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Anomaly Trends for Robotic Missions to Mars: Implications for Mission Reliability

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Since the early sixties, Mars has been an objective of robotic spacecraft from the space programs of several nations. As of the present date, thirty-seven missions from multiple nations have been flown to the red planet with varying degrees of success. More robotic missions to Mars are currently being planned and developed for both scientific research and as precursors for possible manned missions. In support of these future missions, this paper describes methods and results for classifying and identifying trends in the anomalies recorded by the eight orbiter and lander spacecraft managed for NASA by the Jet Propulsion Laboratory over the last two decades. To provide spacecraft designers and operations personnel with recent historical information, anomalies are examined as a function of time, origination, and corrective actions. Predictions and the implications for the different types of anomalies likely to be faced by future missions to Mars are discussed based on the results of this study.

I. Introduction

VISITING Mars and learning more of our neighboring planet has long been a dream for scientists and the public in general. The first spacecraft designed to visit Mars was launched in 1960 by the Soviet Union, only three years after the launch of Sputnik 1.[1,2] Including missions through the summer of 2005 there have been a total of thirty-seven spacecraft launched toward the red planet with varying degrees of success. That attempts were made so early in the history of spaceflight is indicative of the strength of the desire to know about Mars; the fact that the first six missions failed shows how difficult it can be to get to there. Mars continues to be a strong subject of interest in the space community evidenced by the continued development of robotic spacecraft to visit the planet and the renewed interest in manned Mars missions.

While Mars has been the subject of robotic spacecraft since 1960, increased interest has been shown since 1990. Of the thirty-seven total missions direct at Mars, eleven have been launched since 1992: one each by the Russian Space Agency, the Japanese Space Agency, and the European Space Agency, and eight from the National Aeronautics and Space Administration (NASA). With this relatively recent burst of activity, it becomes possible to compare the experiences of several missions and spacecraft on a relatively equal footing since all were conceived and built within a short time span.

For this study, the post launch records of the anomalies recorded by each mission team has been gathered and analyzed to determine trends for the recent Mars missions to help with the planning of future Mars mission teams. Due to the need to examine detailed records for each mission, the scope of this study has been limited to NASA missions whose records are available in electronic form in a problem reporting system maintained at the Jet Propulsion Laboratory (JPL). Anomalous behavior noticed by the spacecraft mission teams after the launch of the spacecraft were recorded as Incident Surprise and Anomaly (ISA) reports. Since recent missions to Mars have included both orbiter and lander spacecraft, and since several missions were not successful upon reaching the red planet, the time period for comparing the missions has been limited to the span covering the launch of the spacecraft

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to its arrival at Mars. After that point, the spacecraft began orbit insertion, descended to the planet's surface, or failed in either attempt. Missions evaluated are shown in Table 1. The recently launched Mars Reconnaissance Orbiter, 2005, has not been included since this spacecraft did not launch until this study was already underway and, as of the writing of this paper, has not yet reached its destination.

Anomaly reports from the included missions were gathered into an electronic database of nearly 1400 reports. Each report was reviewed and categorized by the authors and the results were plotted to locate trends that might provide insight for future mission design and operations personnel. Missions that may benefit from the identified trends include not only the robotic missions currently under review but also future manned missions to Mars.

Table 1. NASA missions to Mars since 1990

Name	Launch Date	Mars Arrival	Spacecraft Type	Results
Mars Observer	25 September 1992	22 August 1993 (Loss of Signal)	Orbiter	Lost contact with spacecraft prior to orbiting Mars
Mars Global Surveyor	7 November 1996	12 September 1997	Orbiter	Successfully entered Mars orbit. Still in operation as of January 2006.
Mars Pathfinder	4 December 1996	4 July 1997	Lander/Rover	Successful landing and rover operations
Mars Climate Orbiter	11 December 1998	23 September 1999	Orbiter	Lost upon Mars arrival
Mars Polar Lander	3 January 1999	3 December 1999	Lander	Lost during decent to Mars surface
Mars Odyseey	7 April 2001	24 October 2001	Orbiter	Successfully entered Mars orbit. Still in operation as of January 2006
Mars Exploration Rover	Spirit: 10 June 2003 Opportunity: 7 July 2003	Spirit: 3 January 2004 Opportunity: 24 January 2004	Rover	Both spacecraft successfully descended to the surface of Mars. Both are still in operation as of January 2006.

