Review of Mishaps in Rendezvous and Proximity Operations

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The need for and complexity of rendezvous and proximity operations (RPO) is growing due to the increasing number of in-space servicing, manufacturing, and assembly missions. Past RPO missions have had historic failures, and while more recent RPO missions have been less catastrophic, mishaps are still present. This paper reviews past historic RPO missions with mishaps, the causes behind them, and the respective lessons learned. An overview of missions include the 1990 STS-32, 1992 STS-49, 1997 Progress-Mir, 2005 DART, and 2007 Orbital Express. Finally, the paper summarizes the most prominent lessons learned from RPO missions with mishaps. This paper aims for future RPO missions to avoid costly mishaps by addressing lessons learned from past operations.

I. Introduction

There is a rising interest in rendezvous and proximity operations (RPO), due to the increasing variety of its uses. For instance, spacecraft RPO offers the ability to remove orbital debris, which is relevant due to the increase of debris in Low Earth orbit that poses a risk to functioning satellites [1]. In another example, RPO is utilized in in-space servicing, assembly, and manufacturing (ISAM) missions, which is also gaining renewed interest. The reason for the end-of-life of many spacecraft is running out of resources, and ISAM operations are able to refuel old satellites.

RPO generally refers to the approach and interaction between spacecraft [2], and the applications of these RPO missions are growing. As these applications become more complex and ambitious, it becomes even more important to remember lessons learned from past operations. Recommendations from previous missions are necessary to prevent the repetition of past mistakes, in addition to improving the efficiency and safety of future missions. While there have been advances in RPO technology, the missions themselves are becoming more complex and demanding; RPO missions still face the risk of failures in their control systems and elsewise. This paper reviews historic mishaps in RPO that offer valuable lessons. By examining these cases, the paper aims to help future RPO missions avoid costly mistakes. Additionally, this review serves as an entry point for students and new researchers to better understand RPO missions—what they entail, the challenges involved, and what past missions have taught us.

This paper is structured as follows: Section II presents five RPO missions in chronological order that experienced mishaps, each analyzed through four subsections—an introduction to the mission's background and objectives, a summary of the actual events, an examination of the causes of the mishap, and a discussion of lessons learned. Section III synthesizes the key lessons derived from these cases, underscoring takeaways for future missions. Finally, the paper concludes with closing remarks.

II. Review of RPO Missions with Mishaps

A. 1990 STS-32

1. Project Background and Purpose

The Long Duration Exposure Facility (LDEF) was a payload meant to investigate the effects of space environment exposure on several different materials. It was deployed in April 1984, and was originally meant to be retrieved in early 1985, but kept being postponed for various reasons. In early 1990, space shuttle Columbia STS-32 was finally launched with two primary objectives- to deploy SYNCOM IV-F5 defense satellite and to retrieve LDEF [3].

2. Description of Project Execution

As per crew procedures, radar lock on LDEF began right before the second star tracker pass, at a range of 148500 ft. Radar acquisition would occur only after the NCC (Corrective Combination Maneuver) burn, as indicated by the

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planned trajectory. Radar data was not to be integrated into navigation until the NCC maneuver was completed. The data appeared to be accurate and Mission Control decided to incorporate it into navigation. During the star tracker pass, the radar range and radar range rate data began to degrade, causing the onboard navigation filter to reject two measurements of the range rate. The radar measurements had more noise than anticipated, resulting in a deterioration of the onboard navigation state quality. Star tracker data processing continued without issue. Mission Control inhibited radar range and radar range rate data and the star tracker pass was completed without further problems. The onboard solution for the NCC maneuver was burned despite it being 4 ft/sec higher than expected, and then radar range, range rate data, and angles were processed. Mission Control again asked to inhibit range rate after there were several range rate data spikes. The NCC burn being higher than expected resulted in a miss of 4.9 nautical miles from the desired next burn. The proximity operations phase with LDEF went without significant issue. The LDEF grapple and berthing was successful.

3. Description of Mishap

Post-flight analysis showed that the radar hardware introduced a range measurement bias at extreme ranges, and this bias increases as the range does. This radar anomaly affects both range and range rata data. The signal strength was not affected significantly by the longer range; the radar's maximum effective range was limited by transmission pulse timing. The radar data was accurate when lock-on was established, but the maximum effective range was surpassed during the second star tracker pass.

