CONFERS SATELLITE SERVICING SAFETY FRAMEWORK TECHNICAL AND OPERATIONAL GUIDANCE DOCUMENT

DRAFT

APRIL 2018

CONFERS Satellite Servicing Safety Framework

Technical and Operational Guidance Document

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SECTION I: PURPOSE AND SCOPE

The purpose of this document is to serve as a point of departure for guidance for the conduct of commercial on-orbit rendezvous and proximity operations (RPO), capture, and robotic servicing operations. Subject Matter Experts in RPO, robotics, and on-orbit servicing from Government organizations including DARPA and NASA contributed to the information provided in this document. The lessons learned and recommendations are intended to assist future satellite servicing mission planners to ensure that these operations will not interfere with other space operations and will not create persistent hazards that could adversely impact other missions in the orbital environment. To begin, this document introduces a **common lexicon and structure (ontology)** in Section II to facilitate clear communications between all satellite servicing stakeholders. Throughout the remainder of the document, it **provides an established set of informed initial and boundary conditions to construct and evolve relevant best practices, guidelines, and standards**. This guidance is based on lessons learned from historical and current government missions; however, these are used as examples that satisfy safety concerns for various phases of a satellite servicing mission, not as a prescription that must be rigidly followed.

The sequence of activities required to accomplish on-orbit satellite servicing has numerous steps of varying complexity (see Fig. 1), each with unique operational and risk management considerations. Section III provides detailed satellite design considerations for rendezvous and proximity operations (RPO) and servicing systems, and outlines unique mission planning considerations. Because some of the risks and risk mitigation measures associated with each activity are unique, they are best analyzed within the context of each of the phases of a servicing mission, and are presented in Section IV. The document concludes with an outline of recommended documents that a satellite servicing organization should consider creating in order to aid in the prevention and recovery of on-orbit anomalies, and to help demonstrate mission safety readiness to costumers and compliance with applicable licensing requirements.

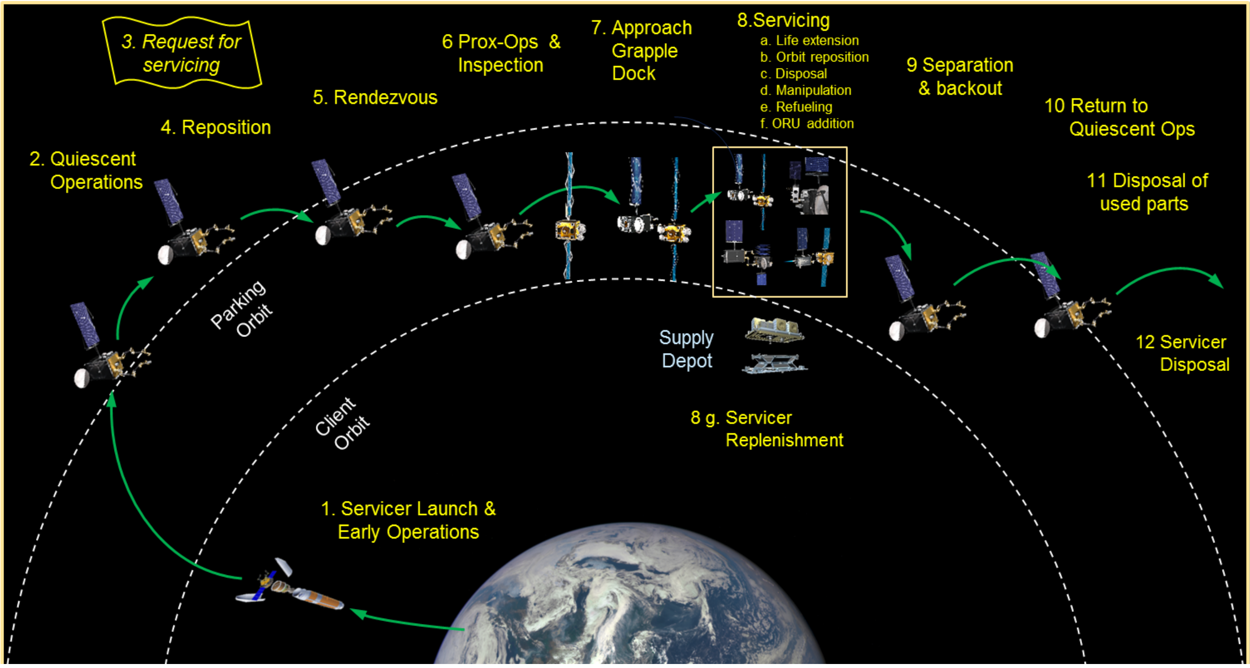


Figure 1. Satellite Servicing Mission Operations

SECTION II: LEXICON

Term	Definition
Assemble	To connect individual elements together forming a larger entity.
Astrodynamics	Motion of spacecraft under the influences of Earth's gravity and its own power.
Automated	Space vehicle **executes** a pre-defined mission plan and makes decisions based on a pre-defined set of situations envisioned and coded by the designers and implementers of the system. The system senses a situation, decides which of its pre-coded situations matches it, or most closely matches, and then takes a pre-defined action formulated by the designs. If presented with an unanticipated situation, most automatic systems safe the situation via fault detection and correction and if unable to get back on task, defer to ground control for guidance or action. *(Asa Clark Keith III RPO Handbook, 2013)*
Autonomous	Space vehicle **develops** and executes a mission plan independently. When presented with a new situation, the system invokes reasoning capabilities incorporated by designers and implementers, considers constraints, limitations, capabilities, and a set of objectives. The system puts together a response from a set of responses or, more typically, a set of fragments of a response. The system then monitors the outcomes of applying its response and adjusts the response by deleting some fragments and adding others until the overall response satisfies a set of objectives and constraints. *(Asa Clark Keith III RPO Handbook, 2013)*
Berth	Attachment of a Servicer Satellite to a Client Satellite via a fixed mount on the Servicer. Accomplished when no common connection interfaces for docking exist on the servicer and client.
Client Satellite	The satellite being assisted by the servicer.
Co-Elliptical	When the Client and Servicer satellites' orbit eccentricity and argument of perigee are equal. This is an orbit shaping process where matching the shape of the orbits is sought. This involves eccentricity and argument of perigee and can also result in matching of semi-major axis. *(Asa Clark Keith III)*
Co-Orbital	When the Client and Servicer satellites' orbit elements are matched with True Anomaly set to a difference to achieve station keeping at some standoff distance. If true anomaly is matched, the two space vehicles are secured together (e.g., docked, grappled, etc.). The difference between the true anomaly of the two satellites, an angular measurement, is the relative phase of the two space vehicles. *(Asa Clark Keith III)*
Cooperative Client	Client satellite that may contain on-board navigational aids such as fiducials, retroreflectors, or other types of navigational target boards intended to assist the servicer in acquisition, track, rendezvous and docking. The client operations personnel coordinate servicing operations with the servicer and assist by performing required maneuvers, attitude adjustments, and disabling of the ADCS during servicing operations.

