STUDY OF SPACECRAFT DEPLOYABLES FAILURES

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ABSTRACT

Unsuccessful deployments of solar arrays, antennas and other spacecraft deployable appendages are one of the main causes of initial satellite failures and reduction in their capabilities with, on average, one failure occurring every two years. Because the spacecraft is 'brand new' but cannot perform as designed and meet its mission objectives, deployables' failures result in extremely large insurance claims. As an example, a total of almost $800M in insurance claims resulted from solar array (SA) failed deployments in the past 23 years. This paper examines spacecraft deployables failures and anomalies that have occurred on a total of 53 different spacecraft, that can be directly attributed to deployment issues. It presents probable causes and best practices in order to prevent future failures. The paper's overall goal is to highlight the criticality of appendage deployments and to share best practices with the ESMATS and AMS communities of mechanisms engineers.

INTRODUCTION

Deployable appendages are extremely critical components of the spacecraft (SC) and their failure has very profound effects on the ability to meet mission objectives. These types of failures were also the precursors of spacecraft servicing. The first ever in-space major repair and servicing of a spacecraft occurred in 1973 when Skylab's astronauts performed a series of spacewalks to free the jammed solar panels of one of the station's solar arrays, and install a replacement heat shield both of which had been badly damaged during launch [1].

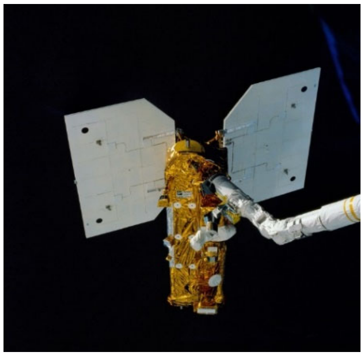

Figure 1.ERBS' Solar Arrays were deployed with help from the Space Shuttle's RMS during STS-41G

When in 1984, the Space Shuttle Challenger (STS-41G) was in the process of releasing the Earth Radiation Budget Satellite (ERBS) into orbit, a solar array failed to deploy while the spacecraft was still attached to Challenger's Remote Manipulator System (RMS). Mission specialist Sally Ride had to shake the satellite with the remotely controlled robotic arm and place the stuck panel into sunlight so that it would extend [2].

A similar situation took place in 1991 when, during the STS-37 launch of the Gamma Ray Observatory, the High Gain Antenna (HGA) did not deploy when it was initially commanded. An astronaut EVA was required to physically shake the antenna to initiate the deployment sequence [2].

In some instances, deployables failures can result in a total or partial loss of the spacecraft and/or the mission. The Galileo Spacecraft had its 16-foot diameter HGA stowed behind a sun shield to help protect it from the intense solar radiation of the inner solar system tour. When it was far enough from the sun JPL's flight team sent the commands to initiate the deployment sequence. The antenna only partially opened due to cold welding and excessive friction in the midpoint restraint pins and V-groove socket of the antenna ribs. Drive torques, in excess of motor capacity, would have been needed to free the pins and permit full deployment. The mission proceeded with Galileo transmitting information back to Earth using the Low-Gain Antenna, which had a much smaller bandwidth. The failure of the High-Gain Antenna full deployment and subsequent reduction in available bandwidth reduced the total amount of data transmitted through the mission. However, 70% of Galileo's science goals were ultimately met [3].

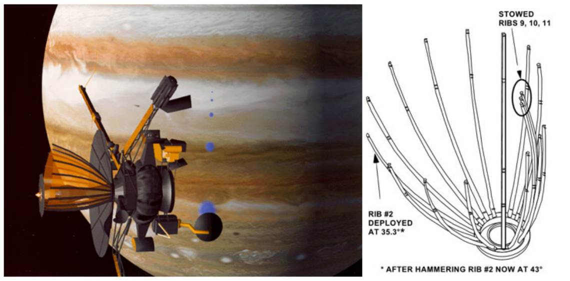

Figure 2. Galileo SC with a partially deployed HGA

Some industry leaders have even shown interest in having a robotic spacecraft that would be capable of repairing these types of deployment anomalies. When in 2011 New Dawn's (Intelsat 28) West C-band antenna reflector, which controls communications in the C-band frequency, did not deploy, the capabilities of the spacecraft were crippled with about half of the transponders on the spacecraft locked out. The final insurance claim amounted to $146M (59.6% of the $245M policy). Intelsat General President, Kay Sears, who runs Intelsat's U.S. government business, stated "Intelsat would have paid to have a robotic servicing spacecraft come over and at least look at the Intelsat New Dawn satellite to see what the problem was. We would like to see a maintenance man in space - an orbiting spacecraft that can rendezvous with troubled satellites, inspect them, and perform necessary repairs" [6]. While refueling spacecraft represents a good business opportunity, an even larger payoff resides in the resolution of initial deployment anomalies. Since these failures occur before the start of revenue life, they have a very large impact and releasing stuck deployments could recover 50-100% of revenues at risk [7].

It is then of utmost importance to understand the main modes of failure of SC deployables. This paper presents an overview and analysis of deployment anomalies as well as a summary of best practices required to prevent them.

REVIEW OF SC DEPLOYABLES FAILURES

There is very limited up-to-date literature published on SC deployment failures, so the authors decided to research the subject using SC databases such as the NSSDC Master Catalog, papers on the subject from the Aerospace Mechanisms Symposia, Space News articles, Space Mechanisms Lessons Learned Studies, AIAA papers, SC failures databases, NASA Engineering Network Public Lessons Learned, and any other sources available on the subject. The research was reasonably extensive and thorough. A complete list of the sources can be found under the References section of this paper. When the literature review process was complete, 53 different SC that suffered deployables failures or anomalies had been identified. Whenever possible, a second source was sought out to confirm the anomaly and its root cause. The list of publicly known SC that have suffered deployables anomalies and failures is shown in the Appendix. This study encompasses cases from as early as 1961 and as recent as 2017. When available, data on insurance claims was also included.

A ***deployable failure*** is defined as an occurrence when a deployable fails to fully deploy resulting in an impact on the performance of the spacecraft in terms of power, communications, or other capabilities. A ***deployable anomaly*** is defined as an occurrence when the deployment is not initially successful but, after a certain amount of trouble shooting, it is eventually completed without significant impact to the spacecraft's capabilities and the scope of the mission.

