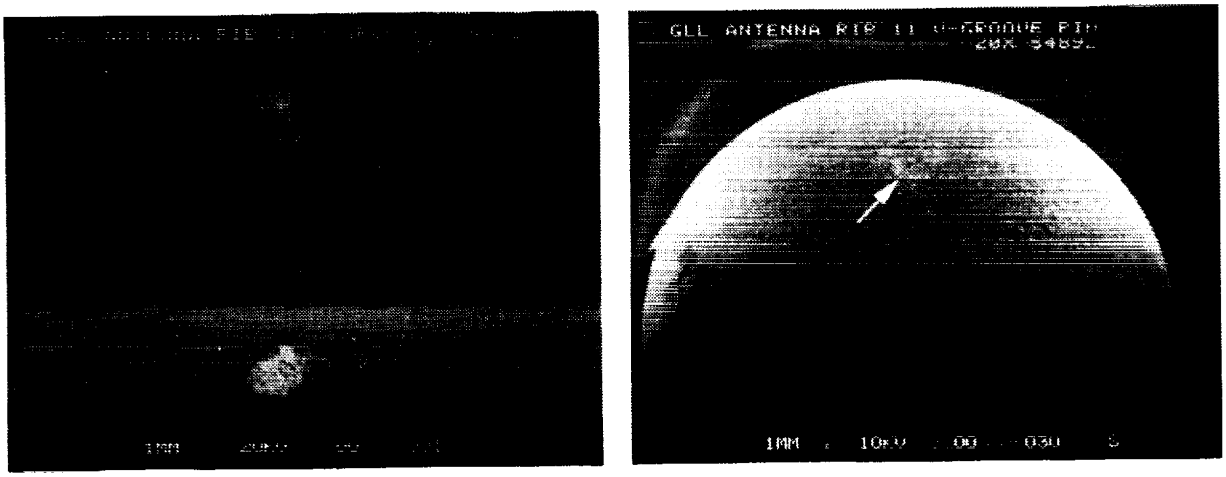


Figure 20.
V-Groove Socket and Pin

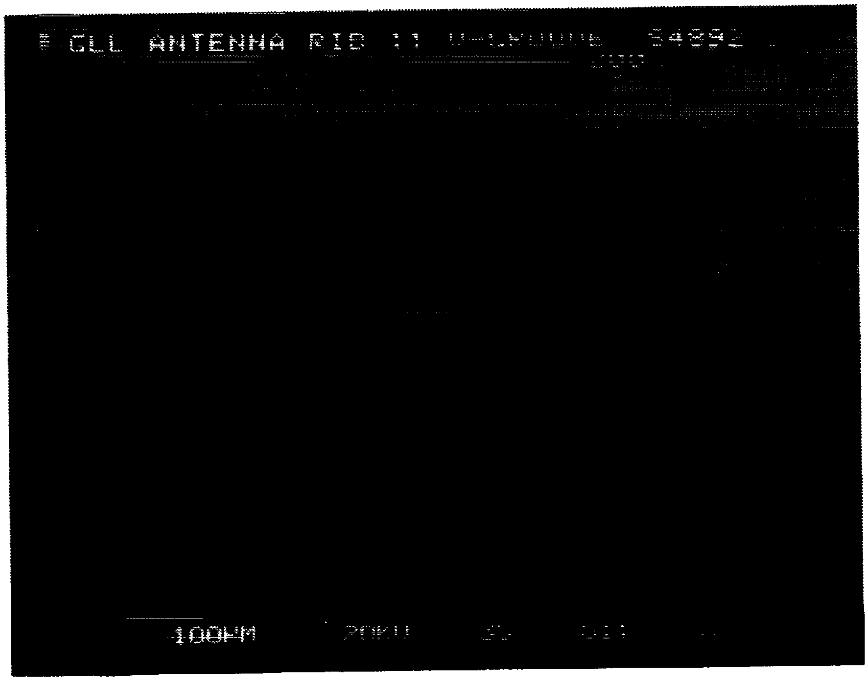


Figure 21.
Magnification of Upper Spot
on V-Groove Socket in Figure 20

deformed and worn away. Scans of the contact surface on the receptacle show a large amount of Ti 6Al-4V, indicating a transfer of base material from the titanium pin.

A series of tests was performed at NASA Lewis Research Center on the friction properties of drylubed and bare titanium against Inconel 718.[3] The results of these tests showed that if the two surfaces are displaced relative to each other under load and in air, then displaced relative to each other under load in a vacuum, the sliding friction between the surfaces increases nearly ten times. When a drylubed and anodized pin was operated in an atmosphere, the drylube surface was quickly destroyed and, as a result, exposed the base titanium. The testing also showed that with an atmosphere present to continue to react with the bare titanium as it was worn by sliding contact, the friction coefficient never exceeded 0.35. However, once a pin's drylube was damaged by operation in air and then operated in a vacuum, the surfaces started to gall and produce coefficients of friction in excess of 1.0.

