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SATELLITE GN&C ANOMALY TRENDS

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On-orbit anomaly records for satellites launched from 1990 through 2001 are reviewed to determine recent trends of unmanned space mission critical failures. Anomalies categorized by subsystems show that Guidance, Navigation and Control (GN&C) subsystems have a high number of anomalies that result in a mission critical failure when compared to other subsystems. A mission critical failure is defined as a premature loss of a satellite or loss of its ability to perform its primary mission during its design life. The majority of anomalies are shown to occur early in the mission, usually within one year from launch. GN&C anomalies are categorized by cause and equipment type involved. A statistical analysis of the data is presented for all anomalies compared with the GN&C anomalies for various mission types, orbits and time periods. Conclusions and recommendations are presented for improving mission success and reliability.

INTRODUCTION

A study of past on-orbit anomalies was undertaken to assess how future satellite program resources might be best spent to ensure mission success. The requirements for future spacecraft include advances in reliability, particularly for deep space missions and long duration Earth observing platforms. The American industry has typically tried to achieve this goal by incorporating redundancy, robustness and fault tolerance in spacecraft designs, and verifying those designs with a thorough test program. This approach has had varying degrees of success; it is not clear whether the benefit outweighs the cost for all cases. Although Launch Vehicle failures have contributed to the majority of past space mission losses, this trend may be changing; in 1998 the bulk of satellite losses were caused by failures of on-orbit satellites. In the last four years, space insurance rates for Geosynchronous Earth Orbit (GEO) commercial communications satellites has risen by 129% and major on-orbit anomalies have risen by 146%[1]. Analysis of on-orbit anomalies can provide greater insight into design and process improvements and help in devising more effective verification methods during integration and test.

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Mission critical on-orbit anomalies were analyzed to determine the number and characteristics of mishaps. A mission critical failure is defined as a premature loss of a satellite or loss of its ability to perform its primary mission during its design life. On-orbit anomaly data used in this study was taken from a number of sources in the public record. Data was taken from databases available on the web including The Satellite Encyclopedia (TSE)[2], Satellite News Digest[3], Mission and Spacecraft Library[4], Airclaims Space Trak[5], and Encyclopedia Astronautica[6]. Data was also taken from the Space Systems Engineering Database[7] (SSED) and the Mission Failure Analysis for NASA Ames Research Center[8]. All anomaly reports collected were unclassified, and almost all were written, archived and reference-able. Wherever possible, records of anomalies were corroborated between multiple sources. Anomalies associated with Guidance, Navigation and Control (GN&C) were scrutinized further, with every attempt made to obtain mishap reports, visit pertinent web sites, or to contact people with insight into the problem. A statistical analysis of the data was undertaken for all anomalies compared with GN&C anomalies, for various mission types, orbits and time periods.

In this study, GN&C is defined as including the on-orbit Attitude Control System (ACS), the on-orbit Propulsion System and all ground operations and software associated with satellite flight dynamics (trajectory planning and determination, navigation and attitude determination).

DATA COLLECTION

Table 1 contains the satellite classifications and categories used for analysis of anomaly trends. Only on-orbit anomalies involving un-manned spacecraft were investigated; launch and upper stage failures were not recorded. Anomalies were investigated for all on-orbit satellites launched in the years 1990 through 2001. The analysis only investigated satellites that were designed and built by companies or government organizations in the United States, Europe, Canada or Japan. An anomaly was recorded only if it occurred prior to the mission fulfilling its design life. Anomalies that occur during an extended mission were not recorded.

Table 1 Anomaly Classification

Classification	**Category**
Satellite	Name
Mission	Space Science, Earth Science, Deep Space, Communications, Military, Technology, Other
Orbit	Low Earth Orbit (LEO), High Earth Orbit (HEO), Geosynchronous Earth Orbit (GEO), Heliocentric, Planetary
Launch Date	1990 through 2001
Design Life	
Anomaly Date	
Impact	Total Loss, Partial Loss, Mission Interruption, Shortened Life, Performance Loss
Failure Subsystem	Attitude Control System, Propulsion, Electrical Power System, Command & Data Handling, Mechanical, Software, Payload, Operations, Unknown

Missions were categorized as space science (including astronomy, observation of the Sun, and Sun-Earth connection) Earth science (including meteorology, remote sensing, observations of the Earth atmosphere, ionosphere and magnetosphere, and geodesy), deep space (Mars, Lunar and asteroids), communications (including telecommunications and Direct TV), military, technology, and other (including test, burial, materials processing and life sciences).