Even though this is an extensive list, it is almost certain that many more deployables failures and anomalies have occurred that were not openly reported. Commercial satellite manufacturers and operators are not required to disclose anomalies. Unless there is a failure of a deployable that affects the performance of the spacecraft, these types of glitches tend to go unreported as they would likely affect business and or insurance premiums. Consequently, even if a solar array fails to initially deploy as planned, if it eventually completely deploys, the anomaly may go unreported. While NASA has always been very open regarding failures and or issues with its spacecraft, space agencies from other countries have historically tried to hide failures of their space programs. Finally, anomalies on spacecraft with military purposes and from classified programs are very unlikely to be reported for obvious reasons. Nevertheless, the list of 53 Spacecraft represents a significant sample size that is likely to capture most of the issues that typically affect deployable appendages. From it, the types of failures that a satellite manufacturer should try to prevent can be ascertained. The table includes the type of anomaly or failure and, if available, the result of the investigation and the consequences to the spacecraft and mission. Please note that anomalies and investigation results listed are probable causes based on published information and actual root causes may differ.

Failures and Anomalies by Year

Spacecraft having deployable related issues as early as 1961 (MIDAS 3), and as recently as 2017 (ViaSat-2), were found. The distribution of anomalies per year is shown in the Figure 3 histogram.

As previously mentioned, it is almost certain that many more failures and anomalies have occurred. Commercial companies and operators are very reluctant to report anomalies, and unless the failure results in a loss of spacecraft capabilities, these occurrences are likely to go unreported. In addition, most of the data collected correspond to US spacecraft as data from other countries was either not located or has not been published. Nevertheless, based on the data available since 1961, there has been an average of approximately one SC deployment failure or anomaly per year thru 2020. Over the past 20 years the average is one failure or anomaly every two years. Looking at the distribution, there are years of two or more failures followed by several years of no failures or anomalies at all. It is possible, perhaps even likely, that this is due to lack of available / reported data.

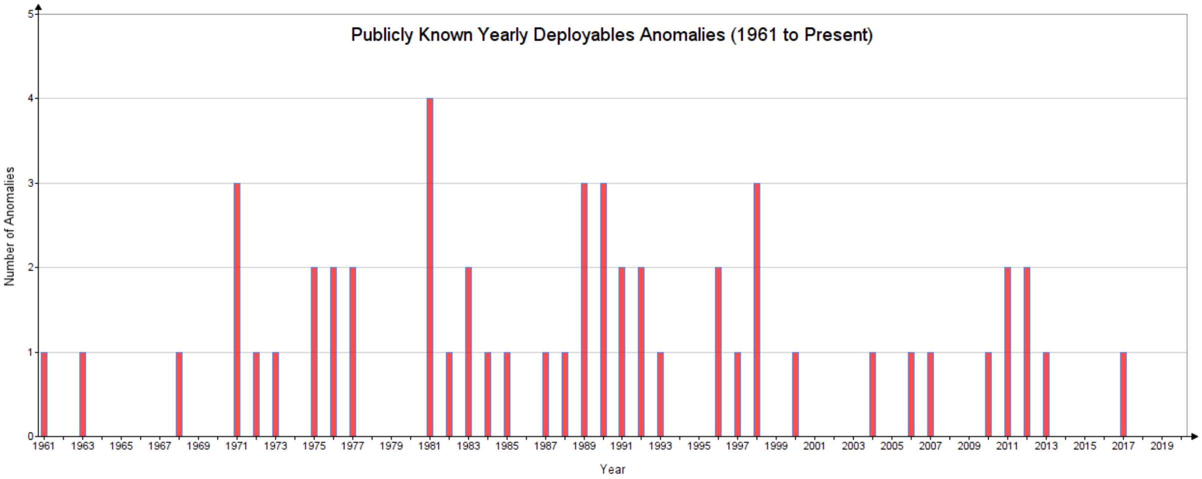

Figure 3. Anomalies by Year

Before seeing this data, one might have expected to see many failures in the sixties followed by a reduction in the number of yearly failures through the seventies and subsequent decades. However, consider that initial number of SC placed in orbit annually has increased significantly through the years. From a few dozen per year in the sixties to now an average of 122 per year [8]. Second, as deployment technologies have been mastered, companies have pushed the envelope by designing larger and larger solar arrays and antennas that provide mobile communications to small devices such as car radios and smartphones. Increasing the satellite antenna size and power means user handsets do not need to generate as much power on their own to capture and maintain a communications link. As an example, the Harris Corporation has gone from building 5-meter (m) diameter L-band antenna reflectors to building 22-m ones, like that used in Skyterra-1 (largest commercial antenna ever built), in the span of just 10 years [9]. This aggressive scaling up has caused problems with the deployment of antennas in the Garuda-1 spacecraft (launched in 2000 / 12-m L-band antenna failed to fully deploy) and on Skyterra-1 (launched in 2010 / 22-m L-band antenna did not initially deploy).

From 2000 to 2013, there were a total of 10 deployables related anomalies and failures reported. For six of these SC, troubleshooting was not successful, and the deployment problem could not be fixed. The average insurance claim was $131M. These 6 spacecraft could certainly have benefited from a robotic servicing mission.

Failures and Anomalies by Type

It is of great interest to also study what types of deployable failures are the most common. Out of the 53 spacecraft surveyed that suffered deployables anomalies, 29 (55%) of them suffered solar array related anomalies, 20 (40%) of them had antenna related deployment problems, and 9 (17%) of them had boom deployment issues. Note that some spacecraft had issues on more than one type of deployable. As we will see later, minimizing the anomalies on SAs and HGAs would save millions of dollars in insurance costs.

