Anomaly Trends for Missions to Mars: Mars Global Surveyor and Mars Odyssey

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Abstract. The long term flight operations of the Mars Global Surveyor and Mars Odyssey spacecraft give us an excellent chance to examine the operations of two long lived spacecraft in orbit around Mars during overlapping time periods. This study examined the anomalies for each mission maintained for NASA at the Jet Propulsion Laboratory. By examining the anomalies each mission encountered during their multi-year missions, trends were identified related to when anomalies occurred during each mission, the types of anomalies encountered, and corrective actions taken to mitigate the effects of the anomalies. As has been discovered in previous studies the numbers of anomalies directly correlate with mission activity and show a decreasing trend with elapsed mission time. Trend analysis also identified a heavy emphasis on software as the source or solution to anomalies for both missions.

Introduction

For the last decade and a half Mars has been a common destination for many of extra-terrestrial spacecraft launched by several nations. In the United States, NASA has launched a total of ten spacecraft to the red planet with varying degrees of success in order to map its surface and study its history through careful examination from both ground-based and orbiting spacecraft. Since more of such spacecraft are planned, it seems prudent to examine the experience of recent missions to let designers and operations teams know how to plan for the future and perhaps provide for an increase in reliability through knowledge of the past. To that end and as a part of NASA's Ultra Reliability Program, the anomaly reports for several robotic missions have been examined for over all trends for the past several years[1,2,3,4]. Past studies have included examinations of all NASA missions to Mars from launch to arrival, surface operations for the two Mars Exploration Rovers (MER), and the anomaly history of the Galileo and Voyager spacecraft to provide a look at non-Martian long lived missions. This paper adds the anomaly history for Mars Global Surveyor and Mars Odyssey 2001, two spacecraft in orbit around Mars.

History

The Mars Global Surveyor (MGS) spacecraft, built and operated for NASA by Lockheed Martin under the auspices of the Jet Propulsion Laboratory (JPL), was launched in November 1996. It was the first attempt to return to Mars after the loss of the Mars Observer spacecraft in 1992 and utilized many of the same instruments with the goal of

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mapping the surface and of Mars and providing a more detailed view of the planet than had been previously possible[5]. MGS entered orbit around Mars in September 1997 and slowly decelerated to its final science orbit utilizing the second application of the still new aerobraking technique[6,7]. Aerobraking phases and science phases were interleaved until the spacecraft was in its final orbit in February 1999 at which time the mapping of the surface commenced along with other scientific endeavors. MGS served as a reference point and relay stations for all subsequent Mars missions until its final loss in November 2006.

The Mars Odyssey spacecraft, also built and operation by Lockheed Martin, was launched in April 2001, a little less than five years after MGS[8]. It was also considered a return to Mars after the losses of the Mars Climate Orbiter and the Mars Polar Lander in 1998. It brought to the planet a more powerful camera and an additional suite of science instruments. Odyssey arrived in October 2001 and entered into an aerobraking orbit lasting through January 2002 when the spacecraft reached its final science orbit. Planned activities for the spacecraft included a continued mapping of the Martian surface and serving as a radio relay for future lander missions such as the twin MER which landed in January 2004 and have been in operation every since.

Mission Anomalies

As with the other papers in this study, the anomalies for these two spacecraft have been collected from the Incident, Surprise, and Anomaly (ISA) report database maintained at the JPL for NASA. All post launch anomaly reports for these two spacecraft through February 2007 were collected and analyzed to identify trends in either when the anomaly occurred or the types of anomalies and resulting actions taken to address them.