Orbits were categorized as Low Earth Orbit (LEO), High Earth Orbit (HEO), GEO, heliocentric, and planetary. LEO orbits were defined as Earth centered orbits having apogee less than 1500 km. HEO orbits were defined as Earth centered orbits with apogee greater than 1500 km.

The anomaly date is defined as the date that the anomaly first occurred. In some cases, a failure can take a significant time period to fully affect the mission. In general, the date of first occurrence of the anomaly was recorded.

The impact was categorized as total loss, partial loss, mission interruption, shortened life, or performance loss. A total loss resulted if a satellite failed so that it could no longer perform the mission, or if it was deactivated or taken out of service due to an anomaly. A shortened life is equivalent to a total loss, although the loss has not yet occurred. The analysis did not include anomalies that resulted in loss of redundancy, or a minor interruption in the mission due to an operational work-around or software patching. Anomalies that occurred within the planned satellite operational checkout phase were not recorded unless they had an effect on the ability to perform the subsequent mission. A mission interruption was only recorded if it occurred for a substantial time period (e.g., more than a week). In general, an anomaly was recorded if an insurance claim was paid.

The subsystem categories were made up of ACS, Propulsion, Electrical Power Subsystem (EPS), Command & Data Handling (C&DH), mechanical, software, payload, operations, and unknown. Mechanical was assumed to include structures, mechanisms and thermal. ACS was assumed to include all sensor, actuator, and ACS software involved with on-board attitude and orbit control. GN&C was assumed to include ACS, propulsion and all ground operations and software involved with flight dynamics. A number of recent anomalies have been associated with crystalline growth on tin relays that short circuit the spacecraft processor; these were categorized as C&DH. EPS anomalies included solar array, battery, bearing and power transfer assembly, DC-DC converter and power regulator problems. Transponder anomalies on communications satellites were categorized as payload anomalies. In a few instances, an anomaly was attributed to two subsystems.

All of the GN&C anomalies were scrutinized further. Table 2 illustrates data that was collected for GN&C anomalies, in order to discern trends specific to GN&C anomalies. GN&C anomalies were categorized as caused by problems in design, hardware, software, verification, operations or the environment. Design includes analysis and models, processes or misapplication of hardware. The design category was applied at the system level; problems with the design of components typically procured (e.g., reaction wheels, gyros) were categorized as hardware. The hardware category includes materials, parts, workmanship and design of components. The verification category was applied where the test effort should have caught the design or process error (e.g. ACS polarity errors not found in test). The environment category was applied where on-orbit events such as magnetic storms caused the anomaly.

Table 2 GN&C Anomaly Classification

Classification	**Category**
Cause	Design, Hardware, Software, Verification, Operations, Environment
Equipment Type	Wheel, Gyro, GPS Receiver, Earth Sensor, Thruster, Tank, Pyrovalve, Processor, Nutation Damper

The GN&C equipment category includes wheel (reaction wheel or momentum wheel), gyro, GPS Receiver, Earth sensor, thruster, tank (fuel tank or pressurant tank), pyrovalve, processor and nutation damper. The equipment did not necessarily have to fail, but was at a minimum involved in the anomaly (e.g. a pyrovalve was fired that induced a propulsion system explosion), or the equipment failure caused the anomaly (e.g. the second of four reaction wheels failed causing the mission to be interrupted for a significant amount of time).

To the extent possible, the subjectivity of anomaly reports was removed to prevent bias in analysis results. Multiple sources were used wherever possible to corroborate events. Every GN&C anomaly was scrutinized by each of the two authors to ensure consistency of reporting. Despite these precautionary efforts, a bias in analysis results does exist. The accuracy of anomaly reports has a direct bearing on the trends observed. Many anomalies are not reported in the public domain, particularly those involving military missions. Satellite insurance claims are not highly publicized due to their proprietary nature. The probability that an anomaly is reported can depend on the severity of the anomaly (i.e. a greater percentage of anomalies causing total loss are reported than those causing performance loss). Many other anomalies are reported, but the details are scarce or the cause of the anomaly is not reported. Being employed by NASA, the authors have greater insight into anomalies on NASA missions than anomalies on other types of missions. In some cases the impact of the anomaly is diminished by the reporting organization. Anomalies were recorded only if they occurred within the satellite design life; the reported design life of a satellite can be subjective. It was assumed that the mission started as soon as the satellite was launched. No value was placed on any of the satellites or the severity of the anomalies. An anomaly that resulted in the loss of a half billion-dollar asset was counted the same as an anomaly that resulted in loss of a University-built micro-satellite. The impact of an anomaly can be a matter of luck; an ACS polarity problem can result in total loss of mission (which would be recorded) or result in the ground catching and uploading software to fix the problem within the planned checkout phase (where it would not be recorded). Finally, the interpretation of an anomaly report and the resulting categorization can be subjective.