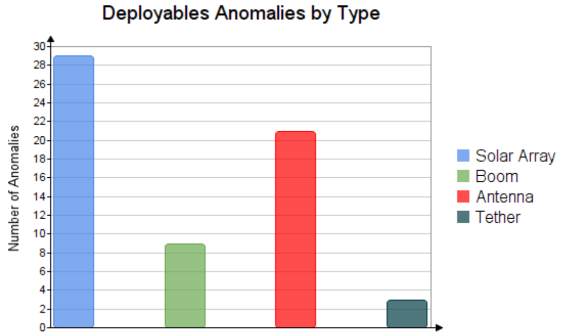

Figure 4. Anomalies by Type

Failures and Anomalies by Cause

Analysis of all the failures yielded the breakdown shown in Figure 5. By far the most common causes of problems are tribology related issues and ***thermal blankets/shields interferences***. Oftentimes, blankets are incorporated late into the Integration and Test (I&T) process and sometimes deployment testing is performed without them. This may result in deployment mechanisms getting caught in the shields and blankets that restrain and prevent their motion. Different variations of this problem happened to the Skylab, Voyager II, CRRES P86-1, Anik E-2, Gamma Ray Observatory, and New Dawn (both on the Ku-band and C-band antennas) spacecraft.

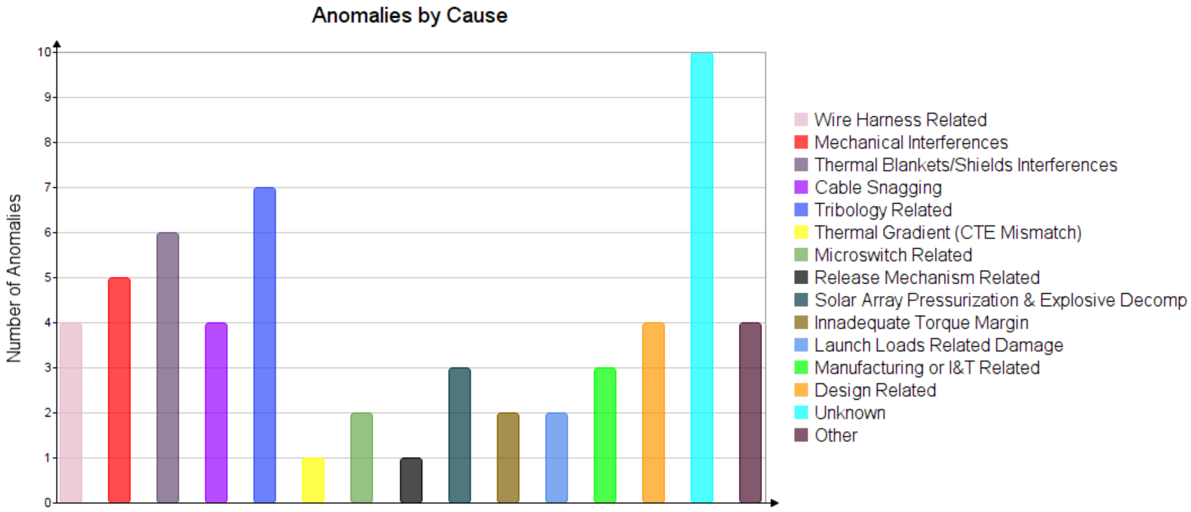

Figure 5. Anomalies by Cause

Tribology related problems seem to be the most common. Under this category anomalies were found due to friction welding (DMSP 5D1 F2), MoS_2 solid lubricant problems (ERBS), cold welding (Galileo, JERS-1), increase in friction due to low temperatures and vacuum (Intelsat V, Voyager II), and thermal binding due to lubricant failure (Insat 1B).

Another relatively frequent problem is due to ***cables and wire harnesses*** that become jammed, pinched or snagged, restraining motion, or because their stiffness increases greatly under low temperatures reducing the torque margin to a point that the deployment is halted. Spacecraft that suffered this type of anomaly include DMSP-5D1F2, TDRS-A and TDRS-D.

Mechanical interferences (ARABSAT 1A, TDRS-C, TSS-1) during all angles of deployment are yet another anomaly deployable engineers need to consider. Also, not all deployables, unless there is a synchronization cable, will take the same path on orbit as they do during ground test, so "zero-g" ground testing must also be carefully considered.

Still ***other types of failures*** include those due to damage to the deployable's structure and/or mechanisms due to the dynamic loads during launch (Skylab, STEP4); problems with the release mechanism (STP 74-1); issues with the end of travel microswitches (DMSP 5D1 F2, Magellan); poor manufacturing or I&T; and inadequate torque margin;

Telstar 14, Telstar 14R and Intelsat 19 all had solar array failures [10, 11]. A thorough investigation revealed that inadvertent solar array pressurization and explosive decompression was the underlying cause. Specifically, during the launch phase, the satellites' solar arrays had actually become pressurized relative to their ambient environment as the launch vehicle rose in altitude. This eventually led to an explosive event, which damaged the array's deployment mechanism and structure [14]. The total insurance claims for these three satellites came out to $421.7M.

Failures and Related Insurance Claims

Looking at the insurance claims data in terms of the type of deployable involved we can see that from 1998 to 2012 close to $800M in insurance claims resulted from solar array failed deployments.

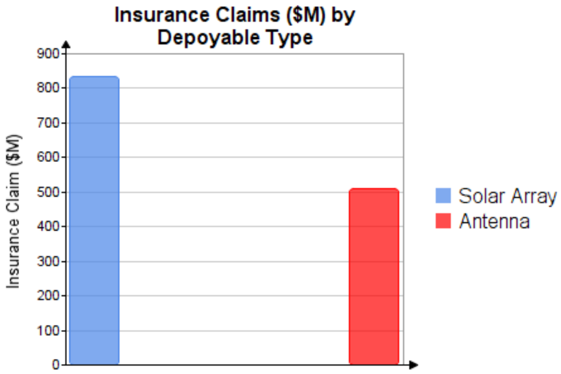

Figure 6. Insurance Claims by Deployable Type

Antenna failures also result in vast insurance losses particularly when reflector antennas from communication SCs are involved, as the reduction in geographical coverage and transponder availability has serious consequences for the satellite operators. Anik E2,