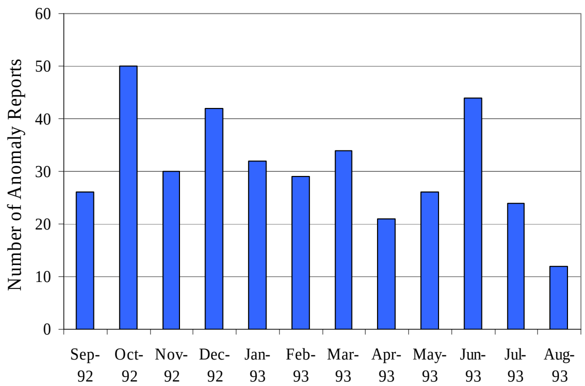
II. Anomaly Reports with Time

All events recorded in the ISA reports are directly related to operating a spacecraft as it progressed towards Mars but are of different types. To obtain useful information from the collected reports for each mission, the ISAs for each were gathered, individually examined, and analyzed in three specific ways: as a function of time, by the source of the anomaly, and by the corrective actions taken to address each one. Each mission was examined separately with the Mars Exploration Rovers considered one mission. Separating the two spacecraft of this mission proved impractical since the majority of ISA reports for these two spacecraft were combined into one in the anomaly database.

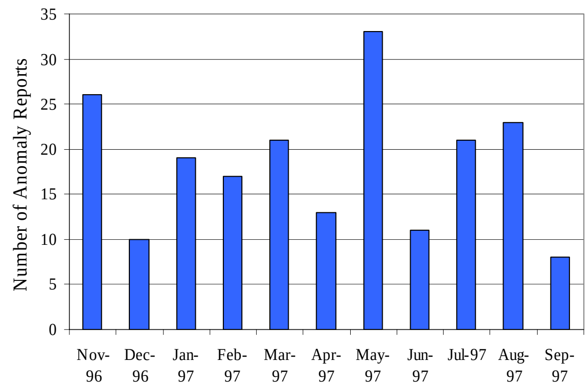
A. Anomalies vs. Time

Since reports occurred continuously and at random intervals over the span of time required for each spacecraft to reach Mars, anomaly reports were gathered in month long increments and plotted as histograms as seen in figures 1 and 2. The time to reach Mars varied from 7 to 12 months depending on launch platform, spacecraft size, and the relative position of Mars at the time of launch.

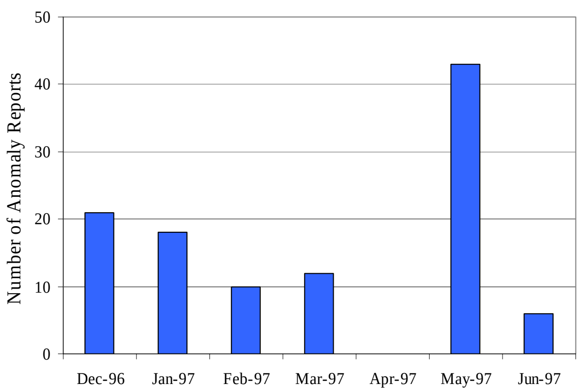
Careful examination of the number of anomalies as a function of time revealed evidence of a learning curve for some of the missions at the outset of flight operations. This initial curve is most evident in the Mars Observer, Mars Pathfinder, and Mars Odyssey missions. In many cases, anomalies are not only reports of unexpected events involving the spacecraft and mission operations, but an indicator of the mission team learning the behavior of their spacecraft, the ground support equipment, and how to work together to fly the mission. This trend has been seen in previous anomaly trending for longer term missions and was expected.[3] In all of the missions plotted in figure 1 there is a discernable decreasing trend in the number of reported anomalies after the first month. An exception to this general trend can be seen in figure 2 showing the collection of ISA reports for the MER mission. This discrepancy may be due to the fact that the first month displays only anomalies from the first of the two spacecraft that compose the mission. In the second month the second spacecraft was launched so instead of the expected decreasing trend seen on the other spacecraft, there is an increase.



