SPACE RENDEZVOUS & PROXIMITY OPERATIONS – SAFETY CRITICAL LESSONS

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ABSTRACT

Integrated spacecraft proximity operations and docking/undocking require multi-dimensional safety considerations and engender significant risk for loss of crews and vehicles. Among other factors, a key element and measure of operational success must be execution of the requisite engineering to certify and manage safety of flight. This effort will provide lessons that may be communicated, considered, and learned to inform planned and unplanned operations expected during lunar missions. It will focus on decades of evolutionary engineering and operations required by the NASA Space Shuttle Orbiter and space station operations. The narrative includes the evolution of engineering and operational methods starting in late 1984, transits the early days of the US space station program, pivots to the extraordinary Mir space station missions, and highlights the challenging times of early International Space Station (ISS) assembly culminating with the "Assembly Complete" milestone.

1. INTRODUCTION

Regardless of automatic or manual, human-rated spacecraft rendezvous, proximity operations and docking pose significant risk for loss of crews and vehicles. Safety of flight for these mission-critical events is paramount but not easily achievable; considerable attention and effort are necessary to maximize mission success and minimize risk. Among other factors, operational success must rely on the requisite engineering to certify and manage safety of flight.

Given automated system potential fallibility, the integrated NASA Artemis/Orion spacecraft flight operations and engineering teams are required (verify) to design, develop and certify a manual capability to safely effect successful rendezvous, proximity operations and docking with lunar mission target spacecraft (e.g. human lander systems). Thus, it follows that previous program experience can inform the embedded risks to meet the associated requirements. That requisite experience must be based on the evolutionary engineering and operations required by the NASA Space Shuttle Orbiter and low Earth orbit (LEO) space station operations – including Mir and, of course, the International Space Station (ISS) [1].

Over the span of 16 years (1995 – 2011), Space Shuttle Orbiters successfully and safely rendezvoused, approached, and docked forty-seven times with the Mir and International Space Stations. All of these missions were conducted (executed) with “humans in the loop” simply because, aside from attitude control, automation was not part of Orbiter on-orbit capabilities. This aggregate achievement was essential for progression and genesis of the ISS. The Mir missions were building blocks and keys to the success of the subsequent ISS missions. Remarkably, the first order elements of how to execute these complex operations/efforts were started in December 1984. This groundwork was based on the (then) highest fidelity on-orbit simulation in the world (author’s opinion), the Systems Engineering Simulator (SES) at the NASA Johnson Space Center (Houston, Texas) [2]. Initially used for Shuttle mission payload/deploy/recovery flight crew training, the SES became the core engineering and operations tool to define, design and develop the Orbiter/space station performance criteria (requirements) necessary to safely effect rendezvous, proximity operations and docking.

2. BACKGROUND

Objectively, the human-in-the-loop (HIL) SES simulations were initially used to establish the “rules of the road” (acceptable docking velocity, lateral position misalignment, and relative attitude misalignment) given NASA astronaut test subjects (commanders/pilots). Key to simulation validity was that the SES was fitted with an Orbiter crew cabin aft flight deck that included decommissioned Orbiter flight hardware (hand controllers, television monitors/camera, control panels/switches, general purpose computer monitor/keypads, etc.). Long before the US space station “baseline” existed, the JSC engineering and mission operations teams were integrated as co-equal entities of the Rendezvous/Proximity Operations Working Group (RPOWG). This unprecedented cooperative teaming was one of the key program support entities to ensure flight readiness, mission success and operations safety. Over many years and hundreds of hours, the “crew-in-the-loop” recorded simulation data were used to identify the requisite sensors, vehicle guidance, navigation, and control capabilities to safely achieve docking, to inform the designs of the early US space station, and equally

important, to satisfy the need for future flight crew training and experience.

The Orbiter rendezvous/proximity operations design using a target-centered local vertical local horizontal (LVLH) reference for the space station was established before the 1984 SES simulation efforts. LVLH reference for the ISS would allow the Orbiter to conduct a direct line-of-sight approach and separation. This plan was not "free" as the ISS would be required to use active attitude control (reaction control system thrusters and fuel cost) to maintain the desired attitude relative to LVLH.

Given the US Space Station program evolution challenges, "teaming" with the Russian human spaceflight programs included the foundation for "flight readiness" to conduct joint Orbiter missions with the Mir space station. Virtually all of the US space station concept-of-operations for rendezvous, proximity operations and docking were easily adapted, and the NASA flight crew operations familiarization was effectively in place. The next big pieces of the effort were:

1) Operations development of all the mission specific training, flight procedures, checklists, simulation upgrades, etc.,
2) Engineering certification for Orbiter and Mir integrated operations to ensure vehicle worthiness (structures, attitude control stability, etc.) to safely conduct RNDZ/PROX OPS/DOCKING, "mated" attitude flight control, and UNDOCKING/SEPARATION,
3) Utilization of the Russian Androgynous Peripheral Attachment System (APAS) a["active" docking mechanism on the Orbiter and passive docking interface on the Mir modules, and
4) Formation of the Mir/Proximity Operations Working Group (POWG) and handover/integration of the ISS RPOWG to drive concept of operations (CONOPS) design and flight documentation products (RNDZ checklists, etc.) for the Mir missions.