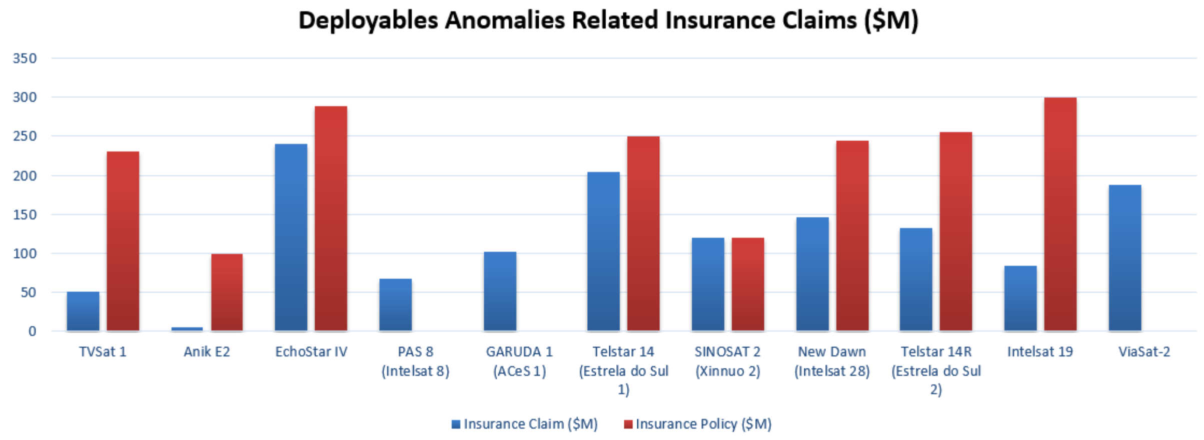

Figure 7. Insurance Claims

PAS 8 (Intelsat 8), Garuda 1, New Dawn (Intelsat 28), and ViaSat-2's antenna issues resulted in insurance claims of $508M. Figure 7 clearly shows that even though these types of failures happen only sporadically, they result in extremely large insurance claims. Being able to prevent them would save millions of dollars.

Failures by Severity Level

The severity of the deployable's failures can range from catastrophic, with complete loss of the spacecraft, to critical, with a complete loss of the mission, to substantial, when the loss of performance is such that leads to partial mission loss.

Table 1. Failure Severity Levels

Level	Final Effect	Definition
I	Catastrophic	Loss of SC
II	Critical	Complete loss of Mission
III	Substantial	Partial Loss of Mission / SC Performance degraded
IV	Minimal	Very small loss of mission goals or SC performance
V	Negligible	No effect on mission or SC performance

Chart shown in Figure 8 looks at the distribution of failures according to their severity level. While 32% of the SC are able to overcome the anomaly without loss of mission goals or SC performance, the vast majority (68%) suffer some degree of mission or performance degradation. Moreover, 32% of the deployment anomalies resulted in the substantial reduction of the spacecraft performance capabilities and/or partial loss of the mission, and in six instances, the spacecraft and/or the mission were completely lost. The main conclusion is that in most occurrences, the deployable failure is serious enough to reduce the capabilities of the spacecraft and affect the mission scope, duration and objectives, and the operators are often forced to carry on and do the best they can with a degraded satellite.

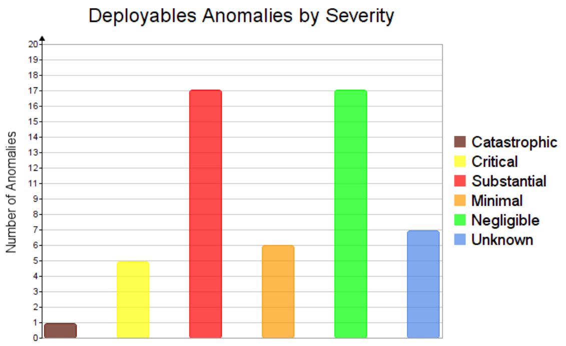

Figure 8. Failures & Anomalies by Severity Level

LESSONS LEARNED AND BEST PRACTICES

Based on all of the data examined, it is critical that a set of good practices are followed so that failure risks are minimized. It is beyond the scope of this paper to discuss all possible reasons that cause deployables failures and present all established best practices required to prevent them. Therefore, there will be a focus on the more common failures based on research, as well as on excellent published literature on this topic from NASA GSFC and NASA LaRC [2, 30].

Most of the spacecraft failures and anomalies observed fall under one of the following categories:

(1) Snagging and interference of thermal blankets / wires /cables. This is challenging because many ground deployment tests can be successful and yet a problem appears after launch. This happens because many of

these items are not used in the ground deployment tests, are added late in the I&T flow, or even after I&T. Subsequently, the ground tests do not reflect the actual flight conditions. Snagging points may not be exposed until flight integration, after flight integration, or after vibration testing. Lack of clearances between moving parts which must account for thermal expansions and static and dynamic deflections can be fatal. The main goal here is to avoid the "Velcro effect" between adjacent parts such as connectors, wires, blankets, thermal tape, boards, sensors, and bonding straps. A classic example is the back of a SA which when stowed may have connectors and wire bundles folded up on top of other connectors leading to the possibility of snagging [2]. Cables and blankets can also shift during launch so it is recommended not to rely on preload and friction to secure these items and instead use a positive mechanical device such as pins, skewers, or interlocking sections [30].

(2) Tribology related. Increased friction typically due to: wrong lubricant selection; degradation or migration of the lubricant during testing; ground handling and transportation or storage; use of sliding surfaces as opposed to rolling motion; hard coatings subject to loads above the bearing yield strength of the substrate metal; or dissimilar material mating surfaces with a high mutual solid solubility. Stiction must be avoided with use of proper lubricants, proper angles above 30 degrees in cone supports to avoid locking, and by incorporating relatively high force and short stroke kick off springs. Small amplitude oscillatory motion between mating surfaces must be prevented as it can result in damage to the lubricating films [2]. Two choices are available for lubrication: wet lubrication with a low vapor pressure aerospace grease, and dry lubrication by means of bonded or sputtered MoS_2 coating. Wet lubricant is generally preferred over dry lubrication as the wet lubricating film is self-healing and frictional behavior is more consistent and predictable. The grease with the most heritage is the Bray 600 series, a synthetic fluorinated oil thickened with micron sized Teflon powder. These greases have extremely low outgassing and minimal contamination concerns for space applications. The wet lube is usable in the -80 to +200 C range. For extreme low temperatures and cryogenic applications, MoS_2 coatings are preferred [2].

(3) Low Torque Margin (TM). Perhaps all friction sources were not accounted for, or the bending stiffness of wire harnesses or blankets that traverse a rotating joint increased sharply with cold temperatures creating a large parasitic torque. Use of a generous TM of 3 and a damper to dissipate the potential energy of deployment springs and reduce the kinetic energy at impact is beneficial [2].

