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Extending the Life of NASA's Tracking and Data Relay Satellite (TDRS)-8: TDRS-8 Power Challenges And Planning for End of Mission

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Abstract

The United States National Aeronautics and Space Administration (NASA) Near Space Network's Space Relay (SR) System provides communication relay services to a number of scientific and manned space missions with its Tracking and Data Relay Satellite (TDRS) constellation. NASA's eighth Tracking and Data Relay Satellite (TDRS) has been experiencing a decline in the health of its power subsystem. Launched in 2000, TDRS-8 is the oldest TDRS built upon a Boeing 601 platform, and as such it is the first TDRS to experience these age-related failures. The most prevalent elements of the power subsystem to decline are the solar array circuitry and the Bus Voltage Limiters (BVLs), which prevent too much power from the solar arrays being transferred to the bus by shunting excess current. This means that while the loss of solar array circuits introduces concerns that the solar arrays will continue providing the spacecraft with enough current to remain power positive, the loss of BVLs introduces a concern that the bus may not be adequately protected from overvoltage events. Spacecraft engineers at the TDRS primary ground terminal, the White Sands Complex (WSC) in Las Cruces, New Mexico, and at NASA's Goddard Space Flight Center (GSFC) have also been working in collaboration with Boeing to develop innovative techniques to extend the serviceable life of TDRS-8.

While NASA has experience in decommissioning TDRSs; however, TDRS-8 may be the first Space Relay Boeing 601 satellite to be retired. As such, it presents a number of unique challenges, such as achieving super-synchronous orbit and depleting fuel with thruster physical burn duration limitations; maintaining line-of-sight from the ground station to the spacecraft throughout orbit raising, fuel depletion, and passivation; and managing onboard power production and consumption for potential power subsystem failure scenarios that ultimately bring about spacecraft end-of-life. This paper will discuss the mitigation techniques and end-of-life planning strategies that are being developed by NASA to optimize the spacecraft's health and safety, as well as operational preparations for end-of-life scenarios in the event of a life-limiting failure.

Keywords: NASA, TDRS, power management, end of life, flight operations

Acronyms/Abbreviations

BPRS: Blossom Point Remote Site
BVL: Bus Voltage Limiter
EOM: End of Mission
EPS: Electrical and Power Subsystem
GRS: Guam Remote Site
GSFC: Goddard Space Flight Center
IEMP: Integrated End of Mission Plan
NASA: National Aeronautics and Space Administration
NASA-STD: NASA Standard (Publication)
NPR: NASA Procedural Requirements
PMD: Propellant Management Device
SR: Space Relay (System)
TDRS: Tracking and Data Relay Satellite
TT&C: Tracking, Telemetry and Command (Subsystem)
WSC: White Sands Complex

1. Introduction

The TDRS constellation is part of the National Aeronautics and Space Administration (NASA) Near Space Network's Space Relay (SR) System, the mission of which is to provide communication relay services to a number of scientific and manned space missions such as the Hubble Space Telescope, the Aqua/Aura/Terra Earth sciences missions, and the International Space Station, including its visiting vehicles. The TDRSs also provide communications services for commercial missions.

The TDRS constellation is currently comprised of ten spacecraft, all in geosynchronous orbit at various locations around the globe, as illustrated in Figure 1.

