PROJECT GALILEO: FINAL MISSION STATUS

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Abstract

After a 14-year odyssey, the historic Galileo mission to Jupiter ended on September 21, 2003 when the spacecraft entered the atmosphere of the giant planet it had studied for almost seven and a half years. The planned destruction of the orbiter was necessary to satisfy planetary protection concerns about Europa, a prime target in the search for extraterrestrial life.

Almost 11 months earlier, on November 5, 2002, the spacecraft flew to within 71,500 km of Jupiter's cloud-tops, sampling the inner magnetosphere and the Gossamer ring. The trajectory allowed Galileo to obtain the first density estimate of Amalthea, a small inner moon. This encounter presented challenges both in preparing for this risky flyby and in recovering from this traverse deep within the radiation belts. By limiting the observations to two primary experiments, radio science and fields and particles, the flight team was able to simplify sequence design and facilitate a robust strategy to continue data acquisition in the event of an anomaly. Based on previous experience, changes were made to onboard fault protection routines to either facilitate recovery or keep Galileo from entering safe mode (and subsequently canceling the science command sequence).

Not unexpectedly, two new types of hardware problems were manifested during this perijove passage. About 16 minutes after Amalthea closest approach, the extreme radiation levels caused erratic behavior in the Command and Data Subsystem phase lock loops. This resulted in multiple swaps of the timing chains and entry into spacecraft safe mode. An autonomous science recovery sequence designed to continue recording fields and particles data was initiated but did not run to completion because of the specific type of hardware anomaly. This problem was resolved as Galileo moved outside the region of highest radiation levels. The second problem occurred when high-energy protons were encountered with sufficient flux to case significant displacement damage in optical electronic circuits responsible for control of the tape recorder drive mechanism. The resolution of this anomaly is discussed in Section 3.2.

Designed to withstand 150 krad inside a 2.2 g/cm^2 shell, the spacecraft is remarkably healthy after sustaining over 650 krad but is showing the effects of both age and radiation. Radiation effects include damage to electronic parts in the attitude control subsystem, the computer memory, the tape recorder and some science instruments. Software patches and modified operating strategies were implemented to work around most of the radiation effects. A summary of spacecraft performance in the harsh jovian environment and a report of final subsystem and instrument status are provided.

1. Introduction

Galileo's fourteen-year journey of discovery ended with the planned entry of the orbiter into the clouds of Jupiter on September 21, 2003. Figure 1 shows the spacecraft's path since it launched on October 18, 1989 including its subsequent progress over halfway around the sun as it orbited the giant planet. Since entering the Jupiter system in December 1995, Galileo has achieved a total of 29 (out of 32) successful encounters,

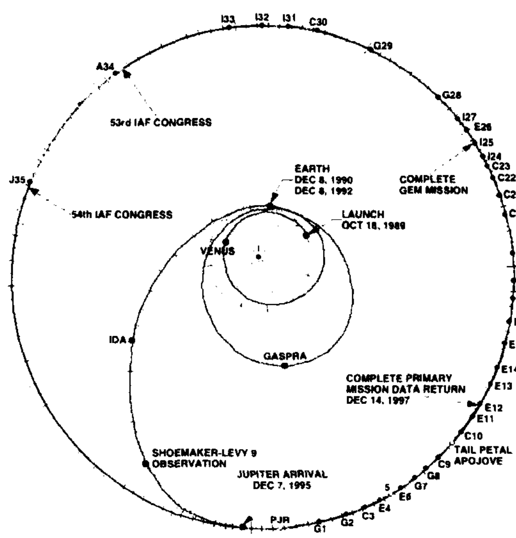

Figure 1. Heliocentric Progress

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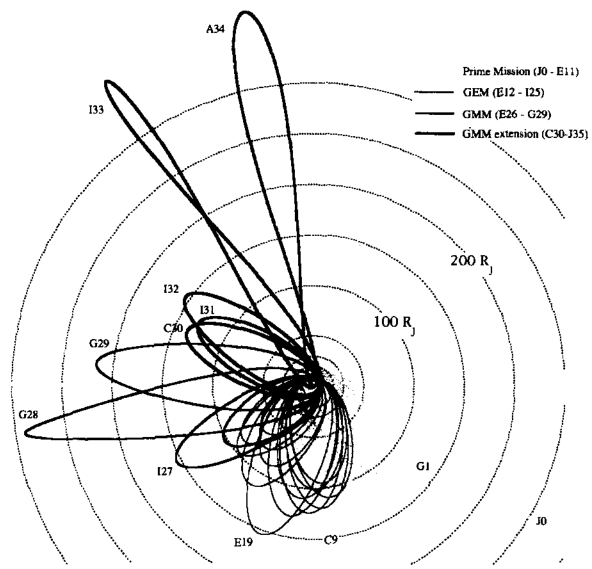

Figure 2. Galileo's Orbital Tour at Jupiter.

exploring the four Galilean satellites (Io, Europa, Ganymede, and Callisto); Jupiter's atmosphere, magnetosphere, and rings; and some of the minor satellites. Figure 2 shows details of the three-phase orbital tour around Jupiter: the prime mission [1,2], the Galileo Europa Mission (GEM) [3,4], and the Galileo Millennium Mission (GMM) [5-7].

Galileo's final year has continued the project's legacy of meeting difficulties, only to overcome them and to make exciting discoveries. Although there was only a single encounter, Amalthea 34 (A34), the nature of that encounter and the harsh environment of the flyby presented challenges to the flight team both in preparing for it and in recovering from this risky passage through the radiation belts (See Sections 3 and 5). The spacecraft fared better than could be expected and the high priority science objectives were achieved despite significant problems (discussed in greater detail below). Obtained one-way and two-way Doppler data yielded the first ever density determination for one of Jupiter's small inner moons. A unique sample of the magnetospheric environment from Io's orbit (5.9 Jupiter Radii, or R_J; 1 R_J is approximately 71,500 km) to just inside Amalthea's orbit (2.5 R_J) was captured on tape before the spacecraft entered safe mode 16 minutes after closest approach to Amalthea. Playback of this valuable data set was jeopardized by a serious, radiation-induced problem with the tape recorder drive system. After a month of activities to anneal the affected optical electronic parts, playback began in mid-December and all of the priority data were returned by the end of February. The spacecraft was then configured for six and a half months of unattended operations, including commands to collect real-time science during the final approach to Jupiter (See Section 7). Starting in March, the Deep Space Network Operations Chief routinely monitored weekly tracking passes, noting status in the daily log, and alerting the project of any tracking anomalies.

