American Astronautical Society
Rocky Mountain Section

AAS 09-065

Rendezvous Integration Complexities of NASA Human Flight Vehicles

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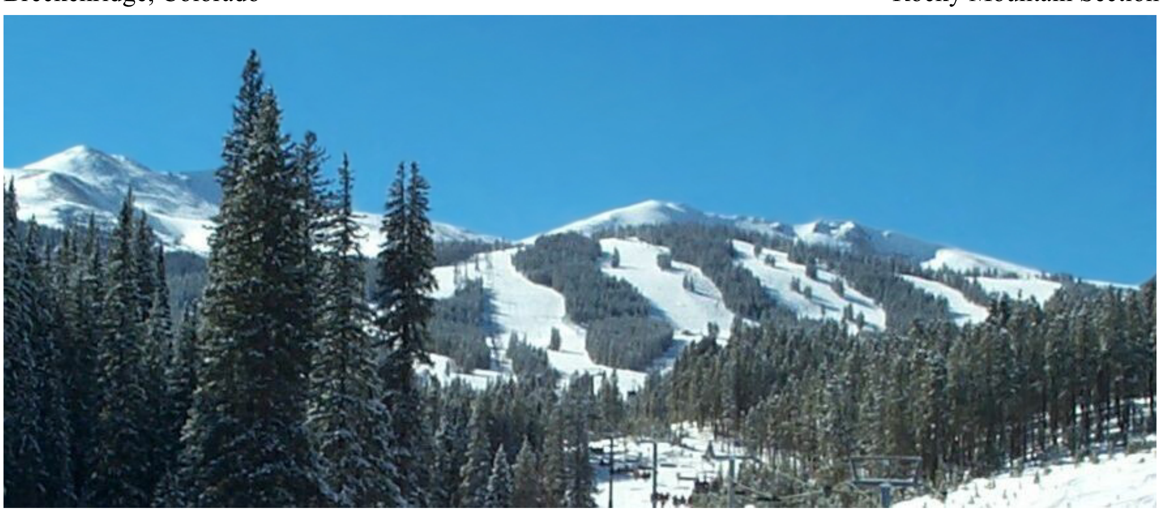
32nd ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

January 31 - February 4, 2009
Breckenridge, Colorado

Sponsored by
Rocky Mountain Section



AAS Publications Office, P.O. Box 28130 - San Diego, California 92198

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Rendezvous Integration Complexities of NASA Human Flight Vehicles*

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Propellant-optimal trajectories, relative sensors and navigation, and docking/capture mechanisms are rendezvous disciplines that receive much attention in the technical literature. However, other areas must be considered. These include absolute navigation, maneuver targeting, attitude control, power generation, software development and verification, redundancy management, thermal control, avionics integration, robotics, communications, lighting, human factors, crew timeline, procedure development, orbital debris risk mitigation, structures, plume impingement, logistics, and in some cases extra-vehicular activity. While current and future spaceflight programs will introduce new technologies and operations concepts, the complexity of integrating multiple systems on multiple spacecraft will remain. The systems integration task may become more difficult as increasingly complex software is used to meet current and future automation, autonomy, and robotic operation requirements.

INTRODUCTION

The Gemini, Apollo, and Space Shuttle Programs have successfully met Rendezvous, Proximity Operations, and Docking (RPOD) mission objectives by performing complex integration of spacecraft systems commonly recognized as RPOD with those that may not appear to be related to RPOD. The Constellation Program faces the same challenge. Systems integration and mission planning to meet programmatic and mission objectives occurs throughout the life of a flight program, beginning with the initial design effort. Integrated spacecraft systems must permit safe and successful accomplishment of mission objectives and be flexible enough to meet current, evolving, and future mission requirements, mission objectives, and constraints. The complexity of orbital operations involving multiple spacecraft, and a variety of government agencies and contractors, and the amount of effort required to successfully perform those operations, is far greater than may be inferred from observing RPOD missions on television.

As with ascent and entry, RPOD is a complex phase of space flight. RPOD is tightly integrated with many vehicle subsystems that work together to provide capabilities required to accomplish rendezvous and docking. A vehicle cannot be made RPOD capable by simply adding a sensor or avionics package. RPOD complexity is reflected in the various types of missions, chaser vehicles, and target vehicles in NASA's human flight program since 1965.[1,2] RPOD is traditionally viewed as the domain of specialists in orbital mechanics, navigation, and hardware capture mechanisms. In reality, it involves complex integration of systems both directly and indirectly concerned with RPOD. Each system influences or depends on other systems to be successful. Personnel in many non-RPOD spacecraft disciplines are included in the RPOD aspects of spacecraft development, mission design, and mission execution (Figure 1).

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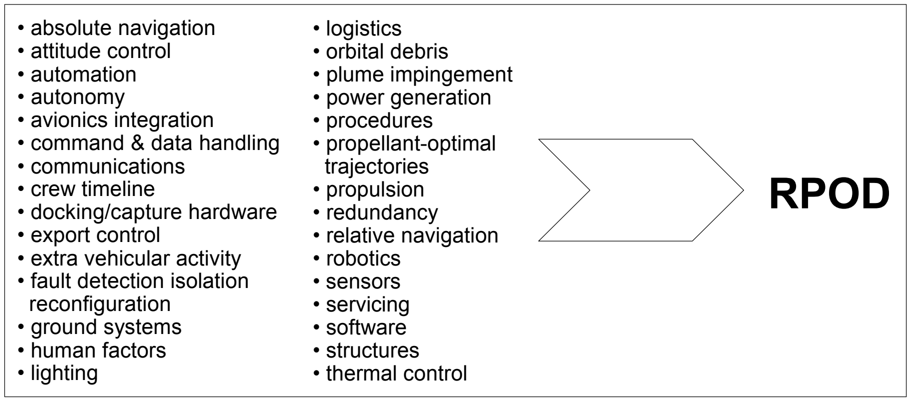

Figure 1 Many systems and spaceflight disciplines directly or indirectly influence sub-systems design and operation for the RPOD flight phase.

This paper covers several areas that are the subject of systems integration for human spacecraft that perform RPOD. These areas include: Rendezvous Missions and Phases of Rendezvous; Design, Development, Test, and Engineering; Chaser and Target Vehicle Integration; Vehicle Design; Integrating Rendezvous and Proximity Operations Systems; Contingency Planning; Applying Lessons Learned to RPOD Integration; and Integrated Teams.

RENDEZVOUS MISSIONS AND PHASES OF RENDEZVOUS

The complexity and content of the rendezvous integration task depends on the flight phase and the nature of the mission. There are two types of rendezvous missions, ground-up and deploy-retrieve. In a ground-up rendezvous, a maneuvering spacecraft (called the "chaser") performs a rendezvous with a spacecraft (called the "target") that typically does not maneuver (Figure 2). Usually the target spacecraft is in orbit before the chaser is launched, although the launch order could be reversed. Most Gemini missions, all Apollo missions to the Moon, and many Shuttle missions flew this type of rendezvous.[1]

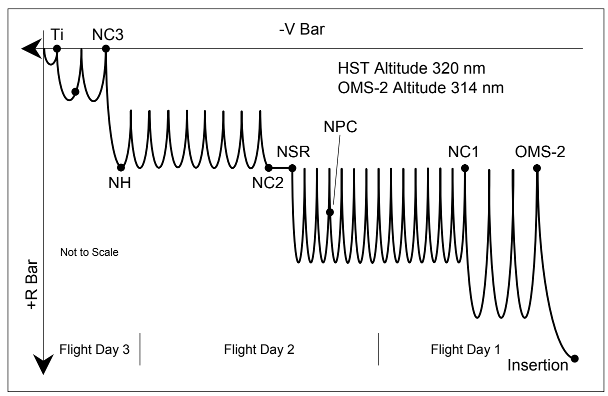

Figure 2 STS-82 Ground Up Rendezvous Profile

A second type of mission, the deploy-retrieve, involves a target spacecraft deployment by a chaser spacecraft (Figure 3). The chaser then separates from the deployed target. During the deployed phase of the mission the chaser and target independently or jointly conduct various mission activities while separated by tens of miles or more. Once target spacecraft tasks have been performed the chaser performs a rendezvous and retrieval of the target spacecraft. Many shuttle missions flew this type of rendezvous.[1]

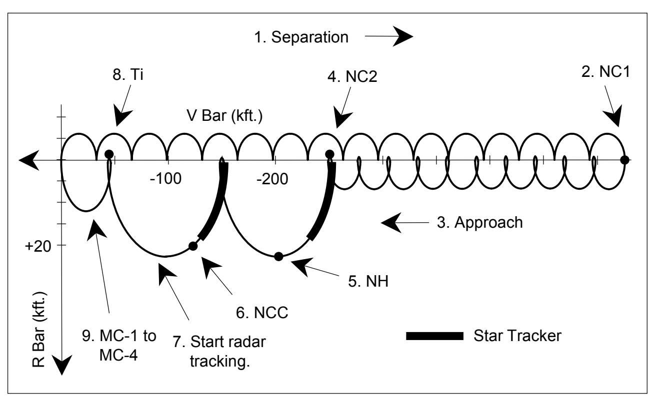

Figure 3 STS-51G SPARTAN deploy and retrieval profile (June 1985).

Both ground-up rendezvous and deploy-retrieve rendezvous missions can be divided into three phases.

