CENTER FOR SPACE POLICY AND STRATEGY

MAY 2018

GETTING IN YOUR SPACE: LEARNING FROM PAST RENDEZVOUS AND PROXIMITY OPERATIONS

REBECCA REESMAN, ANDREW ROGERS

THE AEROSPACE CORPORATION

REBECCA REESMAN

Dr. Rebecca Reesman is a member of the technical staff in The Aerospace Corporation's Performance Modeling and Analysis Department, where she supports government customers in the national security community. Before joining Aerospace in 2017, she was an American Institute of Physics Congressional Fellow handling space, cybersecurity, and other technical issues for a member of Congress. Prior to the fellowship, she was a research scientist at the Center for Naval Analysis, providing technical and analytical support to the Department of Defense, with particular focus on developing and executing wargames. Reesman received her Ph.D. in physics from the Ohio State University and a bachelor's degree from Carnegie Mellon University.

ANDREW ROGERS

Dr. Andrew Rogers is a member of the technical staff in The Aerospace Corporation's Mission Analysis and Operations Department. His expertise is in relative motion astrodynamics, control theory, and space mission design. Rogers supports government customers in the areas of concept-of-operations development, orbital analysis, and small satellite technology development. Prior to joining Aerospace in 2016, Rogers received his Ph.D. in aerospace engineering and a bachelor of science in mechanical engineering from Virginia Polytechnic Institute and State University.

CONTRIBUTORS

The authors would like to acknowledge contributions from Greg Richardson, Josh Davis, Jose Guzman, George Pollock, Karen L. Jones, and James A. Vedda of The Aerospace Corporation.

ABOUT THE CENTER FOR SPACE POLICY AND STRATEGY

The Center for Space Policy and Strategy is dedicated to shaping the future by providing nonpartisan research and strategic analysis to decisionmakers. The Center is part of The Aerospace Corporation, a nonprofit organization that advises the government on complex space enterprise and systems engineering problems.

Contact us at www.aerospace.org/policy or policy@aero.org

Abstract

The continued proliferation of satellites has the potential to provide important capabilities in the civil, commercial, and military domains, but some of these activities may outpace needed comprehensive safety rules. The commercial sector's proposed "mega constellations" will create crowded orbit regimes. Coincident with crowded orbits, mission lifetime extension technologies such as on-orbit servicing will require internationally sanctioned rules for safe and transparent interactions. Using rules developed for the International Space Station and other examples, we draw on lessons learned and make recommendations for future rendezvous and proximity operations concepts. The space station provides a compelling case to study due to the wide number of international agencies that have worked together to create a safe and transparent environment for all stakeholders, whereas NASA DART and DARPA Orbital Express were important technology demonstrations that provided valuable lessons learned. All space sectors can benefit from established rules of the road that can be applied to a range of RPO scenarios. The United States has a long history of leadership in international spaceflight collaboration and is uniquely poised to have a lasting, positive influence on future policy decisions in this area.

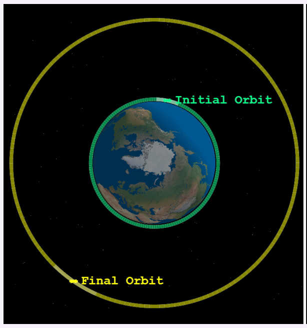
Introduction

The concept and practice of rendezvous and proximity operations (RPO) has been around for decades, though it has recently gained increased industry attention due to interest in activities such as on-orbit servicing. RPO generally refers to orbital maneuvers in which two spacecraft arrive at the same orbit and approach at a close distance. This rendezvous may or may not be followed by a docking procedure. The goal of this paper is to introduce a framework for developing rules of the road for RPO, so we begin by proposing a more formal definition (see insert, p. 3).

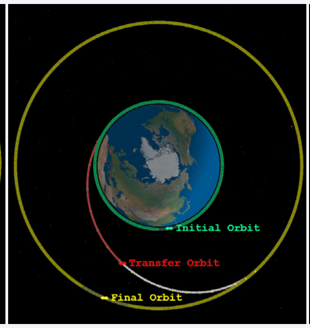
Emerging industries and technical capabilities such as on-orbit servicing, formation flying, and active debris removal make this a necessary topic of discussion. On-orbit servicing requires two satellites to be in the same orbit, in close proximity, and will typically include docking or grappling. Proposed refueling capabilities will require the transfer of fuel.[1,2] Similar capabilities are also used in the on-orbit assembly of sizeable platforms.