The experience of operating a long-lived spacecraft within a high radiation environment and documentation of the hardware effects will aid the design of future missions to the jovian system. Aging and exposure to more than four times the radiation design margins have taken their toll on spacecraft components[8]. Effects were manifested as degraded performance of some engineering subsystems and science instruments as discussed in the performance overview summarizing final spacecraft status as of April 2003 (See Section 2). New and recurring anomalies over the past year are discussed in Sections 3 and 4.

Before the end of mission operations on February 28, 2003, a pair of Jupiter 35 science command sequences (nominal and contingency) were loaded into spacecraft memory. These are planned to kick off 19 hours before impact (12 hours for the contingency sequence). The intent is to capture real-time electromagnetic field, charged particle, and dust data from 14 R_J to occultation ingress at about 1.13 R_J inbound to perijove. Actual entry of the spacecraft into the atmosphere occurs about seven minutes later on the far side of the planet during the communications blackout. Section 7 discusses plans for the final day of Galileo.

2. Orbiter Performance Overview

2.1 Summary

The Galileo Orbiter has proven to be remarkably robust, greatly exceeding design expectations. After fourteen years in flight and withstanding >650 krad of radiation (modeled for a 2.2 g/cm^2 aluminum shell), all major subsystems and all but one instrument are still functioning. Significant damage to parts has been overcome by flight software modifications, changes to operational strategies, and revised science observation plans. Reference 8 discusses hardware failures in connection to radiation affects up through the Io 33 encounter in January 2002. A plot showing the onset of specific failures versus cumulative radiation dose is given in Figure 3.

Table 1 lists each spacecraft subsystem, any anomalous behavior at the Amalthea 34 encounter, previous anomalies since launch, and final status. Because of design issues for the encounter, or serious anomalies in the past year, the Attitude and Articulation Control Subsystem (AACS) and the Data Management Subsystem (DMS) are discussed in more depth in Sections 2.2, 3.1, and 3.2 respectively.

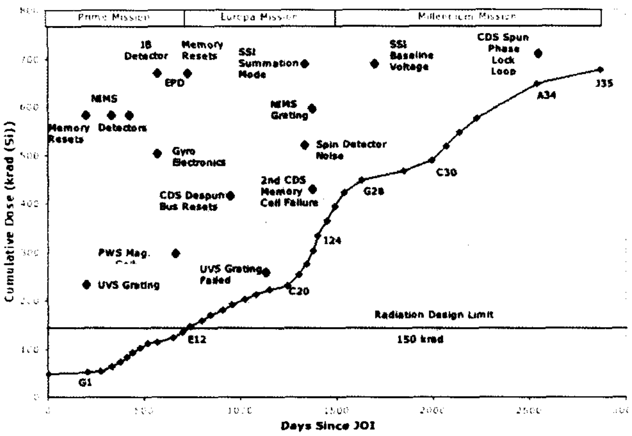

Figure 3. Spacecraft Anomaly Overview.

2.2 Attitude And Articulation Control Subsystem (AACS)

AACS has functioned nominally in the past year. Most of the gyro axes continue their pattern of degradation during encounter and annealing during the cruise portion of an orbit (Figure 4). The maximum discrepancy on the worst case axis was seen 63 days after Amalthea 34 perijove when gyro output was 104.3% more pulses than expected when sensing motion. This is statistically no different than the discrepancy of 103.8% observed 8 days after passing through the intense radiation. This lack of significant annealing supports the theory proposed in 1998 that predicted the maximum degradation would be 100%[4]. At this value, the gyros are putting out twice as many pulses as they should. The gyros were used for the last time on January 14, 2003 to execute an 18° turn, which set up the attitude for tracking the spacecraft in September.

With the absence of remote sensing at Amalthea, the objective of AACS during the encounter was slightly different compared to all previous encounters. All that was required for the fields and particles instruments was an accurate representation of the spin rate. A single bright star (OSAD - one star attitude determination[5,15]) provided the fixed rotor attitude estimate; however, during a period of obscuration of Vega (the OSAD star) multiple restarts of the star scanner's attitude determination software were expected. Besides being an off-nominal condition, these software restarts would cause a disruption in the star scanner's reporting of spin rate and in some of the science instruments' ability to collect data. A hibernation strategy was developed to keep the star scanner software from restarting, even when Vega could not be seen, either due to a physical blockage by Jupiter or due to radiation swamping the star scanner signal.

During the encounter, the instruments received the spin data they required up until the time of the spacecraft entry into safe mode. However, it appears as if environmental effects (e.g., gravity gradient torques) caused the spacecraft to very slightly change its rotor attitude and spin rate during the time the star scanner was "hibernated." Even though this change was only slight, it propagated over a period of hours. When the star scanner was reconfigured to allow for Vega to be seen and processed by the flight software, it was unable to do so accurately and consequently the software autonomously restarted. Within a few hours, Vega was recognized by the star scanner's software and AACS resumed nominal operations without requiring ground intervention.

Given the "once-in-a-lifetime" opportunity of flying through the inner magnetosphere and the demonstrated ability of the star scanner to sense the electron flux[8], AACS was allowed to configure the star scanner in such a manner to collect data even during the hibernation period. This means that the star scanner software would ignore data output by the scanner. Since safe mode cancelled the science sequence, the AACS star scanner was the only subsystem still collecting radiation data through periapsis.

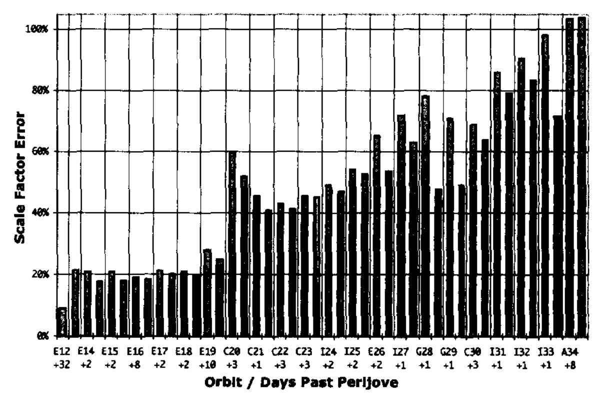

Figure 4. Gyro Performance.