Term	Definition
Delta-V	Expenditure of propellant which causes a change in the velocity vector of the satellite.
Dock	The connection of servicer to client without use of a robotic arm, accomplished via standard connection interfaces specifically implemented to accommodate planned serving activities.
Drifting Natural Motion Circumnavigation	A Drifting Natural Motion Circumnavigation has an orbit period that is not the same as the client (semi-major axis or mean motion being different). The In-Track drift is the result of the center of the natural motion circumnavigation (NMC) ellipse being above or below the target mean altitude. Cross-track or lateral motion can be achieved by cross track maneuver. When drifting, NMC is established with a different period than the target and a cross track motion, a "cork screw" or "spiral" path results.
Dynamic Station Keeping (DSK)	Maneuvers executed to force a satellite to maintain a relative position to a client, or at a point in space, where the position and velocity do not adhere to natural orbit motion and thus require thrusting. DSK essentially negates or "fights" the natural orbit motion to maintain a relative position. DSK is most often employed to maintain a relative position expressed in the Radial, In-Track and Cross-Track frame relative to the target, for example to keep a satellite between the target and a ground site.
Forced Motion Circumnavigation (FMC)	A series of maneuvers enabling a satellite to follow a path around a target to meet mission requirements. FMC typically follows a series of segments where a maneuver occurs to proceed onto the next segment. Unlike the "natural" orbital motion of an NMC, the FMC essentially "powers" its way from waypoint to waypoint, sometimes leveraging natural motion and other times "battling" it to fly the FMC path.
Geostationary Earth Orbit	A circular geosynchronous Earth orbit with 0° inclination, such that the satellite appears motionless to an Earth-based observer.
Geosynchronous Earth Orbit	An inclined earth orbit with an orbital period that is equal to the sidereal period of the Earth.
Intimate Inspection	Collection of imagery of client's components not obtainable via remote inspection (e.g., under blankets, behind panels, etc.)
Legacy Client	A satellite not designed for servicing.
Low Earth Orbit	An earth orbit with an orbit period of less than 225 minutes (or altitude less than 2000 km).
Natural Motion Circumnavigation (NMC)	A maneuver to place a spacecraft into an elliptical path around a client or point in space in the client's RIC frame.. Cross-track motion can be added to an NMC with a cross-track Delta-V executed concurrent with the radial maneuver. The period of the NMC matches the target's orbit period. For nearly circular client orbits, the projection of the NMC ellipse onto the client's orbit plane has a 1:2 minor to major axis ratio.

Term	Definition
Non-cooperative Client	Client satellite that does not contain on-board navigational aids such as fiducials, retroreflectors, or other types of navigational target boards intended to assist the servicer in acquisition, track, rendezvous and docking.
Orbital Elements	The six numerical parameters that define an orbit and satellite position in the orbit: semi-major axis (Size/Km); eccentricity (shape/unitless); inclination (tilt/degrees); right ascension of the ascending node (RAAN) (twist/degrees); argument of perigee (position of perigee/degrees); and true anomaly (position of satellite relative to perigee/degrees). These classical orbital elements have an epoch time and date associated with them that indicates the date and time the orbital elements are valid.
Orbit Period	The time elapsing between two consecutive passages of a satellite through a characteristic point on its orbit.
Passively Safe	Trajectory where no action is required to prevent collision for a specified future time period.
Proximity Operations	Series of orbital maneuvers executed to place and maintain a spacecraft in the vicinity of another spacecraft on a planned path relative to the client for a specific time duration to accomplish mission objectives.
Refuel	Transfer of propellant (fuel, oxidizer) and any necessary support capability (e.g., pressurant) from servicer to client.
Relative Motion Coordinate Frame	An orthogonal coordinate reference framework to describe a client's motion relative to the satellite observing it. This frame is often referred to as the “RIC” frame, where R is in the radial direction and zenith is positive; C is obtained from the cross- product of R with the velocity vector (C is therefore normal to the orbit plane), and I is obtained from the cross product of C with R (I is in the general direction of the instantaneous velocity vector, but only aligned with that vector for circular orbits).
Relocate	To modify the orbit of a client satellite after docking/grappling/berthing.
Remote Inspection	Collection of imagery (visual imaging system-vis, infrared Red-IR, Light Detection and Ranging-LIDAR) via fly around of client—no contact.
Rendezvous	Process wherein two spacecraft are intentionally brought close together through a series of orbital maneuvers at a planned time and place for a short duration. The rendezvous phase begins when the servicer initiates maneuvers to match its orbit plane with the client’s, and continues through any co-elliptic transfer maneuvers necessary to reduce altitude differences and decrease in-track phasing. The rendezvous phase transitions to proximity operations once the client’s bearing and range can be obtained from the servicer’s RPO sensor suite.
Repair	Re-establish functionality of a defective, degraded, damaged client satellite system/sub-system (e.g., correct a solar array failure by freeing it for deployment).

Term	Definition
Replace	Re-establish functionality of a defective, degraded or damaged client satellite system/sub-system by removal of the faulty component and installation of a new component.
Safety Ellipse	Natural periodic relative motion trajectories in which the servicer satellite will fly around the client satellite in an elliptical path centered on the client but with a slightly different orbital eccentricity and inclination. This allows the servicer to naturally circumnavigate the client once per orbit without crossing the client's velocity direction, making the relative motion passively safe. A generalization of this centered safety ellipse is an offset safety ellipse, wherein the center of the ellipse is offset from the client along the in-track direction by a ground-defined phasing angle. The offset ellipse offers an attractive station-keeping option during proximity operations, providing a variable survey view of the client without imposing on the client's RF or optical mission.
Servicer Satellite	Vehicle performing the servicing action.
Situational Awareness Data	Information that can be obtained from ground-based knowledge of each spacecraft and/or from the on-board RPO sensor suite and navigation filter state estimates. Can include Range, bearing, and pose measurements; bearing angles, range, and attitude measurements (or estimates).
Teleoperation	Control of a robotic system via real-time or near real-time control, from the ground.

SECTION III: SATELLITE DESIGN AND MISSION ASSURANCE

This section discusses design, fabrication, test, and mission planning considerations for a servicing satellite and potential risk reduction techniques. This section focuses on the “what and the why” of these risks and provides examples of how previous servicing and RPO missions have addressed these risks without prescribing specific requirements. Satellite servicing operators will likely be required to demonstrate the effectiveness of their risk mitigation approaches via analysis and documentation. Artifacts that can be used to demonstrate compliance are discussed in Section V.

A. Servicing Satellite Design Considerations

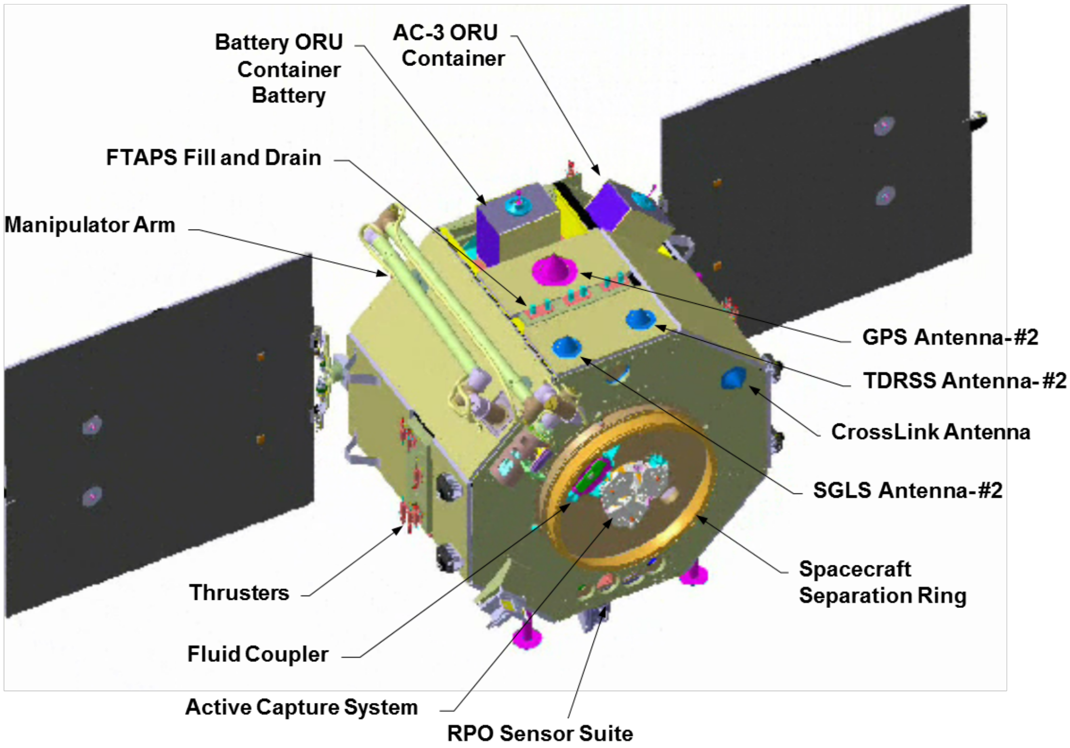


Figure 2. Autonomous Space Transfer and Robotic Orbiter (ASTRO) Servicer from DARPA Orbital Express Demonstration Highlighting Satellite Subsystems Required for Servicing.