Far Field Rendezvous Phase

For a ground-up rendezvous, the first maneuver in the rendezvous sequence starts at lift-off and continues until orbital insertion. At orbit insertion the chaser may be displaced from the target spacecraft by several thousand miles and may lap the target before the rendezvous is complete, therefore this phase is often generically called the far field rendezvous phase (Figure 2, Insertion through NC3). During the Gemini, Apollo, and Space Shuttle Programs, the most accurate navigation state estimates for the chaser and target during this phase were computed on the ground. Maneuver targeting was also performed on the ground due to limited chaser vehicle on-board computer capacity, hence this phase has traditionally been called the "ground-targeted phase." For example, during Shuttle missions ground-based C-band radar, Tracking and Data Relay Satellite System (TDRSS) Doppler, and Global Positioning System (GPS) measurements may be used by Mission Control for chaser and target orbit determination, and to compute chaser and possibly target orbital adjustments. Due to the presence of GPS absolute navigation and greater computer capacity on the Orion vehicle, this phase is known as the "absolute navigation phase" within the Constellation Program. Relative navigation using relative sensor data is not performed during the far field phase as the range between the chaser and target is larger than the acquisition range of relative sensors. However, absolute navigation, maneuver targeting, and burn execution accuracy during the far field phase must be sufficient to place the chaser within the relative sensor acquisition envelope for the near field phase. The length of the far field phase can vary from a few hours to several days. Deploy/retrieve missions typically also have a far field phase as the chaser may separate to a distance outside the range of relative sensors. The NC1 maneuver in Figure 3 is one example.

Near Field Rendezvous Phase

The near field rendezvous phase, also known as the on-board targeted or relative navigation phase, begins when relative navigation sensors on the chaser can acquire and track the target (Figure 4). Orbital adjustments are computed on-board the chaser spacecraft. Maneuver placement and timing is designed to facilitate rendezvous with the proper relative motion and orbital lighting conditions needed for the initiation of proximity operations piloting (human or automated) in the presence of trajectory dispersions. In the event of a primary sensor failure, back-up procedures using other sensors are executed to ensure a successful rendezvous and transition to the proximity operations phase. Overlap of the operating envelopes of multiple sensors is necessary to permit assessments of sensor performance.

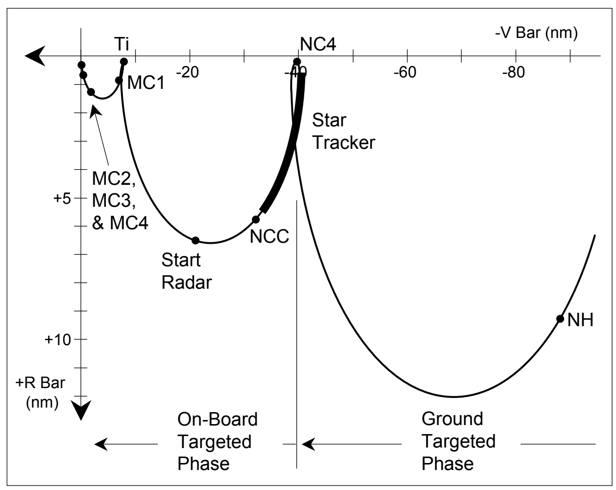

Figure 4 Flight day 3 Space Shuttle rendezvous activities up until the proximity operations phase for an ISS mission.

Proximity Operations Phase

Proximity operations is considered to begin when trajectory control transitions from discrete burns performed at intervals of hours or tens of minutes to near continuous trajectory control based on changes in relative motion (Figure 5). Relative sensors continue to provide measurements to on-board relative navigation. Automated or human piloting tasks are accomplished using cues from a variety of relative navigation sensors. For current Space Shuttle missions the transition to proximity operations occurs at the MC4 maneuver, approximately 2,000 feet from the target spacecraft.

Procedures during this phase can vary depending on the characteristics of the target spacecraft and mission requirements, much more so than during the ground targeted and on-board targeted phases. During

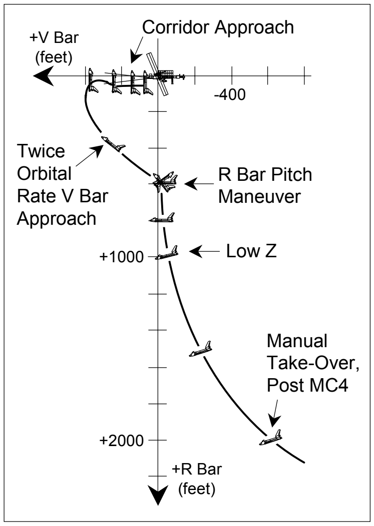

Figure 5 Proximity operations for Space Shuttle Docking with ISS.

Figure 6 Dale Gardner about to capture the Westar-VI (STS-51A, Nov. 1984).

proximity operations the physical characteristics and systems capabilities of both spacecraft become more significant in defining mission requirements, systems requirements, procedures, and constraints on the concept of operations. These vehicle characteristics and systems include vehicle attitudes, masses, and systems such as thrusters, attitude control, communications, thermal control, and power generation. A single anomaly in any one task or system can place the entire mission timeline at risk. The degree of coordination required across multiple chaser and target vehicle disciplines is significant.

If spacecraft servicing or assembly is to be performed, preparations for these activities complicate the proximity operations phase. Robotics systems checkout/activation and Extravehicular Mobility Unit (EMU, or space suit) checkout/EVA preparation can occur at any time between orbit insertion and docking/capture. If the target is to be captured for servicing, robotics activation and/or EMU/EVA preparation must occur simultaneously with proximity operations. Manual capture and manipulation of a target for berthing by suited EVA crewmembers complicates proximity operations (Figure 6). Unique, target-specific hardware must be manually attached to the target spacecraft and used to manipulate it into the berthing cradle in the Space Shuttle payload bay. This hardware is designed, tested and certified during the pre-flight mission preparation phase, and the target spacecraft may not be available for pre-flight mating fit checks.

Chaser separation from the target occurs after the mated activities are concluded. Proximity operations piloting techniques and relative navigation sensors are used to ensure a successful safe separation that minimizes the possibility of re-contact and Reaction Control System (RCS) jet plume impingement.

DESIGN, DEVELOPMENT, TEST AND ENGINEERING

The success of the Design, Development, Test and Engineering (DDT&E) phase of a flight program depends on a clear understanding of programmatic, spacecraft, and system requirements. Personnel on a spacecraft development project or a systems upgrade should have a clear understanding of the mission and "end goal" of the project. This section discusses examination of requirements and constraints, and the advantages and disadvantages of adopting legacy hardware, procedural work-arounds, and simple tools to reduce risk during DDT&E.

Examination of Requirements and Constraints

During the DDT&E phase, new technology, at an appropriate readiness level, is integrated into a vehicle along with selected, flight-proven software algorithms, hardware, and mission operations concepts from legacy programs. Export control regulations may restrict choices of sensors and other hardware.

Project personnel strive to thoroughly understand the requirements, design, and operation of evolving vehicle systems. The integration of legacy and new hardware, software, and mission techniques in all vehicle systems must be closely examined to ensure compatibility. This examination includes changes to non-RPOD systems for impacts to systems traditionally associated with rendezvous and proximity operations.

Spacecraft system development is continually challenged through competition with other spacecraft systems and flight phases, such as ascent and entry, for limited budget, spacecraft weight, volume, footprint, thermal control, power, communications bandwidth, and computer capacity. Resolution of higher risk issues in ascent, abort, entry, and landing can restrict margin and resources available to RPOD developers. This competition can place severe constraints on hardware choices and design margin during DDT&E. The ramifications of these choices can cascade through multiple systems impacting operations concepts and the ability to meet performance and mission requirements.

During proximity operations and after docking/capture, spacecraft systems characteristics and integrated systems considerations become more significant in defining mission requirements and systems constraints. Systems design, operations concepts, and procedures for both vehicles should be examined for impacts and conflicts in the same manner as single vehicle systems. Parallel DDT&E of chaser and target vehicles in the Gemini, Apollo, Skylab, and Apollo/Soyuz Programs permitted early detection of systems and operations concepts conflicts, thereby lowering technical, cost, and schedule risk (Figures 7 and 8). The Space Shuttle performed rendezvous, proximity operations, and capture with many vehicles that were not designed to support servicing or capture by shuttle crew members (Figure 6). Asynchronous DDT&E, inadequate knowledge of target vehicle configuration, and an inability to perform integrated systems tests and capture hardware fit checks, resulted in capture problems on several shuttle missions that were not detected until the missions were flown. However, alternate methods using the Remote Manipulator System or the gloved hands of EVA crew members were used to successfully perform capture.

Figure 7 Gemini and Agena testing before Gemini 6 (September 1965).

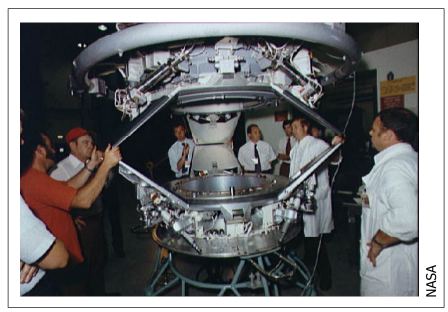

Figure 8 July 1974 fit check of the APAS 75 docking hardware for Apollo/Soyuz.

Integrating Legacy Hardware, Procedural Work-Arounds, and Simple Tools

Cost, schedule, and vehicle margin challenges, such as weight growth and demands for increased capability in thermal control, propulsion, power, and communications during the DDT&E phase, may drive program management to seek alternatives to proposed hardware and operations concepts. These alternatives include, but may not be limited to, the use of legacy hardware, operations concepts, and piloting tools from previous flight programs.

Examining the requirements and design differences between spacecraft under development and legacy spacecraft can help identify areas that may represent cost, schedule, and technical risk. These differences are also keys to understanding why some legacy hardware and operations concepts are not appropriate for a new vehicle. For example, the Space Shuttle has much larger RCS jets than Gemini and Apollo spacecraft, and Space Shuttle rendezvous targets were more sensitive to RCS jet plume impingement. Orion and Altair have automated rendezvous and docking requirements, while the Gemini, Apollo, and

Space Shuttle vehicles did not. Orion uses solar cells for power generation, while previous NASA human spacecraft used fuel cells during RPOD.