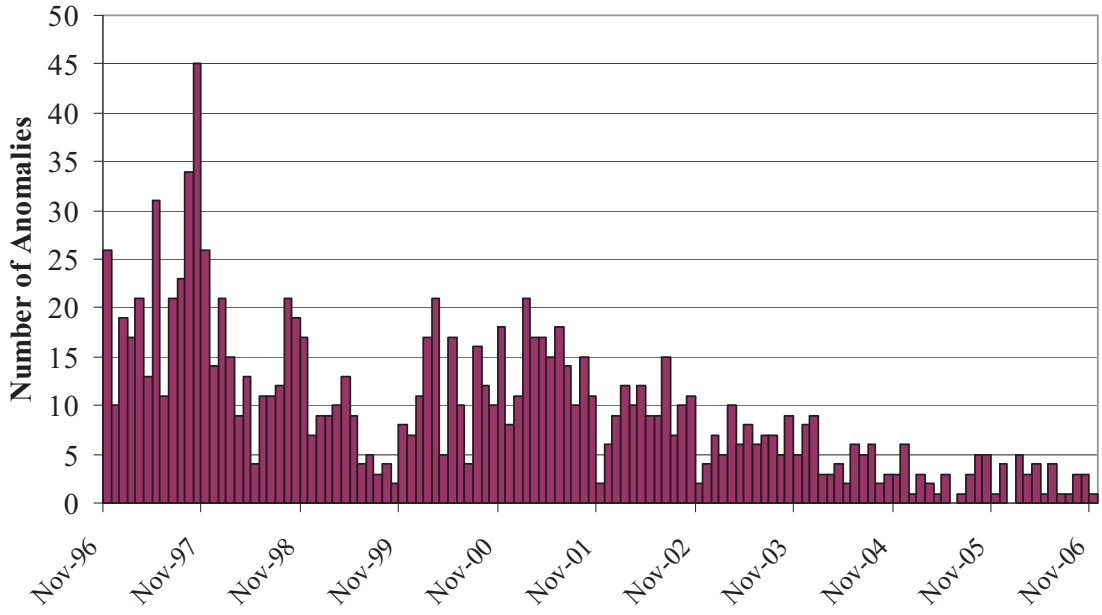

Figure 1. Anomalies for the Mars Global Surveyor mission as a function of time.

Anomalies with time

The first analysis of the gathered anomalies resulted in the creation of plots showing the generation of ISAs as a function of time. For both missions, the anomalies occurring within a calendar month were counted and plotted over the course of the mission resulting in figure 1 for MGS and figure 2 for Odyssey.

The MGS mission lasted from November 1996 though November 2006 providing nearly ten years of service around Mars. When examining the plot of the anomalies per month over it operation life several patterns emerge that are very similar to those seen with other spacecraft. The first trend to note that the majority of anomalies reports to occurred at the beginning of the mission often during the cruise stage and initial orbit insertion. With the MGS mission, this trend is not as definitive as it has been in other missions or as visible in the plots as it is for the Odyssey mission seen in figure 2, but it is still clearly present. In the month including launch and in the following 10 month cruise there were several months in which there were 25 or more ISAs written and no month with less than 10 anomaly reports. The number of anomalies peaked at 45 ISAs in the first month after Mars Orbit Insertion (MOI) in October 1997 after which time the number of anomalies per month can been seen to drop sharply. These peaks early in the mission and at times of high activity such as MOI have been common for all missions analyzed. The reason for these high numbers of anomaly reports seems to stem from the fact that the spacecraft were in actual use for the first time and there seems to be a learning curve for the mission operations team as they fly the craft after launch. Critical operations such as both insertion into Mars orbit and the beginning of aerobraking also resulted in new experiences and heightened awareness of the operation of the spacecreaft. Not all of the anomalies encountered during these peak times are due to spacecraft faults as will be examined later in this paper, but may also stem from the use of new ground based systems and software.

Once MGS had entered orbit there was sharp decrease in anomaly reports possibly due to lowered activity during the aerobraking stage of the mission. While the reduction in anomaly reports after orbit insertion seems to be a common trend, for MGS another possible reason for the reduction in the number of ISAs in this time period and for the year following was the adoption of the "Faster, Better, Cheaper" philosophy. Based on the examination of other missions flown during that paradigm[2] detailed reporting of anomalies seems to have not been as heavily stressed leading to far fewer ISA reports than might otherwise have been registered. As reported in an earlier paper, missions such as the Mars Climate Orbiter (MCO) and the Mars Polar Lander (MPL), which traveled to Mars toward the end of 1998 and first part of 1999, reported far fewer anomalies than did earlier missions such as MGS or later missions such as Odyssey. With the failure of MCO and then MPL, the number of anomaly reports increased again near January 2000 possibly showing an increased effort to report and track anomalies found on either the spacecraft or in the mission operations environment.