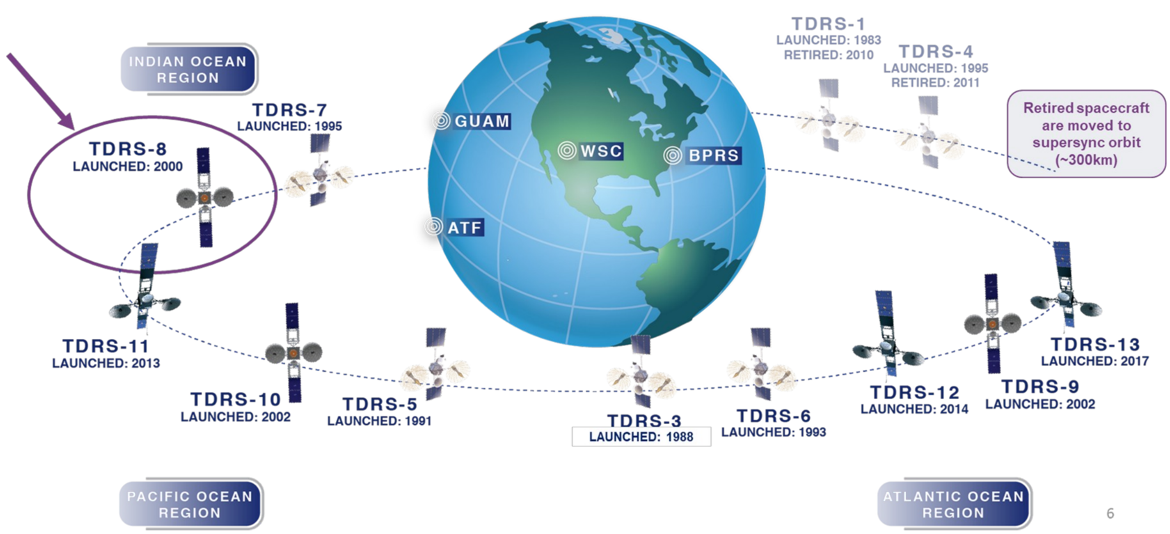

Fig. 1. NASA Space Relay TDRS Constellation

NASA utilizes three distinct types of TDRSs, which are referred to as generations. The first generation, or legacy TDRSs, were built by TRW. A total of seven TRW spacecraft were built, referred to as TDRS-1 through TDRS-7, four of which are still in operation. TDRS-1 and TDRS-4 have been retired, and TDRS-2 was lost aboard the Space Shuttle Challenger.

The second and third generations of TDRSs were built by Boeing. The second generation includes TDRS-8 through -10, which were launched in the early 2000s, and the third generation includes TDRS-11 through -13, which were all launched within the last several years. The most recent addition, TDRS-13, was launched in August 2017.

Regardless of generation, all of the TDRS were designed for a 10-15 year mission life. As such, the oldest TDRSs are over 30 years old, indicating how successfully NASA has been able to extend the life of these satellites. But, not surprisingly given their age, the spacecraft do occasionally experience technical challenges and even onboard failures.

TDRS-8 was launched in 2000, which makes it over 20 years old – well beyond its design life. It is the oldest of the Boeing TDRSs, and over the last few years has encountered a number of, what are believed to be, unrelated failures in the power subsystem. Section 2 addresses these in more detail. In response, NASA has developed some investigative strategies to better understand and characterize the power subsystem, as well as some mitigation techniques to extend the usable life of the spacecraft in the event of additional failures.

However, given that the power subsystem is a life critical system on the spacecraft, planning activities have also commenced about how to respond if the failures impact spacecraft payload operations. While WSC does have TDRS end-of-mission experience from the retirements of TDRS-1 and TDRS-4, the differences between the TRW and the Boeing satellites mean that the EOM techniques used on the Gen-I satellites cannot be entirely applied to TDRS-8. As such, in addition to developing ways to extend the lifetime of TDRS-8, NASA is also looking at how to perform end-of-mission when the time comes.

2. Power Management Strategies

The primary concern of TDRS engineers is to develop strategies to manage onboard power such that TDRS-8 remains operationally healthy and can provide data relay services to the NASA SR customers.

2.1 TDRS-8 Power Subsystem Failures

The first significant power subsystem failure to be exhibited by TDRS-8 was the loss of solar array circuits. The first two failures occurred in 2012 and 2013. Two additional losses were observed in 2016, and two more the following year, leading NASA to begin investigating the overall power subsystem reliability in early 2018. TDRS-8 is now operating on only 25 of its original 32 solar array circuits. Given the power demands of an in-service spacecraft, a loss of four more circuits would impede TDRS-8's payload operations, at which point NASA would begin planning deorbit activities. No additional solar array circuit failures were observed during 2019, but the seventh occurred in early 2020.

Another challenge observed on TDRS-8 focuses on the Bus Voltage Limiter (BVL) units. These units prevent too much power from the solar arrays being transferred to the bus by shunting excess current, and therefore prevent the bus from over-voltaging. However, several of these units have been shunting more current than necessary, referred to as anomalous shunting. Two of the six onboard BVL modules were disabled in order to recover enough of the parasitic shunting to keep the bus adequately powered. This anomalous behavior has been consistently observed on two more BVLs.