In the past two decades, numerous groups have proposed formation flying to collect large numbers of images of Earth through a distributed system of relatively small imaging satellites[3] or to improve the resiliency of space assets.[4] Formation flying describes the relative orbital motion of two or more satellites that are *near* each other. Satellites are considered near each other if the intersatellite distances and speeds are on the order of kilometers and meters per second, as opposed to thousands of kilometers and kilometers per second. Formation flying is a critical component of RPO, as it provides the framework by which to describe the relative motion of the vehicles.

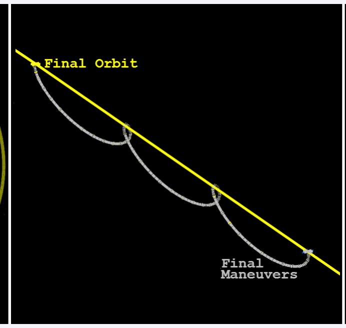
Rendezvous and Proximity Operations



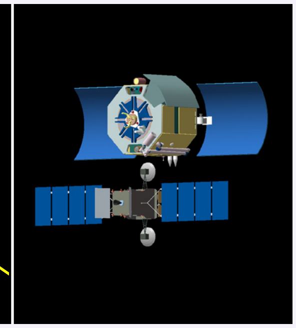
Initial configuration.



The transfer orbit, which effects rendezvous.



Example of a maneuver that corresponds to proximity operations.



Final configuration just before docking.

Definitions:

Rendezvous: matching the plane, altitude, and phasing of two (or more) satellites.

Proximity operations: two (or more) satellites in roughly the same orbit intentionally perform maneuvers to affect their relative states.

Docking: subset of proxmimity operations, where one satellite intentionally performs maneuvers to physically contact another satellite.

Cooperative RPO: information (position, velocity,health/status, etc.) transfer is two-way via crosslinks, ground contact, etc. Example: docking with the ISS.

Non-cooperative RPO: information transfer between vehicles is one-way only. Example: active debris removal.

Active debris removal is a proposed method for removing defunct satellites or loose spacecraft components before their orbits decay on their own.[5,6] It is relevant for orbital regimes where the orbit will not decay naturally (e.g., GEO) or where the orbital traffic is becoming congested or unsafe (e.g., certain altitudes of LEO). Active debris removal may require either cooperative or non-cooperative RPO.

A key distinction to make with respect to satellite RPO is the difference between cooperative and non-cooperative RPO. Cooperative RPO refers to missions where information transfer between the chaser vehicle (the vehicle performing rendezvous) and target vehicle is two-way; health, status, position, pointing, and other information are exchanged between the two vehicles. In other words, the target vehicle is actively supplying the chaser vehicle with information about its state via the navigation and communication systems. This two-way information transfer includes scenarios where the information passes to the ground first before arriving at the other vehicle. Rendezvous and docking with the International Space Station (ISS) is a notable example of this; both the ISS and visiting vehicle are communicating with each other during the process. Non-cooperative RPO refers to missions where the information transfer between the chaser and target vehicles is one-way only; the target vehicle will not actively provide information regarding its own state to the vehicle performing rendezvous. Efforts to service dead satellites or de-orbit orbital debris are examples of non-cooperative RPO.

NASA began rendezvous and docking events in the mid-1960s. In December 1965, Gemini VI and Gemini VII successfully completed a rendezvous of two spacecraft.[7] On March 16, 1966, Neil Armstrong and David Scott successfully docked the Gemini VIII spacecraft with the Agena target vehicle. This was the first ever linking of two spacecraft in Earth orbit.[8] The ability to catch up with already-orbiting spacecraft has been essential for ISS missions.

Current Efforts

Recognizing the need for agreed upon norms of behavior, DARPA established CONFERS, the Consortium for Execution of Rendezvous and Servicing Operations. The mission of CONFERS is to provide "a permanent, self-sustaining, and independent forum where industry could collaborate and engage with the U.S. Government in research about on-orbit servicing, as well as drive the creation of standards that servicing providers and clients would adopt."[9] The historical examples outlined in this paper and subsequent lessons learned can serve as guides for this effort.