(Figure from “Orbital Express: A New Chapter In Space”, Tracey M. Espero, The Boeing Company)

Sensor Suite Design and Calibration

As part of the system design, the guidance and navigation sensor suite needs to provide sufficient, accurate information to safely operate through, and transition between, all mission phases defined in Section I. The sensor suite, along with the calibration operations and processing of the output data, is ultimately responsible for providing sufficient relative orbit position and velocity, as well as the relative orientation of the servicer to the client to safely perform all mission phases.

While there are a variety of ground, on-orbit, and on-board sensors useful for RPO missions in general, and servicing missions in particular, the use of ground tracking and GPS assets typically provide utility only for relative ranges between the servicer and the client of several kilometers and greater. Previous RPO demonstrations have highlighted the utility of having a mid to long range (~10s km) wide field-of-view capability in the RPO sensor suite to acquire and track the client satellite. Relying on ephemeris updates from the ground to identify the client satellite's position and provide pointing information for a narrow FOV sensor on the servicer has proved to be problematic on previous demonstrations. Readily available satellite ephemeris is often 24 hours old or greater, and since the uncertainty in the ephemeris grows with time, 24+ hour old ephemeris is often not accurate enough to provide usable pointing data for a narrow field of view sensor. Attempting to locate the client satellite by scanning a narrow field of view sensor is time consuming and likely to disrupt mission operations timelines, force ad hoc replanning, etc. It is considered a best practice for the RPO sensor suite to include wide / medium field of view sensors to maintain custody of the client satellite during acquisition, track and rendezvous, and provide pointing information to narrow field of view sensors without relying on data provided from external sources.

For close proximity operations from a kilometer down to meters (necessary for close inspection and grapple missions), ground tracking and GPS must be augmented (and ultimately replaced) by on-board active and passive relative navigation sensors. Previous RPO missions have highlighted the challenges in the use of visible-only sensors with on-orbit lighting conditions and in accurately determining range to the client, and the trickle down guidance, navigation, and control (GNC) challenges of maintaining sensor lock on the client. Hence, significant constraints on operations and timelines were imposed when using solely visible cameras for RPO and servicing missions. Thermal sensors (such as microbolometers) typically provide smaller solar exclusion zones and thus enable a larger set of viewing angles over visible-only sensors; nevertheless, they are generally not useful if the Sun is within the field of view of the camera, and their resolution does not currently match that of visible cameras. The primary advantage of both visible and thermal cameras for RPO missions is their natural passivity, with no active energy irradiating the client spacecraft. Previous missions have demonstrated that relying solely on passive visions systems is challenging due to the widely varying lighting conditions experienced during RPO and the difficulties they present in determining and maintaining accurate state knowledge of the client satellite.

For RPO missions requiring close proximity and servicing operations to non-cooperative clients (clients with no on-board navigational aids such as fiducials, retroreflectors, or other types of navigational target boards) active sensors offer a number of advantages. There are currently two options in this category: flash and scanning LIDARs. Flash LIDARS provide a dispersed laser interrogation of the client and a near-instantaneous (i.e., 30 Hz update rate) 3D point cloud obtained on a pixelated time-of-flight detector, useful for determining 6 Degree of Freedom (DoF) pose (relative position and orientation) of the client. Some ranging and spatial accuracy tends to be lost in the point cloud due to the wide dispersion of the laser source and the detector pixel format, but their high-speed video update rate is very attractive and these sensors have been successfully operated on-orbit in recent years. In contrast, scanning LIDARs provide focused narrow-beam laser interrogation of the client, and coverage is obtained through a high-speed scanning mechanism. These sensors provide high range and spatial resolution across the scanning field of regard due to the precision pointing of the narrow beam and the optical time-of-flight photodetector. However, because of the scanning effect required, current operational scanners tend to be limited to an update rate of about 5 Hz for 6-DOF pose. Like their flash counterparts, scanning LIDARs used for client pose estimation have also been successfully operated on-orbit in recent years. Compared to passive optical sensors, LIDARs enable a greater operating window of on-orbit lighting conditions, making them very attractive for close proximity operations and servicing missions. Because of the active nature of laser-based sensors, a concern that is fundamental to these LIDARs (especially the narrow-beam scanning LIDARs) is the energy irradiating any optically-sensitive components resident on the client spacecraft (such as star trackers). This tends to be less of a concern for flash LIDARS than scanning LIDARs, due to the narrow focused energy of the latter. To mitigate this concern, scan profiles, waypoint survey stations, and approach corridors need to be carefully selected to avoid irradiation within fields of view of optical instruments on the client.

Guidance, Navigation, and Control (GN&C) System

The ability to perform RPO requires satellite knowledge of relative state. The GN&C for a servicer must be able to process this data and calculate the appropriate satellite actions in near real time. Furthermore, the servicer's on-board navigation filter should be able to fuse all types of measurements and at different input rates, including ground-based orbit knowledge of each satellite, GPS measurements from one or both satellites (if available), and on-board relative bearing, range, and orientation measurements from passive cameras and active sensors. The GN&C system should be robust to single point failure or data interrupts, be able to simultaneously interrogate and compare similar measurements from different types of sensors for potential sensor fault assessment, and be able to rapidly fuse or switch between RPO sensor inputs. For example, differences in target vehicle reflectivity (specular spikes) can cause difficulties in the navigation filter as interpretation of inputs from different sensors leads to drastically different guidance outputs. Estimation and controller errors should be accounted for in the safety of flight analysis for each of the phases (approach, rendezvous, proximity, servicing, proximity, egress, and back to approach).

A demonstrated best practice is to implement a rigorous 6-DOF robotics laboratory test process during system design and development. Lab testing should include use of representative sensors with flight processors and algorithms, and should test varying approach trajectories and lighting conditions between the servicer and client spacecraft.

Autonomous Fault Detection and System Safety Software Design Philosophies

There are many phases in a satellite servicing mission where a temporary hardware and/or software failure can create risk of damage to the servicer or the client. These phases include approach, grapple and dock phases where response times to avoid creating hazards can be very short and/or approximate modeling of the non-linearities while operating in close proximity may have missed some critical effect. To ensure that safety is maintained, it is recommended that autonomous fault detection and response mechanisms across the system design be implemented to put the servicer in a well-defined, "safe" configuration when a fault is detected to prevent damage to the servicer and client while the mission operations analyzes the fault and creates a recovery plan. The design of the system may not only include on-board detection and response capabilities, but also may rely on positive control through continuous communications with the satellite operations center during some phases of the mission, where servicer operations are halted at pre-defined points and only continue after ground commanded authority to proceed to the next phase. Specific considerations should be made where full redundancy is not designed into the system and recovery time is required from a fault to reboot or reconfigure the system to either abort operations or continue safely. In the worst case for an active client (not a dead / disposing satellite) where the servicer is in an unrecoverable or unknown state, the system solution should address how communication with the client's operations center will be conducted to coordinate execution of an orbit change to the client in order to ensure safety of both satellites.