Flight proven, legacy hardware may not meet requirements for the program under consideration. Furthermore, obsolescence and parts availability issues and associated costs, may make the use of legacy hardware prohibitive. Adoption of legacy RPOD operations concepts may be of value for reducing DDT&E risk, but may not enable a vehicle to meet new programmatic and systems requirements for RPOD. However, many best practices from legacy programs can be implemented to reduce risk to mission success.

Constraints imposed on RPOD activities by RPOD and non-RPOD systems and programmatic resource limitations may be overcome with procedural work-arounds to avoid hardware and software modifications. While this saves money in the near term, long term life cycle and per mission costs may increase. A spacecraft with little or no margin and redundancy in RPOD and non-RPOD systems may be attractive for lowering DDT&E costs, but will have a higher risk of mission failure.

Although the use of manual procedural work-arounds may be intensive in terms of procedures development, crew training, and contingency analysis, it provides simple, robust, and fault tolerant operations. Operational work-arounds have been preferred for the Gemini, Apollo, and Space Shuttle vehicles over hardware and software development and modification to save time, budget, and resources. While the Shuttle has been very successful in rendezvous and proximity operations, this philosophy has resulted in the development of continuously evolving contingency procedures that require extensive pre-flight simulation and analysis. These on-board and ground procedures are labor intensive and additional training for crew and ground personnel is required.

Crews of the Gemini, Apollo, and Space Shuttle vehicles used simple tools to maintain relative motion situational awareness. Simple tools are lower mass, volume, power, cost, and risk alternatives to application of hardware with more advanced technology. These tools often took advantage of sub-systems that were already on the vehicles, such as cameras. Acetate overlays placed on Space Shuttle closed circuit television camera screens have proven to be reliable and effective at providing crews with range data (Figure 9). However, unlike the Shuttle, the future Orion and Altair vehicles will not be equipped with a camera that provides an orthogonal view of the docking mechanisms.

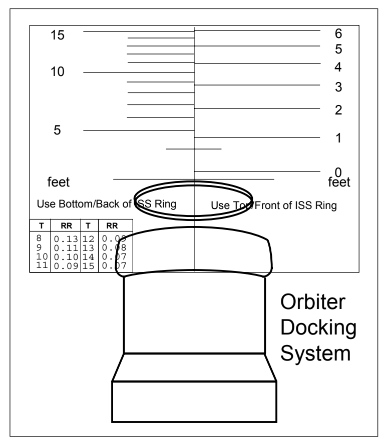

Figure 9 Space Shuttle camera ranging ruler overlay for use during docking with the ISS.

The Crew Optical Alignment Sight (COAS, Figure 10), flown on the Apollo CSM, Apollo LM, and Space Shuttle has proven to be an effective tool for pointing the vehicles during proximity operations and as a backup method of pointing during burn execution and IMU alignment. COAS subtended angles are a backup method of range determination during proximity operations. However, the ability to derive range from subtended angles is dependent on the target maintaining a desired attitude, and orbital lighting conditions. Furthermore, range determination using subtended angles can only be performed at relatively close ranges, and is not accurate enough to meet capture envelope requirements for successful docking. A timer to manually compute range rate from subtended angle range measurements over a time interval has proven to be a simple and effective tool for manual proximity operations piloting.

Changes in mission requirements and performance limitations not apparent during the DDT&E phase may require that additional hardware, software, and tools be added to a vehicle. The original 1970s era shuttle rendezvous architecture was designed for an operations concept that included the same high energy inertial final approaches to the target that were flown during Gemini and Apollo. However, new final approach techniques were developed for shuttle proximity operations that did not subject targets to the high level of RCS jet plume impingement inherent with the legacy Gemini and Apollo final approach. To enable the crew to more effectively fly these techniques, maintain situational awareness, and reduce propellant

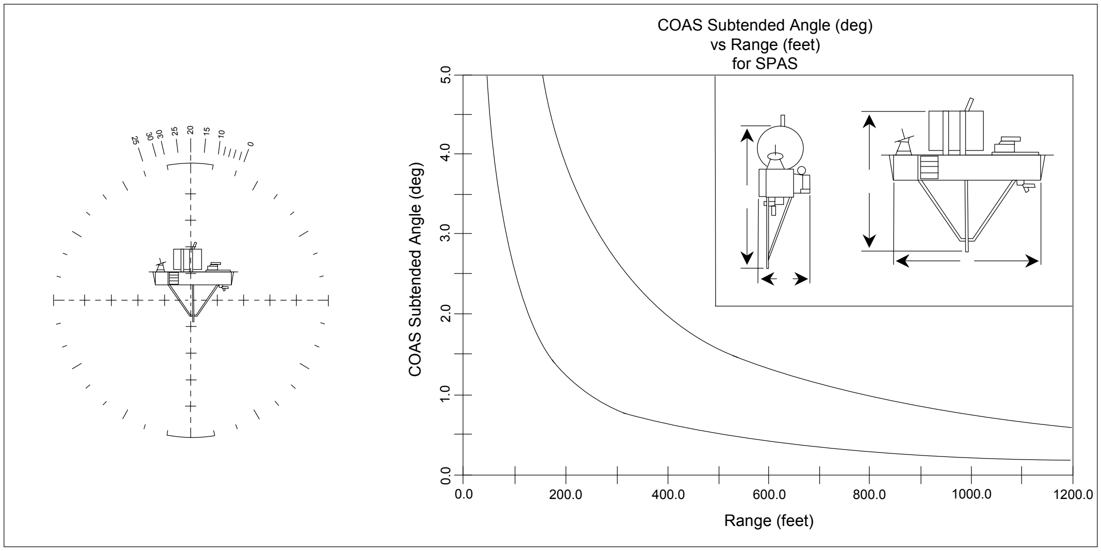

Figure 10 COAS (left) and subtended angles range chart (right) from STS-39 (April-May 1991).

consumption, new proximity operations sensors and new piloting software were added to the shuttle. These tools were the Rendezvous and Proximity Operations Program (RPOP) software, the Trajectory Control Sensor (TCS) lidar, and the Hand Held Lidar (HHL).[3-5] To reduce costs, these new tools were not integrated into the baseline, certified avionics system. They were also not certified to the same level of criticality as the baseline avionics. The legacy rendezvous radar backup techniques, using simple tools, continued to be available in the event of software or sensor failures.

Simple tools are useful as backup during manual piloting or for cross-checking the performance of automated piloting. However, simple tools are not a replacement for more robust and capable relative sensors. The use of simple tools and any associated procedures and mathematical calculations, such as computing range rate by hand, can increase the number of tasks performed by the crew. Operational workarounds, either complex and labor intensive or straightforward, and simple tools can be used to avoid short term hardware and software procurement and modification costs. However, they are not an option if automation, autonomy, and limited crew size requirements are to be met.

CHASER AND TARGET VEHICLE INTEGRATION

Chaser and target spacecraft must be considered an integrated system even before docking or capture occurs. Spacecraft systems not directly concerned with rendezvous and proximity operations can affect planning and operations concepts. Non-rendezvous or generic target system constraints might drive requirements on the chaser systems and trajectory. Shuttle and target non-rendezvous systems are examined for impacts to rendezvous, proximity operations, and capture.

Personnel designing a chaser spacecraft actively investigate the suitability of systems on the target spacecraft that are desired for use by the chaser, such as power, communications, or thermal control. Use of systems on both vehicles during RPOD requires early coordination between systems owners and operations concept developers. Target spacecraft systems may require modifications to support the chaser. The chaser program will have to initiate negotiations with the target spacecraft owner to use the systems in question.

Target and chaser vehicle owners need insight into each other's systems and must understand the roles played by various agencies and contractor organizations to ensure mission success and manage risk. Chaser spacecraft designers may not understand the role the target vehicle owner plays in managing risk and ensuring safety. There is a legitimate need for the target vehicle owner to have insight into chaser vehicle systems design and operation. This insight is necessary when coordinating chaser and target vehicle timelines for configuration of vehicle systems for docking or capture. In addition, systems insight is required for the development of contingency procedures.

Table 1
Vehicles That Dock With The ISS

Type	Vehicle	Year		
		2008	2009 A	2010 A
Human Missions	Space Shuttle	4	5	3
	Soyuz	2	4	4
Robotic Missions	Progress	4	6	5
	ATV	1		1
	HTV		1	1
	COTS		1	1

A Planned and subject to change.

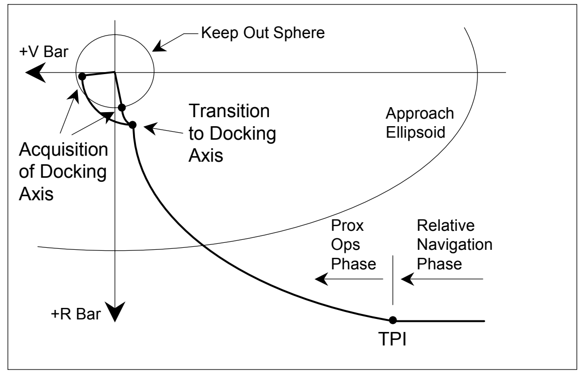

Figure 11 Orion proximity operations relative motion is constrained by the Approach Ellipsoid and Keep Out Sphere.

Four vehicles currently dock with the ISS (Table 1). These are the Space Shuttle, Soyuz, Progress, and the Automated Transfer Vehicle (ATV). In the future the H-II Transfer Vehicle (HTV), Orion, and Commercial Orbital Transportation Services (COTS) vehicles will dock with the ISS as well. Missions to the ISS, from multiple space agencies, present NASA with a complex integration task. Differing cultures, languages, and preferred vehicle design and operations best practices of ISS international partners further complicates ISS mission integration. In addition, export control regulations place restrictions on information exchange between international partners.