Similarly, NASA and the ISS partner agencies have been collaborating to develop international deep-space interoperability standards. The purpose is "to enable industry and international entities to independently develop systems for deep space exploration that would be compatible aboard any spacecraft, irrelevant of the spacecraft developer."[10] The standards are divided into seven sections, including one on rendezvous,[11] which defines in substantial detail the different phases of RPO, regional operations and zones, decision points, and more.

Policy

No national or international policies explicitly regulate RPO. Article VI of the Outer Space Treaty of 1967 requires governments to provide authorization and continuing supervision of nontraditional activities, to include many proposed RPO activities. Article VII establishes that a party that launches or procures the launching of an object into outer space is liable for the object or its "component parts" in air or in outer space.[12] The Liability Convention of 1972 expands upon the principles of liability for damage caused by space objects introduced in Article VII of the Outer Space Treaty.[13]

On-orbit activities such as communication, spectrum usage, and debris mitigation strategies require approval from the Federal Communications Commission (FCC). A couple of commercial companies pioneering the on-orbit servicing market are working to gain regulatory approval in a relatively ad hoc manner. Orbital ATK's on-orbit servicing vehicle, Mission Extension Vehicle 1 (MEV-1), has received approval from the FCC to perform rendezvous, proximity operations, and docking with Intelsat-901, as a demonstration.[14]

Many RPO activities involve the use of cameras for situational awareness, specifically during docking. Generally, approval and licensing is needed from NOAA's Office of Commercial Remote Sensing and Regulatory Affairs if cameras are used to remotely image Earth; however, these RPO activities do not intend to explicitly image Earth. NOAA is on track to give non-Earth imaging approval to Orbital ATK's MEV-1.[14]

Similarly, satellite companies must deal with U.S. export controls, which are designed to prevent the spread of sensitive technologies to foreign actors. There are two sets of regulations: International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR). ITAR is under the jurisdiction of the Department of State and seeks to control items, information, or activities that could be used for military purposes. EAR is under the jurisdiction of the Department of Commerce and controls items and technologies that could be applicable to commercial or military use. RPO will involve a mix of ITAR and EAR technologies and services. Given that spacecraft rendezvous and docking frequently utilizes cameras for the terminal phase, any imagery collected during this phase of a servicing mission would fall under export control regulations.[15]

Precedent and Learning from Experience

When looking to develop guidelines for emerging technologies, it is constructive to draw upon historical examples. These notable cases have helped set a precedent and provide lessons learned. In the succeeding sections, the ISS and DARPA's Orbital Express are examined as key examples. The ISS provides unique insight into international cooperation of a large-scale effort. DARPA's Orbital Express, a demonstration of on-orbit servicing, validated the technical feasibility of many capabilities and highlights important considerations.

The ISS

The ISS includes a crew-habitable environment mounted on a space platform about the size of a football field, in low-Earth orbit (LEO). It is a cooperative effort among the United States, Russia, Canada, Japan, and the European Space Agency. This is not the first crew-inhabited space station, but it has been the most successful, having been continuously occupied for more than 17 years. It took more than a decade to assemble on-orbit, and still regularly receives supplies from both government and commercial entities.[16] Altogether, the ISS provides a unique example to learn from as future RPO activities develop.

The ISS legal framework consists of international cooperative agreements. The overarching document is the ISS Intergovernmental Agreement, which is signed by

14 governments and establishes the framework for the design, development, operation, and utilization of a permanently inhabited civil space station for peaceful purposes.[17] There are four memoranda of understanding between NASA and the partnering space agencies (ESA, CSA, Roscosmos, and JAXA) that describe the roles and responsibilities of each agency. And finally, there are bilateral arrangements that detail how to carry out specific components of the memoranda of understanding.[18]

The Russians were the last to be added, shortly after the breakup of the Soviet Union. In addition to the challenges of bringing in a new partner, NASA had to work within the bounds of export control regulations that needed to be updated to allow for the exchange of technical data with the Russians. This required lawyers from NASA's General Counsel and what is now NASA's Office of International and Interagency Relations to come up with an approach for export control for the ISS. Traditionally, export jurisdiction fell under the Department of State (via ITAR); however, in the 1980s and 1990s, there was a push toward reclassifying civil space assets as commercial products and putting them under the jurisdiction of the Department of Commerce. In the end, NASA was able to treat commercial work aboard the ISS as falling under the jurisdiction of the Department of Commerce. This included a special, bulk license to exchange information with the Russians.[19]