3. Non-Instrument Anomalies

3. 1 Phase Lock Loop Problems

Following the Amalthea encounter the CDS String-B was in the "down" state and the spacecraft fault protection routine had placed the spacecraft in a safe state. Once telemetry was restored it was determined that numerous problems had occurred. Some of these problems had been seen before (i.e., five Despun Bus Resets). A new problem was the swapping of the CDS

Table 1. Final Status of Orbiter Subsystems

Subsystem	A34 Anomalies/Radiation Effects	Previous Anomalies	Final Status
Attitude and Articulation Control Subsystem (AACS)	During encounter: (See Section 2.2) After encounter: minor increase in attitude drift.	Gyro degradation, 1997 – Present[3-5, 7] Star scanner browning, 1997 – Present[4] Spin detector degradation[5]	Gyros: See Section 2.2 Star Scanner sensitivity decrease ~13%, varies with star color. Spin Detector disabled.
Command and Data Subsystem (CDS)	Timing Chain swaps (See Section 3.1)	Despun bus resets, 1989 – Present[3-5, 7, 9-12] One-byte memory corruption, 1994[12, 13], 1999[5]	All flight s/w functioning. 2 bad memory addresses.
Data Memory Subsystem (DMS)	Commutator Failure (See Section 3.2)	Sticking, 1995[1, 2, 12] Sticking, 2001-02[7]	Functionality limited to <1 hr continuous operation. "Stickiness" seems to be getting worse.
Power/Pyrotechnic Subsystem (PPS)	None	AC/DC bus imbalances, 1989 – Present[11, 12]	Steady decrease ~7W/yr. Predicted power 435W as of September 21, 2003.
Rocket-Propulsion Module (RPM)	None	Pressure transducer drift, 1989 - Present[12] Apparent valve problem, 1995[1]	4-17 Kg of propellant remain out of the 959 Kg loaded.
Temperature Control Subsystem	None	None	Cooling due to RHU degradation as expected.
Telecommunications Subsystem	Bit flip in command buffer; no action required. USO frequency decreased ~89Hz (as expected).	LGA drive, 1990 – Present[2, 4, 12] HGA failed deployment, 1991[9,12, 14] Helix current, 1991-92[12] USO aging, 1995 – Present[2, 4, 12] VCO voltage drift, 1996 – Present[3, 12] Unexpected lock changes[3, 12]	S-band is nominal. USO frequency continues to drift, reaching a low of 2294997435 Hz as of May 2003.

Timing Chains and the resultant Power-On-Reset (POR) signals. These caused the CDS to enter recovery software routines and terminated the encounter sequence. The source of both these problems is thought to be radiation effects on the CDS Phase Lock Loops (PLLs). A loss of synchronization between spun- and despun-side PLLs causes Timing Chain swaps. It appears that the higher radiation levels experienced in this encounter affected both the despun PLLs (as expected) as well as the spun PLLs (which have more protection from radiation). Five Timing Chain swaps occurred on CDS String-B and one on CDS String-A, leaving both Strings on the backup timing chain. The CDS has been stable in this configuration since exiting the near-Jupiter environment.

The Galileo CDS has dual strings. Each string can execute all of the required CDS hardware functions and has elements, including a Phase Lock Loop (PLL), on both the spun and despun sections of the spacecraft. These four PLLs provide most of the timing signals for the CDS hardware. Each PLL synchronizes its internal voltage-controlled oscillator to an input signal from one of the CDS Timing Chains that are derived from crystal controlled oscillators. Normally, all four PLLs are connected to the same Timing Chain. However, if synchronization is lost on a spun PLL, both PLLs (spun and despun) on that particular string switch to the backup Timing Chain. If synchronization again fails, then that CDS string has no timing reference and becomes inoperable. If the two strings are each relying on separate timing chains, then any CDS operations requiring both strings become problematic (due to the loss of coherence). Any swap of timing chains by a spun-side PLL generates a Power-On-Reset (POR) signal for that string. However, if a despun PLL loses synchronization, it does not cause a swap to the other timing chain. This is because it receives its timing input from the output of the spun PLL. Loss of synchronization by a despun PLL does generates a despun bus reset signal.

There have been numerous despun bus resets during the Galileo mission, one group occurring primarily during cruise between Earth and Jupiter, and another group which began in 1998, during the first extended mission. The latter are believed to be caused by the radiation effects on the PLLs. Radiation can cause noise within the PLL circuitry itself, which is considered to be the most radiation-sensitive within the CDS. Radiation is also thought to increase the ground noise level between the spun and despun sides. This latter effect would be seen at inputs to the despun PLLs and may explain simultaneous problems with both string's despun PLLs (i.e., the despun bus reset anomalies).

Problems with the spun PLLs were not seen prior to the Amalthea encounter. The spun PLLs are better shielded from radiation than the despun PLLs, which is consistent with the appearance of the Timing Chain swaps only in the high-radiation environment inside ~2.5 R_J.

The first spun POR occurred at 02-309/06:35 (16 minutes after the closest approach to Amalthea, 49 minutes before perijove) at a range of about 2.3 R_J. Overall CDS String-B had five Timing Chain swaps and CDS String-A had one Timing Chain swap which left both CDS strings on the other Timing Chain where they have remained. CDS string-A also had five indications of Despun Bus Resets. The total time from start to end of these events is not known due to an overflow of the error buffers combined with delays in locking onto the telemetry at the tracking station after the near-Jupiter radio occultation. Once contact was re-established, standard recovery files were sent to the spacecraft to obtain more information on the errors and to make the spacecraft fully operational. The timing of the Despun Events is not known in relationship to the other events.