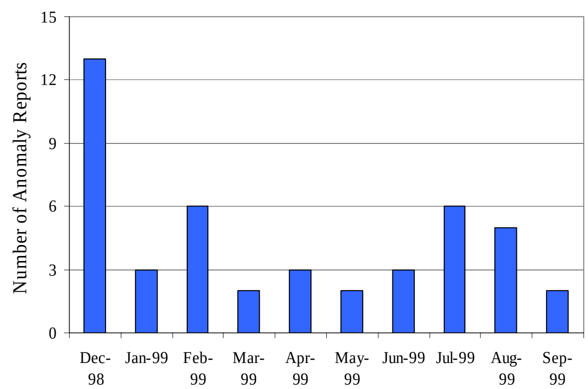
a. Mars Observer



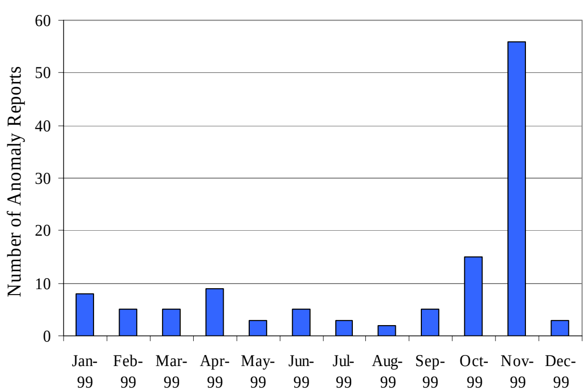
b. Mars Global Surveyor



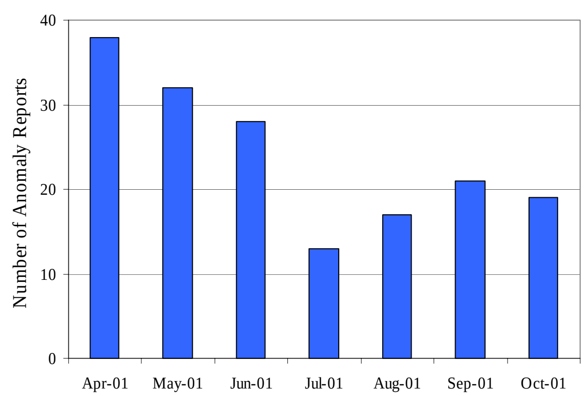
c. Mars Pathfinder



d. Mars Climate Orbiter



e. Mars Polar Lander



f. Mars Odyssey

Figure 1. Number of anomaly reports as a function of time for NASA missions starting in 1990. They are given in chronological order starting with: a. Mars Observer, b. Mars Global Surveyor, c. Mars Pathfinder, d. Mars Climate Orbiter, e. Mars Polar Lander, and f. Mars. Odyssey. See figure 2 for the Mars Exploration Rover plot.

The second trend that is observable from the plots of anomalies versus time is an increase in anomaly reports as the spacecraft approached the planet and the mission team began preparations for the encounter with the planet. All of the missions show this increase as the spacecraft approached Mars. It is of particular interest that the three missions incorporating a lander in the spacecraft display the largest increases in anomalies during this segment of their flight. While the Mars Polar Lander increase may also be due to the extensive examination of the spacecraft after the loss of the Mars Climate Orbiter spacecraft, both the Pathfinder and Mars Exploration Rover ISA vs. time plots show a large bump in the number of anomalies just prior to landing on the planet. The orbiter missions show an increase in anomaly reports as they approach Mars, but to a lesser degree than is seen on the lander missions.

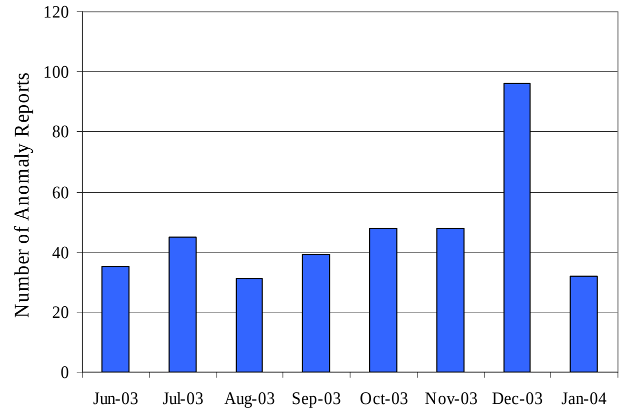


Figure 2. Number of anomaly reports as a function of time for the two spacecraft of the Mars Exploration Rover mission.

B. ISA Quantity

A less obvious trend seen in the plots of anomalies as a function of time involves the number of ISAs recorded by each mission. It is suggested that the number of anomaly reports in this context is a measure of the attention to detail applied to each mission evidenced effort spent in recording of anomalous events. To some degree the number of anomalies is random, having to do with unforeseen events, but since the missions are similar in nature, only a few years apart in construction and launch, and the scope of this study is limited to the time period all mission shared the unpredictability of anomalies is somewhat reduced.