This means that not only does NASA have to figure out how to provide enough current to the bus from declining solar arrays, it also has to figure out how to prevent an overvoltage without the protection of BVLs.

As an additional note, TDRS-8 also has four underperforming battery cells. Generally speaking, batteries are one of the most life-limiting systems for TDRSs, and they are always monitored and analyzed with hypervigilance. However, even with the four underperforming cells, the TDRS-8 battery is not considered to be of significant concern at this time.

2.2 Load Shedding

One mechanism identified to prevent an undervoltage is load shedding. If the spacecraft loses additional solar array circuits and cannot adequately power all of the onboard systems, the engineers would respond by turning some of the payloads off. The least life-critical components onboard are the payloads. After evaluating the spacecraft specifications as well as real-life telemetered data to determine the power draw of each piece of equipment or suite of equipment, engineers developed a set of matrices that can guide decision making in real time if future losses occur. Pre-loaded command stacks were built, validated against simulators, and delivered to the operational system. The payload shutoff procedures have been formally documented and are on standby when and/or if they are needed.

In addition to turning off payload equipment, NASA has explored the idea of turning off the heaters that keep the payload equipment within temperature tolerances. While engineers did discover that the thermal modeling of the White Sands-based simulators was not of sufficient fidelity to perform an in-depth analysis of this technique, the Goddard-based counterparts have a desktop simulator that was able to support a number of analyses on heater operations and their contribution to the overall bus power draw and thermal environment. Those analyses were folded into the payload study and are part of those decision-guiding matrices and priorities that were proceduralized.

2.3 BVL Characterization

Another power management technique applied is the performance of BVL top-off tests. These tests characterize the behavior of the BVLs by quantitatively measuring the amount of anomalous shunting at the time of the test. These tests have been incorporated into the nominal operational posture so that they are routinely performed on all second- and third-generation spacecraft. The idea is that if a large anomalous shunt is observed, the BVL can be disabled so that the spacecraft can remain power positive.

Some of the methods that have been identified to mitigate loss of BVL operations are to increase the bus load, modify battery management strategy so that the batteries absorb potentially extra current, and adapt the power management logic to autonomously or semi-autonomously detect and prevent overvoltage. In addition, NASA has also investigated the possibility of applying a pointing offset to the solar arrays to control power output to the bus.

2.4 Solar Array Characterization

The solar array offset strategy was exercised on May 2019 in order to validate the concept and characterize the power output by the arrays. One array at a time was off pointed from the sun line to an 85-degree offset and then slewed back to its nominal position. To reduce the risk of an attitude upset, the procedure was first executed on multiple simulators and then performed on the actual spacecraft during a deep eclipse in February 2019. The eclipse version of the test did not provide any power characterization data, but it did confirm slew rates and validate the procedure. The full sun version of the test was performed on each array individually two days apart.

While one array was off pointed, the other remained in sun tracking mode. The objective of the test was to turn the array completely perpendicular to the sun, but the offset angle of 85 degrees was selected to prevent the possibility of exposing the back side of the array to the sun as the back side is more fragile to sun exposure and could have induced additional failures. A solar wing bias algorithm was utilized to command the 85-degree offset, and the spacecraft then initiated the slew to a near-right angle to the sun line. Once it achieved that angle, the bias was immediately commanded back to zero and the array returned to its nominal position.

The test served two purposes. The first is that the power output by the arrays was able to be empirically characterized as a function of offset angle. The second is that the comparative performance of the two arrays determined that the solar array circuit failures were distributed fairly evenly between the two arrays. If the failures had been predominantly isolated to one wing, engineers would have had greater confidence in the reliability of the other wing and may have indicated that the failures were the result of a workmanship issue.

The figures below illustrate the data collected during the full sun version of the test. Figure 2 shows that the array rotated at a steady rate to its maximum offset, 85 degrees, and then immediately was commanded to slew back. Figure 3 illustrates how the power output by the arrays changed throughout the duration of the test. Note that TDRS-8 telemetry only reports a combined total of the power output by both arrays, so the data in Figure 3 includes the constant power still being supplied by the array that was not being rotated during the test.

This data will be useful if a no-BVL operating posture becomes necessary. It gives engineers insight into how far the arrays need to be offset to limit the power produced by the arrays that is transferred to the bus.