(4) On-orbit space environment. Deployables can be very sensitive to the hostile on-orbit conditions which include atomic particle radiation, electromagnetic radiation, microgravity, and, most importantly, the extreme temperature extremes a spacecraft undergoes during an orbital eclipse. Large thermal gradients have a profound effect on bearing friction and resistance torque and require the right selection of space lubricants previously discussed. The transition from atmospheric pressure to the vacuum of space is critical as it requires proper spacecraft venting. Inadequate venting leads to two types of deployables failures: a) blankets improperly vented can result in pressure imbalances that can force them to be pushed outward or even become inflated. When the appendage is deployed, interference with the blanket can occur; b) Inadvertent solar array pressurization and explosive decompression can damage the array's deployment mechanism and structure. This catastrophic failure can happen due to two combined manufacturing defects: overly pinching the ends of the solar panels so that their honeycomb cores cannot properly vent air, and insufficiently bonding the layers of the panel, making it susceptible to explosive depressurization [17, 14]. Verifying that lightweight flexible structures, blankets and composite honeycomb structures can vent properly during ascent is highly recommended [30]. Ensure deployable is mounted on the SC using a kinematic mount so thermal I/F deformations do not cause internal stresses, there are no redundant load paths, and jamming of deployable is avoided.

(5) Launch Loads. Deployable appendages can be subject to high launch loads, which can lead to damage. The most well documented example is Skylab. During launch, the micrometeoroid shield ripped loose disturbing the mounting of the workshop SA "wing" number two and caused it to partially deploy. The exhaust plume of the second stage retro-rocket impacted the partially deployed SA and literally blew it into space. Also, a strap of debris from the meteoroid shield overlapped SA "wing" number one. When the programmed deployment signal occurred, SA one was held in a slightly opened position where it was able to generate virtually no power. The station's crew performed the first ever in-space major repair, by deploying a replacement heat shade and freeing the jammed solar panels [1]. Large, lightweight structures and the more fragile deployable structure subassemblies such as solar cells, wiring, interconnects, solder joints and switches are particularly susceptible. Mechanical verification load margins must test for "worst" case load predictions. Verification that deployable structures and mechanisms can withstand pyrotechnic shocks is also recommended. Pyro-shock can produce significant loads affecting the surrounding systems, particularly the smaller mechanisms and components. Flying debris and premature firing are also areas of concern. Finally, thruster plume loading and attitude control requirements should also be accounted for, due to their subtle but often complex nature [30]. Use launch restraints that provide a kinematically determinant mounting so that deployable

is isolated from primary structure high loads.

(6) Assembly and Integration. Designing a system that is easy to assemble, testable, and analyzable is highly recommended. The system should not be over-constrained. Allow the SC to "breathe" by considering thermal distortions, tolerances, and imprecise assembly. For example, hinges that are separated on the same deployment axis should have self-aligning bearings. Making the system testable and analyzable usually means sequencing the deployment into successive sub-deployments of one or two degrees of freedom motions [2]. A rigorous and comprehensive assembly and integration process should be developed and followed throughout. This will make sure loose, non-serialized materials are carefully accounted for during assembly. Keep accurate records of all "non-flight" installations, taking photos and video frequently during assembly and integration. Safe handling procedures should be established early in the program ensuring deployable structures are self-supporting when placed in any orientation relative to gravity while in storage or deployed configuration. Implementing last minute assembly and integration steps can lead to failures, so it is recommended that these are well planned and verified paying particular attention to details such as possible connector mis-mating [30].

(7) Testing. Most failures due to non-realistic environmental test conditions could be prevented by following NASA's "fly as you test and test as you fly" gold rule. This approach requires the testing to replicate the flight environment as closely as possible. Tests should be verifiable in 1-G and done without the assistance of gravity. Deployable structures should also be tested at the highest possible sub-system / system level. This will capture stiffness at critical interfaces (such as at the deployable structure and spacecraft interface) to achieve more accurate responses during testing and to verify that flexible materials, such as wires and thermal blankets, will not impede or jam the deployment. Because ground test equipment (GTE) can mask kinematic performance, designing it to accurately simulate the effects of micro-gravity during deployment is recommended. GTE can also introduce artificial constraints and forces so their effects on test hardware, e.g. due to artificial thermal gradients during thermal testing, must be taken into account [30].

(8) Modeling, Analysis and Simulation. Immature or inadequate modeling/analysis of environments and dynamic loading can result in deployable structures /mechanisms failures. Analytical models should be developed following appropriate and established practices. Simulations should be validated with corresponding test data where possible, and torque margin, kinematic, dynamic clearance, structural, thermal, and plume analyses should be performed early on and continue to be modeled throughout the test program to confirm requirement compliance. It is critical to properly capture thermal gradients, characterize wire harness stiffness across joints, as well as other parasitic torques due to blankets, etc. This will ensure more accurate estimates of the resistive torques. It will also ensure the effects of small forces due to friction, gravity, and air resistance are included in ground models [30].

CONTINGENCY OPERATIONS

On occasion, despite best design and test practices, there may still be deployment problems in space. Once a deployable anomaly occurs there are very few options available to spacecraft engineers to fix the problem. Ground teams would typically begin a series of attitude control maneuvers to try to remedy the situation. The more common maneuvers follow:

1. Apogee maneuver thruster firings are executed to see if the inertial loading will "free up" the impaired deployment system. This was the approach used to deploy the partially damaged South SA on Intelsat 19.

2. Orienting the SC to expose the stuck deployment system to heat from the sun, alternating with exposure to cold, is another maneuver. On occasion, nominal on-orbit thermal transitions from cold to hot will fix the problem. This would be for CTE and tribology issues caused by the increase of friction at extreme low temperatures and vacuum. The EchoStar IV spacecraft, for example, initially suffered the failure of one of its solar arrays. The stuck solar array unexpectedly deployed during routine operations after long-term exposure to the sun, more than 12 years after it had initially failed [15]. Other SC that successfully used this approach after initial deployment failure include JERS-1, and ERBS.