It is recommended that the design of autonomous fault detection and response in light of timelines and available positive control by the ground monitoring satellite operations center be thoroughly reviewed prior to launch. The design and review should provide confidence in the RPO and docking systems, and an ability to actively disengage from close proximity / servicing operations through all credible fault scenarios.

Many times the analysis used for autonomous fault detection and response tree contains many elements that are found in Failure Modes & Effects Analysis (FMEA). Documentation of this analysis would be a useful tool for demonstrating mission assurance in an external review.

Electrostatic Discharge (ESD) Mitigation Mechanisms

Satellites acquire surface charges while exposed to the space environment. More charging occurs in GEO than LEO. A servicer and the client spacecraft will have different surface charges, so the risk of ESD when two satellites first come into physical contact must be evaluated and mitigated.

Satellite Docking and Grappling Mechanisms

Spacecraft docking mechanisms can be used when a client satellite is purpose-built to enable servicing. The simpler "passive" side of the docking mechanism can be installed on the client satellite to minimize the design impacts (such as cost and weight) on the client satellite. Navigation aids such as retro-reflectors or other fiducials can be mounted around the docking mechanism to enhance visibility and simplify RPO maneuvering.

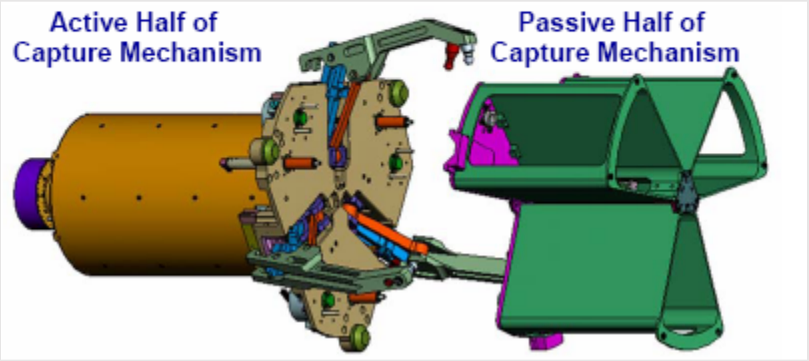


Figure 3. Orbital Express Docking Mechanism. (The active half was installed on the ASTRO servicer and the passive half was installed on the NextSat client satellite).

In addition to this docking mechanism, Orbital Express also demonstrated grappling of the client satellite using a robotic arm. Grappling of the client satellite will be more common for client satellites that have not been purpose built for servicing. While many robotic arm operations were successfully demonstrated on Orbital Express, the robotic arm was designed for a short term mission, and an operational servicer would need its robotics designed and tested to reliably operate on-orbit for many years.

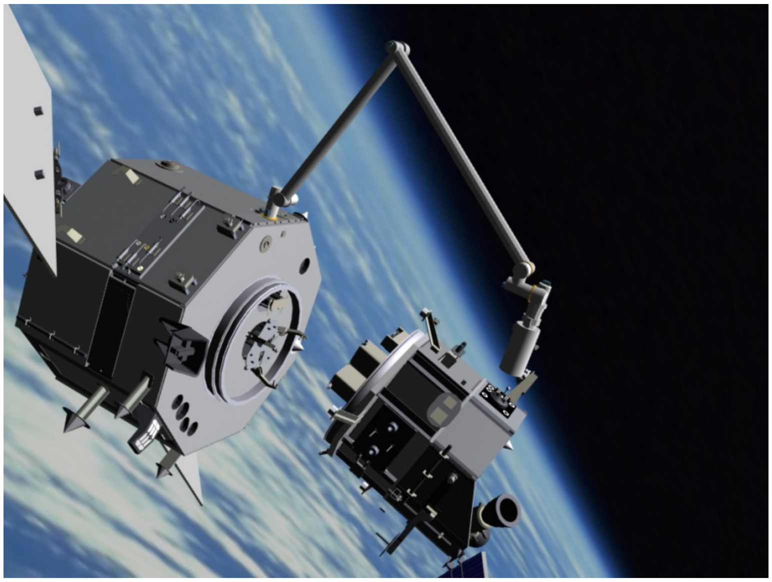
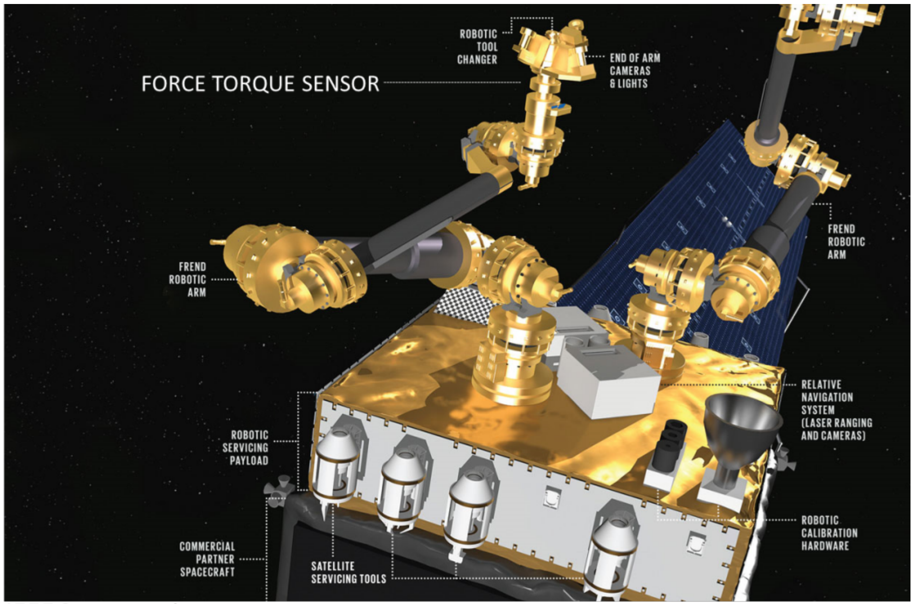


Figure 4. Robotic Arm Grappling Operation on Orbital Express



IEEE Spectrum image

Figure 5. Notional Robotics Payload for RSGS Satellite Servicer. (Robotics have greater complexity and capability than Orbital Express).

Propellant Transfer

The goal of a propellant transfer mechanism is to transfer propellant safely and reliably from a servicer satellite to a client satellite. There are many considerations that should be accounted for during propellant transfer. Some specific considerations for propellant transfer include properly managing pressures and flow. Safety considerations include minimizing propellant release; maintaining fuel and oxidizer within temperature constraints; performing leak checks on the servicer to client connection; and verification of the refueling process via client telemetry. Reliability considerations should include a robust design; use of screened/tested and heritage components; and accurate heritage pressure transfer operations.

Consideration should be given to contamination of the client satellite supply. Each component of the propellant transfer system should be tested in expected servicing environment. It is critical that the entire fluid transfer process be understood from initial assessment on orbit to close-out. Extensive ground experience has shaped the processes for fueling spacecraft. Consideration must be given to how those processes were shaped for a 1-g environment and what might be different in zero g. Other considerations should include variable client / mission pressures, types of tanks to refill, and multiple client fill-drain valve Interfaces.