DATA ANALYSIS

Figures 1, 2 and 3 illustrate the total number of on-orbit satellites investigated in this study. Every on-orbit satellite that originated from the United States, Europe, Canada or Japan is shown by year launched from 1990 through 2001, mission type and orbit. Satellites that were not placed in the proper orbit by the Launch Vehicle or Upper Stage were not recorded. A total of 764 satellites were recorded. It can be seen from Figure 1 that the launch rate for those satellites investigated peaked in 1998, mostly due to the launch of many LEO communication satellites during that time. Figure 2 shows that the majority of satellites launched were communication satellites, followed by those designed for military purposes. Figure 3 shows that the majority of satellites were launched into LEO orbits, with GEO orbits receiving the next largest number of launches. Very few missions were launched into heliocentric or planetary orbits.

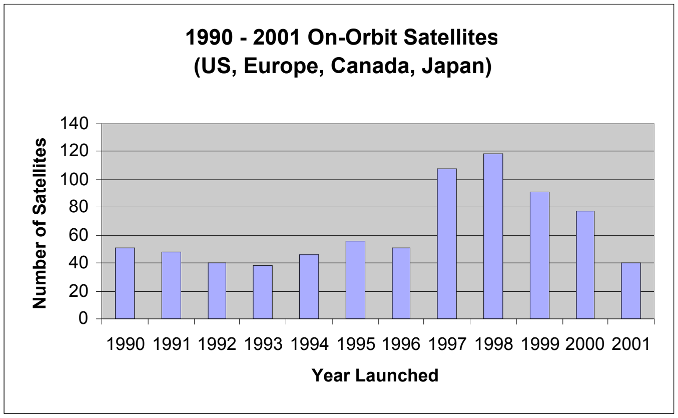

Figure 1 On-Orbit Satellites vs. Year Launched

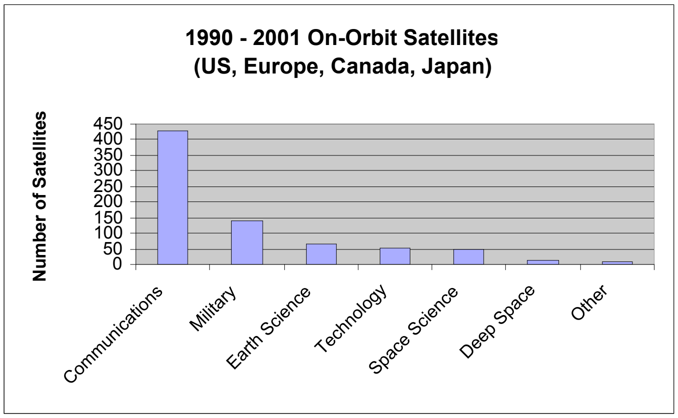

Figure 2 On-Orbit Satellites vs. Mission Type

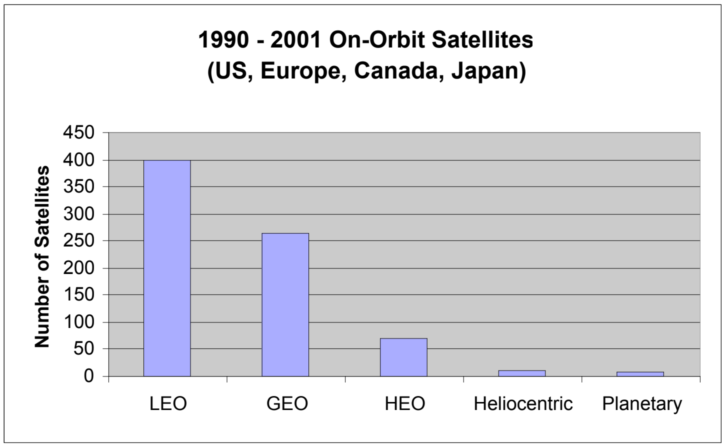

Figure 3 On-Orbit Satellites vs. Orbit

Figure 4 illustrates on-orbit satellite anomalies recorded for satellites launched from 1990 through 2001 relative to the distribution by satellite subsystem. All anomalies are shown, as well as those that resulted in total mission loss. It can be seen that payload, EPS and ACS have a large contribution to reported anomalies. A total of 35 GN&C (ACS, propulsion, and ground operations and software involving flight dynamics) anomalies were reported during the time period investigated, which represents 29% of all anomalies recorded. The GN&C contribution to anomalies that result in total loss is higher, with 13 GN&C anomalies reported representing 37% of all anomalies resulting in total loss.

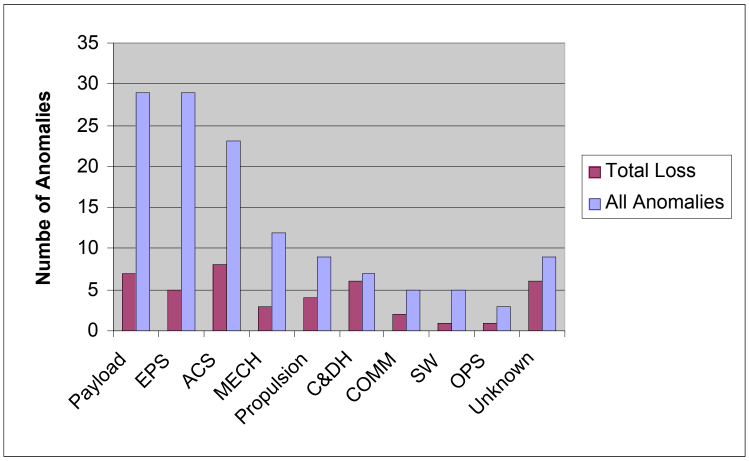

Figure 4 Subsystem Anomalies

Table 3 lists those GN&C anomalies recorded for satellites launched from 1990 through 2001.

Table 3 GN&C Anomalies

Satellite	Launch Date	Mishap Date	Impact	Cause
Anik E2	4/5/1991	1/20/1994	Mission Interruption	Magnetic storm destroyed ACS
Aurora 2 (Satcom C5)	5/29/1991	6/1991	Shortened Life	Motor fault
Clementine	1/25/1994	5/1/1994	Partial Loss	Software error caused spin up and loss of fuel
Deep Space 1	10/24/1998	7/1999	Partial Loss	Target tracking problem due to software
Early Bird	12/24/1997	12/28/97	Total Loss	GPS unit shorted to bus draining batteries
Echostar 5	9/23/1999	7/1/2001	Mission Interruption	One of three momentum wheels fails
FUSE	6/1/1999	12/1/2001	Mission Interruption	Second of four reaction wheels fails