3. For deployables that have motor driven deployment mechanisms, the ground team may command the mechanism up and down to try to un-snag it from the obstruction, perhaps thermal blanketing or sun shield. This approach was used to free and deploy New Dawn spacecraft's Ku-band antenna.

4. The next maneuver nicknamed "rock n' roll", consists of shaking the satellite by alternatively firing the spacecraft thrusters to see if the induced vibration will free the partially deployed solar array or antenna. This approach was unsuccessfully used on the TV-Sat-1 SC.

5. Firing the thrusters to spin the SC is another option. This approach led to the full deployment of the C-band antenna of the Anik E2 spacecraft.

The first, fourth, and fifth maneuvers have the disadvantage that significant amounts of SC life-limiting propellant may be used. So, even if the deployable is freed, the spacecraft's life is reduced because of the unplanned fuel consumption. This is exactly what happened to the New Dawn Spacecraft (Intelsat 28) when operator's attempts to shake loose the C-band antenna used about a year's supply of fuel. These maneuvers are also limited by the inertial loads the spacecraft can apply to the deployable.

Because these maneuvers may carry a significant amount of risk in terms of damage to the deployable or excessive use of fuel, it is advisable to try to simulate them using the dynamic analysis models that have hopefully been developed. Using these models the team on the ground can quickly evaluate the optimal sequence of events, frequency of thrusters firings, and predict loads and responses generated from each operation. Hopefully, these better informed ground commands will overcome the resistance and interferences holding the deployable without damaging it. Time may be a critical factor in freeing a partially deployed system. The James Webb Space Telescope project is proactively planning for contingencies. Worst-case deployment scenarios are being analyzed well in advance of the launch date with the help of advanced dynamic analysis and other tools.

CONCLUSION

In spite of all the advances and progress made over the past 60 years in the field of deployable appendages, deployment failures and anomalies still occur. A review of some of the publicly known spacecraft that have suffered these anomalies shows that in most cases they result in partial and sometimes severe loss of science mission goals and spacecraft performance, leading to insurance claims of up to $200M or more per spacecraft. Therefore, the proper understanding of the failure modes and mechanisms that can imperil appendage deployments is critical. By sharing the database of known spacecraft with deployable problems, their probable causes, and some of the best practices required to prevent them, the authors hope to better inform the mechanisms engineers in the ESMATS and AMS communities with the desire that everybody can benefit and these costly anomalies are minimized in the future.

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APPENDIX: Partial List of Publicly Known Spacecraft that have suffered Deployables Anomalies & Failures

NSSDC / COSPAR ID	SC Name	Anomaly *	Investigation Result *	Insurance Claim **	Ref.
1961-018A	MIDAS 3 (Program 461)	One of the two Agena-B solar arrays failed to deploy	Unknown. Power failure resulted in loss of mission after 5 orbits.	-	29
1963-030A	MIDAS 9 (Program 461)	One of the two Agena-B Solar Arrays failed to deploy fully. IR payload still operated successfully for 96 orbits before power failure terminated the mission.	Mishandling during stowage	-	16, 29
1968-081A	STP 67-2 (OV2 - 5)	Solar Array Booms failed to deploy fully	Field Modification Problem	-	16
1971-?	Program A	Antenna failed to deploy fully	Wire harness binding	-	16
1971-?	Program B	Solar Array deployed late	Silicon rubber sticking	-	16
1971-063A	Apollo 15 Command & Service Module (CSM)	During the Apollo 15 mission, a 7.5 m boom with an attached mass spectrometer was required to retract periodically so that the instrument would not be in the field of view of other experiments. The boom did not fully retract on five of 12 occasions.	Sagging in the power cable because of one of the following reasons: 1. Improper stacking of the power-cable coils into the annulus of the mechanism housing during retraction; 2. Jamming of the power cable either between the experiment support bearing and the mechanism housing or between the guide fingers and the housing.	-	20
1972-039A	Space Test Program (STP) Payload 71-5	Boom not deployed	Dynamic Clearance Problem	-	16
1973-027A	Skylab	Solar Array One failed to deploy. Solar Array Two damaged during launch and Lost.	During launch the micrometeoroid shield ripped loose disturbing the mounting of the workshop solar array "wing" two and causing it to partially deploy. The exhaust plume of the second stage retro-rocket impacted the partially deployed solar array and literally blew it into space. Also, a strap of debris from the meteroid shield overlapped solar array "wing" number one such that when the programmed deployment signal occurred, solar array one was held in a slightly opened position where it was able to generate virtually no power. The station's crew performed the first ever in-space major repair, by deploying a replacement heat shade and freeing the jammed solar panels.	-	1,16
1975-075C	Viking 1 Lander	The sampling arm failed to deploy	Debris in gear train	-	16
1975-099A	Transit Improvement Program 2 (TIP 2)	Solar Array failed to fully deploy	Cable Hung up / anomalous flat trajectory caused high heating rates	-	16
1976-023C	Space Test Program (STP) Payload 74-1 Solrad 11 A & B	Solar Panel Failed to Deploy	Release Mechanism Binding	-	16
1976-091A	Defense Meteorological Satellite Program Block 5D1 F1 (DMSP 5D1 F1)	Single articulated 8 segment solar array failed to deploy	Excessive Wire Harness Stiffness	-	16
1977-044A	Defense Meteorological Satellite Program Block 5D1 F2 (DMSP 5D1 F2)	Solar Array Delayed Release	Friction welding	-	16
		Science Bom failed to fully deploy	Microswitch failure	-	16
1977-076A	Voyager II	Magnetometer Boom misaligned	Unknown	-	16, 21
		Science Boom failed to fully deploy (Science Boom failed to indicate, by microswitch, that it had deployed completely) boom was within a tenth of a degree of the fully deployed position	Equipment interferences, jamming by foreign matter, and excessive friction or binding due to low temperature phenomena. Additional contributing factors may have resulted from late incorporation of a number of cabling thermal blanket, and external surface configuration changes		
1981-050A	Intelsat V	Time required for successful deployment of the north solar array was longer than originally predicted	Significant increase in hinge friction at low temperatures and vacuum	-	17
1981-057B	Arianne Passenger Payload Experiment (APPLE)	One of the two Solar Arrays Failed to Deploy / jammed. SC was able to operate for 27 months until attitude control fuel depletion.	Solar array latch stuck	-	16, 17
1981-070A	Dynamics Explorer 1 & 2 (DE 1,2)	Sensing Antenna failed to deploy	Unknown	-	16