3. 2 Tape Recorder Drive Mechanism

On November 8, 2002 a tape slew command was radiated to the spacecraft. Two sticking events had occurred in the past year[7], and there was a desire to verify that the tape had not stuck after being halted by safing during the Amalthea flyby. The commanded slew resulted in a signature consistent with a stuck tape. Further checkout slews showed the servo current signature matching that of previous tape sticking incidents (Figure 5), but also manifested high current levels indicative of a tape motor stall event. The latter signature had not been seen previously. Two hypotheses were consistent with these data: failure of the tachometer or failure of the commutation logic circuit for the drive motor. In either scenario, radiation would have damaged optical sensors (LEDs and phototransistors) which control the drive motor for the tape. A tachometer failure could lead to uncontrolled tape motion at the motor's maximum speed, but with no reported tic motion. In such a case there was a significant risk of (1) throwing a tape loop and causing an irreversible failure of the DMS or (2) unintentionally moving outside the operating region of tape defined in the wake of the 1995 DMS anomaly[1], which could also lead to irreversible failure. A commutation logic circuit problem, in which a failure

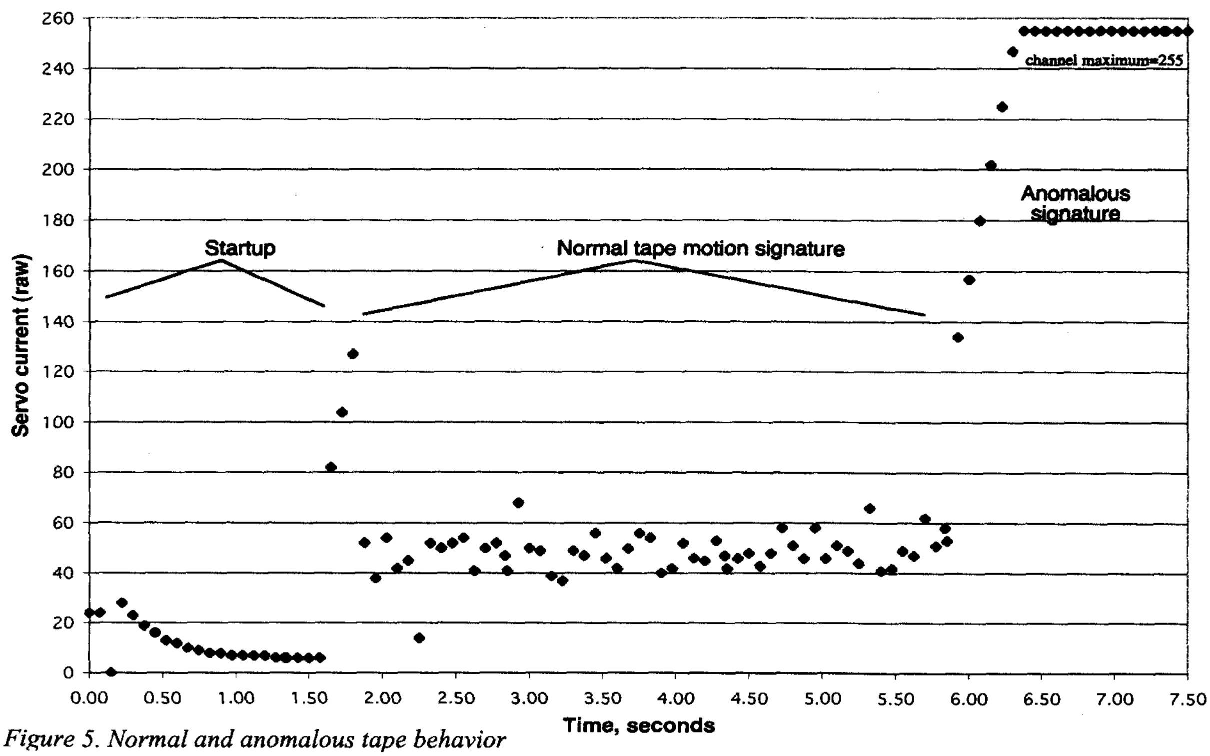

Figure 5. Normal and anomalous tape behavior

of one or more of the three optical sensors controlling drive motor timing occurs, would result in no tape motion. The DMS engineer began running tests on several spare tape recorders in his lab to differentiate between the failure modes.

In the next spacecraft test the servo and bus current signatures matched that of the previous test, but 7 tics of tape motion resulted. The commanded slew should have only caused 1-2 tics of tape motion; suggestive of an intermittent tachometer failure. It was not known how the commutator logic failure could result in 7 tics of motion.

Consultation with JPL radiation experts indicated that GaAs LEDs such as those used in the recorder are subject to radiation displacement damage, and that such damage can be partially annealed at room temperatures by running charge through the LEDs. In order to run current through the optical circuits while avoiding possible high-speed tape motion and/or a high-power stall condition, the recorder was placed into a special hardware lockout mode in which the DMS electronics are powered up, including opto-electronics associated with the tachometer and motor commutation logic, but the motor itself is not being driven. The tape slip monitor was disabled in order to prevent fault protection from prematurely ending the special hardware lockout. The DMS was placed in this condition for 6 hours on November 26 to try to anneal the circuit. Six hours was chosen on the basis of a recommendation to run 100+ coulombs through the electronics. A short forward/reverse test was performed 18 hours later, with short duration of tape movements in order to mitigate risk in the case of a tachometer failure. Telemetry indicated a small amount (0.5 seconds) of normal motion in the forward direction before the DMS re-entered the anomalous state, and a strange signature (momentarily dropping out of the anomalous state after entering it) accompanied by one tic of motion during the reverse portion. The commutation logic was now assumed to be the failure mode, as these signatures did not match a tachometer failure. The 6-hour anneal and checkout were repeated to put more charge through the LED's. When a checkout was performed (4 hours after annealing), the tape exhibited normal behavior for up to 1.8 seconds before entering the anomalous state (Figure 5). The DMS was then placed into lockout mode for 24 hours to add more annealing time followed immediately by a checkout. Interestingly, the entry into lockout mode prior to annealing showed normal tape motion with no sign of anomalous behavior, but both the forward and reverse checkout slews after annealing showed only the anomalous behavior. DMS testing had indicated some temperature dependence of the opto-electronics, with