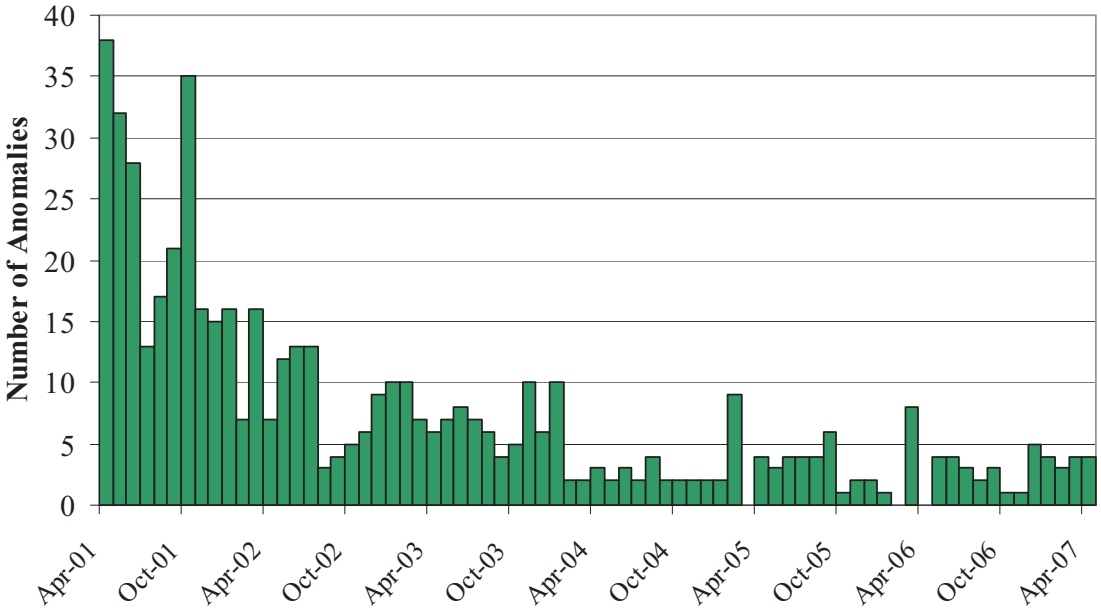

Figure 2. Anomalies for the Mars Odyssey mission as a function of time.

The trend toward most anomalies occurring early in the mission is more readily seen in the plots for the Odyssey mission. Figure 2 shows that the largest numbers of anomalies occurred in the first three months after launch with a secondary peak following MOI in October 2001. The numbers of anomaly repots generated for the remainder of the mission are significantly lower than those seen in the early part of the mission. There are localized peaks throughout the mission but they do not compare to the large number of anomalies from the cruise and orbit insertion stages.

Returning to the plot of anomalies for MGS, figure 1, another overall trend shown is a gradual in anomaly reports with increasing mission time. This trend is again a common one seen in all long terms missions analyzed in this multi-year study and is also clearly seen in the plot of anomalies reported for the Odyssey mission, figure 2. In both mission seen here and in fact in all cases examined in this study, after the spike in anomaly reports early in the mission, the number of reports steadily declined with increasing time of spacecraft operations. In some ways this decrease is surprising since an argument can be made that as the spacecraft is in use for longer periods of time, the number of faults and wear on the mechanisms should produce more anomalous behavior. While that argument may have some validity, and could be seen to some degree in the MER mission[3], there remains an overall decay in the numbers of anomalies reported. Explanations for the decrease in anomaly reports come in many forms ranging from mission team familiarity with the idiosyncrasies of the spacecraft and ground support equipment, to a decrease in the number of operable instrument due shutdowns on failed instruments. One more documented potential cause was found in the earlier study of the anomaly reports for the Voyager and Galileo spacecraft. In that case the numbers of anomalies reported decreased as a rate similar to the decrease in the size of the workforce utilized to operate the spacecraft[1]. With the MER mission, a sharp decrease in anomalies

came at the same time the mission transitioned from round the clock, seven days a week operations to more regular work day timing and a reduction in the number of people directly supporting the mission[3]. For MGS and Odyssey the details of staffing and instrument activity have not been explored for this study, but the decrease in anomalies is likely due to the same sources.

Anomaly types

In addition to plotting the occurrence of anomalies as a function of time, each ISA was read and characterized for the source of the anomaly and the type of corrective action taken in response. To simplify the study and to keep the results consistent with work performed on other missions each anomaly was identified as a flight hardware, ground hardware, flight software, ground software, or procedure anomaly. In similar fashion the corrective actions were identified to be a flight software, ground software, ground hardware, or procedure basis corrective action. In addition taking no corrective action or, to "use as is" was an option. There were a few anomalies where no action was recorded which were categorized as "unknown" corrective action. Definitions used for each category are listed below.