Knowing it would be necessary for different vehicles to interface with the ISS, whether in its construction or for the transportation of astronauts and supplies, a Space Station Program document (SSP 50235) was created.[20] If an entity commits to a contractual agreement with the ISS, they are required to comply with the ISS's technical specifications. The document defines performance and interface requirements for visiting vehicles, stating:

> The responsibility for developing space transportation systems and for making them technically and operationally compatible with the Space Station rests on the provider of the space transportation system. While attached to the ISS, or situated in a proximity of the station and requires ISS support, a [visiting vehicle] is considered to be part of the on-orbit Space Station and shall be compatible with the requirements of the System Specification for the International Space Station.[20]

To reduce the chance of collisions and to make the intent of nearby objects clear, the ISS has a nominal approach ellipsoid around it in space. This ellipsoid extends four kilometers both in front and behind the ISS path and two kilometers above, below, and beside it. The ISS also has defined a 200-meter "keep-out" zone; external vehicles are only permitted to fly in this zone with approval and within a defined approach corridor. There are exceptions to the 200-meter rule, such as missions to survey the ISS.[20]

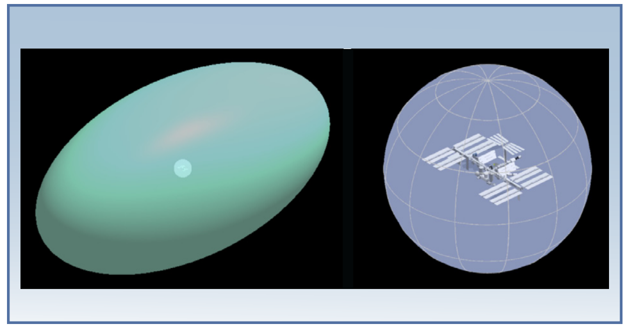


Figure 1: (Left) The space around the ISS has an approach ellipsoid measuring 4 km in the in-track direction, and 2 km each in the radial and cross-track directions. (Right) Immediately surrounding the ISS is a 200 m, spherical keep-out zone.

During final approach to the ISS, the visiting vehicle is generally required to stay at least 2 meters from any external structure. One primary exception is the docking interface with the Mobile Servicing System or Canadarm2. The visiting vehicle docking mechanism must enter a roughly 30 cm spherical capture volume at the docking point and remain there for up to two minutes to allow the Mobile Servicing System to capture and hold the spacecraft.[21]

The overarching philosophy for the ISS is that all operators ensure passive safety of the relative motion. Notionally, passive safety refers to a level of collision avoidance assurance in the event of a communication outage or other type of unanticipated event. Relative trajectories, in general, cannot be guaranteed to remain passively safe indefinitely. For the ISS, a collision avoidance maneuver must result in a trajectory that is passively safe for 24 hours, and once executed, must bring the visiting vehicle outside the approach ellipse within 90 minutes.[22]

Given the ISS's size and the proliferation of satellites in LEO, measures to avoid collisions are a necessity. In some instances, this can result in close approach agreements, such as with the Global Precipitation Measurement (GPM) mission, a joint U.S./Japanese project to observe global precipitation. The GPM and ISS fly in similar orbits, which led to the establishment of agreements to maintain situational awareness of the other's mission maneuver plans and to maintain current contact information for potential contingency situations. Additionally, the ISS routinely releases CubeSats, which led to CubeSat deployment agreements. The ISS plans these deployments months in advance and coordinates with GPM to minimize the risk of collisions.[23]

DARPA Orbital Express

Orbital Express was a DARPA demonstration of autonomous RPO that flew in 2007. Specifically, DARPA sought to validate the technical feasibility of autonomous RPO pertaining to on-orbit servicing.[24] Orbital Express consisted of two vehicles, the Autonomous Space Transfer and Robotic Orbiter (ASTRO) and the Next-generation Satellite/Commodity Spacecraft (NextSat/CSC). As part of the demonstrations, Orbital Express performed transfers of hydrazine fuel, a battery replacement, and a flight computer orbital replacement unit.