Galaxy 4	6/25/1993	5/19/98	Total Loss	Catastrophic attitude control failure due to SCP malfunctions
Galaxy 8i	12/8/1997	9/1/2000	Shortened Life	Three of four xenon ion thrusters fail.
GFO 1	2/10/1998	3/1998	Mission Interruption	GPS receivers fail to maintain nav state; ground-based workaround implemented
Goes 9	5/23/1995	7/7/1998	Total Loss	Taken out of service due to noisy pointing caused by lubrication starvation of momentum wheels.
GPS BII-07	3/26/1990	5/21/1996	Total Loss	3-Axis stabilization failure due to a second reaction wheel failure
Hotbird 2	11/21/1996	12/31/1996	Shortened Life	Fuel tank leak; Apogee transfer anomaly
HST	4/1/1990	11/1/1999	Mission Interruption	Fourth of six gyros fails
IMAGE	3/25/2000	3/25/2000	Mission Interruption	Nutation damper liquid immobilized by surface tension
Intelsat 801	3/1/1997	3/1997	Mission Interruption	Ground command error caused uncontrollable spin
Iridium	6/18/1997	9/1/1997	Total Loss?	Attitude control and propulsion system failure
Iridium	12/8/1997	7/17/1998	Total Loss?	Attitude control and propulsion system failure
Iridium	6/18/1997	11/2/2000	Total Loss?	Failure in orbit – fuel depletion
Iridium 5	5/5/1997	5/5/1997	Mission Interruption	Faulty wheel electronics.
Iridium 11	6/18/1997	6/18/1997	Mission Interruption	Faulty wheel electronics.
Iridium 27	9/14/1997	9/14/97	Total Loss	Thruster anomaly depleted operational fuel
Iridium 42	12/8/1997	12/8/1997	Mission Interruption	Wheel tachometer failure
Landsat 6	10/5/1993	10/5/1993	Total Loss	Satellite exploded when propulsion system pyrovalve was fired, igniting adjacent mixture.
Lewis	8/23/1997	8/26/1997	Total Loss	Design error in ACS; failure to monitor spacecraft during initial operations
Mars Climate Orbiter	12/11/1998	9/23/1999	Total Loss	Failure to use metric units in ground software trajectory models
Mars Observer	9/1/1992	8/1/1993	Total Loss	Probably due to Propulsion System rupture or power short, induced by oxidizer leaking past check valves.
NEAR	2/17/1996	12/1998	Mission Interruption	Main engine fuel burn malfunction due to on-board software limits being exceeded
Nozomi	7/3/1998	12/20/1998	Mission Interruption	Consumed more fuel than expected during Earth swingby due to thruster valve stuck partially open.
Solar A	8/30/1991	12/15/2001	Mission Interruption	Safe mode during solar eclipse, unexpected spin, loss of control
STEP 0	3/13/1994	7/19/1994	Mission Interruption	IMU (gyro) fails
STEP 2	5/19/1994	5/19/1994	Performance Loss	Noisy earth sensor affects pointing accuracy
Telstar 402	9/9/1994	9/9/1994	Total Loss	Propulsion System pyrovalve firing caused explosion
Terriers	5/18/1999	5/18/1999	Total Loss	ACS polarity error controlling magnetic torquer coil
TOMS-EP	7/2/1996	7/2/1996	Mission Interruption	Coarse Sun Sensors miswired; magnetic torque rod polarity error