Electro Magnetic (EM) Interference / Compatibility

Ground testing of the servicer should characterize the EM environment the servicer creates, including the emissions from any active RPO sensors and radios, to ensure the servicer does not interfere with the client satellite (and vice versa).

An electromagnetic interference assessment should consider:

- Client satellite operational mode during the servicing operation, including approach. For client spacecraft that will have operational RF payloads during servicer rendezvous maneuvers, the servicer will need to be hardened to operate through the RF environment (which may be a cost-prohibitive design trade). Thus, it may be preferable to avoid needing to design the servicer to be able to operate in the full power client satellite RF environment at close range by having the client satellite cease mission operations during servicing operations or by trajectory planning to avoid the main RF lobes.
- Ability of the servicer to remain in contact with the ground during rendezvous, proximity operations, and mated operations. For non-direct interference, analysis of multipath interference should be performed to ensure reliable communication is available to the servicer.
- Effect of the servicer's active RPO sensors on the client satellite. This can include a laser ranger or LIDAR impacting sun sensors, star trackers, or any other optically-sensitive instruments on the client satellite during RPO. An assessment of these sensitivities will result in definitions of keep-out zones and viable waypoints to implement during trajectory planning for RPO operations such as surveys and approach to grapple.

Telemetry, Tracking, and Command (TT&C)

In addition to the standard considerations for a satellite TT&C system, TT&C for a servicing satellite will also need to accommodate real time monitoring of robotic /autonomous operations which will require a very large data bandwidth. The TT&C system should include measures to ensure that unauthorized users cannot command and control the servicer.

- GEO applications
    - Need to consider if servicing is only to be done at specific longitudes or if the servicer must be capable of operating at all locations in GEO.
    - For general applications, use of only space-ground link system (SGLS) frequencies requires deconfliction within US government entities.
    - For limited orbit slot registration, customer spacecraft must not interfere with local assigned frequencies to enable relocation for servicing.
- LEO applications
    - A customer spacecraft frequency plan needs to be deconflicted or planned for time-sharing of common frequencies

RPO Mission Planning Modeling and Simulation Techniques and Practices

A foundation of modeling and simulating a space mission can make the critical difference ensuring mission success when faced with potential showstopper anomalies. The Dragon spacecraft had a “propulsion glitch” waving-off its first attempt at docking with ISS, and the Cygnus spacecraft had a “software data glitch” negating its first attempt at docking with ISS. Both programs were, in NASA parlance, “Go to launch and to make an attempt.” A big part of the quick and effective recovery from challenges like these were the high fidelity modeling and simulation efforts that preceded spaceflight operations. They informed crews about the operational limitations and expected responses in various on-orbit situations. Modeling and simulation of a servicer and client space vehicle, and the astrodynamic trajectories needed to complete a rendezvous, proximity operations, and capture (RPOC) of the client space vehicle ensures high probability of a safe and successful mission. Modeling and simulation is applied throughout the mission planning of a servicing mission and is an essential part of planning and executing an RPOC space mission.

Modeling and simulation processes are present throughout the life cycle of a mission from planning, selection of the specific course of action to be pursued, system and crew readiness, and execution of the on-orbit operations. This includes initial mission plan development and assessment, then a more detailed examination of the selected plan that goes beyond the initial mission planning. Higher fidelity and detailed mission planning involves statistical and dynamics analyses of the space vehicle’s performance and trajectory to effect a successful mission. Using statistical and dynamic modeling of systems and trajectories provides mission planners insight into the effectiveness of their plan and offers insight into where to adjust the plan to avoid hazards to safety or where system limits may be exceeded. Modeling and simulation gives planners and operators understanding of “how close to an edge” their plan and path might be. Armed with this insight, operators enter into a mission campaign with insight and confidence on how things should play out. Furthermore, it can support training exercises, mission rehearsals, and ultimately readiness for a servicing mission. This can be done using system simulators that give the operations team a chance to practice, exercise and develop intimate familiarity and team/individual roles and responsibilities prior to a demanding and difficult on-orbit task of a servicing mission.

Modeling of the servicer and client spacecraft systems and subsystems and the RPOC orbit dynamics and operations can involve varying degrees of technical fidelity. There is generally a correlation between the higher fidelity (and cost) of the simulator and the probability of a priori mitigation of on-orbit issues. As seen with Dragon and Cygnus missions to rendezvous with ISS, engaging the operations crews in the details of simulations aids greatly in their reaction to unforeseen issues and ultimately mission success.

Modeling for a satellite servicing mission includes development of a satellite dynamics simulator that contains models of key spacecraft subsystems relevant to the RPOC process. The satellite simulator for a servicing satellite will be more complex than those for traditional commercial satellites because it needs to include feedback from the RPO sensor suite, be able to handle a large dynamic range of maneuver types (from large delta-Vs for orbit adjustments to multiple small burns for proximity operations and maneuver to achieve capture and grapple), and needs to be able to conduct mated vehicle operations (integrate a client satellite dynamic model). If robotic arm operations are part of the servicing mission, these too must be included in the satellite simulator.

GNC system response will depend critically on quality of sensor input, which will vary greatly because of wide variations in lighting conditions (direct sunlight, eclipse, partial shading by solar arrays and other appendages). Other RPO missions with multiple sensors have experienced issues with guidance algorithms having difficulty determining which sensor inputs are valid and which have invalid data such as noise spikes. Often, RPO planning uses Monte Carlo analyses to cover a wide range of environmental conditions and fully map out the range of ACS dynamic behavior, so that predicted behavior has a low uncertainty, i.e., low risk. The results of this modeling could be used as technical data for external reviewers—especially the client satellite operator—to demonstrate safety of flight.

In addition to supporting ground testing, modeling and simulation can be applied to the launch and early orbit operations of a servicer space vehicle to verify capability and performance and provide opportunity to validate (or update) the servicer satellite dynamics model as well as the RPO sensor suite. Servicing mission modeling and simulations results provide quantitative evidence and artifacts that can be used in external safety and mission approval reviews.

B. Mission Planning and Preparations

Notification Protocols

As part of mission planning and mission preparations, a variety of notification methods must be planned. Some critical ones include the following.

a) RPO/Inspection/Servicing/Station-keeping planning practices and guidelines and message notification standards
b) Mission completion notification practices and guidelines and message notification standards
c) Incident notification message standards
d) Laser clearing house (if applicable)

RF Spectrum Management

RF Spectrum Management starts with compliance with ITU and FCC regulations. Missions must reference and be compliant with the following:

a) Reference ITU Radio Regulations Articles – Edition of 2016
b) Reference FCC

Operator Training Best Practices and Guidelines

Charles Murray and Catherine Bly Cox's "Apollo: The Race to the Moon" is a good reference regarding the engineer's point-of-view on how to successfully fulfill the greatest challenges in space, including RPOC operations. The book explains in great detail the value of realistic simulation and scenario-based operator training. Murray and Cox detail the simulation environments which drove alarms in rehearsals that were recalled by the operations team during Apollo 11 Eagle's descent to the lunar surface. The simulations in preparation for "Tranquility Base here, the Eagle has landed" saved the Apollo 11 landing when a computer overflow alarm rang out. Using resources like "Apollo: The Race To The Moon" for operations support teams for RPOC operations helps to set a motivation and mindset that enables the best training and mission readiness possible to be realized.