1. *Anomaly Sources:*
   - Flight Hardware – An event where physical hardware on the spacecraft either acted in an unexpected fashion or failed in its intended operation.
   - Flight Software – Any anomalous action taken by software running on computers physically located on the spacecraft including the results of uploaded instructions or downloaded data.
   - Ground Hardware – An event that occurred due to anomalous behavior or failure of physical hardware not on the spacecraft. These physical systems included mission control computers, Deep Space Network systems, and utilities including power and computer networks.
   - Ground Software – Any anomalous action taken by computer system running on ground based computers. These may be due to improper code, improper data files, unexpected handling of data downloaded from the spacecraft, and prediction files for the DSN.
   - Procedure – An anomaly that occurred due to improper actions taken by human controllers. These anomalies generally stem from either a lack of knowledge of proper procedure, a situation that had not been anticipated, or an error in process.
2. *Corrective Actions:*
   - Use As Is – Effectively to take no action. The response given for flight hardware anomalies where no work around or redundancy was possible. Also used in situations where no action is possible, no action needed due to a lack of repetition, a situation overtaken by events, or for reports of anomalies that were in reality normal behavior but not understood when recorded.
   - Flight Software – A corrective action that involved sending new software or data to the computers operating on the spacecraft. These corrective actions either fixed incorrect information given to the spacecraft, addressed errors in the

software operating the spacecraft systems, or gave instruction on how to deal with anomalies coming from flight hardware.

Ground Hardware – Action taken to fix or replace hardware located on the Earth. These responses were either to repair a system, to upgrade a computer, or to re-establish use of hardware that had experienced an anomaly.

Ground Software – Any change to software or data streams running on Earth based computers. These included upgrades to sequence generation codes used to generate flight instructions, modeling software, data handling software, and any of the other software modules used by the mission teams.

Procedure – Modifications to how the mission team operated either as a group or individually. These corrective actions included changes to mission rules, operational procedures, changes in the use of hardware due to anomalies or failures, or how software was utilized.

Unknown – The electronic anomaly reports give no record of any corrective action.

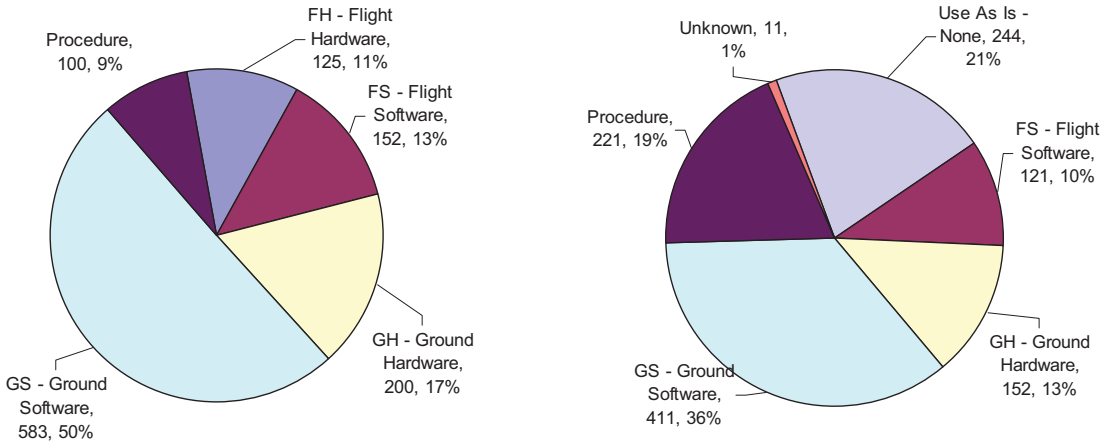

Figure 3. Anomaly Sources (left) and Corrective Actions (right) for the Mars Global Surveyor mission.