The integration task includes ensuring that vehicle missions and systems requirements are compatible with the ISS, and that vehicle systems will enable safe and successful proximity operations under a variety of performance conditions. To ensure safety during proximity operations with automated and robotic vehicles the ISS Program has defined volumes of space around the ISS known as the Approach Ellipsoid and the Keep-Out-Sphere. Specific requirements have been defined governing when visiting vehicles (ATV, HTV, Orion, and COTS) may enter these volumes and what relative motion under nominal and off-nominal conditions is acceptable (Figure 11).

Maintenance of ISS orbital altitude must be performed to provide launch windows for these vehicles, as well as to avoid orbital debris and counter-act orbital decay due to atmospheric drag. Propulsion systems of docked spacecraft, such as the Space Shuttle, ATV, and Progress may be used for orbit raising maneuvers.

Analysis of attitude control of the mated stack after docking is performed. This requires a detailed understanding of attitude control systems on both vehicles. Of particular importance is the comprehension of the failure safe modes for both spacecraft. These failure and safe modes impact planning for contingency procedures for the proximity operations phase. The impact on RPOD of systems and component failures on either spacecraft must be investigated and data to be exchanged and spacecraft-to-spacecraft commanding capabilities during RPOD defined. Items to be negotiated include safe approach and departure trajectories, permission to enter volumes of space surrounding the target spacecraft to perform final approach, use of target systems for relative navigation, and data transfer (including systems status) between vehicles and flight control centers.

Thermal issues on a spacecraft can restrict attitudes that can be flown. This in turn can limit relative navigation sensor activities. Inadequacies in these systems will result in thermal problems, thermal related mission constraints, and delays in gaining access to a spacecraft after mating. Chaser and target vehicle power generation constraints can also restrict available spacecraft attitudes.

Non-rendezvous systems impacts can include, but are not limited to: systems used by both vehicles while mated, space-to-space communications links under nominal and off-nominal scenarios, availability of ground or satellite communications links, solar array visibility to the sun, radio-frequency hazards that create antennae pointing constraints, gaseous or liquid vents and dumps, thermal control; and spacecraft orientation requirements during free or mated flight due to concerns with plume impingement (contamination, static and dynamic loads, thermal), attitude control, antennae or sensor visibility, and structural clearance. Plume impingement concerns for solar arrays or radiators may force deactivation of some RCS jets used during approach and capture.

Spacecraft operations concepts may assume that on-board and ground software will no longer be modified once a vehicle is operational. Experience from past programs indicates that ground and on-board software will evolve throughout a program, particularly on-board software associated with flight control, capture mechanisms, and robotics. Impacts of software changes and hardware upgrades on chaser and target vehicles and supporting ground systems must be assessed.

VEHICLE DESIGN

Development and operational challenges in the more safety critical areas of ascent and entry may limit the remaining resources devoted to developing and certifying rendezvous and proximity operations capabilities. The Space Shuttle was not optimally designed for rendezvous and proximity operations. Mission plans, procedures and additional hardware and software were developed to permit accomplishment of various missions, but with higher operational costs and complexity. A vehicle with limited systems to support RPOD can still perform RPOD missions through creative mission planning and procedural development. However, limited RPOD capability can result in more operational complexity, increased life cycle costs, and increased risk to mission success.

Redundancy in both rendezvous/proximity operations systems and non-rendezvous/proximity operations systems raise the probability of mission success in the presence of systems failures or dispersed trajectories. Generic system redundancy can lower the probability of a generic system issue affecting rendezvous or proximity operations. A "minimalist" design, meaning non-redundant systems and limited systems capability, may be perceived to be attractive from the standpoint of reducing development and operations costs. However, such a vehicle has a high risk of mission failure and may even have risks associated with flying a nominal mission with expected dispersions. Low levels of redundancy and minimal system performance margins complicate mission planning and increase life cycle costs.

Accounting for servicing and assembly considerations will impact vehicle design. Whether a vehicle is envisioned for robotic-only interaction or human EVA interaction, these capabilities will drive the design of many aspects of the vehicle. This is true even for systems that are seemingly unrelated to servicing and assembly, such as electrical systems, thermal control, and avionics. Systems normally thought of as being uninvolved with servicing will be forced to accommodate issues such as mass limitations, volume constraints, contamination potentials, etc. Therefore servicing capability imposes requirements upon vehicle design. The importance of including EVA, robotics, and RPOD operational expertise from the onset of the design process cannot be over-emphasized.[6]

INTEGRATING RENDEZVOUS AND PROXIMITY OPERATIONS SYSTEMS

Selection, design, integration, and operation of systems that perform specific rendezvous and proximity operations tasks require a thorough understanding of mission requirements. These systems may primarily be located on the chaser or may exist at varying levels of integration on both the chaser and target vehicles. Division of rendezvous/proximity operations systems and tasks between the spacecraft is an important consideration. A target may only possess mating hardware compatible with the chaser or, at the other extreme, may perform rendezvous maneuvers in coordination with the chaser and have active relative navigation sensors of its own.

Use of only ground radar measurements for chaser spacecraft orbit determination constrains maneuvers to be planned around periods of chaser visibility to ground tracking stations. Such opportunities may not occur on every orbit. The use of space based tracking, such as TDRSS or GPS, in conjunction satellite communications, removes this constraint and permits more flexible mission planning.

Relative navigation sensors may drive requirements for other systems. Those systems involving radio-frequency transmission may have restrictions due to radiation exposure limits of other systems on the chaser, target, or even astronauts. Radio-frequency reception may be affected by multi-path from the chaser and target structure and may require steps to minimize multi-path, such as solar array feathering. Attitude requirements may also be driven by the systems.

Relative navigation sensor placement for minimizing the heat path during entry and landing may degrade sensor performance. Not minimizing the heat path may prevent sensor re-use on a later mission. Significant maintenance may have to be performed to return the sensor to a flight worthy condition. Mass and volume constraints will also drive the selection of relative sensors. The type and level of redundancy may drive a need for more complex software algorithms to support redundancy management.

Relative sensors may also support multiple applications. The Apollo CSM sextant was used for IMU alignment, cis-lunar navigation, lunar landmark tracking, and relative navigation during rendezvous. The Space Shuttle star trackers are used for IMU alignment and relative navigation. The Space Shuttle rendezvous radar antenna is also used for communication with the TDRSS satellites. Multiple uses for hardware can reduce mass, volume, and development costs. This will require coordination between multiple systems owners to ensure that performance requirements will be adequate and that conflicting operations requirements do not compromise the ability of the spacecraft to meet mission objectives.

Priorities and procedures for shared use of sensors and other RPOD systems must be coordinated to permit successful operations. Sharing sensors between applications can also complicate spacecraft system upgrades after the flight phase of a program has begun. A communications system may provide critical measurements for relative navigation, and may support vehicle inspection or public affairs as well. Cameras may be used for several tasks that may have conflicting requirements. Optimal placement of cameras to support a task, such as an EVA, may not be optimal to support proximity operations piloting.

Propulsion system design may be driven by factors that have higher priority and more criticality than RPOD considerations. These include control authority during ascent and entry, as well as plume self-impingement on solar arrays and other spacecraft structure. Propulsion system design that is not optimal for RPOD can result in plume impingement on target spacecraft, cross coupling, excessive propellant consumption, lengthy burns, thermal constraints on RCS jet operation, insufficient control authority, and insufficient redundancy. Plume impingement can result in undesirable target spacecraft rotation and translation that the target spacecraft may not be able to counteract. This can result in compromise of structural integrity and contamination of sensors and scientific payloads. Procedural work-arounds to overcome these issues will complicate mission planning, risk management, and increase life cycle costs.

CONTINGENCY PLANNING

Space flight, robotic or human, is expensive, high risk, and highly visible to government leaders, the news media, and the public. Systems or performance anomalies may arise that can limit the ability of the spacecraft and crew to accomplish mission objectives. Mission failures, catastrophic or non-catastrophic, negatively affect users of spacecraft services and complicate the budget process. Designing spacecraft systems architecture and associated operations concepts to handle contingencies is a complex integration task.[7]

The overall rendezvous phase of a mission may vary in length from hours to days. During this time numerous issues may arise that require complicated, time consuming, and coordinated crew and Mission Control responses to ensure that mission objectives will still be met. More time is available during rendezvous to conduct anomaly investigations and formulate and implement work-arounds. This can complicate automation and autonomy considerations for contingencies. In contrast, ascent (~11.5 minutes for an Apollo Saturn V, ~8.5 minutes for the Space Shuttle) and re-entry (~14 minutes for an Apollo lunar mission, ~30 minutes for the Space Shuttle) are much shorter. Responses to performance anomalies during ascent and entry are more scripted than during on-orbit.

Non-catastrophic systems and dynamics issues can arise on-orbit, that could prevent successful completion of a mission or limit the time available for on-orbit activities (Table 2). While some types of system anomalies can be postulated during ground analysis pre-mission, other anomalies that can occur during a

Table 2
Anomalies That Can Occur During RPOD Missions

• degraded camera performance due to extreme variation in orbital lighting conditions	• optical sensor contamination
• misalignments due to uneven thermal gradients across work surfaces	• capture hardware anomalies
• bent pins from mating or demating of electrical connectors	• communications difficulty
• failed mating attempts that induce multi-axis rates	• thermal control problems
• RCS jet or other propulsion system failures	• artificial lighting failures
• degradation of materials on-orbit	• trajectory perturbations
	• power system failures
	• fluid coupler leaks
	• stuck fasteners
	• sensor failures

mission cannot be as easily postulated. Systems anomalies can cause performance degradations that cascade throughout multiple spacecraft systems.[**]

The level of operational flexibility of a spacecraft and ground support system will determine the ability to respond to unanticipated failures. A program should assess the criticality of vehicle operations and determine how much preparation is required to handle in-flight anomalies. Ensuring the success and safety of high risk, high profile space flight operations such as the Space Shuttle and ISS requires planning for contingency operations and work-arounds to protect against systems failures. Contingency planning requires participation of personnel from any number of chaser and target vehicle disciplines. However, other programs, such as robotic vehicles, may be willing to accept a higher risk of mission failure and may not have to go to such extraordinary lengths to ensure mission success.