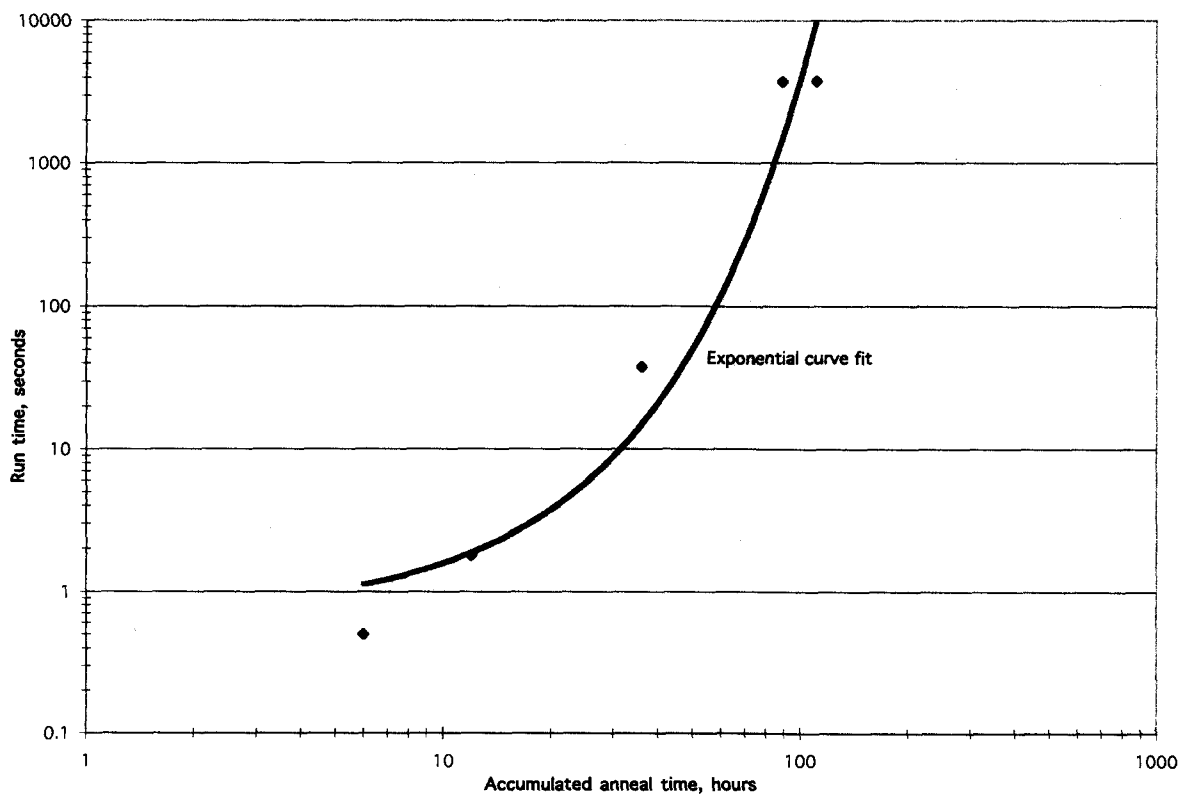

Figure 6. DMS anneal vs. run time

temperatures outside a relatively narrow range yielding decreased performance. Heat dissipation by the DMS electronics was observed to raise DMS temperature about 1°C in 3 hours. Hypothesizing that optoelectronic performance was improved by decreases in temperature, the checkout portion was redone after the DMS had cooled about 12 hours and both a short forward and reverse motion exhibited normal behavior.

The flight team then decided to try slewing the tape about 4 hours, on December 6, with the intent of starting playback of the highest-priority science data from the Amalthea 34 flyby. Disappointingly, the tape only moved 38 seconds before entering the anomalous state. The DMS was then placed back in the lockout mode over the weekend.

It appeared that there was possibly a logarithmic relationship between anneal time and length of motion (Figure 6). The recorder optoelectronics had accumulated 36 hours of anneal time to that point; an additional 53 hours (89 total) were added over the weekend. A long slew was attempted on December 9 and the recorder moved for 62 minutes before temperatures rose enough to return the recorder to the anomalous state. Lockout mode was entered for a further 22 hours (111 hours total anneal time), and a long slew was tried again on December 10. This time the extra annealing had no effect, and the tape only moved for 63 minutes. It was decided that as further annealing may have no effect, playback would have to be subject to the observed limitations on recorder heating. Although it appeared the tape could safely run for an hour before overheating, a conservative approach using a 20% duty cycle was chosen. The tape was run for 20 minutes and then paused for 80 minutes for the reposition slews. The playback strategy itself had to prevent the occurrence of any slews longer than 20 minutes. Despite these constraints playback was initiated on December 11 and successfully completed on February 28, 2003.

The source of the problem was almost certainly displacement damage to LEDs in the tape recorder's opto-electronics caused by a high flux rates of high-energy protons known to be present in Jupiter's inner radiation belts. Similar damage has been observed in LEDs aboard Earth-orbiting spacecraft, and the annealing strategy used by Galileo was proposed on the basis of experience with such events. It is remarkable that the damage to the LEDs was sufficient to keep the recorder from operating prior to annealing, but that with annealing, enough function was restored to operate the DMS for sufficiently long intervals to allow playback of recorded data. Had the range in temperature in which the recorder would operate been much higher or lower, or had the time interval during which the recorder could move been a few minutes instead of approximately one hour, it is likely that little or no data could have been returned from the inner radiation belts of Jupiter.

4. Instrument Status

Status for each instrument, any anomalous behavior at the Amalthea 34 encounter in November 2002, and a summary of previous anomalies since launch are all shown in Table 1. There have been no substantive changes to the instruments in the past year.

5. Galileo Performance at Amalthea

The flyby of Amalthea and accompanying perijove pass represented an extraordinary challenge to the aging Galileo spacecraft and the small extended mission Flight Team. Galileo, with its complement of six fields and particles instruments, was to fly far nearer to Jupiter than any spacecraft except Pioneer 11 and the Galileo probe. During the single flyby, the orbiter was expected to absorb approximately 75 krad – one-half of its design lifetime dosage – after already receiving >600 krad over the previous seven years of operation in the Jovian System.

As reported previously[7], the risks posed by this flyby and a number of strategies to mitigate those risks were examined during the months leading up to the Amalthea encounter. This process was significantly complicated by the stuck-tape anomaly that occurred in April 2002[7]. Analysis of the anomaly, and the painstaking efforts to safely restore the tape recorder to a useful condition required nearly all of the attention of key members of the Flight Team for most of the period May through August. Despite this difficulty, significant contingency plans were conceived, tested, and implemented in time for the riskiest flyby of Galileo's mission.

Below, we describe the techniques that were implemented to increase the likelihood of success at Amalthea 34, along with an assessment of each one. We then discuss some aspects of the approach taken by the Galileo Team and lessons learned which might be useful to future missions. It is clear that good fault protection, hardware designed for "worst-case" conditions, and a robust nominal command sequence represent the most effective mitigations against the risk of unique or unknown environments.