In a more academic approach, Section 3.1.2 of AEROSPACE REPORT NO. TOR-2013-00293, Mission Assurance Practices for Satellite Operations, June 3 2013, provides a good overview of best practices for training of satellite operations personnel. This technical operating report was produced as a collaborative effort of the Aerospace Mission Assurance Improvement Workshop, with contributions by multiple authors and subject matter experts throughout the government and the aerospace industry, and serves as a good framework for addressing and discussing satellite operator education and training practices and guidelines. From this report:

> *"The ultimate goal of training is to ensure mission success and vehicle safety through development of a knowledgeable and disciplined operations team. Training also minimizes the risk of personal errors. The development of training and certification plans should be given careful consideration for every operational program. Standardized training plans establish the minimum level of knowledge that is required for every operations team member and mission support personnel such as systems engineers and operations managers to successfully complete their expected tasks. Everyone involved in*

> *supporting the daily operations of the satellite should have training commensurate with their position. To effectively create such a training plan all operations tasks (i.e., subsystems trending, mission planning, pass-plan execution, etc.) need to be well understood and in most cases defined in procedures. The training plans should include definitions for individual/positional roles and the required tasks that a team member is expected to accomplish proficiently. This ensures key knowledge is held by more than a single team member and helps establish standardized processes by which the task is performed. This also prevents personnel from becoming indispensable as their knowledge is contained within the procedures and processes that all team members use on a daily basis during operations."*

Satellite servicing missions involve on-orbit operations that are considerably more complex than typical satellite mission operations. Development of mission plans, rehearsals, and crew certification will also need to occur for servicing, with the goal of convincing the client satellite operator that that there will be a high probability of servicing success and a low probability of negative consequences to the client.

SECTION IV: SATELLITE SERVICING OPERATIONS SAFETY

This section details the sequence of events in a satellite servicing operation (shown in Table 1) and maps the risk reduction considerations described in Section III to specific phases of a satellite servicing operation.

Table 1. Servicing Mission Phases and Risk Considerations

Mission Phase	Risk Areas
0. Design and Build	Validate system requirements and design to accomplish servicing mission
1. Servicer Launch and Early Operations	Check out robotic servicing systems
2. Quiescent Operations	Monitor servicer state of health
3. Request for Servicing	Create and coordinate servicing plan with client Mission simulations
4. Reposition Servicer (to Client)	Verify identity of client object Collision Avoidance (COLA) Perform orbit transfer to move servicer close to client Monitor telemetry, tracking, and control (TTC) system for interference during transit
5. Rendezvous	Establish relative navigation Robotics / docking mechanism checkout
6. Proximity Operations & Inspection	Ranging, position and orientation
7. Approach /Grapple / Dock	- Electromagnetic interference (EMI) between the servicer and the client: (This includes the servicer's RPO sensor suite on the client satellite) - Shadowing of client antennas, solar arrays, etc. by the servicer - Collision between the servicer and the client - Effect of the servicer's thruster plume on the client - Electrostatic Discharge (ESD) when the servicer first contacts the client - Debris creation caused by the servicer's grappling mechanism - Attitude control of the mated spacecraft stack
8. Servicing	For All: Operation and control of mated satellite stack
a. Mated Mission Extension	Enable command and control (C2) by client mission operation center C2 of mated stack
b. Repositioning (mated) to New Active Orbit	COLA Perform orbit transfer
c. Repositioning (mated) to Disposal Orbit	Comply with debris and disposal regulations
d. Manipulation	Robotic correction mechanical anomalies
e. Refueling	Transfer propellant
f. ORU Transfer	Robotic Correction mechanical anomalies
g. Servicer Replenishment	Same process but with a supply depot instead of a client satellite
9. Separation and backout	- Sudden changes in attitude behaviors as stack separates - Collision between the servicer and the client - Effect of the servicer's thruster plume on the client
10. Return to Quiescent Operations	COLA
11. Disposal of used parts	Collision between the servicer and released debris
12. Servicer Disposal	Loss of control before all safing activities completed

A. Satellite Servicing Mission Sequence

1. *Launch and Early Operations (LEOPS)*

All satellite subsystems, including the servicing subsystems, should be activated and checked out during LEOPS. Any remnants of the launch vehicle or adapters that remain near the servicing satellite could be used to calibrate the RPO sensors during this phase. It is recommended that testing include "certification" of servicer readiness as defined by the servicer owner.

2. *Quiescent Operations*

It is recommended that the servicing subsystems be periodically exercised to ensure readiness for servicing operations. Servicers need to balance between too little mechanism activity (cold welding, etc.) and too much (lubrication migration, etc.)

3. *Request for Servicing (Development of a servicing mission plan)*

The development of a servicing mission plan should include:

- Consideration of communications required between the servicer and client mission operations centers
  - Voice, text, chat [Voice loops, inter-MCC chat "texting," effective Flight Director and specialists communication. Video (face to face discussions). Data (Common Operating Picture—top level & system/discipline specific display for both MCCs]
  - At all times, understand each spacecraft state: orbit, attitude and control, functional state (spacecraft and systems)
- Consideration of potential ground intervention or positive control points (go/no-go decision points) or autonomous abort
- Consideration of what actions the client may need to take prior to servicing, e.g., does a GEO client need to move out of its active slot to make the servicing easier?
- Consideration of what part of the fault response requirements can be satisfied by the client, e.g., could the client maneuver for Collision Avoidance (COLA)
- Consultation of operational working groups when considering servicing in busy/highly desirable orbital regimes.

4. *Reposition*

This phase assumes that the servicer is at a position far away from the client and must perform an orbit transfer / maneuver in order to move close to the client satellite.

- The primary safety considerations in this phase are:
  - Collision avoidance (COLA) and
  - Radio frequency interference (RFI) with other satellites in orbit (other than the servicing client).
- The approach maneuver is planned based on client ground truth orbital data and may be augmented with measured satellite position data from the catalog (TLEs – Two Line Element set) and does not assume that the sensors on the servicer have acquired the client satellite.

This process should be based on the procedure currently used when a satellite operator needs to reposition a satellite from its initial operation orbit to a new orbit.

5. *Rendezvous*

The principal risks in this phase are the inability to locate the client and collision with the client satellite.

The definition of phase transitions in the rendezvous process creates points where the servicer can safely hold and station keep while the ground verifies state of health and readiness for all the servicers systems, akin to the pre-planned hold points in a launch sequence.

In order to maintain safety to both the client and servicer satellites, all RPO missions should implement passive safe relative orbit strategies when possible and practical. These include, but are not limited to:

- The use of passively-safe phasing maneuvers (i.e., radial-burn phasing hops that return the servicer to the initial primary burn station if the second burn isn't performed)
- Out-of-plane safety ellipses that avoid crossings of the client's velocity axis
- Low-speed final approaches along the radial direction.

These strategies greatly reduce the statistical likelihood of collision if the client's control system is inadvertently disabled after the initial maneuver burn. Furthermore, before any maneuver is performed on orbit, high-fidelity ground simulations should be exercised to evaluate the relative trajectory of the servicer/client pair and the statistical probability of collision in the aftermath of the planned burn over a period of at least two orbits.

- When the rendezvous is initiated, the client satellite may be out of range of the servicer’s sensors, so the servicer may perform rendezvous maneuvers based on the position of the client satellite provided by the mission operations center. The positions of the servicer and the client should be monitored by the ground during this phase.
- During the rendezvous, the servicer will search for the client satellite with passive sensors. At some point in the approach, the servicer will acquire the position of the client satellite. Position of the client should be monitored from the ground to verify.
- Once the client is acquired, the servicer will establish a track on the client (position and distance) with its internal sensors. A rendezvous will be complete when the servicer has established a stable orbital position (less than TBD km) from the client and maintains this position based on relative navigation using its internal sensor data. The on-board navigation filter should have sufficient time to converge to a steady-state solution on all of its states, and be in statistical agreement with predicted ground-based state estimations.
- It is considered best practice to hold the servicer at a stable rendezvous position before beginning transition to proximity operations. A series of rendezvous points, successively closer to the client, may be used.