The time of occurrence of satellite anomalies within their design life was investigated. Figure 5 illustrates when satellites were observed to fail for all anomalies, and those involving GN&C. In this figure, an anomaly was counted only if the satellite completed its design life by the end of 2002, or would have if the anomaly did not occur. It can be seen that the majority of anomalies (51% of all, 50% of all GN&C) occur within 10% of the mission design life.

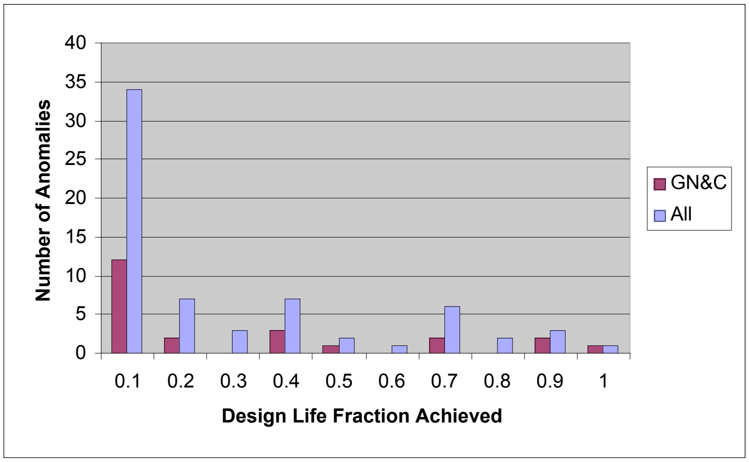

Figure 5 Anomaly Occurrence in Satellite Design Life

Figure 6 shows the time relationship of cumulative anomalies as a function of mission day, for both all anomalies and GN&C anomalies. It is interesting to note that the slope is not equal to 1, which would be expected if satellites exhibit constant anomaly failure rates. It can be seen that a large number of anomalies are observed on the first day of the mission. After reaching 10% of a satellite design life, the anomaly failure rate declines precipitously and continues to decline thereafter.