1981-100B	UoSAT 1	Bistem gravity gradient boom damaged during deployment. Had to be retracted and SC operated in spin-stabilized mode.	The cable to the magnetometer, which also had to be drawn out, snagged causing the still unreeling boom to buckle and bend.		19
1982-031A	Insat 1A	The C-band antenna could not be deployed for 12 days; Solar Array failed to deploy completely but after it had heated up in sunlight it was released by firing the thrusters; Mast with Solar Sail failed to deploy.	Inoperative mechanical latch (solar sail mast); other unknown	-	17, 19
1983-026B	Tracking and Data Relay Satellite A (TDRS-A)	Field of view of one of the single-axis antennas was restricted	Pinched or snagged electrical cable that runs across one of the single-axis antenna gimbal joints	-	2
1983-089B	Insat 1B	Unable to position Solar Array. Eventually deployed after 2 weeks of contingency ops.	Thermal binding of deployment mechanism caused by lubricant failure		17, 29
1984-108B	Earth Radiation Budget Satellite (ERBS)	Solar array failed to deploy while the spacecraft was attached to the Space Shuttle Challenger's remote manipulator system. Mission specialist Sally Ride had to shake the satellite with the remotely-controlled robotic arm and then finally place the stuck panel into sunlight (SA hinge line rotated into the sun) for the panel to extend when the temperature climbed above 0 C.	Combination of cold temperatures (-44F), thermal gradients and excessive bearing friction experienced due to poor characteristics of molybdenum disulfide (MoS2) solid lubricant at cold conditions (under these conditions due to the "balling up" phenomenon of MoS2, moisture molecules create frozen balls in the path of the rolling elements impeding available driving torque) led to insufficient torque margin.		2
1985-015A	ARABSAT 1A	Failure to deploy solar array & C-band antenna	Mechanical Interference		17
1987-095A	TV-Sat-1	The satellite was to deploy one of the four segments of each of its two solar panels spanning 20 meters for power during early operations. However telemetry showed that only one array had deployed correctly. The other panel remained locked, and resisted attemts to free it by spinning or shaking the satellite.	Some of the hold-down clips that had been used to secure the panel during ground handling had not been removed. Mission was a total loss.	$51M	17
1988-091B	Tracking and Data Relay Satellite C (TDRS-C)	Single-axis antenna delayed deployment by nearly 3 hr	One of the compartment attachment lugs came into contact with the compartment kick-off spring mechanism. It freed itself without any action from the ground.	-	2
1989-021B	Tracking and Data Relay Satellite D (TDRS-D)	One of the single-axis antenna drive motors stalled	Biax service loop harness became pinched between the boom and compartment. Motor was reversed to relieve the pinch, and deployment proceeded normally.	-	2
1989-033B	Magellan	Solar Array failed to latch at end of travel/ "panels-latched" telemetry indication was not transmitted, i.e. microswitch did not close.	Microswitch misadjusted: anomaly was due to the combination of marginal microswitch actuation stroke and zero-g effects on the solar array hinge mechanism. This combination caused one or both of the series-wired microswitches to fail to close. During the IUS burn, a small shift of the panels resulted in microswitch closure and provided the proper telemetry indication.	-	16, 22
1989-084B	Galileo	High-gain antenna, which opens like an umbrella, never reached the fully deployed condition	Cold welding and excessive friction in the midpoint restraint pins and V-groove socket joint of the struts, which required mechanical drive torques in excess of motor capacity to free the pins and permit deployment.	-	3,16
1990-037B	Hubble Space Telescope	When the + / - Primary Deployment Mechanisms (PDM) on both arrays were actuated there was no indication that the motor had stopped	Unknown. Ground command used to stop motor	-	12
		Trouble experienced during deployment of the -V2 Solar Array resulting in a slight deploy delay.	Intermitent open ground in tension sensor. Tension circuit had to be disabled.		
1990-065A	Combined Release and Radiation Effects Satellite (CRRES P86-1)	Magnetometer Boom failed to fully orient	Interference between thermal blanket velcro and wiring harness	-	16
1990-043A	Mac Sat 1,2	Gravity gradient boom on one of the S/C failed to deploy	Inadequate Force Margin	-	13, 16
1991-026A	Anik E2	Ku-Band antenna deployed after two days C-Band Antenna did not fully deploy.	Thermal Blanket Interference; Full deployment achieved by spinning spacecraft. Rescue maneuvers used a year's worth of fuel. Lessons learned applied to Anik E1 which had no deployment anomalies.	$5M	16, 19
1991-027B	Compton Gamma Ray Observatory (CGRO)	High-gain antenna did not deploy when it was initially commanded. An astronaut EVA was required to physically shake the antenna to initiate the deployment sequence.	A portion of the antenna release mechanism (close to the antenna dish) was caught by a piece of insulation thermal blanket. This occurred because of large relative motion between the antenna and its support structure which allowed an exposed bolt to be caught by the neighboring thermal blankets.	-	2
1992-007A	JERS-1	Radar imaging antenna failed to deploy	One of six pins holding the 12x2.5 meter antenna had either jammed or cold welded. Several weeks later, after the pin had been warmed by sunlight, it popped open.		19
1992-049	Tether Satellite System (TSS-1)	Reel-out mechanism jammed. The tether could only be released to about 840 feet out of the planned 12.5 miles.	Screw added for structural margin interfered with reel-out mechanism	-	13, 16
1993-026A	ALEXIS	One of the four solar panels prematurely deployed damaging the magnetometer in the process affecting attitude control.	Bracket that held its hinge assembly was insufficiently rigid. Solar Array was not rididly deployed affecting attitude dynamics. Attitude determination and control system had to be completely redesigned to save the spacecraft and mission.		19
1996-012B	TSS-1R	Five hours after deployment began on February 25, 1996, with 19.7 km (of 20.7 planned) of tether released, the tether cable suddenly snapped near the top of the deployment boom (within 12 m). The TSS satellite separated from the orbiter and shot away into a higher orbit	The TSS-1R Mission Failure Investigation Board established that the tether failed as a result of arcing and burning of the tether, leading to a tensile failure after a significant portion of the tether had burned away.		13
1996-062A	Mars Global Surveyor	One of the solar panels failed to latch properly when deployed and subsequenlty showed unexpected motion and moved past its fully deployed position when aerobraking began.	Input shaft of the viscous damper that was meant to prevent the hinge overshooting sheared when the array was deployed, possibly because inboard panel was still moving when outboard one was locked into position.		13, 19