4. Lessons Learned and Recommendations

The range over which the bias phenomenon can occur was not an unknown fact; it was simply not properly addressed. It was known early in the shuttle program, but the information had not been properly noted and documented. After lessons were learned accordingly, procedures were changed so that radar data would only be measured at sensor's optimal ranges, where measurements were still accurate. The most important lesson learned is as follows:

1) **The design and performance characteristics of sensors must be thoroughly documented, both within and beyond their certified performance envelope.** Sensors may show varying degrees of reliability outside this envelope. Any limitations in design or performance should be carefully recorded and incorporated accordingly, preventing the usage of unreliable data.

B. 1992 STS-49

1. Project Background and Purpose

In 1990, when the INTELSAT VI (F-3) was initially launched, it was unable to reach its intended orbit. The mission of the STS-49 was to rendezvous with the INTELSAT in order to attach a new Perigee Kick Motor (PKM). The rescue and repair plan included capture of the satellite with a capture bar controlled by an astronaut on a restraint mounted on the shuttle's robotic arm called the Remote Manipulator System (RMS). An astronaut inside the shuttle would maneuver the extra-vehicular activity (EVA) astronaut into an optimal position to capture the INTELSAT. After the docking of the capture bar to the INTELSAT, RMS would attach to the capture bar and move the INTELSAT in the payload bay so that the EVA astronauts that were inside could berth it. The crew would then attach the new PKM to the INTELSAT.

2. Description of Project Execution

On Flight Days 4 and 5, several attempts were made unsuccessfully to capture INTELSAT. These attempts failed due to an inability for the capture latches to trigger onto the INTELSAT, as the capture bar was unable to stay connected with the INTELSAT for a long enough period. Thus, Mission Control and crew members agreed for the crew to use their hands to capture the satellite rather than the capture bar. Flight Day 6 was spent planning for the new capture technique. On Flight Day 7, after a successful execution of two star tracker passes and a NCC maneuver N maneuver, the targeting attempt for the next maneuver called Transition Initiation (Ti) was unable to converge. The Lambert targeting code worked without problem several times throughout this mission, but was the source of the targeting failure. The crew reloaded new GNC software into the GNC computers, suspecting that the GNC software was corrupted. However, the targeting failure occurred again nonetheless. The anomaly of the Lambert targeting code made Mission Control decide to manually compute Ti and subsequent maneuvers and transmit it to the crew. The reload of new GNC software erased prior radar data and statistical information about the star tracker passes, so Mission Control decided to perform the Ti-Delay Maneuver to provide more time to update the on-board navigation data. Ti-Delay (computed by Mission

Control) was performed, and 2 of the 3 on-board troubleshooting Ti targeting attempts were successful. After orbital sunrise, the INTELSAT's flight path was followed as expected, and the proximity operations phase could start. Finally, on Flight Day 7, INTELSAT successfully had PKM attached and was deployed. PKM functioned successfully and INTELSAT commenced its operation.

3. Description of Mishap

The Lambert Targeting anomaly was traced back to an instance of mixed precision in a double precision mid-value selection library function. There was an assigning of single-precision values to double-precision variables and a comparison of single-precision variables with double-precision variables [4]. The failure and anomaly did not occur in the first 35 times it was used throughout STS-49, nor did it happen in prior simulations with Mission Control. The Ti maneuver was the only maneuver that could be affected by the anomaly. STS-56, the following RPO mission, used a similar software to STS-49 but with a loosened convergence criteria. No anomaly occurred.

4. Lessons Learned and Recommendations

STS-49 is considered one of the more challenging space shuttle missions, due to the complex INTELSAT capture and repair, as well as the technical issues that arose during the flight. Despite these challenges, the problems were resolved, and the mission was successful, offering valuable lessons to be learned.