5.1 Contingency Preparations

Prior to the Amalthea flyby, there were four major perceived challenges posed by the extremely high radiation levels Galileo would experience:

- Maintaining attitude knowledge during a period of up to seven hours when the star scanner would be blinded by high levels of radiation-induced

Table 2. Final Status of Orbiter Science Instruments

Instrument	A34 Anomalies	Previous Anomalies	Final Status
DDS (Dust Detector Subsystem)	None	Memory corruption, 1991[12]	Nominal
EPD (Energetic Particle Detector)	None	Autonomous shutdown 1996[1, 2] Power-on reset, 1998[3] Voltage drop, 1999[5] Temperature fluctuations, 2000[5] Transient memory corruption, 2000-2001[6]	Unexpectedly enters standby mode. Instrument memory reloaded by sequence.
EUV (Extreme UV spectrometer)	None	None	Nominal
HIC (Heavy Ion Counter)	None	None	Nominal
MAG (Magnetometer)	None	Transient memory corruption, 1997 – Present[2, 3] Flipper did not flip, 1996[2]	Nominal
NIMS (Near Infrared Mapping Spectrometer)	Not in use	Transient memory corruption, 1996 – Present[1,7] 2 detectors failed, 1996-97[2] Grating failure, 1999[5]	2 out of 17 detectors failed. Stuck grating limits observations to thermal and compositional mapping. Periodic software halts accounted for by reloading memory by sequence.
PLS (Plasma Subsystem)	PLS experienced a POR which failed to re-load its memory. 2 days later temperatures indicated shut off of either the instrument or a supplemental heater.	Stuck memory bit, ?? [2] Parity error, 1998[4]	The PLS was powered on and its memory reloaded. 3 out of 6 electron detectors are nominal.
PPR (Photopolarimetry/ Radiometry subsystem)	Not in use	Filter wheel sticking, 1996[2] Loss of radiometry channel, 1999[4]	Nominal
PWS (Plasma Wave Subsystem)	None	Magnetic coil data degradation, 1997[3]	Electric field measurements are nominal. 5 Hz to 3.5 kHz magnetic search coil failed.
SSI (Solid State Imager)	Not in use	Summation mode corruption, 1999[5] Baseline stabilization voltage anomaly, 2000 – Present[6, 7]	Summation data modes not being used due to radiation-induced timing problems. Damaged opamp or JFET in sample and hold circuitry. Erase mode permanently disabled[16].
UVS (Ultraviolet Spectrometer)	Not in use	Grating stepping problems, 1996 – Present [2]	Grating cannot be controlled. Declared non-operational 1999[4]

noise, and with gyros that were known to be vulnerable to radiation.

- The potential for spurious electrical signals across the spin bearing assembly between the rotating ("rotor") and non-rotating ("stator") portions of the orbiter. These events, which appeared as spurious despun bus POR signals and/or parity errors, had been remedied by a patch to flight software. A new manifestation occurred at the Io 33 encounter[7], causing loss of most of the observations planned for that flyby.
- A recurrence of the stuck-tape anomaly.
- A radiation-induced SEU or permanent bit-hit, causing a major subsystem failure.

The strategy for maintaining attitude knowledge during the flyby is described in Section 2.2. Although there was some drift in the attitude estimate during the period of star scanner blindness, the technique was entirely successful in providing attitude information to the fields and particles instruments up until the post-Amalthea safing event.

Two options were considered for dealing with despun bus-related problems. The first was a patch to the existing flight software modification, allowing it to reject anomalies that were manifested as parity errors only, without a spurious POR signal. This patch would allow Galileo to ride through a repeat of the Io 33 encounter anomaly without canceling the sequence of science observations. A second proposed approach was more radical, and would essentially make the orbiter insensitive to any and all errors occurring in the despun portion of the spacecraft. Although both techniques were implemented and tested on the Galileo testbed, only the former was used on the spacecraft. Galileo experienced multiple spurious despun bus resets during the flyby. All would have been caught by the original flight software patch. There were no recurrences of the Io 33 encounter event, nor were there any new problems that could be traced to the spin bearing assembly or the communication of signals across it. Neither approach would have been effective mitigation for the Phase-Lock Loop problems described in Section 3.1.

Recovery from the stuck-tape anomaly in late Spring of 2002[7] included a long-running series of activities intended to condition the tape and ensure that it could be used for the Amalthea flyby. Although options were considered for onboard response to a tape stick event, the success of the conditioning activities indicated that much of the risk of such an event had been mitigated. In addition, an autonomous onboard response during the encounter might put at risk any data that had been recorded prior to a tape stick. Thus, there were no major changes to software made for this particular issue.

The occurrence of an SEU or bit-hit to an important or critical portion of memory was a real concern. Such an event caused the loss of a significant fraction of the planned observations during the Io 24 encounter[5]. In addition, it was recognized that the high radiation levels near Jupiter could cause anomalies that had neither been expressed previously nor could be predicted. To deal with such anomalies, two approaches were used. The first was the now-standard Galileo process of preparing contingency commands and/or command sequences for use in the case of anomalies that occur within specific time periods. The second was to make a number of specific alterations to fault protection routines onboard which would (a) make it easier to recover from a fault and return to collecting science via ground command and (b) allow fault protection routines to kick off a series of commands to science instruments and the tape recorder to resume observations in the event of all but the most critical spacecraft anomalies.

Changes to fault protection included allowing instrument data to flow to the tape recorder if one of the two flight computers was taken down by fault protection, to place tape recorder track and tic information into bus tables where they'd be readily available to flight software, and to avoid turning off particular instruments in the event of a fault. These changes did simplify recovery after the timing chain-related anomalies.

The addition of an autonomous safing response that included the collection of science data was the most ambitious of the contingency plans assembled for the Amalthea 34 flyby. It was implemented by changing the function of an essentially unused branch of the fault protection logic to start up a contingency sequence to do the minimal necessary configuration of science instruments, restart the tape recorder (which is stopped by the initial call to spacecraft safing), and monitor and control the recording so that it would continue through at least the region inside Io's orbit. Tape recorder tic and track information were obtained from bus tables (see above), and were monitored to allow recording to continue over multiple tracks, regardless of the starting point. The routine was also designed to be re-entrant, allowing for recovery even after multiple anomalies.

Although the autonomous response was triggered by the first call to safing during the encounter, the character of the anomaly did not allow the response to proceed. The response had been designed such that if indicators showed power-related problems, the sequence of commands would not be carried through. Since the Phase Lock Loop anomalies produced these indicators, the response was halted. Given the nature of the anomalies, little or no useful science data would have been collected had the contingency sequence run to completion. Moreover, repeated attempts to restart the science sequence could have placed the data already obtained at risk.