For example, Shuttle ascent propulsion problems (such as an early main engine shutdown) may limit the ability of the Shuttle to fly the planned rendezvous profile to the ISS. Contingency plans, coordinated with the Russians, have been developed for the ISS to lower its orbit to accommodate a revised Shuttle rendezvous profile.[9] Numerous CSM or LM active rendezvous contingency plans were developed for the Apollo lunar missions in the event of LM performance problems that prevented execution of the nominal rendezvous profile.

Hardware or software anomalies on either spacecraft could force development of alternative procedures before launch or at any time during flight.[7] The impact of an anomaly is assessed before implementing a fix or procedural work-around. The impact may be less than initially thought, and a proposed fix or work-around could have worse implications than the original anomaly.

APPLYING LESSONS LEARNED TO RPOD INTEGRATION

Mitigating cost, schedule, and technical risk is facilitated by studying lessons learned and experiences of legacy programs.[8] Of particular interest are the challenges that were encountered during the DDT&E and flight phases, and how these challenges were eventually overcome. Two of the four examples in this section, late addition of VHF ranging to the Apollo CSM and Space Shuttle plume impingement, highlight the importance of early and thorough evaluation of vehicle design impacts on RPOD performance. Early identification of design issues that may prevent the spacecraft to meet performance requirements should be made to permit resolution of the issues during the DDT&E phase.

Late Addition of VHF Ranging To the Apollo CSM

Most spacecraft development programs undergo requirements and vehicle design scrubs to improve margins in areas such as weight, thermal control, and software. However, it is important to ensure that vehicle systems will still possess sufficient performance to meet requirements after the scrub is completed.

The original CSM design included a rendezvous radar to support contingency CSM active rendezvous with a disabled LM in lunar orbit. However, the CSM radar was deleted in the fall of 1964 during a weight reduction effort. Alternate means of obtaining range measurements were studied, such as modification of

[**] Reference 8, *Lessons Learned From Seven Space Shuttle Missions*, contains examples of the use of contingency procedures and the unanticipated impacts of performance degradation through multiple systems.

the CSM/LM Very High Frequency (VHF) communications system. However, at the time it was believed that the use of only the line-of-sight angle measurements provided by the CSM sextant was sufficient to support contingency CSM rendezvous with the LM. By the summer of 1967, studies revealed that the CSM pilot did not have enough time to acquire a sufficient number of sextant marks. In addition, an insufficient amount of propellant was available to support sextant only relative navigation. Ground tracking was not considered a viable alternative due to unexplained perturbations in Lunar Orbiter spacecraft tracking data, later identified to be the result of lunar mass concentrations. Several means of obtaining relative range measurements were studied. In September 1967, the Apollo Program issued direction for the modification of the CSM VHF communications system to supply range, and modification of the Entry Monitoring Subsystem to display range data to the CSM pilot. VHF ranging was first flown on the Apollo 10 (May 1969) mission to the Moon.

Late Recognition of Space Shuttle Plume Impingement

It is particularly important to research and understand the impact of new vehicle design characteristics on performance. An example of this is the Space Shuttle plume impingement issue. From March through June of 1973, a total of 491 human-in-the-loop simulations were conducted to evaluate Space Shuttle docking with a notional space station. The objective was to determine if any changes to the Preliminary Requirements Review (October 1972) baseline orbiter design were required in the areas listed in Table 3.

Based on the study, many recommendations were made concerning docking contact conditions, crew displays, crew station arrangement, cameras, stand-off cross targets, sensor data, target vehicle attitude control, orbiter flight control modes, RCS jet selection, propellant consumption, and cross coupling. The study concluded that more simulations were needed to take into account changing orbiter systems configuration during the DDT&E phase so that docking requirements could be more precisely and realistically defined.

Also in 1973 shuttle RPOD personnel became concerned about the possibility of RCS jet plume impingement contamination of target spacecraft and associated scientific payloads and other sub-systems.[1] The size of the orbiter RCS jets was much larger than the Gemini and Apollo jets. However, the implications of plume impingement on RCS system design were not examined in the 1973 docking simulation effort (Table 3). Plume impingement math models for simulations did not become available until 1976.

Table 3
Topics Examined During 1973 Space Shuttle Docking Study

- Maneuver rates
- Required minimum impulse for translation and rotation
- Flight control requirements
- Attitude hold requirements
- Effects of control modes on center of gravity variations
- Target motion
- Hand controller location and logic
- Reduced RCS thrust levels
- Target displays
- Range, range rate, and attitude display requirements
- Station-keeping
- Docking contact criteria
- RCS propellant requirements

By April of 1977 the concern about plume impingement impact on the ability of the shuttle to meet basic requirements for rendezvous with and retrieval of satellites was receiving attention from upper level program management. This occurred after completion of much of the DDT&E phase, and well after the February 1975 shuttle Critical Design Review. Not only was contamination of target vehicle systems a concern, but plume induced target rotational and translational motion could prevent shuttle crew members from grappling the target using the Remote Manipulator System. Methods of attitude control of some target spacecraft may not have been able to counteract the effects of plume induced dynamics.

A considerable effort was undertaken by the Shuttle Program to develop new trajectory and piloting techniques and to identify potential shuttle hardware and software modifications to overcome the plume impingement issue. New piloting and trajectory techniques were developed as part of the newly defined “proximity operations” phase of rendezvous. The orbiter flight control system software was modified to perform braking with a set of RCS jets that lowered the risk of plume impingement. A local vertical local horizontal attitude hold mode was also added. Shuttle hardware modifications and associated DDT&E impacts were avoided. The development and verification of custom proximity operations trajectories and piloting techniques, for most shuttle missions involving RPOD, increased mission operations life cycle costs over the life of the Shuttle Program. While the 1973 docking study examined many important areas of vehicle performance (Table 3), it was another four years before the plume impingement issue and the negative impact on shuttle RPOD performance was fully understood at higher levels in the Shuttle Program. This recognition came too late to influence vehicle design.

Balancing Automation, Autonomy, and Authority

Automation, autonomy, and the authority of crew and ground personnel to control spacecraft operation are important aspects of spacecraft and operations concept design. Automation is the ability of the vehicle to operate without human control and intervention, but the crew or ground may serve in an oversight role and provide input and control if required. Autonomy is the ability of a vehicle to perform a function without external support. For a human spacecraft autonomy is not limited to on-board systems, but also includes troubleshooting and decision making activities by crew members. Authority is the ability of the crew and ground personnel to exercise control of vehicle systems under both nominal conditions and off-nominal conditions caused by performance anomalies or failures.[2] [††]

The level of automation or autonomy and division of tasks between the crew, onboard flight computer, and Mission Control varies based on the flight phase and complexity of the tasks. An appropriate balance between crew and ground authority, spacecraft automation, and spacecraft autonomy is required to ensure mission success, safety of flight, and to lower risk to cost and schedule during the vehicle development phase. However, the appropriate balance is not necessarily the same for all vehicles and missions.

The 2007 Orbital Express mission was a technology demonstration of autonomous and automated robotic serving, rendezvous, and proximity operations. However, attitude control, computer, and sensor issues arose that threatened the success of the mission. Orbital Express ground personnel had enough authority to re-plan the mission, correct software problems, and implement procedural work-arounds to address the performance issues. In spite of the problems encountered during the mission, Orbital Express accomplished objectives for autonomous and automated rendezvous, proximity operations, and robotic servicing. Orbital Express is a good example of a mission that had an appropriate balance of automation, autonomy, and authority.[10]

By the 1980s the Russians regularly performed automated rendezvous and docking with the Salyut space stations, although manual dockings were occasionally performed in response to systems anomalies during proximity operations. During the Soyuz T-8 mission to dock with Salyut 7 in April of 1983, the on-board Igla system did not supply relative measurements required to support either automated or manual rendezvous and docking. In spite of the lack of relative sensor data, the plan was for the crew to fly proximity operations and docking using only the periscope and verbal piloting cues provided by flight controllers on the ground. While ground-based precision orbit determination placed Soyuz T-8 within 1 kilometer of Salyut 7, the crew was not able to sufficiently control relative motion to achieve a safe final approach and docking. The next mission, Soyuz T-9, successfully docked with Salyut 7.[11]

In June of 1985 the Soyuz T-13 spacecraft was launched in an attempt to dock with and reactivate the Salyut 7 space station after a loss of telemetry. Like the Soyuz T-8 mission, data from the Igla sensors were not available to support either automated or manual rendezvous and docking. Nor was Salyut 7 able to control attitude to support the docking. However, precision orbit determination by Russian Mission Control, improved manual piloting training, and the use of a laser rangefinder and night vision device by the crew enabled the Soyuz T-13 to successfully dock with Salyut 7. The crew later returned Salyut 7 to an operational configuration. Additional manual approaches to Salyut 7 were flown by the Soyuz T-13 crew at the end of the 3 month mission to further evaluate manual approaches.

In 1986 the Russians began flying the upgraded Soyuz TM spacecraft. The automated rendezvous and docking capability was improved with the Kurs system replacing Igla. Manual piloting was improved as well. A forward looking window was added to the Soyuz orbital module to improve situational awareness beyond that provided by the periscope. A second set of translational and rotational hand controllers was added to the orbital module as well. A laser rangefinder and a night vision device also became standard equipment.[11] The current Soyuz TMA is similarly equipped.

