ASSESSMENT OF IN-FLIGHT ANOMALIES OF LONG LIFE OUTER PLANET MISSIONS

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ABSTRACT

Three unmanned planetary spacecraft to the outer planets have been controlled and operated successfully in space for an accumulated total of 66 years. The Voyager 1 and 2 spacecraft each have been in space for more than 26 years. The Galileo spacecraft was in space for 14 years, including eight years in orbit about Jupiter. During the flight operations for these missions, anomalies for the ground data system and the flight systems have been tracked using the Jet Propulsion Laboratory's anomaly reporting tool. A total of 3300 incidents, surprises, and anomaly reports have been recorded in the database. This paper describes methods and results for classifying and identifying trends relative to ground system vs. flight system, software vs. hardware, and corrective actions. There are several lessons learned from these assessments that significantly benefit the design and planning for long life missions of the future. These include the necessity for having redundancy for successful operation of the spacecraft, awareness that anomaly reporting is dependent on mission activity not the age of the spacecraft, and the need for having a program to maintain and transfer operation knowledge and tools to replacement flight team members.

1. INTRODUCTION

Long lived missions to the outer planets with remote sensing spacecraft have been successfully operated well beyond their original design life. The two Voyager spacecraft launched in 1977 having successfully completed their flybys of several different outer planets and now are leaving our solar system and flying trajectories that are taking them to interstellar space. Based on current consumables usage and continued mission operations attention the spacecraft are expected to continue to return data until 2020. The Galileo orbiter of Jupiter was launched in 1989 and was impacted into the atmosphere of Jupiter in 2003 just before its consumables were depleted. These spacecraft were conceived, designed, manufactured, tested, launched, and operated by engineers and scientists who were rigorous in their attention to processes and details. The basic designs for the Voyager and Galileo spacecraft were based on the following premises: rigorous parts program, qualified electronic packaging, simple redundancy, and good assembly level and system functional and environmental verification programs. Even with this design and verification rigor, in-flight anomalies occurred during the primary and extended phases of the missions.

A long life spacecraft is one designed to function reliably for ten or more years in the space environment. Although not designed as such, Voyager and Galileo can be viewed as prototypes for long life spacecraft. By examining these spacecraft, future designers can gain a better understanding of the technology and management approaches needed to build machines that can fly to the edges of the solar system and into interstellar space.

2. MISSION AND TECHNOLOGY DESCRIPTIONS

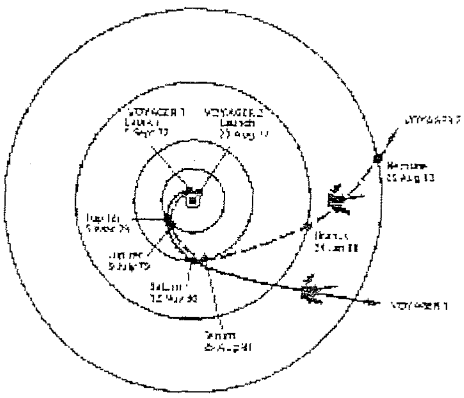
The technologies used on the Voyager and Galileo missions were state of the art when the spacecraft were designed, but by modern standards the electronics are obsolete. In the case of the Voyager missions, however, the spacecraft continue to transmit scientific and engineering data from deep space: 91 Astronomical Units (AU) from the sun for Voyager 1 and 73 AU for Voyager 2. These aging systems must continue to be actively monitored and maintained by the flight team as these spacecraft continue on their extended missions. Any long life mission needs to recognize this built in obsolescence when designing both the spacecraft and managing flight personnel for the mission team.