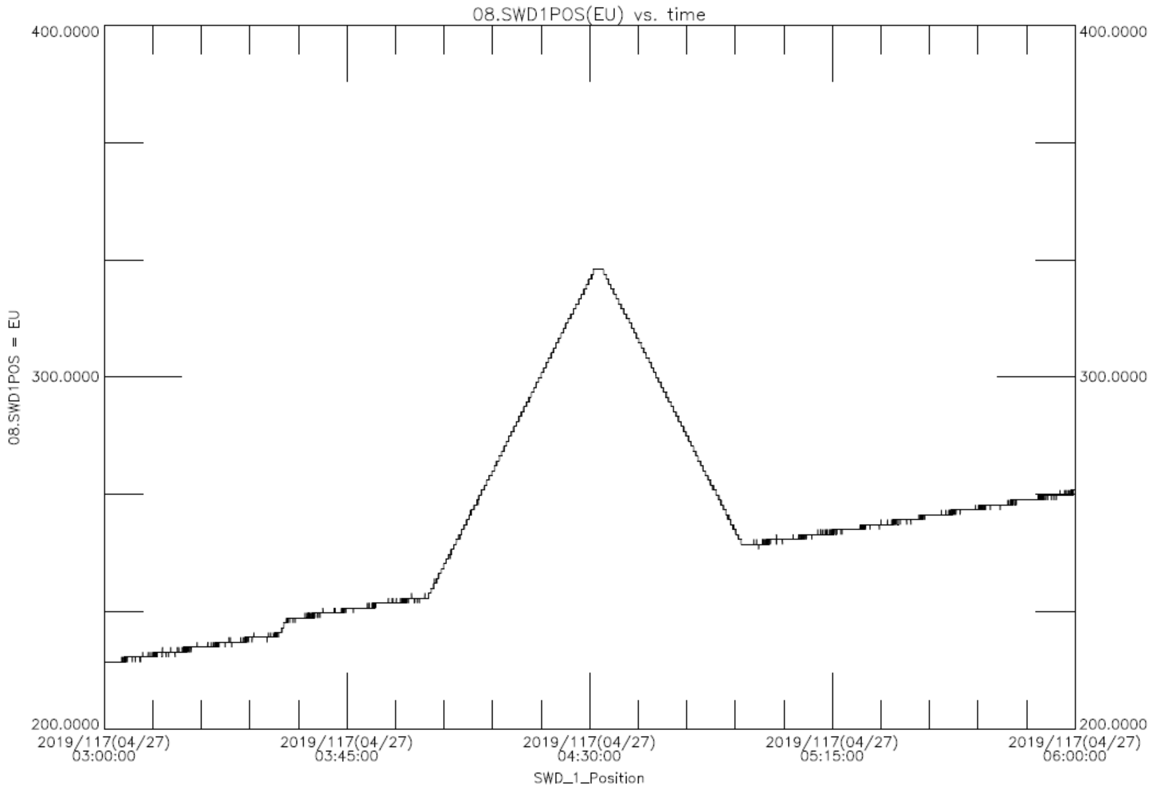

Fig. 2. TDRS-8 Solar Array Offset Angle

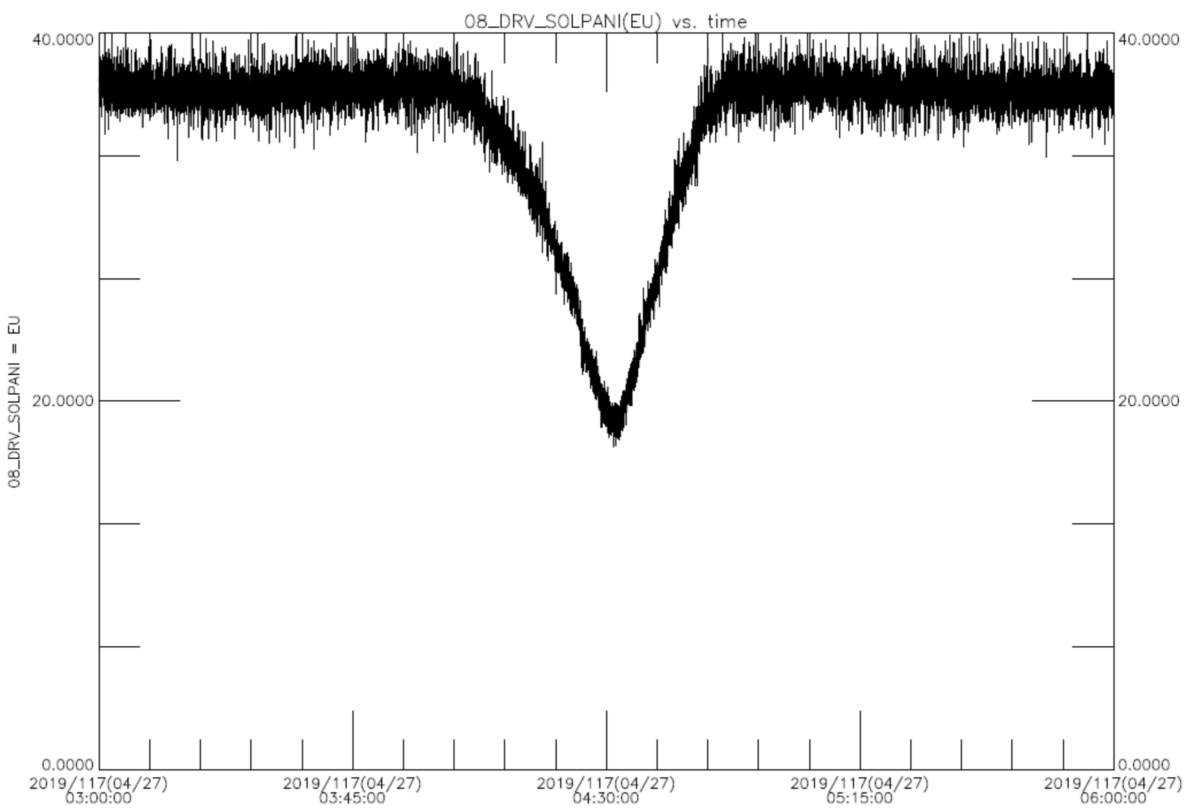

Fig. 3. TDRS-8 Solar Array Power Output

3. End of Mission Planning

In addition to extending the life of TDRS-8 by mitigating power subsystem challenges, NASA has also been considering End of Mission (EOM). In the event that life-extending techniques are insufficient to keep the spacecraft within power limits or become operationally burdensome to implement over long periods of time, TDRS engineers will need to be prepared to retire the spacecraft.

3.1 Defining the Spacecraft Requirements for End of Mission

Spacecraft retirement is not yet a routine operational activity, at least in the geosynchronous belt, so the first step in defining an EOM plan is to understand what it means to "retire" a spacecraft. NASA has published two guiding documents related to this topic that provide a solid framework. Debris management edicts captured in NASA Procedural Requirements (NPR) 8715.6, Procedural Requirements for Limiting Orbital Debris [1] provide a requirements baseline for a spacecraft's onboard and orbital end state to be considered retired, and the NASA standard 8719.14A [2] provides some general direction on how to achieve that end state. Those documents define the three main components to spacecraft retirement as transferring to a supersynchronous orbit, depleting all fuel, and passivating all stored energy and power systems.

Supersynchronous orbit, or the parking orbit, is defined as having a perigee of at least 303km above the geosynchronous belt for the TDRS spacecraft – preferably closer to 350km – with an eccentricity of no more than 0.003.

3.2 Thruster Constraints

With TDRS-1 and TDRS-4, achieving supersync was a fairly simple concept: ignite the thrusters until the appropriate orbital change is accomplished. However, for second and third generation spacecraft, including TDRS-8, thruster constraints must be taken into consideration. The east/west thrusters have an operational constraint of 10 seconds. The total burn duration required to achieve supersync is estimated to be a minimum of 24 minutes, so being limited to 10-second burns is certainly a challenge. NASA has considered the possibility of relaxing this constraint to 20 seconds, but even so, orbit raising would require a significant number of maneuvers. An additional constraint is that maneuvers must be spaced by at least 30 minutes due to thermal considerations.

One alternative that has been considered to avoid the east/west thruster constraints is to tip the spacecraft on its side and perform orbit raising using the north thrusters. However, these thrusters are physically constrained by a Propellant Management Device (PMD) to 50 seconds, and replenishment of the PMD requires at least two hours between burns. This limits any advantages of the tip-burn-tip technique.