1) **The flight control team must be experienced and integrative.** Having an interdisciplinary and experienced flight control team was essential for this complicated flight to be successful despite the technical challenges. They quickly found a solution to an unexpected problem. When there was an anomaly in an area of code that had not previously produced problems, Mission Control wisely opted for Ti-Delay and an additional orbit for more time to fix on-board navigation data. They did not rush in making an executive decision for the mission to run successfully, but still executed a decision within a safe time frame.
2) **Changes made to code within iteration loops must be properly and thoroughly tested.** Alterations in code within iteration loops affect the ability of the code to converge. The Lambert targeting code had changes in its library function after the flight previous to the STS-49, and while it was simulated numerous times, it would have been beneficial to test it under a wider number of parameters, including those outside of what would be used in the mission. The use of mixed precision parameters is risky, as some coding standards require justification before mixed-precision expression to a single-precision variable. Thus, use of mixed precision parameters should be especially examined.
3) **Analysis and technical reports must be properly reviewed.** As aerospace operations become more complex, more specialized knowledge is required to review procedures. Therefore, independent review by multiple personnel in several specialties is required for ensuring quality and robustness. Documentation should be made accessible to all personnel so that small possible causes of errors can be identified significantly before the mission.
4) **Documents describing software requirements for those who do not specialize in software should be created.** This type of document would be beneficial for the functionality of the entire project. Understanding of software requirements is essential for resolving technical issues, development of procedures, and analysis of performance. Having a document catered to engineers and other personnel can reduce risk of miscommunication, leading to more efficient collaboration and fewer costly errors.

C. 1997 Progress-Mir collision

1. Project Background and Purpose

In March of 1997, the crew of the Space Station Mir received orders from the Russian Federal Space Agency Mission Control Center (TsUP) to test a backup manual system titled Teleoperated Rendezvous Control System (TORU) on the unmanned spacecraft Progress-M 34. TsUP would position Progress above Space Station Mir before transferring control to TORU operator Vasiliy Tsibliyev [5]. A camera mounted on Progress would transmit a television feed to Mir, allowing Tsibiliyev to see Mir's docking station from the point of view of Progress. Thus, Tsibilyev would control the movement of Progress accordingly to dock with Mir.

2. Description of Project Execution

In this initial test, Tsibilyev's screen was blank, ultimately leading him to abort the docking. Progress missed Mir by a mere 200 meters. Soon after, the Mir crew was once again asked to test TORU with Progress. To address the blank screen, TsUP turned off the emitter that TsUP thought interfered with the camera signal. Turning off the emitter prevented the Mir crew from having data regarding range and range rate. Ground control members had to manually calculate this data. This time, Tsibiliyev's screen worked. However, as Tsibiliyev got Progress closer to Mir Space Station, members worried that they could not see Progress from the windows when it should have been in visual range. When Progress suddenly became visible, appearing behind one of the solar arrays of Mir, it was going at a high relative velocity and missed the docking station of Mir. It collided into a module of the space station, puncturing a hole into it, depressurizing the module and putting the crew's lives in danger. Crew members sealed off the leak of the module and communication with ground control put the station oriented so that its solar panels could use the Sun. The crew and rest of the station were safe.

3. Description of Mishap

Subsequent investigations showed that the Mir crew did everything correctly and could not be placed at fault for the collision. The collision happened due to multiple reasons. Tsibiliyev was not given the practice needed to perform the test proficiently without telemetry. Performing the test without radio contact with the ground prevented TsUP from having information that would allow it to assist the Mir crew. The Progress had been found to have an offset center of gravity. All of this led the Stafford Commission, who conducted an investigation to look into this collision, to agree that the Progress could not dock safely and that it was not the crew's fault.

4. Lessons Learned and Recommendations

The investigation into the Progress-Mir collision revealed several key issues that contributed to the mishap, many of which could have been avoided with more robust planning, communication, and preparation. These recommendations focus on improving communication, system reliability, and ensuring the well-being of the crew under stressful conditions.