Key features of the Voyager and Galileo spacecraft and missions are summarized in Tables 1 and 2. Of particular interest is the lack of computer memory and data storage on all of these spacecraft and the slow communications data rate due to hardware limitations when they were designed and , for Galileo, the unavailability of downlink high data rates because of the high gain antenna failure to deploy. The primary power sources for these missions are Radioisotope Thermoelectric Generators (RTGs). Primary long distance communications for these missions is in both the S and X bands using the National Aeronautics and Space Administrations Interplanetary Network receiver stations. Examples of the mission trajectories for Voyager and Galileo are given in

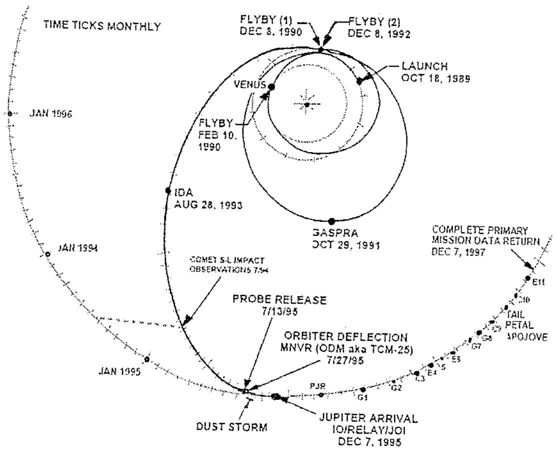
Figures 1a and 1b, and are both examples of trajectories that utilized gravity assist techniques during flybys of planetary bodies. A summary of the comprehensive environmental test program implemented for the Galileo spacecraft is given in the references [1].

Table 1. Spacecraft and Mission for Outer Planet Missions

Attribute	Voyager 1 and 2	Galileo Orbiter
Spacecraft		
Power Source	RTG (3) (Multihundred watt)	RTG (2) (General Purpose Heat Source)
Beginning of Mission May 2001	480 watts 320 watts	570 watts 449 watts
Science Instruments	10	9 Orbiter / 6 Probe
Mass	815 Kg (1797 lb)	2561 Kg (5646 lb)
Electronic Parts Engineering & Science Instruments	61,953	85,681
Temperature Control Design	Passive, louvers, RHUs, electrical heaters	Passive, louvers, RHUs, electrical heaters, closed loop computer controlled heaters
Temperature Control Operations	Active Sequence of Heating	Pointing Constrained for Shading Bus Shade (and local shading)
Solar Distances Design Range	1 AU to 10 AU	0.6 AU to 5 AU
Primary Mission Design Life	Through Saturn encounter	Five (5) Jovian orbits
Mission		
Launch Vehicle	Expendable Titan IIIE, Centaur	Shuttle w/ Inertial Upper Stage
Mission Type	Flyby	Orbiter with probe
Destination	Jupiter and Saturn	Jupiter
Launch Date Gravitational assists from	1977 Jupiter Saturn Neptune Uranus	1989 Venus Earth (2)
Distance from Sun AU (June, 2004)	Voyager 1: 91 AU Voyager 2: 73 AU	Jupiter Impact 2003



a)Voyager



b) Galileo

Figure 1. Representative Mission Trajectories for Outer Planet Missions using Gravity Assist

Table 2. Spacecraft Subsystems Technology-Engineering Subsystems

Vintage	Voyager 1 & 2 Early 70's	Galileo Late 70's
Engineering Computers Architecture Number (inc. redundancy)	Central 6	Distributed 10
Memory Type Word size	Plated wire Memory (4) CMOS (2) 18 bit word (4) 16 bit word (2) 4K words (4) 2K words (4)	CMOS (TCC244) CDS: 8 bit word (6) AACS: 16 bit word (4) CDS: 192K words/string AACS: 3 K words/string
Data Storage Type	5.1×10^8 bits Tape recorder Dual redundant	9×10^8 bits Tape recorder Single string
Communications Links Probe Radio Science/Radar TWTA RF Output Power (max) X Band S Band Data Rates Range (bits/s=bps)	S band up and down X band down 10/20 watts 10/28 watts 16 bps to 1400 bps 115.2 kbps at Jupiter	S band up and down X band down (planned) S band 10/20 watts 10/28 watts 10 bps to 134.4 kbps at Jupiter (Planned with High Gain Antenna. Actual was 160 bps effective, using source coding and the Low Gain Antenna)

Notes: CDS= Command Data Subsystem, AACS= Attitude and Articulation Control Subsystem
CMOS= Complementary Metal Oxide Semiconductor, bps=bits per second

3. IN-FLIGHT ANOMALY ASSESSMENTS

For flight missions managed by NASA's Jet Propulsion Laboratory (JPL), all in-flight anomalies are documented by Incident, Surprise, Anomaly (ISA) reports. During the flight operations for Voyager to date and for Galileo until mission end in September, 2003, nearly three thousand three hundred ISAs were generated. These were processed in a hard copy format and were subsequently transferred to an electronic database in the JPL Problem Reporting System. The assessments that have been performed for this paper are based on both the electronic versions of these ISA reports retrieved from the electronic data base and on earlier assessments from these missions [2], [3]. Because of the large quantity of anomalies recorded, an in depth assessment for all the Voyager and Galileo ISAs was beyond the scope of this study. The scope of this report was limited to determining and examining programmatic trends in the data base to improve spacecraft design, reliability, and operations for long life missions.