3.3 Power Subsystem Constraints

Another important consideration is that TDRS-8 EOM will most likely be the result of substantial failures to the power subsystem, which may introduce additional constraints on EOM methodology. This consideration is more difficult to quantify in advance and is considered a "known unknown".

3.4 Ground Visibility Constraints

Another unique aspect of performing end of mission on TDRS-8, compared to the previous two TDRS retirements, is that TDRS-8 has more limited visibility during orbit raising because it is being operated from the Guam Remote Site (GRS), and orbit raising will carry the spacecraft to the west. This means that the spacecraft will experience a period of no visibility when it leaves Guam's field of view but has not yet entered Blossom Point's or White Sands'. Ideally, all orbit raising maneuvers and passivation activities would be performed prior to exiting Guam's field of view, which constrains the execution timeline. To mitigate this, a significant amount of fuel depletion will be completed prior to orbit raising, which deviates from the fuel depletion approaches utilized for the TDRS-1 and TDRS-4 retirements.

3.5 Integrated End of Mission Plan

As NASA has been working through the technical constraints and challenges, the TDRS engineers have been populating a document referred to as the Integrated End of Mission Plan, or IEMP. By developing it in conjunction with the technical discussions on how to execute EOM, it has provided continuity for the planning of each phase. The basic framework of the plan starts with turning off all payload equipment utilizing established procedures. This is an activity that is periodically performed during normal operations, so it does not represent any unique challenges.

The second phase is to perform initial fuel depletion. NASA's plan is to use the longer-duration north thrusters to burn off as much propellant as can safely be done at geosynchronous orbit while still retaining enough for the supersync maneuvers.

Phase three is orbit raising. This will most likely be the most time-consuming phase of the mission. After simulating a variety of orbit raising methodology, NASA has honed in on an approach that leverages Hohmann transfers. Maneuvers will be performed in sets of two six-hour burn windows centered 12 hours apart. Each burn window will be comprised of 13 maneuvers executed 30 minutes apart. These maneuvers will have the effect of reducing orbital eccentricity, which is already within the retirement specification for normal operations; therefore, eccentricity will remain within specification throughout the transfer process. Orbit raising will require 11 burn windows spread over six days. Contingency planning for open-loop thruster operation has been included in the event of bubbles in the propellant. This technique for orbit raising addresses the ground visibility constraint, as TDRS-8 will be visible from GRS for seven days once orbit raising begins.

Once orbit-raising is completed, final fuel depletion and passivation can be completed. This will likely be the most challenging phase of the mission due to the fact that the fuel depletion technique will have to account for the possibility of bubbles in the propellant that could cause imbalances in thruster performance.

After burning off all remaining fuel, the next phase is spacecraft passivation. The Electrical and Power Subsystem (EPS) passivation will be executed first. Any payload and thermal units that remain powered on will be shut down at this point, and then battery charging will be disabled. This is also a very straightforward phase utilizing established procedures already in hand.

Attitude Control System passivation includes powering down of the gyros and the momentum wheel platform assemblies, followed by the earth sensors and spacecraft control processors.

Finally, EPS and Tracking, Telemetry and Command (TT&C) passivation will involve turning off telemetry streams and disabling communication. Once this final step has been completed, all communication with the spacecraft is effectively and irrevocably locked out, and the satellite is officially retired.

4. Conclusions

These planning and investigation activities are ongoing. Substantial progress has been made over the last couple years, but there is still work to be performed.

The next steps will be to continue researching, simulating, and testing strategies that could extend the serviceable life of TDRS-8. NASA obviously wants to preserve the health of the systems on the spacecraft to the greatest extent, but is also working to develop ways to operate it if additional failures were to occur.

If it does experience additional failures, TDRS engineers need to have emergency response procedures ready for execution. This includes anticipating possible future failures and training engineers and operators on how to execute those procedures.

Third, the fuel depletion and supersync methodologies are not yet finalized. In particular, optimized thruster duty cycles, impacts of fuel slosh, and attitude perturbations due to propellant bubbles are still being characterized through complex simulation scenarios. Once that characterization activity is complete, it will be incorporated into the IEMP. This is a high priority action primarily because it is one of the most significant technical challenges associated with end of mission.

References

[1] NASA Procedural Requirements (NPR) 8715.6, Procedural Requirements for Limiting Orbital Debris
[2] NASA Standard (NASA-STD) 8719.14A, Process for Limiting Orbital Debris