1) **Information essential to mission success and safety must be shared.** The Russian Space Agency was hesitant in sharing much information about the docking to NASA. NASA did not know about the TORU test. Had they known, they could have recommended ground simulations that would have revealed the many flaws and risks of the maneuver. Additionally, American engineers were not informed that the Mir crew would be given manually calculated data instead of having the emitter give telemetry, range, and range rate data. Such information is vital to mission success and safety, and should thus be shared. Since this historic collision, it has been a mutual agreement in international spaceflight partnerships to share such essential information.
2) **Be aware of the economic and social pressure that an organization is facing and the effects of this pressure on missions.** The automated system Kurs that vehicles used to dock with became too expensive for the economic pressure that Russia was facing. This was the reason for testing the backup system of TORU. Successful testing of TORU would alleviate funds that were going to the original system Kurs. Moreover, Tsibiliyev was under both physiological and psychological stress after the unsuccessful initial test of TORU. Ground controllers and physicians both became increasingly aware of Tsibiliyev's nonoptimal condition, but hesitated to speak out about it because they felt TsUP would move on regardless. In short, the pressure that TsUP and all the crew were under could have made them feel desperate and rushed the process, decreasing chances of success.
3) **Favor a safer redesigning of a docking system rather than trying to force docking on a faulty system.** The reason the crew used the "hot approach" to dock, in which the docking vessel is at high speeds until it brakes in the last few moments, is because the Russian Space Agency feared that the navigation system would build up errors if the docking did not occur quickly. This hot approach made it so that when the crew finally saw the Progress, braking thrusts would be ineffective in preventing a collision. Rather than forcing this fast, dangerous approach on the crew so that the navigation system would not accumulate errors, it would have been safer and more successful to use a better navigation system.
4) **Perform maneuvers while having radio contact with ground control.** Had the crew been in radio contact with ground control, TsUP could have helped the crew with its data and/or controls, and increased chances of mission success and crew safety. Attempting the docking without this radio contact put the crew in unnecessary danger.

D. 2005 DART

1. Project Background and Purpose

The Demonstration of Autonomous Rendezvous Technology (DART) spacecraft was designed to maneuver around the Multiple Paths, Beyond-Line-of-Sight Communications (MUBLCOM) satellite. Because of the intention for it to be autonomous, DART was not designed to receive commands from the ground; ground control could do nothing to help if the demonstration had errors [6].

2. Description of Project Execution

In the first 8 hours of the demonstration, DART performed as intended. The launch, early orbit, and rendezvous were fully successful. However, during the proximity operations phase, DART started using more propellant than expected. 11 hours into the demonstration, DART detected that it was out of propellant and initiated its department and retirement sequence. Ultimately, it collided with the target MUBLCOM satellite [7].

3. Description of Mishap

The DART's software-based navigational system executed computational resets because of the significant difference between the estimated and measured position. This made the DART restart its estimated position and speed using measurements from the GPS. However, this primary GPS receiver was inaccurate, and consistently produced a measured velocity 0.6 meters per second off of what it actually was. This inaccuracy made the estimated and measured positions become significantly different again, leading to another computational reset. This cycled, causing frequent resets that elicited extra thruster firings. Thus, an excessive fuel usage that caused DART's premature departure and retirement. This could have been avoided on many different accounts. There was a software fix for this consistent inaccurate measurement of velocity, but this fix was not implemented. The design requirements of the navigational software were not strict enough, as they had said that velocity measurements had to be accurate to within 2 meters per second; the software diverged simply from a 0.6 meters per second difference. Furthermore, a feature in the computational logic called "gain" was changed and did not go through sufficient testing. This gain determined how important the estimated data was in comparison to the measured data in the final calculation of differences. The mishap investigation board (MIB) found that the original gain setting would break the cycle of diverging data and software resets. In short, DART's premature retirement resulted from several software errors and incorrect navigational data. These include a significant initial calculated difference between DART's estimated and measured position that activated software resets, inaccurate velocity measurements that made the software resets cyclic and continuous, a navigational software design that was overly-sensitive to erroneous data, and poor setting and lack of testing of the gain control in the calculation scheme. As DART approached MUBLCOM, it missed a position in space that would have activated a full transition of its navigation data source from GPS to the Advanced Video Guidance Sensor (AVGS) , which was the mission's primary sensor. Missing this waypoint prevented AVGS from supplying accurate navigational data. The inaccurate perception of DART's distance from MUBLCOM did not allow DART to take action necessary to avoid the collision. There was a lack of sufficient design review and no anticipation for navigational data to be so inaccurate.

4. Lessons Learned and Recommendations

DART was a disaster; it had many problems that intertwined and built upon each other. A Mishap Investigation Board (MIB) was assigned to investigate DART, and its report made clear several lessons learned.