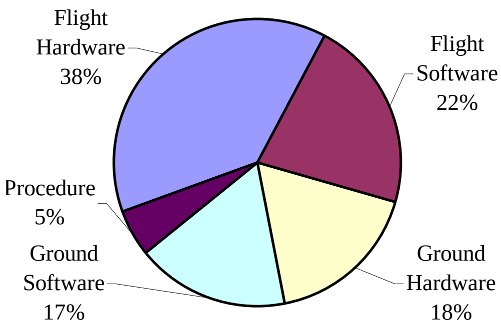
The first of the missions included this study is Mars Observer (MO), launched in 1992. This mission is unique in this study as it is the only mission that can be considered a "Class A" mission meaning that it was the given the time and degree of detail given to such flagship projects as the two Voyager missions, Galileo, and Cassini. As a result, it is no surprise that the number ISA reports is quite large compared to other missions. This mission was the first NASA mission to Mars since the Viking missions of the 1970's and as such was seen as a key event for the agency's interplanetary program. In the twelve months between launch and the eventual loss of signal just before arrival at Mars the mission team recorded 370 ISA reports, more than any of the other missions in this study.

The next mission launched after the Mars Observer was the Mars Global Surveyor (MGS) launched in November of 1996. This mission was not considered a Class A mission, but the large number of ISAs, 202 over eleven months, indicates the degree of attention given to the operation of this spacecraft. For this mission, the detailed attention was due, at least in part, to the failure of the Mars Observer mission. As an early example of the "Faster, Better, Cheaper" missions the 1996 Mars Pathfinder mission in appears to have a decreased requirement for anomaly documentation seen both by a drop in the number of anomalies to 110 over seven months and in the fact that there did not seem to be a unified system for anomaly reporting. In order to collect sufficient data for this mission it was necessary to gather reports from additional databases to augment the ISA reports.

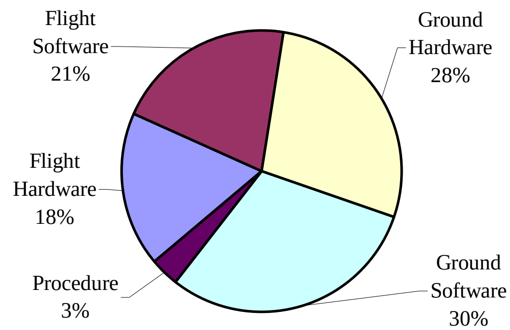
Following Mars Pathfinder were two missions where the number of anomaly reports is quite small compared to the previous missions. The Mars Climate Orbiter (MCO) and the Mars Polar Lander (MPL) were constructed during the peak of the "Faster, Better, Cheaper" paradigm and show a definite decrease in the detail given to anomaly recording likely brought on by a decrease in funding allocated for documentation. The MCO mission reported only 45 ISAs during its 10 month journey to Mars; the MPL mission reported 119 over eleven months, but more than half of these were in the last month after the loss of the MCO spacecraft. Ultimately, both spacecraft were unsuccessful.

After the loss of both the MCO and the MPL spacecraft, the next mission sent to the red planet was Mars Odyssey launched in 2001. Due to the failures of the previous two missions, it was critical that Odyssey succeed. The degree of detailed anomaly reporting applied to this mission is evident in the increase ISA reports to 168 over the seven month journey to Mars. A similar degree of detailed documentation also can be seen with the twin MER spacecraft. In this case the anomaly reports for both spacecraft were combined into one database. Over the eight that months the two spacecraft were in transit a total of 374 ISA reports were written. In all three cases, the missions were successes.

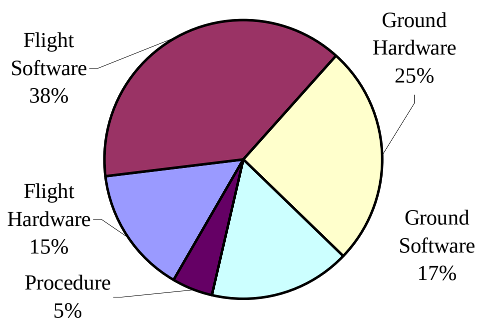
While the number of anomaly reports is not directly related to the success or failure of a mission, there is evidence of a trend toward higher reporting activity on successful missions.