Orbital Express performed completely autonomous RPO from distances of up to 200 km to physical docking, manipulation, and undocking. To accomplish each stage of the demonstration, Orbital Express employed a suite of redundant sensors that included narrow field-of-view tracking sensors, wide field-of-view tracking sensors, infrared sensors, a laser rangefinder, and a laser-based tracking system. These sensors (used in different combinations depending on the stage of the demo) collectively provided complete relative trajectory and attitude knowledge for ASTRO.

During a planned proximity operation, there was a major failure in the sensor computer onboard ASTRO, nearly ending the demonstration early. The anomaly required significant effort on the part of the contractor and ground operators to develop solutions to circumvent the problem. The anomaly caused the navigation subsystem to reject new information. This caused previous navigation information, which intrinsically had error in it, to compound upon itself, further degrading the navigation fix. Consequently, ASTRO and NextSat had poor knowledge of their relative position, velocity, and attitude, making RPO hazardous.

A NASA postmortem technical report provided detailed findings, observations, lessons learned, and recommendations based on the Orbital Express anomaly and recovery.[25] They are broadly partitioned into three categories:

1. Navigation/flight software/sensor considerations
2. Preflight planning and vehicle testing considerations
3. Ground operation/ mission control considerations

Most striking among the various findings, lessons learned, and recommendations is the impact the navigation software had on the mission performance. A key issue with space-based navigation is that the precise state of a system (such as the relative position, velocity, and orientation of two spacecraft performing RPO) is rarely, if ever, known perfectly. The intrinsic errors in relative navigation require redundant, robust navigation systems with highly trained ground operators standing by during critical moments of the mission, such as docking.

A key issue with space-based navigation is that the precise state of a system is rarely, if ever, known perfectly.…

Another class of results that can inform future missions involves the importance of extensive preflight validation and verification of flight software. Key among these findings is that exquisite, high-fidelity simulation and testing should be performed as an integral part of the system requirements verification. Recommended simulation and testing addresses the fidelity with which the initial simulations of a system are performed, as well as the transition from computer modeling to hardware-in-the-loop testing. Preflight hardware-in-the-loop testing should be as realistic as possible, including the stress-testing on the navigation suite. During the development of Orbital Express, this level of fidelity was not available to the mission designers subject to time and budget constraints; however, as technology and testing systems have improved, this capability may be more readily available now.

Key to future RPO missions is the identification of varying levels of autonomy and authority. To construct these varying levels for Orbital Express, the mission planners made the following definitions:

1. **Authority to proceed (ATP)** refers to a step in the sequence of events in an activity where the spacecraft would stop operations and wait for ground approval to proceed. ATP was further partitioned into level 1 (minor events) and level 2 (major events).
2. **Authority** refers to ground operators selecting which ATPs to enforce. Authority was broken down into three more levels: stop at both ATP 1 and ATP 2; stop at ATP 2 only; and do not stop at ATP.
3. **Autonomy** refers to the combinations of activities and the enforcement of their associated authority levels (e.g., for a given sequence of events, how much authority did Orbital Express have during that sequence).

Using these definitions, the mission planners created seven different categories encompassing a range of autonomy levels; they ranged from level 0, ground adjudication of every single action on orbit, to level 6, in which the spacecraft performed multiple sequences of activities at authority level 3, potentially without any ground contact.

Other Examples

In 2005, NASA deployed the Demonstration of Autonomous Rendezvous Technology (DART) spacecraft, which was designed to autonomously rendezvous with and maneuver around a designated communications satellite. DART performed as planned during the first eight hours of the demonstration, but then started using more propellant than expected. At 11 hours into the 24-hour mission, DART detected that it was out of propellant and initiated its retirement sequence and ended up colliding with the communications satellite it was intending to maneuver around. A subsequent mishap report found that incorrect navigational data onboard DART caused higher-than-expected propellant consumption. The mishap investigation board determined that inadequate guidance, navigation, and control software development processes played a major role, in addition to a poorly managed risk posture and associated systems engineering.[26]

NASA's space shuttle program included a significant number of RPO exercises; from June 1983 to August 2005, 57 shuttle missions included at least one RPO objective. Autonomous RPO capability was established as a system requirement in 1974. It is interesting to note that this capability actually had humans in the loop, and referred to the *astronauts* executing a series of commands without positive mission control confirmation. This is a significant departure from autonomous RPO as defined in later demonstrations such as DART and Orbital Express. The limited onboard computing capability of the mid-1970s made autonomous maneuver planning a difficult requirement to meet.