5.2 Evaluation of Approach to Risk at Amalthea

Conditions for the Galileo Project at the Amalthea flyby allowed a somewhat different approach to risk for this encounter than had been adopted in the past. Because this was to be Galileo's last encounter, and because the spacecraft was already known to be on an impact trajectory with Jupiter (subsequent to the Io 33 flyby), it was possible to consider strategies that had more than the minimum risk that the spacecraft would be unusable after the flyby. The approach adopted was to (1) place highest priority on creating a robust nominal plan of commands and observations for the encounter and (2) allow investigation and implementation of contingency procedures that would not have been considered previously. The latter activities included most of the flight software and fault-protection changes that are described above.

The willingness to take on additional risk and try new approaches was strongly tempered by a desire to avoid mistakes that might imperil the nominal encounter observations. Although not as comprehensive as would have been possible in prime mission, considerable analysis, testing, and review was conducted before any changes were accepted by the Project and placed onboard. The availability of key personnel and the Galileo Testbed were critical enablers for allowing changes to be made safely.

It is clear that few of the contingency processes put in place were actually used in the Amalthea flyby, and none of them added significantly to the science return. Neither did any of them create problems or cause the loss of any data. A sound plan for the nominal encounter sequence of observations, backed up by well-tested fault protection responses designed primarily to do no harm, executed on a spacecraft that was built and designed with generous margins appear to be the most effective approaches to ensuring mission success (i.e., the return of valuable science data) from unknown, hostile environments like the inner radiation belts at Jupiter.

6. Summary Of Amalthea Encounter

The final encounter of the GMM and first targeted flyby of a minor satellite of Jupiter occurred on November 5, 2002 at 06:19 UTC, when the spacecraft flew 163 km above the surface of Amalthea (Figures 7a and 7b). The speed of the spacecraft relative to Amalthea was approximately 18.4 kilometers per second (41,000 miles per hour), taking less than 15 seconds to pass by. The spacecraft entered Earth occultation 22 minutes after closest approach to Amalthea, at 06:41 UTC, during which it passed closest approach to Jupiter at 2.0 R_J, only 71,500 km above the visible cloud tops, at 07:24 UTC. This is nearly three times closer than during Jupiter Orbit Insertion in 1995. Approximately 16 minutes after zipping by the tiny satellite, as the spacecraft neared perijove, the intensity of the radiation caused the timing chain problems and calls to safing discussed in Section 3.1. Prior to entering the safe mode, the spacecraft successfully captured nearly two full tracks of recorded science data, including the orbiter instruments' first taste of the environment well inside 4 R_J. Fields and particles science data was recorded until 06:35 UTC, inside of 2.5 R_J.

The Amalthea 34 encounter sequence began at 10:00 UTC on November 2, 2002, and was designed to last for 7 days until November 9, 2002 at 10:00 UTC. Following safing and termination of this sequence on November 5, real-time recovery activities lasted until November 13, 2002 at 15:00 UTC, when a cruise sequence was loaded on the spacecraft. Science observations of the relatively unexplored region of the Jovian system focused on in-situ measurements of the magnetosphere and the Gossamer ring along with radio science experiments. The fields and particles instruments began collecting real-time science approximately 12 days prior to the beginning of Amalthea 34, during Io 33 cruise, near the bow shock of the magnetosphere. Several dumps of the multi-use

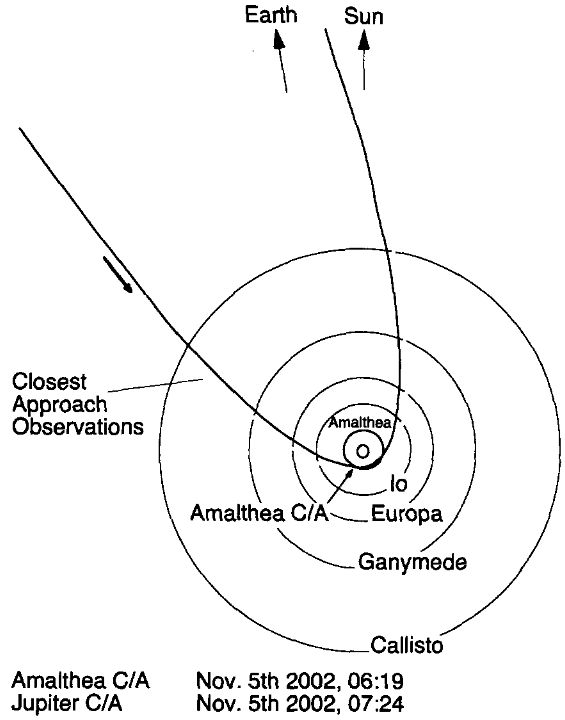

Figure 7a. Amalthea 34 Encounter Trajectory

buffer (used for short term science data storage) to the tape recorder were performed to provide continuity in the real-time science data prior to the encounter. Once the spacecraft reached approximately 32 R_J inbound, instruments started to record data on track 4 around plasma sheet crossings, studying the auroral region in high resolution. Six plasma sheet crossings recordings were executed, at 31.6 R_J, 29.2 R_J, 26.5 R_J, 23.8 R_J, 20.7 R_J, and 10.3 R_J; each lasting approximately 45 minutes and centered around the expected plasma sheet crossing time. Following this, the instruments began continuous recording for approximately 9 hours, from 7.6 R_J inbound to 6.5 R_J outbound. The plan was to use three full tracks of tape (Tracks 1 – 3).

Tracks 1 and 3 used a strategy of alternating tape usage between longer periods of low-rate recordings and shorter, high-rate "jail bar" recordings of PWS data. With brief (~47 seconds) periodic snippets of high-rate data, the PWS was able to search for wave features with both high spectral and high temporal resolution. The most obvious known phenomenon to study with such observations were lightning whistlers, which were observed by Voyager but had not yet been seen by Galileo (because of the primary use of lower rate waveform data instead of the higher rate). Also during this time period, the dust detector (DDS) was set to capture data from the passage through the Gossamer Ring. No in-situ data were available from

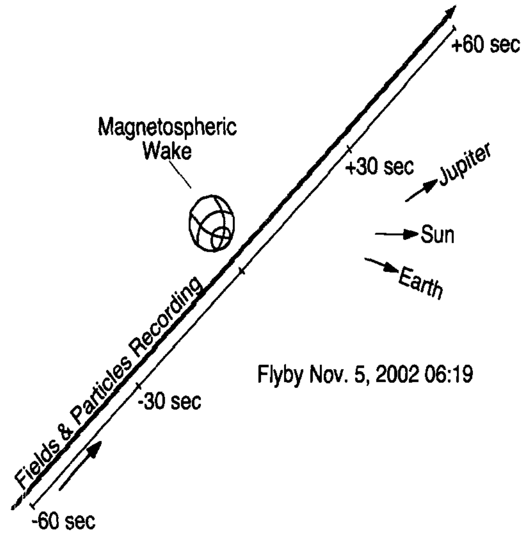

Figure 7b. Amalthea 34 Flyby Geometry.

the gossamer ring region prior to this flyby. Dust measurements in the ring complement existing remote sensing data, which have been used to infer particle sizes and the spatial distribution of dust in this region. The DDS instrument did obtain samples from within the Gossamer Ring prior to spacecraft safing.