  - When possible, ground and space based space situational awareness (SSA) sensors should be used to monitor rendezvous to provide independent verification of servicer and client satellite positions.
  - Built-in hold periods to ensure relative navigation convergence after maneuvers

6. ***Proximity Operations & Inspection***

   During this stage, the primary risk is damage to the client and/or servicer from inadvertent collision and creation of debris. Proximity operations may be performed for an inspection to verify the status of the client or as a prelude to grapple/docking.

   - Transition to direct approach for grapple / docking.
   - Relative navigation sensors should provide range and, if possible, range rate data as well as angles (if range rate measurements are not directly provided, the on-board navigation filter should provide estimates of those states).
   - Proximity operations approach methods include v-bar, r-bar, z-bar maneuvers
   - Natural motion circumnavigation, forced motion circumnavigation, or partial force-motion waypoint-to-waypoint inspection are often employed to provide surveys of the entire client or regions-of-interest of the client from a variety of aspect angles. Offset passive safety ellipses can also be employed as a useful passively-safe inspection technique.
   - The servicer “images” the client satellite to provide updated 2-D (passive visible and/or IR sensing) and 3-D (point cloud) representations of the client physical configuration. The 3-D representations can be achieved from multiple views using passive cameras (stereo imaging), or active LIDARs. For servicing missions that encompass close approach and grapple/docking, these updated models are critical for providing the ground with knowledge of the client’s current geometric condition, and for generating updated 3-D reference models that may be utilized by the on-board RPO sensor suite to improve pose estimation accuracy during approach and close proximity operations.

[Note: Some servicing missions will only consist of satellite inspection, so the following phases will not be applicable]

7. ***Approach / Grapple / Dock***

   Approach begins when the satellite makes a forced maneuver that will bring the servicer into physical contact with the client. The principal safety considerations for this phase are:

   - Electromagnetic interference (EMI) between the servicer and the client. This includes the effect of the servicer’s RPO sensor suite on the client satellite.
   - Blocking / shadowing of client antennas, star trackers, solar arrays, etc. by the servicer and vice versa.
   - Collision between the servicer and the client.
   - Effect of the servicer’s thruster plume on the client.
   - Electrostatic Discharge (ESD) when the servicer first contacts the client satellite.
   - Debris creation caused by the servicer’s grappling mechanism.
   - Attitude control of the mated spacecraft stack. The ACS of the client satellite will need to be inhibited.

Autonomous fault detection and responses are most important in this phase because actions to prevent collisions often must be made on a much shorter response time than can be commanded by the ground.

Client operators command state changes to the client satellite before physical contact occurs. If possible, the client's ACS should transition to a wheel momentum-bias mode, wherein the reaction wheels are held at constant wheel speeds and all thrusters are inhibited. If this mode is not available, the ACS should disable the wheel controller and allow the wheels to spin down to zero momentum with thrusters temporarily maintaining attitude control, then inhibit all thrusters.

8. Servicing

Servicing begins after the mated stack's residual rates have been removed, using a combination of the servicer's thrusters and reaction wheels.

a) Mated mission extension

Servicer remains docked to client for an extended period of time, performs station keeping and pointing for the client without repositioning. This only requires a mechanical connection between the servicer and client. The principal risk is attitude control of the mated stack.

b) Repositioning (mated) to new active orbit

Servicer docks to the client, the servicer propulsion system is used to reposition the mated stack to a new orbital position, and the servicer separates. This only requires a mechanical connection between the servicer and client. The principal risks are:

- Attitude control of the mated stack
- COLA and RFI with other satellites during the repositioning maneuver

c) Repositioning (mated) to disposal orbit

Servicer docks to the client, the servicer propulsion system is used to reposition the mated stack to a disposal orbit and then the servicer separates. This only requires a mechanical connection between the servicer and client. There is a need to comply with orbit debris requirements for disposal.

d) Manipulation (mechanical)

The principal risks in this operation are creation of debris and damage of the client satellite. The servicer uses robotics to reposition some component on the client, e.g., extend a solar array that has only partially deployed. The servicer remains mated only until the mechanical manipulation is complete. Operations should minimize the creation of debris. Any operation that has substantial chance of generating debris above 1 mm should be considered for execution outside of the active GEO orbit (i.e., servicer moves stack to GEO, performs ops, and returns stack to GEO). Operations generating debris should be carefully reviewed for possible impacts on the sensors and actuators of the servicer and client.

e) Refueling

Servicer establishes a fluid connection to the ground fueling port of the client satellite. The servicer records pressure, fill level, and other relevant telemetry data and provides this data to the servicer MCC where the propellant transfer process is controlled and monitored. The servicer remains mated only until the propellant transfer is complete.

f) ORU transfer / addition of capability to the client

The principal risks in this operation are creation of debris, damage of the client satellite, and disposal of any used components taken off of the client

The servicer permanently affixes/ installs a modular component into/onto the client. The servicer remains mated only until the addition / replacement is complete. If failed or used components are removed, they must be secured to the servicer for disposal.

g) Servicer Replenishment

The servicer docks with a depot full of new ORUs, tools, fuel tanks, etc. The servicer picks up new parts and fuel, and may transfer used parts to the depot. Depot disposal will eventually be required.

9. Separation and Backout

Verification is required of the client health. The servicer remains docked to the client until client functionality is confirmed.

For release, the servicer stows gear as needed to minimize any chance for inadvertent contact with the client during the separation maneuver. The servicer releases the docking or grapple mechanism and retreats from the client, being careful to minimize pluming (contamination, imparting torque, etc.).

Consider external survey of client to verify all external elements are in their expected configurations.

10. Return to quiescent operations

Servicer subsystems perform calibration and diagnosis as needed. The servicer stands by for the next Request for Servicing. The servicer is repositioned to a parking orbit.

11. Disposal of Used parts

If the parking orbit is not an acceptable debris release orbit, reposition to a disposal orbit is required. The servicer activates imaging systems to track debris release. When debris is released consider logging orbital information at release, such as debris separation rate and debris rotation rate. If the parking orbit is not an acceptable debris release orbit, reposition to the parking orbit.

12. Servicer Disposal

At the end of the servicer's operational lifetime, the servicer should be disposed of in accordance with standard procedures for its orbital regime. For example, see ISO 26872:2010 Disposal of Satellites Operating at Geosynchronous Altitude, "U.S.

Government Orbital Debris Mitigation Standard Practices," and "SMC Orbital/Sub-Orbital Hazards and Debris Mitigation User's Handbook."

SECTION V: SERVICING MISSION SAFETY PACKAGE

The following are examples of typical documents that could be used by a servicer to demonstrate compliance and provide evidence of safe operations and assurance that the mission to service the client would be successful. Having these types of documents and analyses on hand ahead of operations can both help avoid on-orbit failures and provide a list of actions to consider in the face of an on-orbit anomaly. In addition, some of these may be required for licensing.