Despite the large number of RPO exercises performed, the actual execution of these operations varied significantly. This variation between missions required extensive contingency analyses, making RPO anything but routine. The mission profiles enabled by RPO for the shuttle included various technology demonstrations, satellite servicing, deployment and retrieval of scientific payloads, retrieval of satellites for return to Earth, and docking with the Russian Mir space station and ISS.

What Can We Learn?

The preceding section outlined important RPO examples from which a precedent has (potentially) been set and lessons learned. Important and common threads are outlined below.

Agreements and Specifications

Given its size, purpose, and international underpinning, the ISS is a unique asset that can require visiting vehicles to conform to its specifications. As commercial servicing capabilities proliferate, they will be able to offer services to assets that are compatible with them. However, it is clearly in their interest to design interoperable servicing capabilities in conjunction with potential customers. Ultimately, consensus-based standards should inform how RPO interactions are defined. The ISS partners have a wealth of knowledge and experience and encompass a wide-range of stakeholders that should be utilized. Furthermore, the ISS's multiple agreements are necessary to outline the roles and responsibilities as well as to detail technical specifications.

This is a common approach for government-to-government collaborations.

Commercial companies also operate via contractual agreements. As an example, Orbital ATK has agreements with Intelsat to service a couple of their satellites.[27] Initial efforts to conceptualize and craft what this type of contractual and operational relationship could and should look like will set a precedent for this type of service. Important considerations include:

- **Regulatory approval.** Both the servicer and the servicee need licensing approval from the appropriate government agencies.
- **Export controls.** Observance of ITAR or EAR rules is required when dealing with foreign clients; this includes making sure images and technical specifications are only shared with the necessary people.
- **Autonomy.** The automated RPO processes, including authority-approval points, must be jointly understood and technically compatible.
- **Safety.** Passive safety protocols must be in place to avoid collisions.
- **Contingency plans.** Communication and recovery protocols should be established for response to anomalies and mishaps.
- **Quality control.** The owners and operators of the satellite being serviced may prefer a servicing satellite to surpass a certain fault-tolerance threshold.

Ground Operations

Ground support has been a critical component of every space mission to date. As autonomous RPO becomes more commonplace, the important role played by ground support will change, but will certainly endure.

During the shuttle's RPO demonstrations, the ground systems generated a significant number of the maneuver plans; "autonomous" maneuvers were those planned onboard. Ground systems are inherently more capable of onerous computing tasks, since they are not typically as severely constrained by size, weight, and power.

Orbital Express was a demonstration of autonomous RPO, yet the ground operators played a critical role in the success of the mission. Were it not for the ground team's timely intervention during the anomaly event, the system would have suffered severely degraded performance or even damage to the vehicles. In future RPO missions—even autonomous ones—ground operations will likely be an important component. Additionally, Orbital Express defined the levels of autonomy in the system by the amount of ground intervention present in a mission sequence.

Flight Navigation Software

A common theme among the shuttle RPO, DART, and Orbital Express demonstrations is the vital role of software. Future RPO software must have extensive autonomous fault management and redundancy to provide gapless support through the duration of an RPO activity.

While the shuttle had a requirement for autonomous RPO (as defined in 1974), the limited computing power available made this a difficult requirement to satisfy. Additionally, during a software requirements overhaul in 1976, the computation of burns not supported by onboard navigation was moved to the ground control.

Future RPO software must have extensive autonomous fault management and redundancy to provide gapless support…

Flight software—and more specifically, the interaction between the onboard estimate of the vehicle's state and the output from the navigation sensors—played a critical role in DART's inability to achieve its mission objectives. While the root cause of the software malfunction was eventually determined, the failure of DART emphasized the importance of highly detailed, thorough software-in-the-loop and hardware-in-the-loop testing for RPO flight software. Additionally, the mishap investigation board noted that poor documentation and software engineering yielded numerous errors that were found after the fact. Chief among the recommendations to NASA was that the simulations and mathematical models used to validate flight software be validated to the same level as the actual flight software.