1) **Quality of training and experience must be ensured.** The design team did not have significant training and experience regarding "actual flight system design and operation", and the lack of this experience was what made the team ignore expert advice. Such experience or expert advice for such a high-valued mission could have prevented mishaps. There should be resources to fill in any knowledge or skill gaps.
2) **The guidance, navigation and control software development process must be rigorous.** An insufficient GNC software was one of the major causes of the mishaps. As changes were made, they were not properly documented, making many members of the DART team ignorant to some features of the software. Thus, it was learned that the simulations and math models used to validate flight software should go through a just as thorough inspection as the flight software itself.
3) **Management checks should be required to prevent launching improper vehicle configurations due to schedule pressure.** Schedule pressure made it so that there was not sufficient testing for the gain setting. To

work with schedule pressure, there must always be checks required to prevent launching faulty configurations.

4) **Require a risk assessment for high-priority flight missions.** The DART insight team had an insufficient test of project technical risk, preventing them from seeing issues that led to the mishaps. For high-priority flight missions, there should be a thorough risk assessment.
5) **High-priority and highly complex flight missions must use engineering peer review, and team members must formally address the recommendations from this peer review.** The DART team did not use experts on the subject matter. For future similar cases, high-priority flight missions must be peer reviewed, and recommendations from such a review must be properly addressed.
6) **Degraded functionality must be considered.** Analyses for the DART used inadequate conditions that would lead to mishaps. For instance, instead of considering a somewhat loss of functionality of components of the navigation system, analyses only focused on a complete loss. Future similar occasions should consider degraded functionality as well.

E. 2007 Orbital Express

1. Project Background and Purpose

The Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) system was intended to demonstrate the feasibility and effectiveness of on-orbit satellite servicing with autonomous techniques [8]. The demonstration included transfers of hydrazine fuel and orbital replacement units of the battery and flight computer. The system included two satellites; the chaser vehicle that was to perform the servicing was the autonomous space transfer and robotic orbiter (ASTRO), and the satellite that was to be serviced by ASTRO was the next generation satellite/commodity spacecraft (NextSat/CSC). One of the main objectives of the OE system was to demonstrate an autonomous guidance, navigation, and control system (AGNC) for on-orbit satellite servicing.

2. Description of Project Execution

The OE conducted 5 operations, in addition to one that was part of the decommissioning sequence. In the second operation, as ASTRO attempted to dock with NextSat, a major failure in ASTRO's sensor computer caused it to miscalculate its position and orientation. This error resulted in ASTRO drifting unexpectedly and approaching NextSat at an incorrect angle. The spacecraft then entered an unplanned configuration, triggering an automatic safety abort. However, due to the nature of the malfunction, ASTRO was left in a compromised state, requiring immediate manual intervention from ground operators to stabilize the system. After this, ASTRO was able to dock with NextSat. Solutions were made accordingly to the problems that ASTRO had, and it performed its remaining operations without significant issues.

3. Description of Mishap

The major failure in ASTRO's sensor computer caused ASTRO to execute an abort procedure. The advanced video guidance sensor (AVGS) continued to supply its normal measurements throughout the pre-planned abort path, although the autonomous rendezvous and capture sensor system (ARCSS)'s data was lost due to the failure of the sensor computer. Data from IR sensor became available after ARCSS was recovered with a backup sensor computer, but this data was rejected by the navigation filter. This led to the accumulation of errors in the previous navigation data, causing them to compound and further deteriorate the navigation fix [9]. Ground control placed ASTRO into coasting flight mode until operators found a setting under which the IR sensor could accept data from the filter. Using the data, ASTRO positioned itself 2.5 km from NextSat, allowing reliable LRF data acquisition. The navigation filter processed the IR and LRF data, enabling an approach to 150 m. Despite a thermal issue with a thruster, the AVGS performed well, and the recovery was completed eight days later.

4. Lessons Learned and Recommendations

The DARPA OE was able to recover from its mishaps, but only with substantial help from ground control. It was a success, but not without its issues. The following are some of the lessons learned.

1) **Personnel should be conscious of any assumptions made regarding navigation.** The ground operators did not always fully understand the position of ASTRO relative to NextSat, and they had to dedicate extra time to identify this relative position. Knowledge about navigation can be specialized, making it difficult to fully understand

what is happening. A deeper grasp of navigation could have saved valuable time in this mission.