A. Types of Analyses

- Probabilistic Risk Assessments (PRAs) for all mission phases
- Failure Modes and Effects Analyses (FMEAs) for mission critical subsystems
- Maneuver Dispersion Analysis

B. Types of Developed Procedures

- Flight Rules
- Guidelines, constraints, and limitations associated with the overall mission and specific phases of the mission

C. Safety/mission specific zones

- Keep out zones, NTE speed (relative velocity) limits, free flight trajectory paths relative to keep out zones

D. Abort criteria

- Flight Rules (describe conditions that result in an abort)

E. Design Questions (Part of Safety Verification Process)

- Fault tolerance
- System Design
- Orbit regime

F. Testing/Safety Verification Processes

- Best practices
- Test Verification matrix/methods (inspection, demonstration, physical test and analysis)

G. Hazard Identification and Consequences

“Potential hazards may be identified from a number of internal and external sources. Generally, hazards are initially listed on a Preliminary Hazard List (PHL), then grouped by functional equivalence for analysis. Prior to risk analysis you must also include the consequence (undesired event) resulting from the hazard scenarios. Hazard scenarios may address the following: who, what, where, when, why and how. This provides an intermediate product that expresses the condition and the consequences that will be used during risk analysis.”

H. Risk Analysis and Risk Identification

“Risk analysis is the process whereby hazards are characterized for their likelihood and severity. Risk analysis looks at hazards to determine what can happen when. This can be either a qualitative or quantitative analysis. The inability to quantify and/or the lack of historical data on a particular hazard does not exclude the hazard from the need for analysis. Some type of a risk assessment matrix is normally used to determine the level of risk.”

ADDENDUM: LIST OF REFERENCES

Rendezvous and Proximity Operations (RPO)

Carrico, Tim. "Proximity Operations for Space Situational Awareness Spacecraft Closed-Loop Maneuvering Using Numerical Simulations and Fuzzy Logic." (2006).

This paper provides a framework for modeling rendezvous and proximity operations (RPO) within an existing simulation environment. Maneuvers, fuel use, and other parameters are documented and compared.

Barbee, Brent William, et al. "Guidance and navigation for rendezvous and proximity operations with a non-cooperative spacecraft at geosynchronous orbit." (2010).

This paper presents guidance and navigation strategy for rendezvous and proximity operations with a noncooperative spacecraft in Geosynchronous Orbit.

Lee, Daero, Guidance Navigation and Control System For Autonomous Proximity Operations and Docking of Spacecraft. (2009). *Doctoral Dissertations. 1942.* (http://scholarsmine.mst.edu/doctoral_dissertations/1942)

This study develops an integrated guidance, navigation and control system for use in autonomous proximity operations and docking of spacecraft. A new approach strategy is proposed based on a modified system developed for use with the International Space Station.

Goodman, John L. History of Space Shuttle Rendezvous. (2011)

This paper presents an introduction to RPO history of the Space Shuttle Program with details on the programmatic constraints and technical challenges encountered during shuttle development in the 1970s and over thirty years of shuttle missions. Examples include Mercury, Gemini, Apollo, Skylab, and Apollo/Soyuz.

Luo, Yazhong, Jin Zhang, and Guojin Tang. "Survey of Orbital Dynamics and Control of Space Rendezvous." *Chinese Journal of Aeronautics* 27.1 (2014): 1-11.

This paper surveys the studies on rendezvous orbital dynamics and control (RODC), a key technology for operating space rendezvous and docking missions.

Keith, Asa Clark and Baker, Jim. “A Non-Technical Overview and Discussion of Rendezvous and Proximity Operations (RPO).” Aerospace Corporation Report TOR-2013-01086 (2013)

This report was written by Asa Clark Keith III, XSS-11 Flight Director and ANGELS space experiment program mission designer. The report was largely completed before final publication and the untimely death of its author. Dr Jim Baker saw to its completion. The report captures the knowledge, experience and insight of a man who was passionate about the understanding and comprehension of rendezvous and proximity operations. There are many academic and operational essays on RPO, this report is a conversation with technical rigor and easy to understand explanations by a man who explained a lot to senior leaders and ensure his flight control team always comprehended the science and art of RPO.

Guidance Navigation Control Modeling and Simulation

Roscoe, Christopher W.T., Westphal, Jason J., MacMillan, Robert T. “Reusable Bird’s-Eye View for On-Orbit Satellite Servicing Using Cubesats.” American Astronautical Society: AAS 16-046 (2016).

> *This paper presents a mission concept—the Augmented Situational Awareness Satellite (ASAS) mission—for a reusable CubeSat to provide a bird’s-eye view for an on-orbit satellite servicing mission, built on technology developed for the NASA CubeSat Proximity Operations Demonstration (CPOD) mission.*

Roscoe, Christopher W.T., et al. “Guidance, Navigation, and Control Algorithms for Cubesat Formation Flying.” American Astronautical Society: AAS 15-113 (2015).

> *This paper outlines the design of the innovative RPO GNC system and underlying algorithms used for the NASA CubeSat Proximity Operations Demonstration (CPOD) mission.*

Schulte, Peter Z., and David A. Spencer. "Development of an integrated spacecraft Guidance, Navigation, & Control Subsystem for Automated Proximity Operations." *(2014)*

> *This paper describes the development and validation process of a highly automated Guidance, Navigation, & Control (GN&C) subsystem for a small satellite on-orbit inspection application. The paper focuses on the integration and testing of GN&C software and the development of decision logic to address the question of how such a system can be effectively implemented for full automation.*

Boge, Toralf, et al. "Using robots for advanced rendezvous and docking simulation." (2012).

> *This paper descries the challenges of simulating rendezvous and docking process of an on-orbit servicing mission and how these challenges are solved by using the new robotics based simulation system EPOS 2.0*

Williams, Austin. “CubeSat Proximity Operations Demonstration (CPOD) Mission Update.”

> *This is a PowerPoint presentation on CubeSat Proximity Operations Demonstration (CPOD) Mission Update*

Spacecraft Charging

Mikaelian, Tsoline. "Spacecraft Charging and Hazards to Electronics in Space." (2001).

> *This paper presents a brief review of two types of hazards to earth-orbiting spacecraft: spacecraft charging and radiation hazards to spacecraft electronics, with emphasis on the natural environmental factors and interactions which contribute to these hazards.*

Davis, V. A., et al. "Spacecraft of Charging Analysis of the Hughes 702 Satellite." *6th Spacecraft Charging Technology*. 2000.

> *This paper presents an analysis of the spacecraft charging of the Hughes 702 satellite.*

Garrett, Henry B., and Albert C. Whittlesey. *Guide to Mitigating Spacecraft Charging Effects*. John Wiley & Sons, 2011.

> *This book contains suggested detailed spacecraft design requirements and procedures to minimize the effects of spacecraft charging and to limit the effects of the resulting electrostatic discharge. It contains supplementary material and references to aid in understanding and assessing the magnitude of the phenomenon.*

Norgard, John and Randall Musselman, "EMI from Spacecraft Docking Systems."

> *This paper presents analytical and numerical models of the Orion Crew Exploration Vehicle (CEV) simulated to predict the worst-case potential difference between the CEV and the visiting vehicle when the CEV is unbiased (solar panels unlit: eclipsed in the dark and inactive) or biased (solar panels sunlit: in the light and active).*

Bacon, John B. "Electrostatic Discharge Issues in International Space Station Program EVAs." (2009).

> *This is a presentation on the electrostatic discharge issues in the International Space Station Program EVAs.*

Additional Materials

Childers, Rex K., "Mission Assurance Practices for Satellite Operations." Aerospace Report No. TOR-2013-00293 (2013)

> *This document provides guidelines for implementing mission assurance practices in mission operations from prelaunch through decommissioning. Best practices provide guidance for future operations and assist teams in constructing and outlining processes necessary to increase mission success and minimize on-orbit risks*

Musgrave, Gary E., Axel Larsen, and Tommaso Sgobba. *Safety Design for Space Systems*. Butterworth-Heinemann, 2009.

> *This text book provides a detailed look into the discipline of space safety to include chapters on Collision Avoidance System (chapter 8) and Robotic Systems Safety (chapter 9).*