3.1 Redundancy Usage

Redundancy for a flight spacecraft can be achieved by the following methods: block (simple) and functional. The block redundancy consists of a duplicated hardware set that replaces a failed unit when a failure is detected. Functional redundancy consists of replacing performance function(s) by utilizing performance aspects of other subsystems. As an example, functional redundancy is used for the spacecraft high gain antenna since dual redundant large diameter antennas are not practical. A fault tolerant design for this subsystem could use a medium gain (or low gain) antenna at reduced data rates as a degraded, but acceptable, redundant system. In this case, the redundant system is not a direct duplicate of the original system but provides the same function even if in a reduced capacity. As previous assessments have noted, the use of redundancy in Voyager and Galileo has been necessary. The use of block and functional redundancy for these missions is summarized in Table 5. These redundant systems have been used during all phases of the missions: launch phase, cruise phase, encounter phase, and extended mission phase. The flight team's monitoring of engineering data, reaction, and timely assessment are key aspects of maintaining and utilizing robustness that needs to be designed into long lived spacecraft. In this regard retaining robustness in communication links is of primary importance. On board autonomous swapping of critical subsystems must also be built into the architecture of the spacecraft system when communication links are many hours long due to the distance between the spacecraft and earth. Redundancy and its usage must be evaluated in the design and resources trades that occur for long life missions. Catastrophic failures would have been the outcome for the Voyager and Galileo missions if redundancy had not been available.

Table 5. Voyager & Galileo In-Flight Failures Salvaged by Redundancy

Spacecraft	Failure Description	Subsystem	Cause	Time of Occurrence	Redundancy Applied
Voyager 1	X-traveling wave tube 2 performance degradation	Radio Frequency Subsystem	Unknown, possibly random aging	10.2 years	Block X-traveling wave tube #1 selected by ground command
	Lost S band downlink	Radio Frequency Subsystem	Component failure: ultra stable oscillator; possibly random aging	15 years	Block Automatic exciter swap & auxiliary oscillator in new exciter used
Voyager 2	Pyro amps "A" missing at RTG boom release	Power/Pyro Subsystem	Unknown	0 year (at launch)	Block Pyro circuit is inherently redundant
	Receiver 1 failed 20 minutes after turn on	Radio Frequency Subsystem	Hardware design	7.5 months	Block
	Lost S/C Data when memory "B" Block 256 memory failed	Flight Data System	Part Failure	4.1 years	Block Switch to memory A for rest of mission & S/W upload changes
	Rapid degradation in yaw limit cycle	Propulsion Subsystem	Thruster plugged	22 years	Block Automatic swap to redundant branch
Galileo	High gain antenna failed to deploy	Antenna Subsystem	Unknown	17.8 months	Functional Used low gain antenna & operational workaround

3.2 Anomalies versus Time

A look at anomaly reporting trends with respect to time for the Voyager and Galileo spacecraft provides a perspective on when anomalies are likely to be reported on long term missions. Unsurprisingly, the number of anomalies was largest at the outset of the missions when the spacecraft systems are being operated in flight and in the space environment for the first time. After one to two years of flight in the cruise phase of the missions anomalies of all types decreased for all three spacecraft presumably as systems and procedures were worked out and adjustments made to the operation of the spacecrafts. Prior and during major encounters, however, the recorded number of anomalies tends to rise sharply. This trend can be seen in the ISA versus time plots for both of the Voyager spacecraft and for Galileo (Figs. 2 and 3).