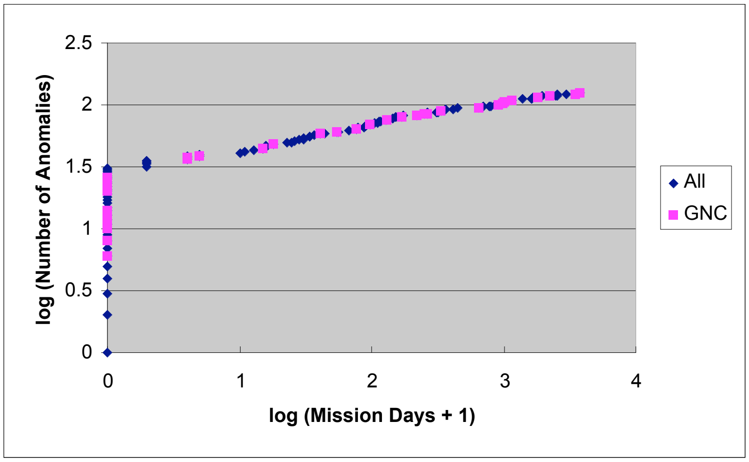

Figure 6 Cumulative Anomalies vs. Mission day

Mishap rates as a function of launch year, mission category and orbit category were investigated. Mishap rate was defined as the number of anomalies per satellites launched. Mishap rates shown in the following figures are for all anomalies recorded, using the total mission population whether or not the mission has completed its design life. Figure 7 illustrates the mishap rate distributed by year launched. The mishap rate over 1990 through 2001 appears to be fairly constant, especially when considering that the satellites launched later have not yet achieved their design life, making their status as success or failure as yet undetermined. The mishap rate due to GN&C anomalies is fairly constant as well, although it appears that GN&C anomalies have fallen recently, with few GN&C anomalies reported for satellites launched in 2000 or 2001. Although mishap rates observed are fairly constant, the number of reported anomalies has increased dramatically since 1997 due to the large number of satellites launched in 1997 through 2000.

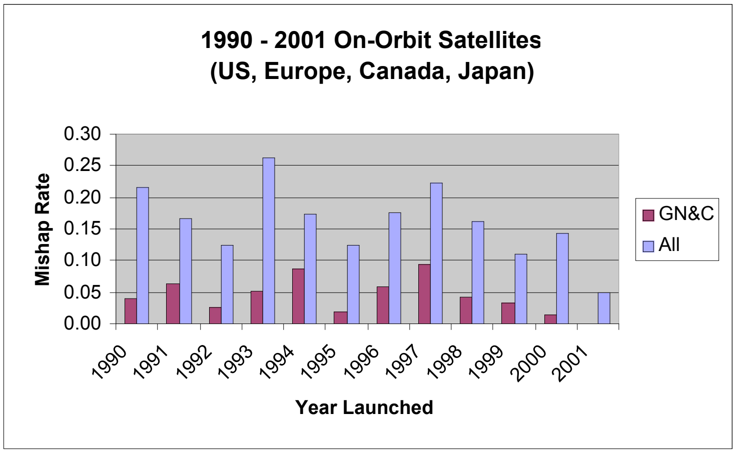

Figure 7 Mishap Rate vs. Year Launched

Figure 8 shows the mishap rate distributed by mission type. It can be seen that a large variation in mishap rate exists for various mission types. In general, mission types with a large number satellites (communications and military) have a lower mishap rate than missions types with few satellites launched (deep space), which is as expected. Deep space missions have very high mishap rates when compared to other mission types, and the GN&C contribution to these anomalies is very high. The high mishap rate may be explained by the inherent complexity of deep space missions. Deep space missions require high levels of autonomy and have limited communication time with the ground. In addition, the deep space environment is not as well characterized as for other mission types. The deep space thermal environment is extreme, and solar electric power generation may be problematic. Military missions have slightly lower mishap rates than expected when comparing to other mission types; this can probably be explained by under-reporting of anomalies for military missions. Technology missions are seen to have a low GN&C mishap rate when compared to their total mishap rate; this may be explained by the fact that technology missions by their nature have higher mishap rates due to their usually complex technology payload rather than due to any satellite bus subsystem.