1997-063A	STEP 4	Solar panels failed to deploy properly. Mission declared a failure soon after.	Satellite/launcher resonance, which was known but not addressed, caused vibration damage		28, 29
1998-028A	EchoStar IV	South solar array did not deploy properly (2 of 5 panels did not unfold) resulting in a reduction of power available to operate certain transponders on the satellite	Unknown: Stuck solar array suddenly deployed on its own without warning during routine operations after long-term exposure to the sun on Sept. 6th, 2010, more than 12 years after it had failed.	$214M	7, 8, 25
1998-055A	STEX	ATEx (Advanced Tether Experiment), a 6 km tether with TiPS heritage, was to be deployed but failed after deploying only 22 m of tether.	The jettison was triggered by an automatic protection system designed to save STEX if the tether began to stray from its expected departure angle, which was ultimately caused by excessive slack tether.		23
1998-065A	PAS 8 (Intelsat 8)	2 out of 3 Ku-band Antennas Misaligned affecting geographical coverage as 26 of the Ku band transponders could not be used.	Unknown	$68M	7, 25
2000-011A	GARUDA 1 (ACeS 1)	12 m diameter L-band antenna failed to fully deploy significantly reducing the satellite's communications / calling capacity (1.4M a day instead of 2M planned)	Unknown	$101.5M	24, 29
2004-001A	Telstar 14 (Estrela do Sul 1)	North solar array only partially deployed. South solar array fully deployed. Satellite entered service with reduced capacity (17 transponders)	Inadvertent solar array pressurization and explosive decompression damaged the array's deployment mechanism and structure	$205M	7, 14, 25
2006-048A	SINOSAT 2 (Xinnuo 2)	Deployment of solar arrays and communications antennas unable to be completed. S/C deprived of power to operate and unable to be put into broadcasting and telecommunications services. Total loss.	No detailed explanation provided. Official explanation is that Sinosat-2 and Nigcomsat-1 both failed in orbit due to problems related to the DFH-4 platform's solar array deployment system.	$120M	25, 26
20007-003A	Beidou 2A (1D)	Fails to deploy solar arrays on Feb. Problem resolved in April 2007.	Satellite suffered from a control system malfunction which resulted in SA panel unable to deploy. After some contingency work from ground control problem was solved	-	29
2010-061A	SkyTerra1 (MSV 1)	22m diameter L-band antenna reflector (largest commercial reflector ever built) on the SkyTerra 1 satellite intially failed to fully deploy.	Unknown: after problem dectected a team was assembled that included the antenna manufacturer to assess what maneuvers could be performed to correct the problem. One month after launch antenna was fully deployed.	-	4, 29
2011-016A	New Dawn (Intelsat 28)	Ku-band antenna failed to deploy initially	Ku-band antenna's deployment mechanism also got caught in its sun shield, a thermal blanket that covers the back end of the antenna to protect the satellite from the extreme temperature spikes that occur in orbit. Ku-band reflector had a motor-driven deployment mechanism which ground teams used to move the Ku-band deployment system up and down, and free it from the sun shield.	$146M	5, 29
		West C-band antenna reflector which controls communications in the C-band frequency did not deploy. Attempts to shake loose the antenna used about a year's worth of fuel. Flying SC with antenna tucked against its frame likely to cut New Dawn's commercial life by another year.	Antenna's spring-loaded deployment mechanism got caught in the billows of its sun shield. The antennas have four hold-down points, or clamps, which are released on command. The clamps were placed not on the outside of the sun shield but inside it; the clamps released, but the mechanism designed to deploy the antenna got caught in the billowing sun shield. Unlike the Ku-band antenna, the C-band antenna deployment mechanism was not motor driven. The thinking was — and this is common to many communications satellite designs — that to fine-point the C-band antenna, the satellite's entire body could be oriented, obviating the need for a second motor.		
2011-021A	Telstar 14R (Estrela do Sul 2)	North solar array failed to fully deploy diminishing the amount of power available for S/Cs transponders and reducing the life expectancy of the satellite.	Initially blamed on a cable clip that came loose eventually root cause was determined to be inadvertent solar array pressurization and explosive decompression damaged the array's deployment mechanism and structure due to two combined manufacturing defects: overly pinching the ends of the solar panels so that their honeycomb cores could not properly vent air, and insufficiently bonding the layers of the panel, making it susceptible to explosive depressurization.	$132.7M	10, 14
2012-007A	SES 4	SES had trouble completing deployment of one of its solar arrays. Deployment eventually occurred, with the panels locking into place	The problem appears to have been that one of the two side panels on one of the two five-panel solar arrays did not lock into place immediately on deployment	-	31
2012-030A	Intelsat 19	South solar array damaged and failed to deploy. South solar array eventually deployed on June 12th 2012 following four apogee maneuver firings and appears to have lost 50% of its capacity, leaving the satellite with 75% of its design power capacity.	Inadvertent solar array pressurization and explosive decompression damaged the array's deployment mechanism and structure	$84M	11, 14
2013-017A	Progress M-19M/51P	Once in orbit, the Progress 51P spacecraft failed to deploy one of the five Kurs antennas used for the automated docking system. Specifically, the ASF-2 failed antenna is used to "measure the orientation" of the ship. Efforts by Russian controllers to jar or free the antenna from its launch latch mechanism with thruster firings and exposure to alternating periods of sunlight and darkness during the transit were unsuccessful.	Unknown: Russian flight controllers had to upload a software patch to mask the ASF-2 antenna's normal function of providing orientation and roll .	-	27
2017-029A	ViaSat-2	Two antennas malfunctioned reducing capacity from 300 Gbps to 260 Gbps due to "some deployment issue"	Unknown	$188M	18

**** Based on published and publicly available information. Actual root cause may differ.***

***** Based on published information. Actuals may differ.***