The Voyager spacecrafts were launched in 1977 and encountered Jupiter in 1979 and Saturn in 1980 and 1981. After Saturn, Voyager 1 moved out the ecliptic plane and began moving toward interstellar space. Voyager 2 continued on to visit Uranus in 1986 and then Neptune in 1989 before heading out of the solar system. In both cases (Fig. 2), the number of reported anomalies showed localized peaks at or near an encounter with a planet. Note that the ISA totals combine the reported anomalies for both Voyager 1 and Voyager 2. Reasons for these increases in reported events include uploading of maneuver software, refinements from the ground data system developed during pre-event testing, and the reactivation of instruments that had been in a dormant mode during the cruise stage leading up to an encounter with a planet. In the latter case, any abnormalities or changes in the instruments due to time or space environmental effects would be reported as anomalies in the JPL reporting system and boost the number and frequency of ISA reports. After the Saturn encounters in 1980 and 1981, only Voyager 2 continued on to visit Uranus and Neptune so increases in anomalies due to reactivations associated with spacecraft planetary encounters decreased.

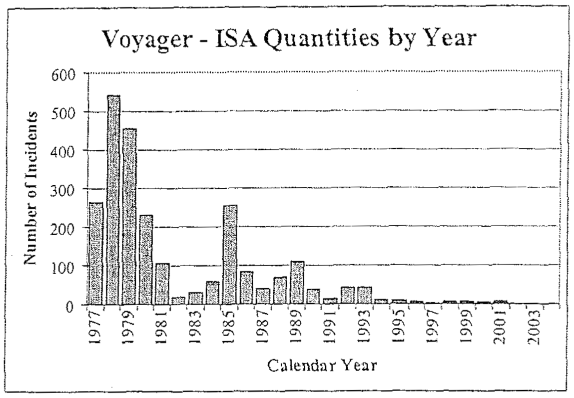


Figure 2. Total number of Incident, Surprise, and Anomaly (ISA) reports per year since the beginning of the Voyager missions. Note that ISAs for both Voyager 1 and Voyager 2 are included in the totals.

The Galileo plot of anomalies as a function of time (Fig. 3) shows a similar increase in reported anomalies in the early stages of the mission. Though the major planetary encounter was with Jupiter and its moons starting in December of 1995, there were other encounters while the spacecraft was in its cruise phase. These encounters were gravity assist encounters with Venus and Earth in 1990, a second gravity assist encounter with Earth in 1992, and asteroid flybys in 1991 and 1993. The reported anomalies peak in 1990 corresponding to both the first year of operations and two planetary encounters. Once Galileo reached Jupiter it entered orbit around the planet as opposed to the flybys performed by the Voyager spacecraft. Galileo had a total of 35 encounters with the planet and its moons. The plot of anomalies for Galileo shows a slight increase in activity in 1995 as the craft was readied for insertion into orbit around Jupiter and a large increase in anomalies in 1996 corresponding to the first set of Jupiter moon encounters.

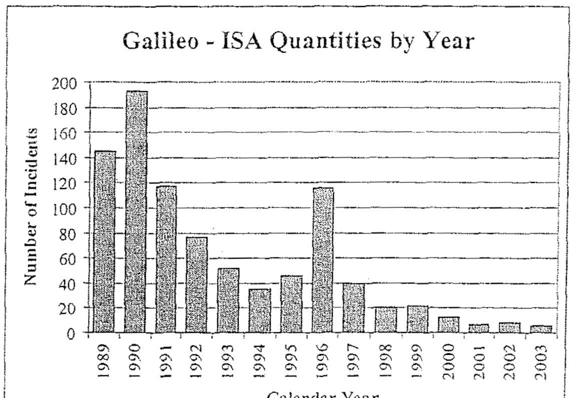


Figure 3. Total number of Incident, Surprise, and Anomaly (ISA) reports per year since the beginning of the Galileo mission. The Galileo spacecraft was intentionally crashed into Jupiter in late 2003.

What is surprising about all of the plots showing the number of ISAs by year is that the number of anomalies reported for all spacecraft sharply declines with increasing time. This trend is in direct opposition of the expectation that the spacecraft will become less and less operational with time as the devices on board age and absorb more planetary and cosmic radiation. To give some clue as to the reason for this last trend it is useful to examine the plot of the number of reported anomalies and the total workforce dedicated to the project.