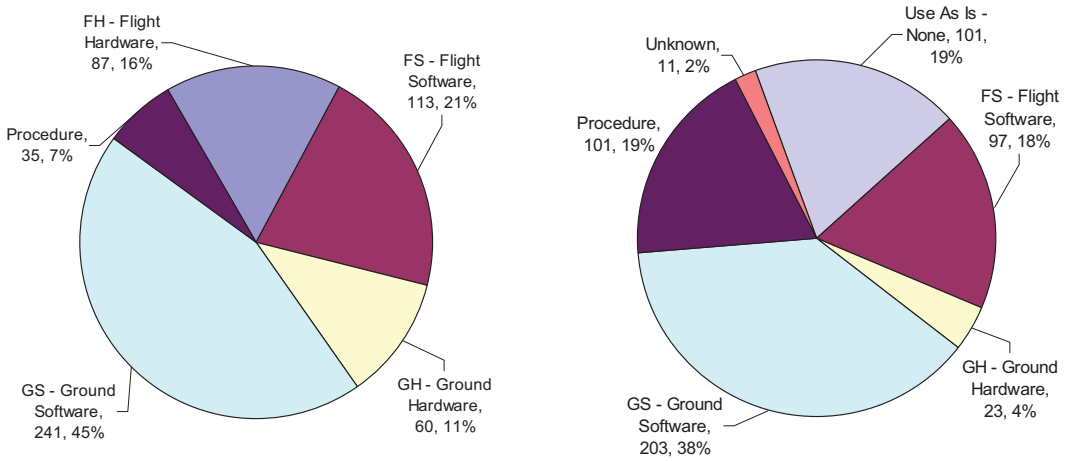

Figure 4. Anomaly Sources (left) and Corrective Actions (right) for the Mars Odyssey mission.

For both MGS and Odyssey, pie charts were created to display the relative percentage for each type of anomaly source or corrective actions. The plots generated for all anomalies generated are shown in figures 3 and 4. When first looking at these pie charts, it should first be pointed out how similar the percentages are between the two missions. The similarities are particularly interesting considering that fact that MGS was launched five years prior to Odyssey and had roughly twice the number of anomalies in the ISA database. The fact that both missions were constructed and operated by the same company may have something to do with the common trends for these two missions, but it is still remarkable. The other long life orbital mission that was analyzed at the beginning of this study produced pie charts with quite different percentages[1]. On the other hand, the percentages for the Mars Exploration Rovers during surface operations[3], seen in figure 5, were somewhat similar to those displayed here for MGS and Odyssey. The similarities for the charts produced for MGS, Odyssey, and to a more limited extend, MER allows for a few potential trends to be identified.

Looking first at anomaly sources, the most obvious and important trend is that ground software anomalies are by far the most numerous type of anomaly for all missions. For MGS, they represented 50% of all anomalies while for Odyssey, anomaly reports generated from ground software sources accounted for 45% of all anomalies. Since much of the work of the mission teams involves use of ground based computers, these numbers are perhaps not wholly unexpected, but it seem important note that half of all anomalies reported in the ISA database for both missions were due to use of Earth based computer systems. To be fair to the teams operating these missions, all anomalies were counted in this study without regard to the how critical the anomaly was to the success or failure of the mission. Additionally, ground software anomalies most likely encompassed the widest range of anomalies covering problems with databases, login failures, and issues regarding tracking predictions at DSN stations to listing only a few specific recurring anomalies. A few of the peaks in the time plots shown above are due to such recurring ground software issues that were encountered multiple times within a given time period

before being effectively addressed with either a software fix or a procedural work-around.

Continuing to examine the anomaly sources charts, the anomalies not due to a ground software incident were fairly evenly split between the other four anomaly sources. The exact percentages were not the same for both missions, but they are remarkably close considering the different ages of the spacecraft the number of ISA reports in the system. MGS experienced a greater number of ground hardware anomalies than Odyssey, but only by 6%. These were for the most part problems with the DSN or with the communication links between the mission teams. Odyssey experienced more flight software issues, but again only by 8%, a relatively small number.

Continuing on to examine the corrective actions taken to address the anomalies reported for both spacecraft in can been seen that again the charts show very similar number for both spacecraft. Given that half of all anomalies originated with ground software issues it follows that ground software fixes were the largest response for both missions. The numbers do not, however, exactly match. For both missions, ground software anomalies were generally addressed with a fix to the ground software, but other types of corrective actions were taken as well with the decision to "use as is." In fact this response, to "use as is," or in effect to take no corrective action, was the second most common response for both missions. In other missions studied to date, the "use as is" response has generally been either the most common corrective action or, as in the case of these two missions, the second most common response. In most cases this type of response was due to either the absence of any viable corrective actions because either no action is possible as with issues with flight hardware, or no action was needed since the reported anomalous behavior was in fact a normal response of either the spacecraft or the ground support system.