RIB RETENTION MECHANISM

The first time the ribs were stowed to their full preload, plastic deformation of the contact points on the V-groove pins destroyed the ceramic coating on the titanium that was the bonding surface for the drylube material. During the four trips across the country the antenna was exposed to enough of a vibration environment to cause relative motion between the pins and sockets. This motion was amplified by the cantilever mounting of the antenna in its shipping container. The pins that were on the top and bottom (with the antenna horizontal) saw the greatest amount of relative motion with respect to their sockets. Since this occurred in an atmosphere, the drylube surfaces on the pins were worn. During vibration testing of the antenna at JPL, further damage to the drylube occurred. The vibration testing was done along the same axis as the gravity vector during ground transport, causing the same pins and sockets to experience the greatest amount of relative motion. By launch, the drylube was probably completely worn off the contact points between the pins and V-groove sockets. After launch, the spacecraft was exposed to a vibration environment from the upper stage that caused more relative motion of the pins and sockets. Since this occurred in a vacuum with bare titanium pins (due to the destruction of the contact patch on the V-groove receptacles), the pins and sockets galled together requiring more force to deploy the ribs than can be generated by the MDS.

Also, several other ribs spaced around the antenna were stuck by this same mechanism at the start of the deployment. Since the ballscrew did not have a large moment applied to it due to the spacing of the ribs, the ballscrew generated enough force to eject most of the ribs (which explains the acceleration detected by the Spin Detector). When the only ribs remaining stuck were on one side of the antenna, the ballscrew moment started increasing significantly, increasing the torque losses in the drive system. The increased losses, coupled with the reduction of force at the pins and sockets on the remaining stuck ribs, ended up stalling the DDA before the forces were large enough to eject the last three ribs.

The failure mechanism requires a special set of circumstances in a specific order to cause the deployment anomaly. The events necessary to produce the failure of the Galileo HGA are summarized, in the required order of sequence, below:

1. Generate a high enough contact stress to plastically deform the titanium pins and break the ceramic coating that was used to bond the drylube.
2. Produce relative motion between the pins and sockets in an atmosphere to remove the damaged coating and drylube from the contact areas and to produce a rough surface on the mating parts.
3. Produce relative motion between the pins and sockets in a vacuum to remove the oxidized and contaminated titanium from the surface of the pins and then gall both parts so the friction is very high.
4. Produce an asymmetric deployment of the ribs so that the ballscrew has a large moment applied to it and cannot produce the force necessary at the mid-point restraint to eject the ribs.

Without the relative motion of the pins and sockets in a vacuum, (number 3 above) the lower coefficient of friction of the interface in air allowed all ground deployment tests of the antenna to be perfectly successful due to the V-groove socket internal angle of 90 degrees. As long as there is an atmosphere to react with any free titanium generated by any relative motion, the friction between the pins and sockets is maintained at a value that will not prevent the antenna from deploying. Also, a vacuum deployment test without the relative motion of the parts in the vacuum, would also be successful due to the oxides and contaminants on the bare titanium pins. A vacuum deployment of the flight antenna was done and was successful because of the lack of relative motion between the pins and sockets in the vacuum.

CONCLUSIONS

The high contact stresses on the V-groove pin/socket interfaces destroyed the integrity of the lubricant film and started the chain of events that led to the deployment anomaly. The conical sockets and pins were exposed to all of the same environments as the V-groove sockets and pins, but the lubricant surface was not breached. A low enough friction level was maintained such that the conical sets did not inhibit the antenna deployment. The main difference between the cone sockets and V-groove sockets is the contact stress level.

The use of drylube, specifically molybdenum disulfide, on a mechanism that is going to be operated in an atmosphere should be carefully evaluated. The wear rate of the MoS2 in air is so much higher than in a vacuum that any coatings could be worn out by in-air testing and not provide the desired lubrication when needed. The pins and sockets on the HGA that received the greatest amount of relative motion due to the shipping method were the same ones that were exercised most by the vibration testing. These are also the same pins and sockets that are stuck on the spacecraft. One solution to the problem of ambient testing wearing out the lubricant coating would be to replace the lubricated components just prior to launch so there is a virgin lubricant surface for the flight operation.

The failure of the Galileo HGA was not detectable with in-air testing, due to the choice of titanium for the pin material. Since this material reacts with oxygen so readily, the in-air friction change, due to the damaged surfaces, was not detectable because the higher friction coefficient (0.35 vs. 0.05) was not high enough to be restrained by the 90 degree included angle of the receptacles. As a result, more deployment tests in air would only have worn out the drive system. Also, the vacuum deployment test of the flight antenna did not exhibit this failure mode due to the lack of pin and socket relative motion. The test conditions were not adequate for finding this problem, indicating that just a functional test in vacuum is not always appropriate.

EPILOGUE

Although the Galileo spacecraft has no operating high gain antenna, workarounds using the Low Gain Antenna (LGA-1), new data compression techniques, and the spacecraft's recorder have been developed that will meet 70 percent of the mission objectives (Reference 4).

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