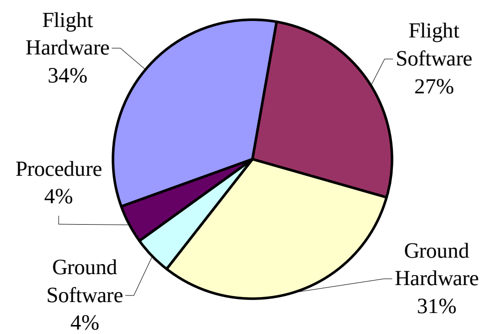
a. Mars Observer



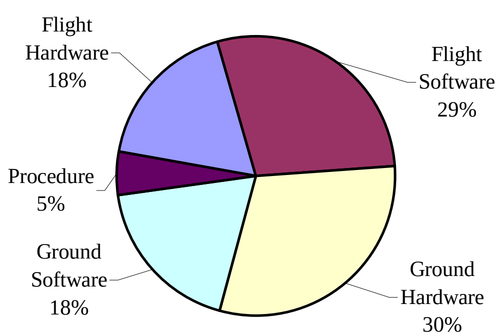
b. Mars Global Surveyor



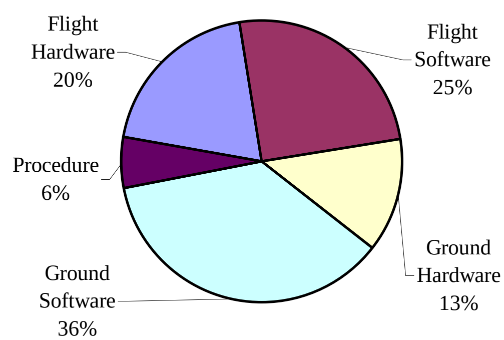
c. Mars Pathfinder



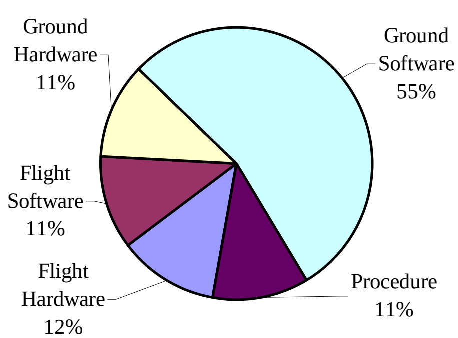
d. Mars Climate Orbiter



e. Mars Polar Lander



f. Mars Odyssey



g. Mars Exploration Rover

Figure 3. Anomaly sources percentages for NASA missions to Mars 1990-2004 from launch to arrival. Missions are listed in chronological order: a. Mars Orbiter, b. Mars Global Surveyor, c. Mars Pathfinder, d. Mars Climate Orbiter, e. Mars Polar Lander, f. Mars Odyssey, and g. Mars Exploration Rover (including both spacecraft).

III. Trends in Anomaly Sources

Beyond an examination of quantity of anomaly reports over time, an attempt was made to find trends in the origination of the anomalous behavior. ISA reports from the launch of each spacecraft through its arrival at Mars were individually reviewed to determine the source of the anomalous behavior. To simplify the process, sources were limited to five categories: flight hardware, flight software, ground hardware, ground software, and anomalies due to mission procedures. The resulting charts for all seven missions can be seen in figure 3.

Flight hardware anomalies were events that occurred to the physical hardware of the spacecraft. Anomalies that might fall into this category include higher or lower than normal readings from temperature sensors, star tracker errors, or communication equipment problems. Out of the total anomalies for each spacecraft, flight hardware accounted for 12% to 38%. Of the spacecraft examined, Mars Observer had the most anomalies due to flight hardware and the Mars Explorations Rovers the least.

The other kind of anomaly directly related to the spacecraft itself was an event due to flight software. For an anomaly to have been considered to have a source in flight software, the event had to have originated in software operating on the spacecraft at the time of the anomaly. Typical anomalies that had flight software sources were due to errors in previous versions of the software, instructions that set alarms limits incorrectly, or instructions that set communication parameters to the wrong values. Flight software anomalies accounted for approximately 20% to 40% of documented anomalies. Mars Pathfinder had the most anomalies with flight software origins at 38% in contrast to having the least number of anomalies whose source can be traced to flight hardware issues. The Mars Exploration Rover mission has the least at 11% of all ISA reports. Combined, anomalies originating directly on the spacecraft accounted for roughly 50% (or a little more) of the total anomaly reports for each mission. All other anomalies reported occurred within ground based systems.

Any anomaly that had a hardware source that was not on the spacecraft itself was considered a ground hardware event. This type of anomaly accounted for 20-30% of the total. Frequently these anomalies were associated with the computers in the mission operation center or activities at the Deep Space Network (DSN) stations. One large section of anomalies classified as ground hardware dealt with spacecraft tracking difficulties encountered by the DSN stations due to incorrect predictions, communication equipment errors, or transmission errors. These two broad categories, computers and communication equipment, made up the bulk of all ground hardware ISA reports.

Software-based anomalies that did not originate with code actually running on computers on board the various spacecraft were considered to have a ground software source. While a great many of the anomaly reports under this category were events concerning only software for ground based computer systems, there were some connections to flight software either through issues with code used to create flight software or code used to interpret the information returned by flight software. Typical anomalies found in this category were issues with the sequence generation software used to generate the next set of instructions for the spacecraft or software that took in telemetry data and either plotted the results or evaluated the returning information and looked for errors and alarm conditions. Another typical ground software issue was communication software used between the DSN stations, mission operations, and the various science groups working with spacecraft data. Anomalies originating in ground based software typically composed 15% to 35% of the ISAs; the Mars Climate Orbiter at 4% and the Mars Exploration Rovers at 55% are outlying data points that show the extremes for the missions to Mars.