The interaction between software and sensor inputs was again a prominent cause of operational difficulties for

Orbital Express. Recalling that, subject to budget and schedule constraints, an exquisite, high-fidelity hardware-in-the-loop simulation was not available, one may draw the conclusion that future RPO missions should allow budget and schedule margins during the requirements definition and verification phases. The up-front investment in validating and verifying the navigation and flight software has the potential to buy down a major risk component. Consequently, if made into an industry standard practice, this could dramatically improve mission assurance and the likelihood that future RPO missions can be safely integrated into existing space systems.

Collision Avoidance and Relative Navigation

Navigation and flight software also play a critical role in collision avoidance and relative navigation. We make the distinction between two types of collision avoidance, co-orbital and non-co-orbital. An example of the latter is the flight safety planning between the ISS and GPM. The two satellites are in different planes at the same altitude, which means that a collision between the ISS and GPM would have a high terminal velocity, much like the Iridium/Kosmos event of 2009, which resulted in a catastrophic debris event. Co-orbital collision avoidance refers to the prevention of two satellites bumping into each other during proximity flight. A co-orbital collision would resemble the 1997 Progress M-34/Mir collision, where the collision caused some structural damage to Mir that raised the question of crew habitability, but no notable debris was released.

For RPO, co-orbital collision avoidance and relative navigation are a function of both the flight software and fault management subsystems. Input from the navigation suite provides information needed to determine the relative positions and velocities of the individual vehicles. Information from relative navigation feeds into collision avoidance; if each vehicle knows where the other is, they may be able to discern where *not* to go. The ISS provides a great example of this with the requirement that no visiting vehicle shall come within two meters of any surface of the ISS. Satisfaction of this requirement mandates that the visiting vehicle have precision knowledge of the relative position and velocity, which in turn is used to avoid collision.

Orbital Express demonstrated the important role that fault management plays in collision avoidance. The navigation system failure precluded Orbital Express from maintaining the requisite position and velocity knowledge, which raised the question of whether ASTRO would collide with NextSat. A collision was avoided through meticulous ground intervention; however, a fully autonomous RPO system will require a significant amount of fault management to handle the myriad ways system errors can occur. System-level go/no-go decisions should be an integral part of the flight software so that in the event of a sensor malfunction leading to degraded relative navigation, the system can respond appropriately, even in the absence of positive ground contact.

Autonomy

In 1974, as the shuttle was being developed, autonomous operations referred to the astronauts performing maneuver computations with little ground intervention. Thirty years later, autonomous operations referred to a robotic satellite such as DART performing its own maneuver computations with little or no human involvement. Orbital Express extended the concept of autonomous operations further by introducing different levels of autonomy.

Truly autonomous RPO requires input from a navigation suite, a robust method of processing these inputs and turning them into commands, and a defined set of flight-safety rules with support for various fault management CONOPS. Truly autonomous RPO is analogous to the highest level of autonomy demonstrated by Orbital Express—namely, no ground ATP for multiple activity sequences.

Conclusion

Past and present RPO activity offers lessons learned as we look to future on-orbit activities. Examining the ISS and DARPA's Orbital Express as well as NASA's DART and space shuttle, highlighted key considerations: the importance of ground operations, flight navigation software, collision avoidance and relative navigation, autonomy, and agreements and specifications. Guided by these considerations, the United States should facilitate the development of industry consensus standards for how RPO is conducted. The standards and norms of behavior should be dynamic to adapt to new lessons learned and future ideas of on-orbit activities.

Establishing defined behavior for RPO and gaining industry-wide concurrence will help standardize what constitutes safe flight. For example, this may include definitions of keep-out zones, the appropriate level of ground intervention for various operations, and notification procedures in the event of mishaps. Additionally, standardizing how RPO flight software is tested and validated will help build confidence across both the service provider and customer sides of the industry.

The lack of specific policy or guidance for RPO has meant that pioneering companies navigate a slow and ad hoc process to gain approval. A regulatory framework that is transparent and predictable is needed. The framework should support the use of consensus-driven standards and norms of behavior that will be crucial to safe and effective operations. It will need to address non-Earth imaging, export control issues, and notification for on-orbit flight plans.