In the same timeframe as the buildup to Shuttle/Mir missions, the ISS mission CONOPS and engineering certification accelerated given baselined ISS architecture/design and assembly evolution, integration of the Russian APAS docking capability and integrated ISS vehicle hardware partnership (the US and Russian "segments").

Common technical challenges to both the Mir and ISS architecture were the Orbiter-induced integrated loads and docking capture success. Both challenges were driven by the Orbiter vehicle design:

Orbiter primary thrusters (870 lb) were principally used for translation control (position and velocity) to guide the line-of-sight trajectory relative to the space station docking interface. The single string (zero failure tolerant) vernier thrusters (25 lb) were nominally used to control the Orbiter attitude. Primary thrusters were also used for Orbiter attitude control and all space station PROX OPS flight design assumed that the vernier thruster system would "fail-off" – this assumption and vernier thruster limitations would drive trajectory design and the constraints required to protect the space station solar arrays and radiators exposed to primary thruster firing exhaust plume impingement effects (pressure loads and exhaust effluent contamination).

Successful APAS docking capture was essential to prevent collision and excessive solar array/radiator plume impingement loads. The Orbiter design and APAS integration with the crew airlock in the forward section of the payload bay complicated the dynamics for successful capture given that the Orbiter mass centre was 30 to 40' aft of the docking mechanism. To maximize capture success (docking certification requirement 100% simulated), a pre-planned crew initiated primary thruster firing sequence was used to force capture thereby preventing the Orbiter from colliding with the Mir/ISS in the event of an APAS failed capture. Crew activation (push-button-indicator) of the thrust manoeuvre was time critical (~1 to 2 seconds relative to initial docking interface contact).

Separate from Mir, the ISS was beset with significant operational risk given the need to "feather" the US segment solar arrays and thermal control system radiators to mitigate/minimize Orbiter primary thruster [exhaust] plume impingement loads. These ISS flexible appendage load limits would significantly constrain the Orbiter flight control thruster configuration during approach to dock and undocking/separation. Management of the closing and opening velocities (given Orbiter thruster firing induced cross-coupling dispersions) was essential to complete these mission critical operations safely and successfully.

3. INTEGRATION CHALLENGES

From something as simple as a line-on-line tolerance error on a mechanism interface drawing to program managers that lack experienced support staff, integration of complex vehicles or their systems can break down and compromise elements of mission success or, worse yet, engender unmitigated risk.

Over the course of the Shuttle/Mir/ISS era, there have been many significant and lesser but bothersome disconnects to robustly integrate target/chaser vehicle operations and joint missions. This is not criticism as it

is simply the intrinsic nature or a side-effect "feature" of operating complex systems. A recent complex system example in the media was the communication failures during the Artemis 2 post-landing crew and vehicle recovery. At face value, there was no apparent safety or obvious risk to the parties involved but the progression of events was uncomfortable for the flight crew and recovery forces. This is cited given the possible applicability and associated complexity during joint Artemis/Human Landing System missions. Just imagine the problems caused by ship-to-ship or ship-to-ground to telemeter data or communicate or both and the impacts to contingencies such as an emergency evac and separation with additional crewed vehicles.

The following are more challenging integration examples or known "compromises" experienced over the 16+ years of the Shuttle/Mir/ISS flight operations era:

1) Joint US-NASA Russian-Roscosmos language/communications/translation, culture, philosophy (engineering, operations and safety): All these considerations were contended with starting with the earliest Phase 1 technical discussions to the present day with integrated ISS Guidance, Navigation & Control (GN&C).
2) Russian APAS Constraints: The Russian docking mechanism adopted for Orbiter Mir and ISS docking was remarkable and a proven design that seemed to have no significant/failures or anomalies. However, there were US flight control knowledge gaps that were encountered on several missions.
3) "Late" pre-flight accommodation of non-technical mission objectives, requirement/performance changes and failures [3].
4) Emergency evacuation joint separation/collision: This contingency was very challenging for Mir missions – for ISS, it was nightmarish considering the separating vehicle count, integrated departure relative motion trajectories, and no margin for vehicle-to-vehicle delays. This is a "best effort" to maintain vehicle minimum safe distance and coordination for all ships and the ground.
5) Go/No-Go Coordination: Target spacecraft contingencies, chaser spacecraft delays, etc.
6) Mission/Flight Rate/Cadence: Not at the top of the list, but this concern is real given staffing, burnout and workforce experience gaps.
7) Target Spacecraft Requirements: Critical to preserving/ensuring HIL capability and mission success. Examples include: attitude control performance, active lighting, alignment/retro-reflector targets, chaser spacecraft, "health & status" reporting/indicators (loss of ground communications and other contingencies), etc.
8) Target Spacecraft Collision Recovery: Characterized by some as the worst on-orbit human spaceflight incident. It precipitated cascading events impacting Mir operations, crew survival and, to a problematic extent, delayed the next Shuttle mission despite its criticality to prevent complete loss of the Russian space station: The remotely piloted Progress collision. In context, the crippled Mir was in question for Orbiter docking structural survivability as well as integrated mated attitude control.