In summary, the Russians upgraded both the automated and back-up manual piloting systems for Soyuz. These upgrades, along with expanded crew training, resulted in a balance of automation, autonomy, and authority that could better ensure mission success in the presence of system failures.

†† Reference 2, "Challenges of Orion Rendezvous Development," contains a more detailed discussion of automation, autonomy, and authority. The appendix of the paper describes the levels of automation in the Mercury, Gemini, Apollo, Space Shuttle, and Orion vehicles.

Sensor Risk Reduction Through Flight Testing

NASA personnel studied the lessons learned and experiences of several flight programs with relative navigation sensors. Experience has shown that it is difficult for a ground test facility to duplicate all aspects of the space environment that impact relative sensor performance. On-orbit testing may be required in addition to ground testing, to subject new hardware and software to a wider range of flight conditions than can be performed on the ground. As a result NASA has proposed a test of Orion RPOD sensors on the STS-133 Space Shuttle Mission to the ISS (Figure 12). The test would fly part of the Orion rendezvous and proximity operations profile after the orbiter has separated from the ISS.

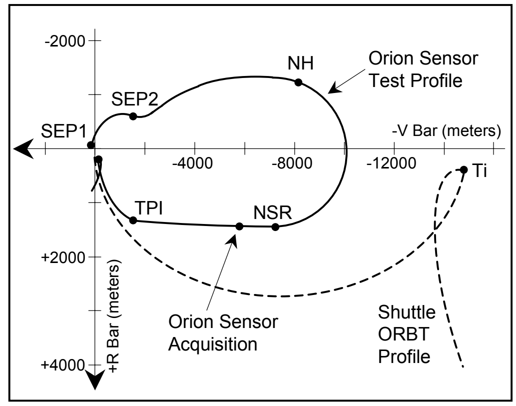

Figure 12 One of several proposed profiles for a Space Shuttle test of Orion sensors.

INTEGRATED TEAMS

The successful integration of new and legacy technology and development of spacecraft systems, operations concepts, mission plans, and successful execution of a mission depends on team work. The contribution of integrated teams to the technical success of a flight program applies to both human and robotic spacecraft. The success of RPOD development and operations in the Gemini, Apollo, Skylab, Apollo-Soyuz, Space Shuttle, and ISS Programs was in part due to the existence of integrated teams. Personnel freely communicated across corporate and civil servant/contractor boundaries in a badge-less, collaborative work environment. In addition, the participation of other nations in a flight program, such as the ISS, requires open communication and team work across cultural and language barriers.

Open communication of technical details between development and operations personnel was conducted on these programs, and is essential to mitigate risk. Availability of requirements, source code, and details of technical issues to all participants for a variety of on-board and ground systems led to widespread understanding of system requirements and technical difficulties. Software requirements and source code were custom developed for space flight and were not proprietary. Comparisons of simulation data among civil servant and contractor organizations helped debug simulation software and led to rapid identification and resolution of performance issues and avoided problems that required re-work to be performed.

Team work and development of an integrated crew timeline is an important factor in the successful execution of RPOD, servicing, and assembly tasks by astronauts. Rendezvous and proximity operations tasks may not be the only activities performed by a crew. This is particularly true of the Space Shuttle (Table 4). Most Shuttle missions also fly multiple secondary payloads. These payloads are lower in priority than the primary payload, but have the same priority relative to each other in terms of requirements for crew time and spacecraft resources such as thermal control, communications bandwidth, and power. Tasks associated with the primary payload and secondary payloads are often worked by crew members in parallel with RPOD preparation and procedure execution. Some shuttle missions performed dual shift crew operations during RPOD, as depicted in Figure 13 from the STS-66 mission. Integration of secondary payload and house-keeping tasks, RPOD tasks, available crew time, and resource requirements such as attitude, over flight of ground stations, or maneuvers during crew sleep periods must be coordinated before and during the flight.

During servicing or assembly, the concept of an “EVA mission within a space mission” dictates the need for the crew and ground personnel to function as a highly integrated team during RPOD, servicing, and assembly hardware development, pre-flight planning, and real-time mission execution. Independent timelines for servicing or assembly are performed within the overall mission timeline. Crew members and teams on the ground must concurrently manage proximity operations piloting, space suit life support systems operational verification/activation, EMU donning by crew members, EVA tools assembly/checkout, robotics systems activation and checkout, plus in-suit pre-breathing for decompression sickness prevention. These tasks would be impossible without interdisciplinary coordination and communication.

Table 4
Major Shuttle Crew Activities During ISS Rendezvous

Flight Day 1	Flight Day 2	Flight Day 3
• Crew Wakeup at KSC	• Post-Sleep Activities	• Post-Sleep Activities
• Suit Up	• OBSS Unberth	• Maneuvers & Piloting
• Travel to Launch Pad	• Starboard TPS Survey	• Docking
• Crew Ingress	• EMU Checkout	• Leak Check
• Launch and Ascent	• Nose and Port TPS Survey	• Hatch Opening
• Post Insertion Activities	• OBSS Berth	• Safety Briefing
• Cockpit Setup	• Maneuvers	• OBSS Unberth
• Maneuvers	• Docking System Checkout	• OBSS H/O to RMS
• RMS Checkout	• Rendezvous Tools Checkout	• Pre-Sleep Activities
• Pre-Sleep Activities	• Pre-Sleep Activities	• Sleep
• Sleep	• Sleep	

EMU – Extra Vehicular Mobility Unit, **H/O** – Hand Over, **KSC** – Kennedy Space Center, **OBSS** – Orbiter Boom Survey System, **RMS** – Remote Manipulator System

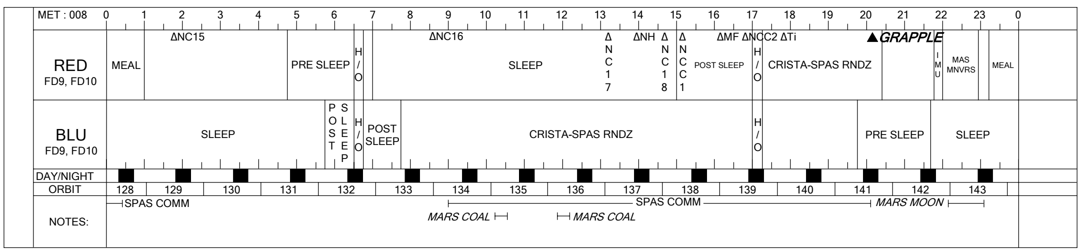

Figure 13 Crew timeline for the CRISTA-SPAS rendezvous and grapple on STS-66 (November 1994). Note the dual shift (RED and BLUE) crew operations, rendezvous maneuvers (NC15, NH, etc.) during crew sleep, and grapple with both shifts awake.

RPOD, EVA, robotics, and other personnel at Mission Control and other ground locations must function in multiple roles. They are, first and foremost, working as part of the larger mission team. Any activity or issues arising with the chaser or target spacecraft must be monitored for impacts to the servicing and assembly objectives. Simultaneously, during execution of the proximity operations, EVA, and robotics timelines, the same personnel must monitor their own separate "spacecrafts." These are the chaser, target, and EVA crew members.

SUMMARY

RPOD integration is a far more complex problem than treating propellant-optimal trajectories, relative sensors and navigation, and docking/capture mechanisms as separate, unrelated disciplines. The success of NASA human flight RPOD since 1965 is due to the coordination of system development, vehicle integration, and mission planning efforts of multiple, seemingly unrelated spacecraft and ground disciplines. Involvement of specialists outside of disciplines traditionally associated with rendezvous and proximity operations is required. These include not only specialists in EVA, robotics, and docking hardware, but extend to virtually every discipline associated with designing a vehicle and flying a mission.

Early detection of performance issues and constraints requires a thorough understanding of mission requirements and involvement of knowledgeable personnel representing all spacecraft systems. Integrated requirements for both vehicles have to be defined and managed. This can become complex as it usually involves multiple contractors and government agencies. Many constraints on systems and operations concepts may not be discovered until after the DDT&E phase is well underway or even after flights have begun. Additional constraints may be discovered as mission requirements evolve or new requirements are introduced over the life of the flight program.

Integrated teams, open communication, detailed knowledge of spacecraft systems, and use of various types of simulations are required for effective mission planning, procedures development, and anomaly resolution. Sufficient consumables, systems redundancy, and control margins must exist to handle failure modes and off-nominal performance issues. These anomalies are unanticipated and, most assuredly, inevitable, and often cannot be anticipated for inclusion in pre-flight simulations.

While current and future spaceflight programs will introduce new technologies and operations concepts, the complexity of integrating multiple systems on multiple spacecraft will remain. The RPOD systems integration task may become more difficult as increasingly complex software is used to meet automation, autonomy, and robotic operation requirements.

ACKNOWLEDGMENT

Gerald E. Miller of United Space Alliance provided insight into EVA and servicing considerations.