On Track 2 was a continuous recording of high rate PWS data, allowing traversal of this track in only 28 minutes. All four tracks were planned to have been fully recorded at this point, but the intent was to continue with outbound plasma sheet crossing recordings on half of track 2, overwriting 14 minutes of previously acquired data near Perijove. Due to the safing, science data collection was terminated 85% of the way through Track 1 recording, and real-time science data collection was terminated as well.

A planned Radio Science Occultation Experiment was unsuccessful because of a failure to lock on to the two-way signal at the beginning of the tracking pass for egress. At the time of the flyby, the success of the Amalthea gravity experiment was questionable because two-way Doppler was not achieved. Four attempts to acquire two-way data were made in the 5 hours leading up to the flyby, but frequency variation across the pass was larger than anticipated in determining the predict uplink acquisition sweep. However, the Radio Science and Navigation teams were able to obtain a mass determination using one-way Doppler data and post-navigation reconstruction of the fly-by trajectory.

Following the safing recovery, it appeared that the spacecraft systems, though showing expected additional wear and tear due to the radiation exposure, were all still in operating condition. The highly anticipated return of the unique fields and particles data recorded inside Io's orbit was delayed by the radiation damage to the tape recorder-driven mechanism (Section 3.2). The tape recorder was recovered in time to begin playback on December 11, 2002 and, before the end of playback operations on February 28, 2003, 58% of the original data volume planned for was returned, including a continuous profile of the inner magnetosphere from Io's orbit to just inside Amalthea's. The Galileo Project extended operations a month-and-a-half beyond the planned mission end date in order to continue playback. Other projects using the Deep Space Network released tracking time to facilitate the return of this valuable data set.

7. Jupiter Impact

Galileo's historic journey comes to an end September 21, 2003 at 18:57 UTC as the spacecraft plunges into the atmosphere of Jupiter. Current estimates of the impact time, entry angle, location, and velocity, as referenced to the 1 bar pressure level, are given in Table 3 and the flight path is shown in Figure 8. Disposal of the spacecraft, as mutually agreed upon by the Project and NASA Headquarters, is desirable for planetary protection purposes: a result of the mission's own success. Evidence supporting the existence of liquid water on Europa raises the possibility that life may have developed on that frozen moon. The planned destruction of Galileo removes any risk of forward contamination of Europa by an inadvertent impact if the spacecraft were left in an uncontrolled orbit.

Table 3. Impact Characteristics (Estimated)

Impact Time	21 Sept. 2003 18:57:16 UTC
Inertial Flight Path Angle	-22.2 deg
Body Relative* Flight Path Angle	-27.8 deg
Latitude	-0.2 deg
Longitude	191.6 deg
Inertial Velocity	59.7 km/s
Body Relative* Velocity	48.2 km/s

* Relative to the Jovian atmosphere

In its final twelve hours, Galileo is set to sample the magnetosphere and rings with its suite of fields and particles instruments. The magnetometer is deselected from the real-time data stream at about 3 R_J, at which point its detectors are saturated. Science data return at a rate of 20 bits per second continues until the spacecraft enters occultation about 7 minutes before impact. The science strategy is designed such that the onboard data storage buffer will be empty at this point, ensuring that the higher priority data can be processed and sent to the

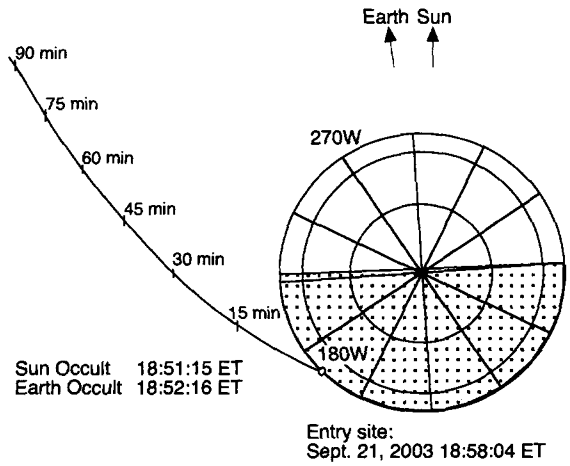

Figure 8. Jupiter35 Impact Trajectory

ground before losing the communications link. Radio science is planning a propagation experiment during the occultation ingress.

One of the significant challenges is maintaining signal lock as Jupiter's gravitational pull causes a shift in downlink frequency. The strategy is to switch to residual carrier about five and a half hours before impact to increase the probability that open loop receivers will be able to stay locked on the carrier and telemetry longer than using suppressed carrier and closed loop receivers. No uplink for either commanding or Doppler is planned over the final two passes. Other engineering strategies are based on those implemented for the Amalthea encounter last year. As Galileo passes once again inside of 2.5 R_J, it is expected to experience similar radiation issues as it did in November and will enter safe mode. No feasible workarounds were identified to protect the spacecraft and science sequence from problems such as the phase lock loop anomaly discussed in Section 3.1.

8. Summary

The overwhelming success of the Galileo Project is a testament to the dedicated and talented individuals who worked together to overcome major obstacles to leave a fourteen-year legacy of discovery. Few projects have made contributions in such wide-ranging areas of investigation: Venus, the Earth- Moon systems, asteroids, interplanetary dust, cometary impact into gaseous planets, and all aspects of the Jupiter system. The advances to science are already part of educational textbooks, inspiring the next generation of explorers, just as the results give impetus to current plans for future missions to the Jovian system. Farewell to a great team and a great mission.

9. Acknowledgements

The success of the Galileo Project results from the individual efforts of a large number of people. The Galileo Europa and Millennium Mission teams have persevered through many challenges to accomplish outstanding science results within limited resources. The work of the current team would not be possible without the efforts of team members from the past and of the science teams.

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