3.3 Anomalies versus Workforce

The plots showing the number of Incident, Surprise, Anomaly (ISA) Reports and total workforce employed on the flight portion of the mission for the both the Voyager missions and Galileo are given in Figs. 4 and 5. In this case the total workforce includes both JPL employees and contractors and is given for each fiscal year (as opposed to the calendar year used for the ISA totals). The Voyager missions (Fig. 4) show a fairly strong relationship between the workforce total and the number of anomalies reported with peaks at both at the mission start and at each encounter thereafter. The workforce totals show a diminishing trend overall, but drop significantly after the last Voyager encounter with Neptune in 1989 with a corresponding drop in the number of anomalies reported for both spacecraft.

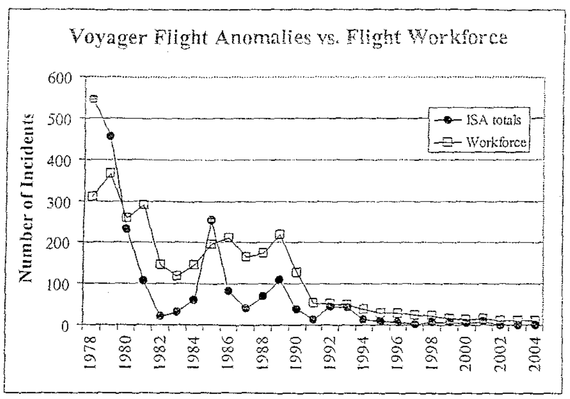


Figure 4. ISA totals plotted with the total workforce on the Voyager missions. Note the fairly close tracking of workforce totals with the ISA totals. Values for both Voyager 1 and Voyager 2 are combined in this plot.

When examining these workforce plots, it is important to keep in mind that the number of anomalies reported can be related to the decreasing amount of spacecraft maneuvers required when the spacecraft is in a steady state cruise configuration as well as the shut down of some of the science instruments on board both of the Voyager spacecraft. For both of these reasons the number of personnel working on the mission during extended interstellar mission flight has decreased significantly.

The plot of anomalies reported along with the workforce totals for the Galileo mission (Fig. 5) shows far less correlation between the two plots than could be seen in the plot for the Voyager missions. The divergence of the number of anomalies and the number of personnel working on the project is most likely caused by the early difficulties encountered by the Galileo mission (i.e. the High Gain Antenna deployment difficulties and AC/DC bus imbalances). To understand and work around the problems encountered in flight, the workforce increased during the cruise stage of the mission and only decreased after Jupiter Orbit Insertion (JOI) in late 1995. Specifically, 80% of the lines of code for the on board software (ie 80 % of ~70k lines of code) in the command data subsystem had to be modified prior to JOI because of the new mission plan to perform the mission without a high gain antenna. Subsequently for code maintenance and corrections only two percent had to be revised [4]. After JOI, the number of anomalies and the workforce totals follow more closely together until the end of the mission in 2003.

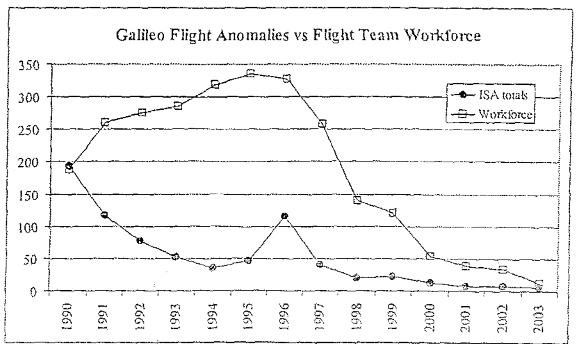


Figure 5. ISA totals plotted with the total workforce on the Galileo mission. Note that the increase in workforce before 1996 is in response to the early problems encountered on the way to Jupiter.

As with the plot for the Voyager missions, the number of anomalies reported for the Galileo mission and the workforce totals decreased with time especially after a major encounter. With the Galileo mission, however, the spacecraft did not leave the vicinity of Jupiter but continued to make encounters with the planet and its several moons on a regular basis with periods of non-activity in between each encounter. It is therefore interesting that the number of anomalies followed the Voyager trend and continued to drop with time and that workforce numbers track this decrease. The number of anomalies reported may be due to a decrease in the number of maneuvers planned and tested (i.e. new types of activity) as well as a decrease in the number of instruments active on board the spacecraft with increasing time.