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Rendezvous Integration Complexities of NASA Human Flight Vehicles

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AAS GNC Conference
January 31 - February 4, 2009


YEARS
NASA

RPOD is often depicted as consisting of three unrelated disciplines:

1. Propellant-optimal trajectories
2. Relative sensors and navigation
3. Docking/capture mechanisms

RPOD is systems integration:

- absolute navigation
- attitude control
- automation
- autonomy
- avionics integration
- command & data handling
- communications
- crew timeline
- docking/capture hardware
- extra vehicular activity
- fault detection isolation reconfiguration
- ground systems
- human factors
- lighting
- logistics
- orbital debris
- plume impingement
- power generation
- procedures
- propellant-optimal trajectories
- propulsion
- redundancy
- relative navigation
- robotics
- sensors
- servicing
- software
- structures
- thermal control
- export control

absolute navigation

thermal control

attitude control

structures

automation

autonomy

software

avionics integration

servicing

command & data handling

robotics

Propellant-optimal trajectories

communications

redundancy

Relative navigation and sensors

crew timeline

propulsion

Docking/capture mechanisms

extra vehicular activity

procedures

power generation

export control

plume impingement

fault detection isolation reconfiguration

orbital debris

ground systems

lighting

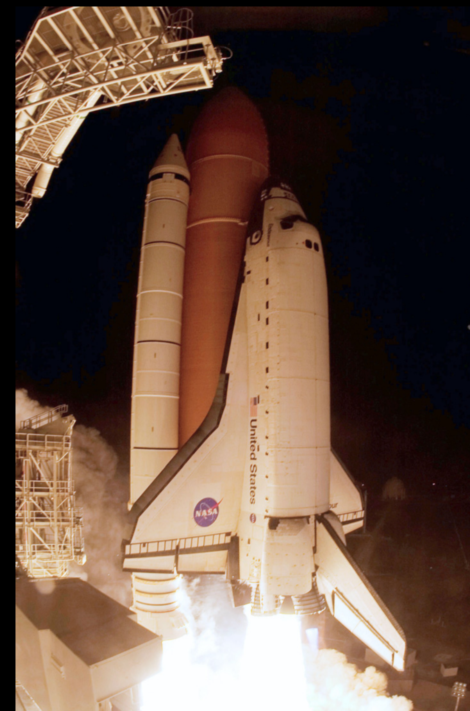
human factors

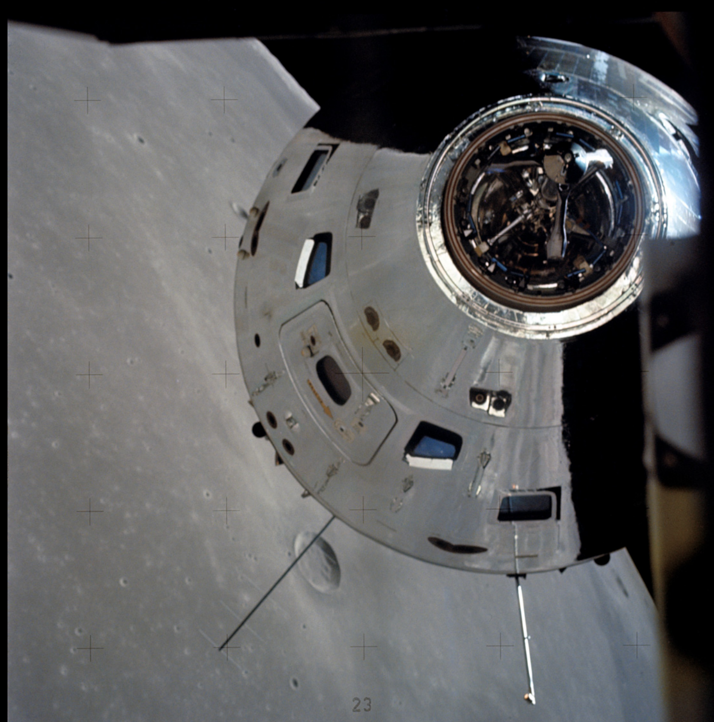
Phases of Rendezvous

Far Field

Near Field

Proximity Operations



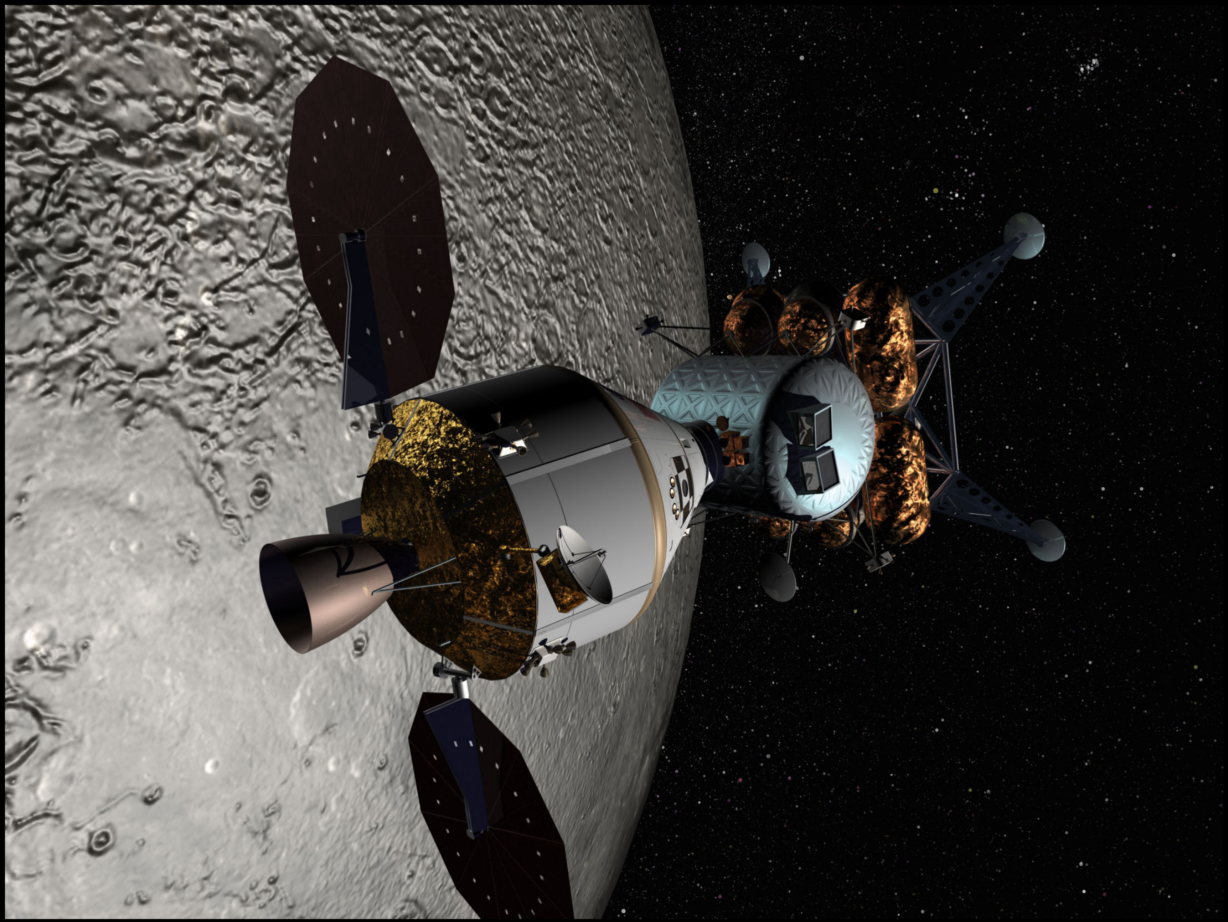


Examination of Requirements & Constraints

RPOD and non-RPOD Sub-Systems

The challenge of understanding evolving vehicle systems.

Competition between flight phases.

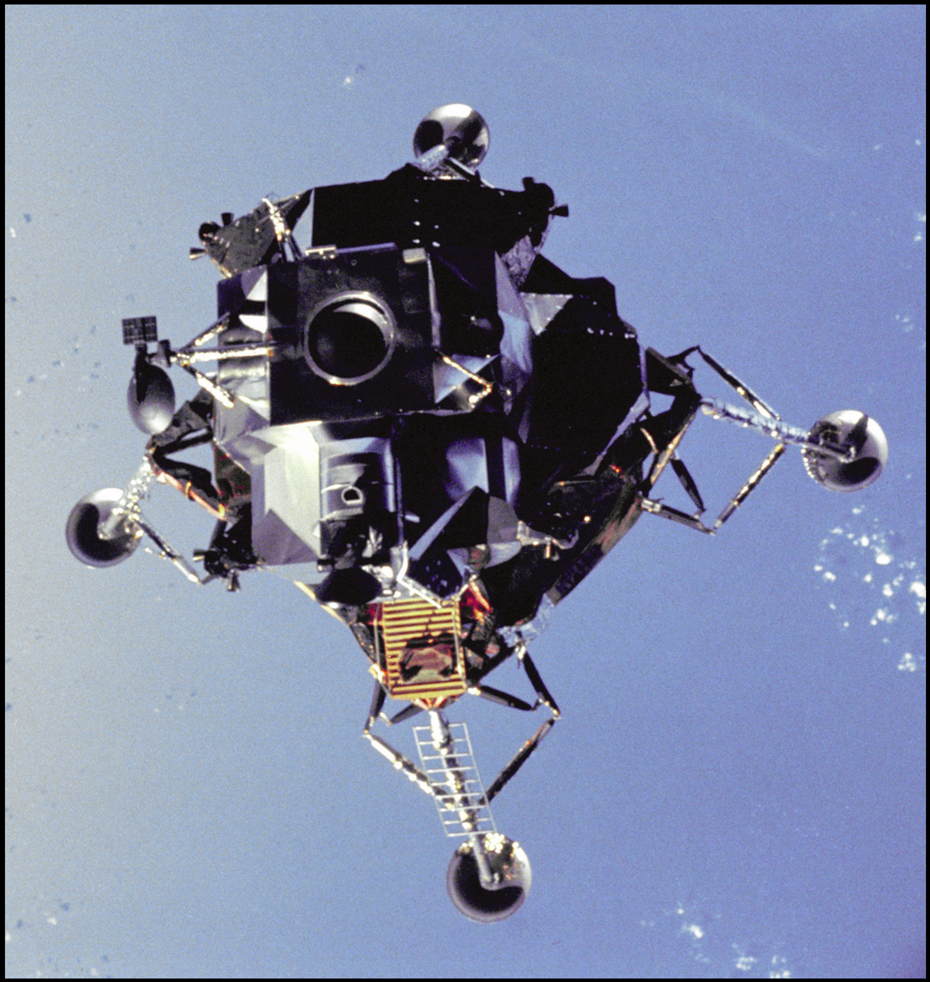


Integrating Legacy Hardware, Procedural Work-Arounds, & Simple Tools

Examining vehicle differences to identify risks.