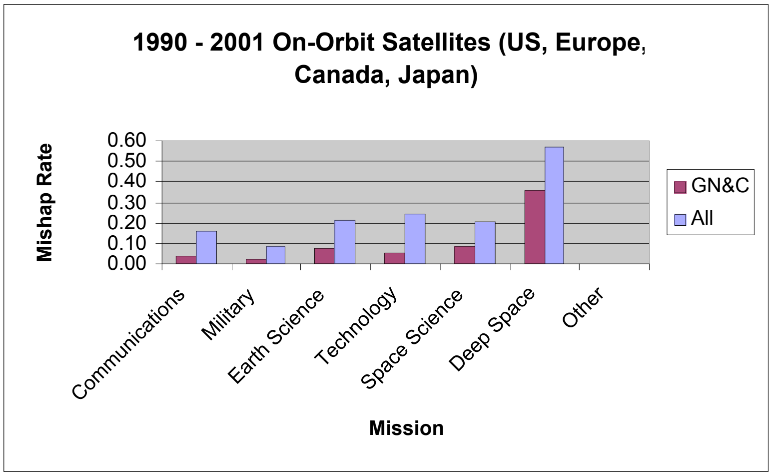

Figure 8 Mishap Rate vs. Mission Type

Mishap rates distributed by orbit also show variations depending upon the orbit category. Figure 9 shows that GN&C anomalies make up a rather large percentage (roughly one third) of LEO anomalies compared with GEO anomalies; this can be attributed in part to the large number of EPS problems that GEO communication satellites have exhibited recently. The average power level of GEO communication satellites launched from 1996 through 2001 has tripled[1], which has resulted in an increase in EPS technical complexity. It can also be seen that the GN&C contribution to anomalies in heliocentric and planetary orbits is very large; this may be partly explained by the fact that heliocentric and planetary missions cannot rely on magnetic control and require a propulsion system, whereas this is not the case for LEO missions. The large percentage of GN&C anomalies can be also attributed to the difficulty of getting to heliocentric and planetary orbits. Missions in heliocentric and planetary orbits have the highest observed mishap rate.

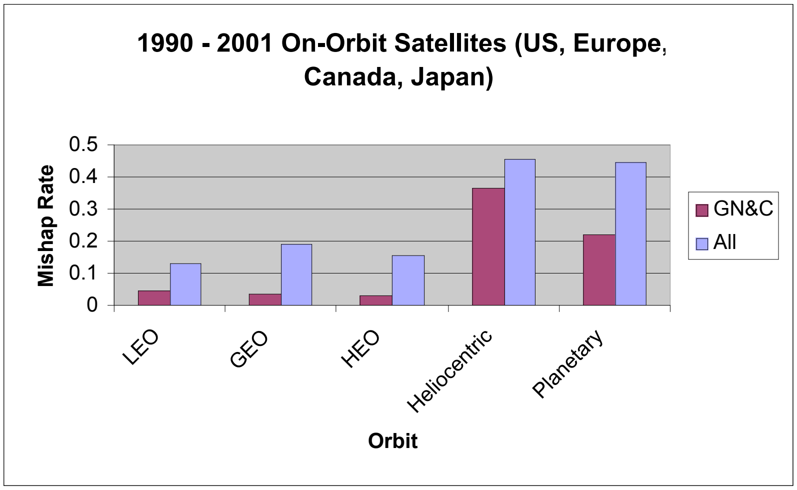

Figure 9 Mishap Rate vs. Orbit

Figure 10 shows the GN&C failure categories observed. It can be seen that the largest number of GN&C anomalies can be attributed to hardware problems. Design, software and operations problems are the next major cause categories for GN&C anomalies, although more design problems result in total loss. All anomalies categorized as verification were ACS polarity errors.