The remaining source of anomalous events was a procedural error that caused an anomaly to occur. Procedure based anomalies generally fell into two categories: misunderstanding of established procedure and procedures that needed to adapt to actual mission flight conditions. In the missions considered for this study, procedure based anomalies hovered around 5% of the whole suggesting that for the time from launch to arrival at Mars, procedures established for the mission teams needed little change or reinforcement for the correct operation of the spacecraft.

In almost all categories, the Mars Exploration Rover mission was an exception to the rule due to the large percentage of ground software related anomalies. Many of these anomalies were issues

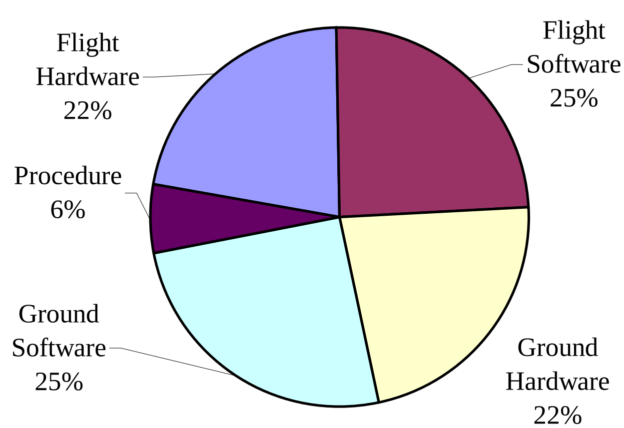
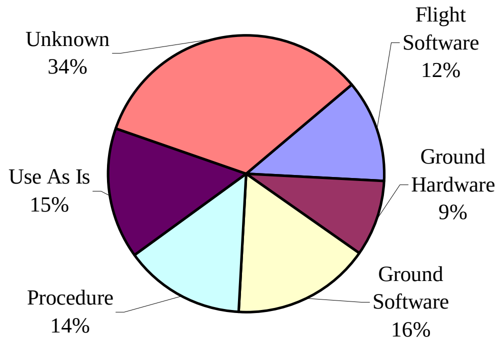


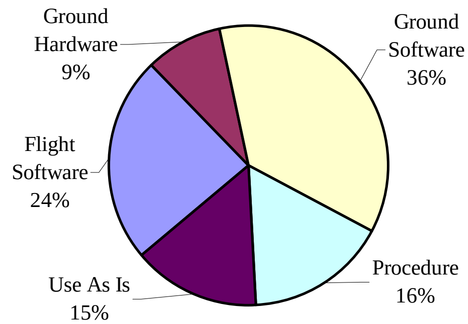
Figure 4. Anomaly source percentages for all NASA missions to Mars from launch to arrival, 1990 to 2004.

with software used to generate instructions to be uplinked to the spacecraft, or later, to the rovers themselves.

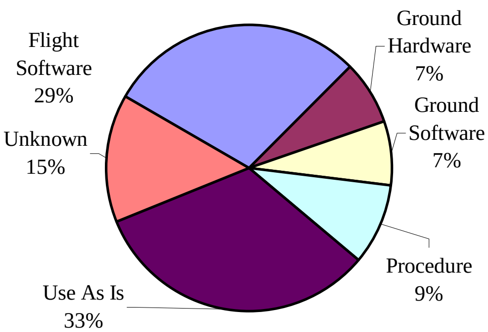
Combining the individual anomaly source percentages to get an overall trend for Mars missions during the time from launch to arrival gives the results shown in fig. 4. From this figure anomalies that occur on the spacecraft account for 47% of the anomalies with almost equal distribution between hardware and software issues. Anomalies