3.4 Corrective Actions Taken

For the Galileo mission, a closer look was taken of the types of anomalies reported in the ISAs and the corrective actions used to resolve them. Each ISA was reviewed and categorized by both the system where the anomaly was noticed and the corrective action taken to address the anomaly. The systems were the anomalies were reported were intentionally simplified to Procedure, Ground Hardware, Flight Hardware, Ground Software, and Flight Software. Likewise the corrective actions taken were categorized as Undetermined, Use As Is, Ground Hardware, Ground Procedure, Flight Procedure, Ground Software, and Flight Software. The results of this assessment of the ISA reports are shown in Figs. 6 and 7.

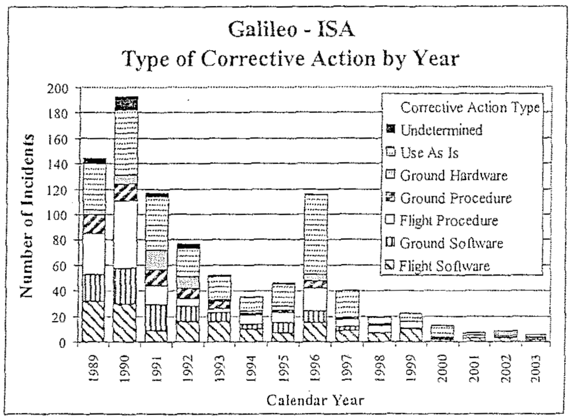


Figure 6. ISA totals for the Galileo mission. Each year bar is subdivided to show the type of corrective actions taken for the anomalies reported in that year.

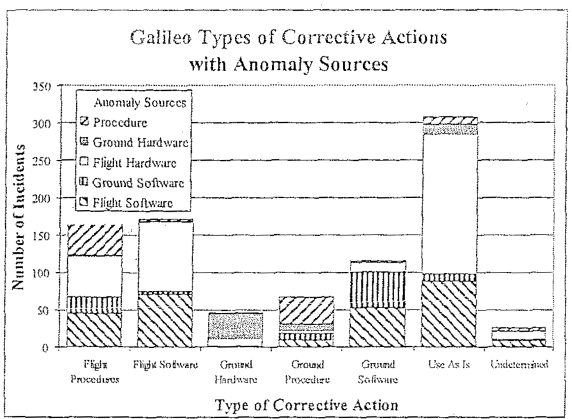


Figure 7. Types of Corrective Action are shown for the Galileo Mission. Each corrective action type is subdivided to show the system seen as the source for each anomaly.

The decision to "Use As Is", or take no corrective action, was consistently the most common response to anomalies reported over the entire Galileo mission. This is true both when examining the anomalies from each year (Fig. 6) and when looking at the corrective action totals over the life of the mission (Fig. 7). In the latter case, it can be seen that it was decided to take no action for more than a third of all anomalies.

When each type of corrective action is subdivided to show the system where the anomaly originated (Fig. 7) flight hardware was the most common source for anomalies where no action could be taken either because the system was unfixable or the anomaly was not mission threatening. The "Use As Is" response was also commonly used for anomalies that happened only once or for incidents that were considered to really reflect normal behavior (i.e. an incident that was surprising at first but was determined to be within normal mission parameters upon closer examination). Of particular interest is that in 1996, the first year after reaching Jupiter when instruments reactivated and first put to use in the Jupiter environment, the number of anomalies increased significantly and the most common response to the incidents was to "Use As Is."

When an anomaly could be addressed by corrective action, the most common action was a software modification. When looking at the timeline of the Galileo mission, software corrective actions peaked at the beginning of the mission and decreased with time with a slight increase following the arrival at Jupiter. For this analysis, software corrective actions were divided into two types of corrective action, those involving software radiated to the computers flying in the Galileo spacecraft and actions addressing software used on ground based computers. Of the two changes to flight software were most numerous. Together software corrective actions almost equal to the number of "Use As Is" responses to anomalies and represent another third of the total corrective actions.