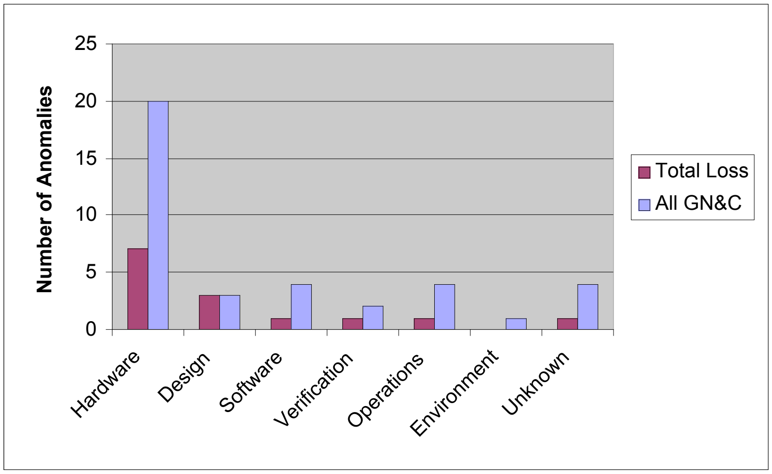

Figure 10 GN&C Anomalies vs. Cause Category

Figure 11 shows GN&C anomalies categorized by equipment type. Not all GN&C anomalies have an obvious associated equipment type (e.g., an ACS polarity problem with the magnetic system was not given an equipment category). It can be seen that the largest number of GN&C anomalies are attributed to wheel failures. Pyrovalve induced anomalies have been a problem for both propulsion system applications as well as payload applications, and tend to result in total loss of mission. Pyrovalves by themselves are reliable, but in these cases the adjacent systems have not been able to withstand the mechanical or electrical shock generated by the pyrovalve. A number of anomalies have been caused by faulty processor operations. Faulty thrusters have caused a number of anomalies. A number of gyro failures have occurred, but many of them have occurred after the satellite design life was reached so were not counted in this analysis. A number of missions have recently developed gyro-less attitude determination software, so gyro failures now tend to result in mission interruption or performance loss instead of total failure. It is interesting to note that no anomaly records were found involving star trackers; it appears that most star tracker anomalies can also be solved with software uploads.

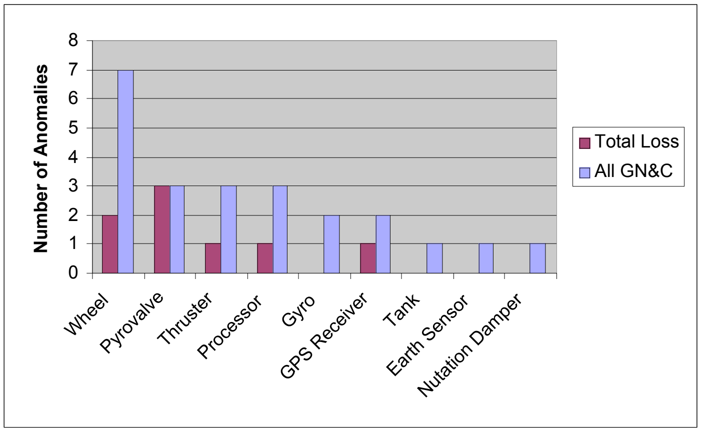

Figure 11 GN&C Anomalies vs. Equipment Type

CONCLUSION

A study of past on-orbit anomalies was undertaken to assess how future satellite program resources might be best spent to ensure mission success. Spacecraft anomaly trends were surveyed over the last decade, with the hope of learning ways to improve the process of GN&C system development, to reduce the failure rate of future missions. One conclusion that was apparent during the data survey was that industry-wide data is not shared on a routine basis. It is difficult to learn from history if anomaly records are kept out of the public domain.

As expected, most anomalies were observed to occur early in the mission. This indicates that design flaws and latent manufacturing defects have a greater effect on mission success than materials contamination or fatigue/overstress. The standard spacecraft integration and test process already invests significant effort to expose design flaws and physical defects before launch. The fact that some mission critical faults get through shows that this effort is not excessive. Is more testing needed? Not necessarily; other studies have drawn a correlation between parts failures and stress due to excessive testing. It is recommended, however, that testing be done in as flight-like a configuration as possible (e.g. flight harnesses for polarity tests), and that all test results be understood. This may seem obvious, but history shows that test anomalies have been overlooked, only to be found in review of test data after an on-orbit failure.

An exception to the trend of anomalies occurring early in the mission is wheel anomalies. Wheel anomalies tend to occur later in the mission, which suggests that mechanical wear-out is an increasingly significant factor. Since wheel anomalies are the most common GN&C failures, the most significant reduction in GN&C failures may be realized by improving wheel reliability over time. The satellite industry may benefit from investing in more robust life test programs for wheels.

Aside from wheels, the most troublesome GN&C components appear to be pyrovalves. While the pyrovalves themselves are reliable, they are apparently easy to misuse, leading to catastrophic damage of other components. This is counted as a design flaw, not of the pyrovalve but of the system that employs it. The mechanical and electrical interactions of the pyrovalves with surrounding systems must be thoroughly understood.

Many recent anomalies have been caused by EPS problems associated with solar array and battery anomalies. It is apparent that the increase in technical complexity and design lifetime for GEO communication satellites has increased the risk of failure in this subsystem.

Deep space missions and missions in planetary and heliocentric orbits have very high mishap rates when compared to other types, and the GN&C contribution to these anomalies is very high. The GN&C effort for these missions is inherently more technically complex due to the complex orbit trajectory requirements, the need for high levels of autonomy and their dependence on propulsion systems. A higher level of funding, testing and oversight of the GN&C effort for these missions is warranted.

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