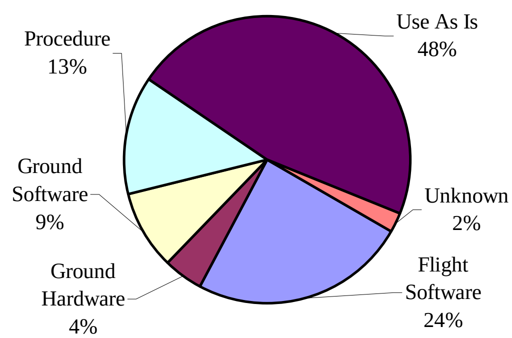
a. Mars Observer



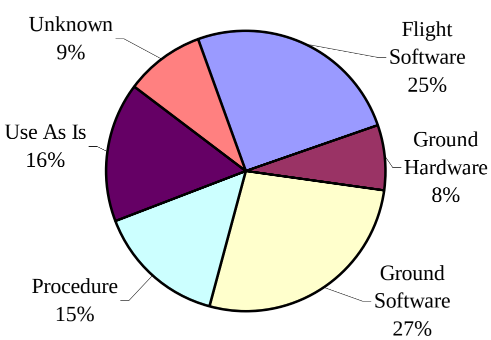
b. Mars Global Surveyor



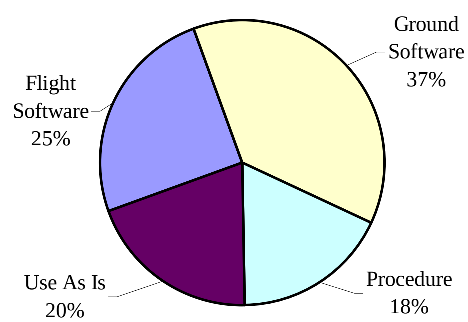
c. Mars Pathfinder



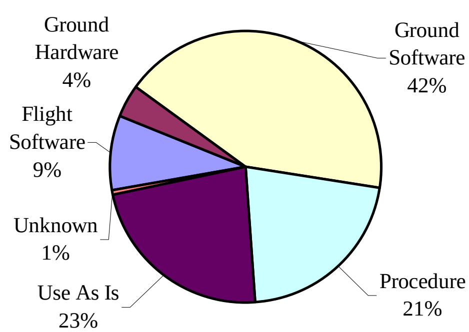
d. Mars Climate Orbiter



e. Mars Polar Lander



f. Mars Odyssey



g. Mars Exploration Rover

Figure 5. Corrective action percentages for NASA missions to Mars 1990-2004 from launch to arrival. Missions are listed in chronological order: a. Mars Orbiter, b. Mars Global Surveyor, c. Mars Pathfinder, d. Mars Climate Orbiter, e. Mars Polar Lander, f. Mars Odyssey, and g. Mars Exploration Rover (including both spacecraft).

from ground hardware systems at 22% are slightly less likely than ground software which represents 25% of the total anomalies. Procedural anomalies make up the final 6% of the total. Hardware issues, combining both flight and ground systems, represent 44% of reports while software concerns of both types account for a nearly equal 50% of all anomalies. From this data there is no one clear type of system that provides the majority of anomalous behavior. Instead, anomalies seem as likely to derive from ground operations as from flight systems, and software nearly as likely to exhibit surprising behavior as will hardware systems. The only anomaly source that is historically a low percentage relates to mission procedures.

IV. Anomaly Corrective Actions

In addition to sorting each anomaly by its source, the corrective actions taken in response to each anomaly were analyzed and sorted into similar categories to examine how each kind of anomaly was addressed. As was done for the anomaly sources, corrective actions for each ISA report were sorted into several broad categories: "use as is," flight software, ground software, ground hardware, and procedure. Most ISAs included a report on the anomaly analysis and a corrective action, but some reports left these sections blank so it was necessary to add an unknown category to the list of corrective actions. The charts in figure 5 display percentage use for each type of corrective action.

The categories for corrective actions were intentionally made to be very similar to those used to sort anomaly sources. Many of the same descriptions for the anomaly sources can be applied to the corrective actions category with the exception of the "use as is" corrective action. This corrective action represents a decision to take no action as the anomalous behavior was either unable to be fixed (as in the case of flight hardware that could not be software modified), an issue deemed to be a singular event and unrepeatable, an event with no significant impact, or a normal event that was not understood and reported as anomalous behavior. Several anomalies given this kind of corrective action recommendation were due to environmental interactions and single event upsets. For this group of ISAs, 15-30% of them have corrective actions sections with a "use as is" recommendation with the nearly Mars Climate Orbiter as an outlying data point at nearly 50%.

Flight software corrective actions involved changing software operating computers on board the spacecraft and represented approximately 25% of the anomalies reviewed for this study. Flight software corrective actions were most commonly used to address a flight software anomaly, but almost as likely to address a problem with flight hardware. In both cases, new software was uploaded to the spacecraft in flight with instructions to modify the spacecraft behavior. In the case of corrective actions addressing flight hardware anomalies, the software commonly either activated or deactivated a piece of hardware, or changed the limits the spacecraft computers used to determine if hardware was operating within expected boundaries.