Of the remaining corrective actions, a change to the mission team's procedure was the next most common response and was nearly as common as the decision to "use as is." The balance between flight software corrective actions and changes made to ground hardware were where the primary differences exist between MGS and Odyssey. The mission teams for MGS needed to make more changes to their ground hardware systems either due to issues with communication lines, receiver problems at the DSN locations, or unexpected power outages or computer failures. Odyssey required a greater number of flight software fixes which were often used to address either sequencing issues, problems with primary flight software, or to remotely address flight hardware issues when possible.

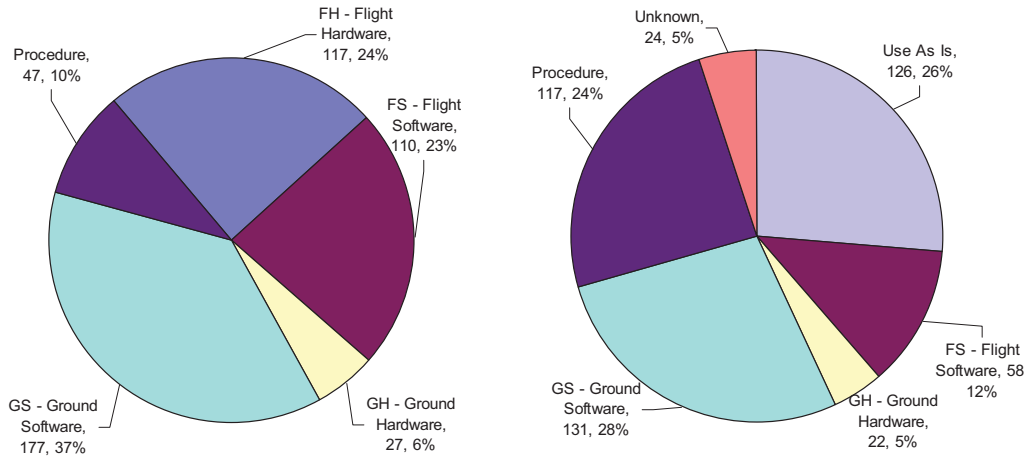

Figure 5. Anomaly Sources (left) and Corrective Actions (right) for the Mars Exploration Rover mission, surface operations[3].

To provide another sent of data points for comparison it seems instructive to examine the anomaly sources and corrective actions from the Mars Exploration Rovers which were examined in a previous paper in this multi-year study[3]. While the spacecraft are quite different with MGS and Odyssey as orbiting platforms while the two rovers landed on the surface of Mars, a great deal of similarities can be seen in the plots for their anomaly reports. As seen in figure 5, the greatest source of anomalies for the MER mission was again ground software. The percentage is not as high as seen with MGS and Odyssey, but it is again the largest single source for anomalies. Flight hardware issues were more numerous for MER as were flight software issues, but these may be due to the differences between surface and orbital missions. For corrective actions, ground software based actions were again the largest type of response with "use as is" and procedural changes not far behind. The differences may well stem from the differences between types of spacecraft, but the fact that there are such similarities help propagate the trends seen in the anomaly reports for MGS and Odyssey.

Conclusion

While it is difficult at best to draw meaningful conclusions concerning spacecraft anomalies from only two data points, when viewed along with the previous work several trends start to emerge.

The greatest numbers of anomalies occur early in the mission and at key milestones in mission operations. This trend tends to indicate a steep learning curve for mission teams and has been seen in the plots of anomalies as a function of time for all missions examined over the duration of this study. Localized peaks in anomalies tend to form with heightened mission activity though they may not be as pronounced as the peaks at the beginning of the mission.

With increasing mission time there is a general trend toward decreased numbers of anomaly repots. This trend has again been seen for all missions analyzed to date and seems to be a recurring trend. This decrease has been previously shown to track with the workforce numbers for missions like Galileo and, to a lesser degree, the Mars Exploration Rovers, but there are potentially multiple sources for the decrease in anomaly reports ranging from decreased activity to increased familiarity with ground and spacecraft operating conditions.

For missions in the last decade the largest source of anomalies is software operating on ground based computer systems. These anomalies are of varying types but in the case of both MGS an Odyssey they represented half of all anomalies. The remaining four categories for anomaly sources were fairly evenly distributed over the remaining half of the anomaly reports. The results of the MER mission support this trend to a degree limited by the differences between orbital and lander missions.

Corrective actions taken in response to the reported anomalies tended to respond in kind with ground software fixes comprising the largest percentage. The decision to "use as is" was also quite common and as was a procedure change. The percentages for flight software fixes and ground hardware corrective actions varied for these two missions depending on the conditions faced by the mission teams.

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