2) **IR sensors are relevant and essential.** Initially, the IR sensor was viewed as a supplemental feature. However, it was the primary sensor the mission used to be able to recover. Other sensors are more affected by lighting conditions, and can thus be unreliable.
3) **Interdependence between sensor and navigation software is prone to reinforcing problems.** Problems can negatively and mutually reinforce each other; thus, tight coupling may reduce system effectiveness. For instance, the sensor software and navigation filter aided each other, and when the sensor started seeing optical artifacts, and the navigation filter processed this data. Thus, resulting in the filter's biased state estimate and increased state uncertainty. In contrast, one of the reasons OE was able to recover despite a major failure in the sensor computer was due to the variety of data types. Having a separation and independence between sensor suites can ensure that any failures will not cause more.
4) **For effective calibration, the target vehicle should be out of the sensors' view, and potential image distortions should be considered.** The original on-orbit sensor calibration did not reveal the optical artifacts that caused problems with the navigation filter and sensor software. Changing the calibration to having bright objects imaged and taking NextSat out of the field of view allowed ground control to remove most of the artifacts.
5) **Missions should allow for interference from ground control.** The recovery of OE was made possible because of the intervention from ground control. In most cases, OE restricted autonomous contingency responses to situations where ground operators could not intervene in a timely manner that aligned with the mission's operational tempo. The different design in this scenario proved to be beneficial and essential for OE's recovery.

III. Most Prominent Lessons Learned

After analyzing several mishaps in RPO missions and lessons that were learned accordingly, some reoccurring lessons learned and recommendations stand out.

1) **Changes across systems must be thoroughly tested and properly documented.** The bias phenomenon of STS-32 was known before the flight, but not properly documented, leading to use of a sensor in ranges where it no longer gives accurate measurements. The limitations of sensors should be tested and known, before being properly recorded so that it can be considered in project design. STS-49 had risky alterations in its code within iteration loops, and although it worked numerous times without issue, this change in code was what produced an anomaly. Testing this change under more various conditions could have allowed the team to identify potential vulnerabilities and prevent the anomaly from occurring during the mission. DART had a change in its gain setting that did not go under thorough testing, and the prior gain setting would have broken the cyclic diverging measurements and computational resets that helped lead to the collision. Modifications in software, sensors, and other systems must be rigorously tested both in and out of conditions that would be used in the mission. Limitations should be properly documented, so use of these systems outside of their optimal ranges can be avoided.
2) **Be cognizant of the pressure a company may face and the effects of this pressure on projects.** Spacecraft failures happen as a result of 'faulty engineering', but this faulty engineering has often been attributed to the social or economic pressure of a mission. In the Progress-Mir collision, schedule pressure allowed Tsibiliyev on the mission despite an obvious decreased ability. Economic pressure was what pushed the testing of TORU initially- it would have reduced costs. Similarly, the NASA DART was under much schedule pressure, which did not allow for substantial and necessary testing of a changed gain setting. To combat loss of robustness while following deadlines, regular management checks are recommended.
3) **Personnel and crew members should be interdisciplinary and well-experienced.** In DART, the design team's knowledge gap and lack of significant experience led them to reject expert advice that would have proven to be extremely beneficial. Their lack of expertise was part of what caused an unsuccessful mission. In contrast, STS-49 had a well experienced flight control team that was necessary for the mission to recover from its unexpected challenges. A mission can be greatly benefited if its project members are knowledgeable and experienced. If any knowledge gaps exist, there must be resources to help bridge those gaps.
4) **Avoid designs that preclude intervention from ground control.** The success of STS-49 and OE despite unexpected technical challenges is due to input from ground control. This directly opposes DART, which was not designed to receive commands from Mission Control, due to the intention for DART to be truly autonomous. This makes it so that even if ground control could see an error coming up, they could do nothing about it. Similarly, the Mir crew could have greatly benefited from being in radio contact with ground control. The role of

ground control and support is vital, especially in helping a mission recover from unforeseen obstacles.

IV. Conclusion

While much has been learned from previous RPO missions, mishaps have still occurred in recent years. Fortunately, these incidents have been of much smaller magnitude compared to some of the more catastrophic events from earlier missions, but these mishaps are present nonetheless. Mishaps are inevitable, as these operations become increasingly complex and in more uncertain conditions. By systematically incorporating lessons learned from past operations, we can prevent the recurrence of previous mistakes, thereby minimizing unnecessary mishaps. This approach will ultimately enhance safety, improve cost-effectiveness, and ensure the continued success of future RPO missions.

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