Corrective actions characterized as ground software performed a similar function for computers operating on Earth by correcting both hardware and software anomalies. Several missions used a software change to ground based computers to address 25-35% of the recorded anomalies though a few missions, such as Mars Pathfinder at 7% and Mars Climate Orbiter at 9%, appeared to use very few changes to ground software to address the reported anomalies. With missions such as Mars Global Surveyor, Mars Odyssey, and Mars Exploration Rover ground software corrective actions were the most dominant response to anomaly reports. Unsurprisingly, all three of these missions also had a large number of anomalies whose origin was in ground based software. It should also be noted that when DSN stations reported difficulties in tracking spacecraft due to faulty tracking predictions, corrections to these predictions were considered to be ground software corrective actions.

Though many ground hardware based anomalies were addressed using ground based software, this kind of corrective action was not always utilized. Ground hardware corrective actions, representing 5-10% of the whole, were used to replace defective computers, network routers, displays, and printers among other physical pieces of equipment used by the mission teams.

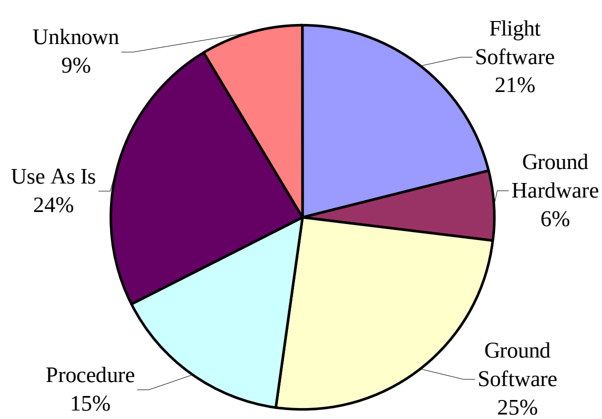


Figure 6. Anomaly corrective action percentages for all NASA missions to Mars from launch to arrival, 1990 to 2004.

Other types of ground hardware corrective actions involved hardware at the DSN stations and other non-computer related needs such as facility issues. In all missions studied, ground hardware corrective actions accounted for the smallest percentage of all anomalies considered.

Procedural issues accounted for the least number of anomalies, but changes in procedure were more common as a corrective action. Modifications in how to use the spacecraft, how to build the flight software, how to utilize ground software and computer systems were all considered procedural corrective actions. These changes were used as a fix for approximately 15% of the anomalies reported for each mission.

For an overall picture of the corrective actions trends as reported in the ISAs for these missions, the percentages for each type of corrective action were averaged. This method was used so that missions with large numbers of ISAs didn't skew the results which are displayed in fig. 6. This graph shows that corrective actions utilizing software dominate with a combined flight and ground software total of 46%. Taking no actions or responding with a "use as is" corrective action is the next most common at 24% followed by procedural changes at 15%. Hardware based corrective actions are the least likely at only 6%. Unfortunately, several missions had a large number of ISA reports where there was no recorded response which is shown here in the 9% of unknown corrective actions. The majority of anomaly reports with no recorded corrective action were from failed missions where resolving the issue identified in the ISA was no longer warranted.

V. Conclusion

While there have been many missions launched toward Mars since the early sixties, the number of spacecraft directed there has increased rapidly in the last decade and a half. By examining the Incident Surprise and Anomaly reports for the missions sent to Mars by NASA and by limiting the time frame to one where all missions are performing similar functions, trends can be observed. Larger quantities of anomalies can be expected at the outset of each mission as the mission teams learn "on-the-job" how to operate their spacecraft, work with their ground support equipment, and come together as a mission team. Another increase in anomalies can be expected as the spacecraft approaches Mars with a particular increase evident with lander missions.

The most successful missions are those that tend toward careful documentation as evidenced in these missions by the larger quantities of anomaly reports. More anomaly reports do not equate to a successful mission, but it does give evidence of the mission culture toward attention to detail.

Based on the missions examined, anomalies seem to be spread evenly between ground and flight operations and between hardware and software issues. Few anomalies in the launch to arrival time span seem to be due to mission procedure. The most common actions taken to address anomalies are software fixes with ground and flight software repairs equally distributed. One quarter of the anomalies observed in this study received no direct corrective action and were "used as is." Procedure changes were utilized more often than there were procedural anomalies, but were again less common then software fixes or the decision to take no action. A change to ground based hardware is the least likely anomaly response.

These results are taken exclusively from missions utilizing robotic spacecraft, but the results are likely to be similar for manned missions with an added degree of complexity introduced by the flight hardware necessary for life support. The trends for increased anomaly reporting immediately post launch and just prior to arrival at the planet will likely be the same. It should be of interest to designers of both manned and unmanned missions that anomalies were almost equally distributed between spacecraft events and ground based incidents implying that care must be taken when designing and constructing both flight and ground support systems.

Acknowledgments

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