This is an exciting time for the space community, as many commercial companies are planning new and innovative on-orbit activities that will require RPO. Consistency and predictability in on-orbit RPO will create a safer environment for all stakeholders.

References

[1] "Restore-L Robotic Servicing Mission," NASA; https://sspd.gsfc.nasa.gov/restore-l.html.

[2] "Robotic Servicing of Geosynchronous Satellites," DARPA; https://www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites.

[3] Burns et al. "TechSat-21: Formation Design, Control, and Simulation, 2000.

[4] Brown and Eremenko, "The Value Proposition for Fractionated Space Architectures," 2006.

[5] "Brane Craft Proposal Wins 2017 NASA Innovative Advanced Concepts Phase II Award, The Aerospace Corporation; http://www.aerospace.org/news/highlights/brane-craft-proposal-wins-2017-nasa-innovative-advanced-concepts-phase-ii-award/.

[6] "Active Debris Removal: Recent Progress and Current Trends." C. Bonnal, J. Ruault, M. Desjean. *Acta Astronautica*, Vol. 85, pp. 51–60, 2013.

[7] https://www.nasa.gov/multimedia/imagegallery/image_feature_709.html.

[8] https://www.nasa.gov/image-feature/march-16-1966-geminis-first-docking-of-two-spacecraft-in-earth-orbit.

[9] https://www.darpa.mil/news-events/2017-10-04.

[10] https://www.internationaldeepspacestandards.com.

[11] International Rendezvous System Interoperability Standards (IRSIS) Draft C, February 2018; https://www.internationaldeepspacestandards.com/wp-content/uploads/sites/45/2018/02/Rendezvous_020918_R1.pdf.

[12] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, January 27, 1967.

[13] Convention on International Liability for Damage Caused by Space Objects, September 1972; http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html.

[14] Henry, Caleb, "FCC begins approval of Orbital ATK satellite-servicing mission for Intelsat-901," *Space News*, 2017; http://spacenews.com/fcc-begins-approval-of-orbital-atk-satellite-servicing-mission-for-intelsat-901/

[15] *Introduction to U.S. Export Controls for the Commercial Space Industry*, 2nd Edition, 2017); http://www.space.commerce.gov/wp-content/uploads/2017-export-controls-guidebook.pdf.

[16] Visiting Vehicle Launches, Arrivals and Departures https://www.nasa.gov/feature/visiting-vehicle-launches-arrivals-and-departures

[17] Agreement between the United States of America and Other governments; https://www.state.gov/documents/organization/107683.pdf.

[18] ESA website about ISS; http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/International_Space_Station_legal_framework.

[19] NASA Johnson Space Center Oral History Project, Melanie Saunders; https://www.jsc.nasa.gov/history/oral_histories/ISS/SaundersM/saundersm.htm.

[20] Interface Definition Document (IDD) for International Space Station (ISS) Visiting Vehicles (VVs), International Space Station Program Office, SSP 50235, Feb. 10, 2000.

[21] "Designing and Validating Proximity Operations Rendezvous and Approach Trajectories for the Cygnus Mission," P. Miotto et al., AIAA Guidance, Navigation, and Control Conference, August 2010.

[22] "ISS Rendezvous, Proximity Operations, Docking, and Berthing Considerations," A. DuPont, NASA/JSC/Aeroscience and Flight Mechanics Division, 2015.

[23] Pawloski, J. et al., "Global Precipitation Measurement (GPM) and International space Station (ISS) Coordination for CubeSat Deployments to Minimize Collision Risk," Advanced Maui Optical and Space Surveillance Technologies conferences, 2016.

[24] Orbital Express Factsheet; http://archive.darpa.mil/orbitalexpress/pdf/oe_fact_sheet_final.pdf.

[25] Dennehy, C. and Carpenter, J., "A Summary of the Rendezvous, Proximity Operations, Docking, and Undocking (RPODU) Lessons Learned from the Defense Advanced Research Project Agency (DARPA) Orbital Express (OE) Demonstration System Mission," NASA/TM-20110217088, April 2011.

[26] Overview of the DART Mishap Investigation Results; https://www.nasa.gov/pdf/148072main_DART_mishap_overview.pdf.

[27] http://spacenews.com/orbital-atk-lands-second-intelsat-satellite-servicing-deal/.