Alternatives to overcome cost, schedule, & performance margin challenges.

Procedural work-arounds favored during DDT&E.



United Space Alliance

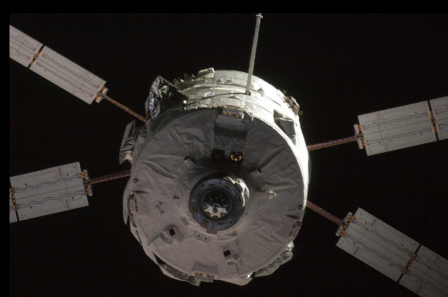
Legacy tools are robust but may not enable new vehicles to meet new requirements.

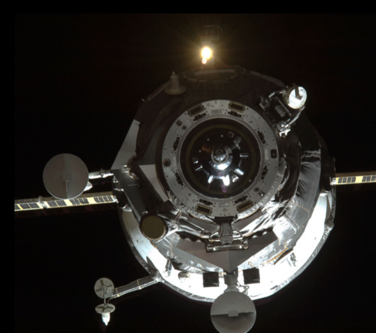
Chaser & target(s) are an integrated system.

Chaser & target personnel need insight into each other's systems.

Integration covers RPOD & mated flight.

Non-RPOD systems impacts can be mission planning, trajectory, & procedure drivers.



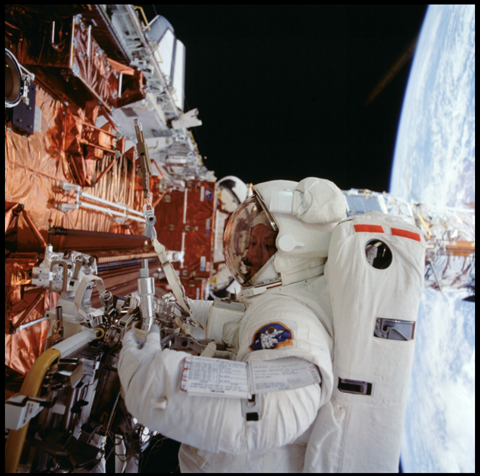


Vehicle Design

Competition with ascent & entry.

Resist the temptation to build a “minimalist” vehicle to lower DDT&E costs.

Servicing and assembly must be considered. This includes robotics and EVA.



Integrating RPOD Systems

Requires thorough understanding of requirements.

Division of tasks between vehicles.

Multiple users of hardware.

Priorities for shared use.

Sensor placement.

Propulsion design impacts.

Contingency Planning

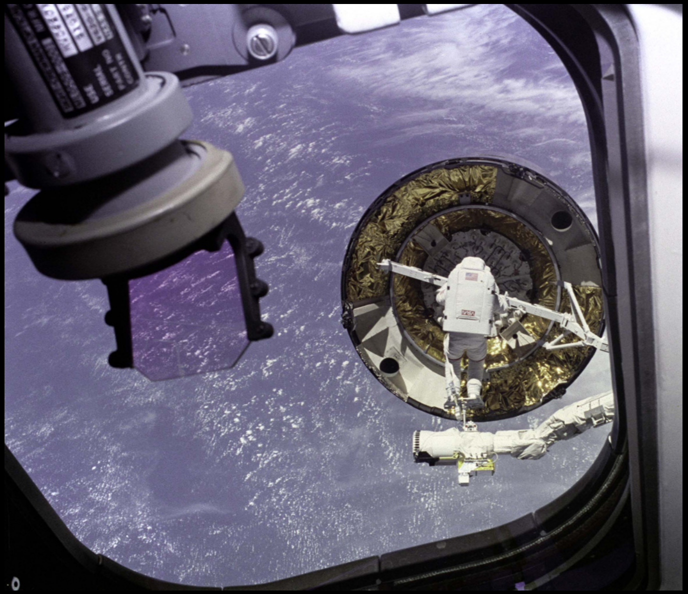
Space flight is high risk, high cost, and very visible.

Anomalies WILL occur that require contingency procedures.

More time available to work problems than ascent/entry.

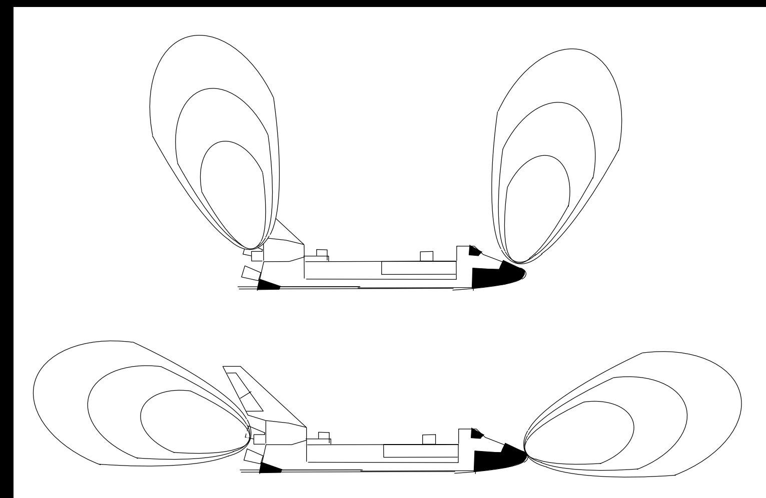
Many anomalies cannot be anticipated.

Vehicle and ground flexibility is the key to overcoming anomalies.



Applying Lessons Learned to Integration

Late recognition of Shuttle plume impingement.



Balancing automation, autonomy, and authority.

Autonomy

Automation — Authority

Successful integration of new and legacy technology depends on team work.

Badge-less, collaborative work environment.

Open communication.

Close coordination between multiple disciplines during DDT&E, mission planning, & flight.

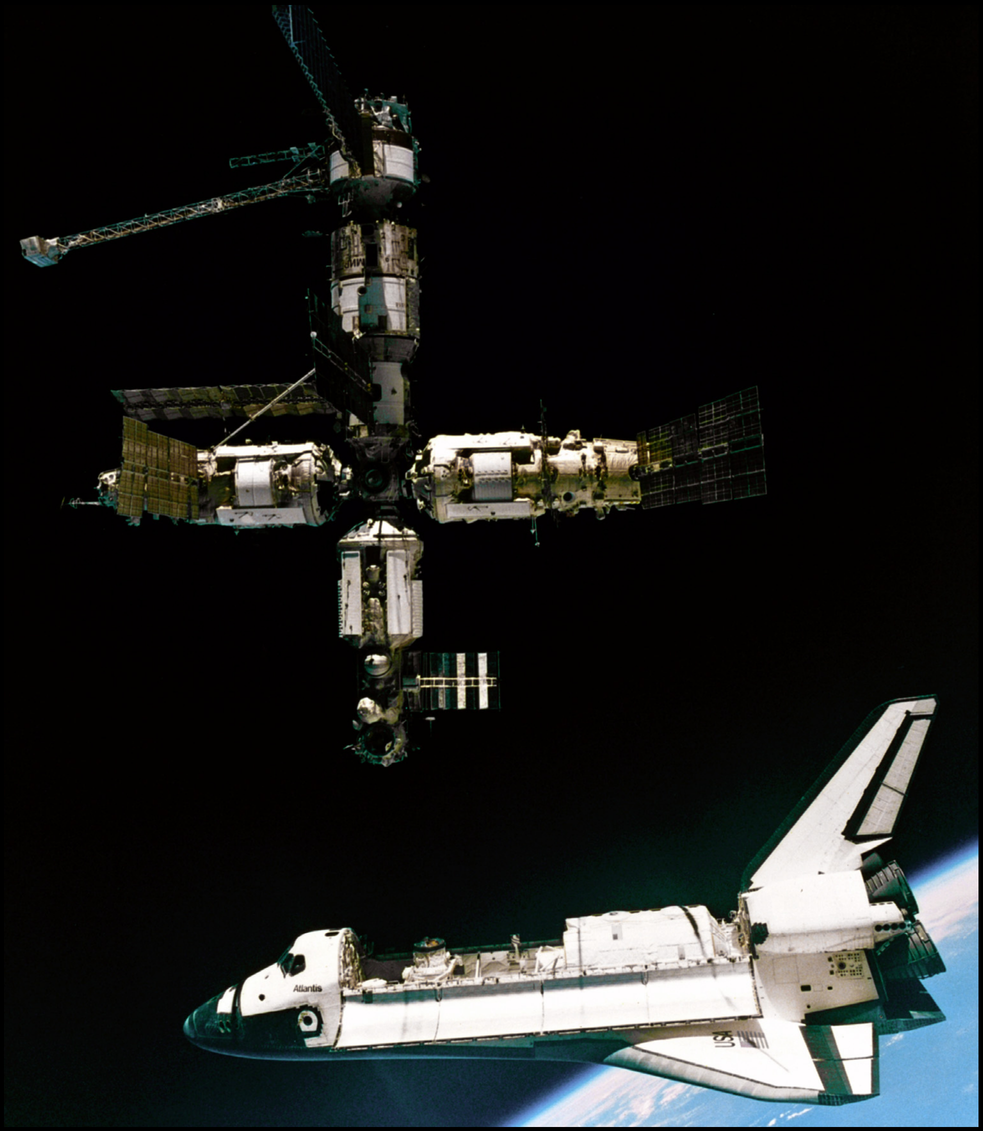
Summary

Close cooperation across multiple disciplines, government agencies, & contractors.

Early detection of performance issues & constraints.

Detailed knowledge of systems, requirements, & emerging constraints.

RPOD systems integration may become more complex with increasing level of automation & autonomy.



Questions