Flight software corrective actions were most often made as a response to anomalies found in hardware on the spacecraft. Typical corrective actions of this type included powering on or off particular instruments or subsystems or enacting a workaround procedure so that the mission could continue. Other anomalies that required a flight software corrective action most commonly originated in previous versions of radiated flight software. Some of the corrective actions involving flight software were incorporated into scheduled software updates while others were done in real time in response to a reported anomaly that needed to be addressed immediately.

Corrective actions involving changing software for ground based computers were fewer in number than those radiated to the Galileo spacecraft but sometimes they intersected with flight software issues. Some of the ground software corrective actions were to ground software that created the sequences eventually radiated to the spacecraft. This kind of fix was counted as a ground software fix, but it clearly directly related to software radiated to the spacecraft. Other ground software corrective actions addressed anomalies found software in use in ground based computers. A small amount of ground software corrective actions were made to work with flight hardware based anomalies that could not otherwise be addressed.

The third most common type of corrective actions was a procedural change, either for procedures related to flight operations or for those dealing with ground operations. Flight procedural corrective actions, i.e. revisions to flight mission rules used to determine spacecraft operations, were most common in the early part of the Galileo mission and in 1996 following Galileo's arrival at Jupiter. It is supposed that procedural changes were at their peak during these times since the mission team was learning how the spacecraft operated in flight. This supposition is supported by the decrease in flight procedural corrective actions with time after the first two years of flight and after the arrival at Jupiter.

All other procedural corrective actions were considered to be ground based. These corrective actions follow a similar trend to flight procedural corrections in that they were more numerous in the beginning stages of the mission. They differ, however, in that they do not seem to be as closely correlated to Galileo's arrival at Jupiter.

Flight procedural corrective actions addressed anomalies originating in flight hardware, flight software, and existing procedures in nearly equal numbers as seen in figure 7. Ground procedural corrective actions most commonly addressed issues arising from existing procedures.

The two additional types of corrective actions determined in this study were those related to ground hardware and those here classified as "Undetermined." Ground Hardware corrective actions involved changing or modifying ground support equipment either in Mission Control or at one of the Deep Space Network locations and were generally made in response to some ground or flight hardware need. Undetermined corrective actions were those where the ISA is unclear regarding the type of corrective action taken. Since this report is based on the form of the ISAs electronically stored in the JPL problem reporting system, this generally refers to reports whose corrective actions were detailed in attachment files missing from the electronic database.

4. LESSONS LEARNED

The lessons learned from the assessments of the flight anomalies that have occurred during the accumulated flight time of sixty six years for unmanned outer planets mission are.

- Block and/or functional redundancy have been necessary for the successful operation of the spacecraft.

- Robustness in the underlying architecture of the system design has to be built in and a knowledgeable, experienced cadre of operations personnel must have access to the information.

- Number of anomalies is dependent on mission activity with peaks occurring during launch and early cruise, pre-encounter testing, and during an encounter.

- The corrective action most frequently noted was "Use As Is", the second was a software update and the third involved changes to procedure. Resource planners for future long life missions must provide the operations staff and the skill resources to process and disposition the anomalies and appropriate actions.

5. SUMMARY

Anomaly reports, specifically JPL's post launch Incident Surprise and Anomalies (ISA) reports, have been analyzed for three deep space spacecraft with an accumulated flying time of more than 66 years. In addition, key operations personnel were interviewed to collect impressions of some of the lessons learned from supporting long life missions. Functional or block redundancy was used on all of these missions to provide continuation of the mission and the return of useful data to the science teams. From these sources it is seen that for future long life missions redundancy should be required and must be carefully selected and analyzed during prelaunch development. On board fault protection strategies need to be developed and tested. Although rigorously analyzed prior to launch, flight teams must continue to monitor spacecraft health and evaluate trend data throughout the mission life. The number of anomalies noted for the spacecraft analyzed for this paper increased as preparations for major in flight events occurred, such as trajectory correction maneuvers and encounters with target bodies. Flight software changes require extensive testing on the ground prior to uploading to the spacecraft lest they become a source of later anomalies. If a flight system is stable, onboard flight software changes should be avoided. Two management problems for flight operations teams for long life missions have been identified: skill retention in progressively obsolete systems and knowledge management for systems and instrument control.

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