4. Space Shuttle/Space Station Flight Experience

Examination of the successful Mir and ISS mission experience reveals that there were many exposed to latent and insidious risks – both unanticipated and unrecognized. Over the course of the 10 Mir and 37 ISS missions, a surprising number were subject to anomalous or off-nominal events. Many could be cited as being "close calls" or "near misses" such that unexpected contingencies or "escapes" were discovered. Some of these events were examples of operations or engineering certification gaps – of these, several posed a large collision risk such that a "positive" outcome was arguably a matter of luck.

It's clear that integration lapses played a roll during some of these anomalous or off-nominal events and that mission success and, more important, flight crew safety were exposed to unknown risk. During some flights, the mission operations and engineering teams would be wont to say "Well . . . that's not supposed to happen!" The integration failures occurred at both program and engineering management levels as well as across physical and virtual interfaces that may've been isolated or "siloed" by mistake – such as communication breakdowns or other miscues. During a handful of missions, it was apparent that there were failures to "Sim like you Fly – Fly like you Sim" leading some to have benign performance dispersions. However, there were instances of elevated risk for collision or failure to dock.

Space Shuttle Orbiter docking to the Mir and ISS were generally successful given the communication, coordination and cooperation of fully integrated operations and engineering teams. Mission-to-mission ISS configuration changes did levy additional constraints and manifest additional but manageable specialized training.

Two simple risk take-aways from the Shuttle/Station mission operations era:

1) Expect the unexpected – unforeseen circumstances/failures can and will happen.
2) And, more problematic is that many instances will unfold with "cascading" (multiple and uncorrelated) failures.

4.1. Flight Experience Lessons Learned – Mir Anomalies, Contingencies & Close calls:

Of the ten missions, the Shuttle/Mir flight experience was beset by "off-nominal" events during the five cited in the following table. Using annotations and acronyms for brevity, the table column content includes salient details as listed:

STS/Mir: Mission number, the nature of the "off-nominal" incident, whether there were pre-flight changes and associated (correlated) in-flight incidents.

Operation: Applicable mission objectives, tasks, actions, etc.

Incident: Precipitating operations, events and resulting category (near miss, close call, etc.)

Shuttle Risk: Hazard exposure from events, failures or cited incidents

Mir Risk: Same as Shuttle

Possible Effect: Aggregate safety hazard consequence

Outcome: Operation result/completion

Acronyms: OPS (operations), LOAC (loss of attitude control), FSW (flight software), config (configuration), PVA (photo-voltaic array), CDR (commander), PLT (pilot), HHL (hand held lidar), ZFT (zero fault or failure tolerant), RSA (Russian Space Agency), PROP (propellant), MCC (Mission Control Center), AUTO (automatic)

STS/Mir	Operation	Incident	Shuttle Risk	Mir Risk	Possible Effect	Outcome
STS-71 L-2 weeks OPS plan/change; in-flight incident	Photo-Op; Soyuz undock/station-keep for Orbiter separation	Mir LOAC; FSW uplink fail during Orbiter fly-around; very close call	Collision (Mir & Soyuz)	Collision (Shuttle & Soyuz)	Loss of both crews and vehicles	Expedited Soyuz redock and safe Orbiter separation
STS-74 L- 6 months Mir config change – collision risk	Docking module install after Krystal PVA reconfiguration	Orbiter Mir PVA minimum clearance; close call	Orbiter crew cabin Krystall PVA Collision	Orbiter Docking Adapter & Krystall PVA Collision	Loss of both crews and vehicles	Nominal docking after JSC full-scale mockup training for CDR/PLT situational awareness
STS-81 In-flight/PROX OPS incident	Orbiter hand-held-lidar ranging operations	Aft flight deck reconfiguration; minor impact; near miss	Ranging data gap	Excess plume loads; dispersed closing velocity	Higher Mir PVA plume & docking loads	Nominal docking HHL range data continuity maintained
STS-86 L – 2 weeks Flight Go/No Go? Mir GN&C ZFT after Progress collision	Last GN&C computer fail - Mir LOAC post STS launch Orbiter	Unsuccessful Orbiter manual rotation - failed capture & collision; very close call	Collision Mir, loss of mission/repair materials, US Astronaut stranded	Collision Orbiter; Mir GN&C failure – crew emergency separation & abandon ship	Loss of both crews and vehicles	CDR/PLT "No-go" after simulations Mission delayed for Mir GN&C computer reliably redundant Nominal docking
STS-91 In-flight/RNDZ incident	Terminal phase RNDZ	RSA crew observer error; Orbiter GN&C set to FREE LOAC; close call	Trajectory & attitude error with breakout; prop margin loss (2nd RNDZ)	Excess plume loads; loss of mission objectives	Shorter mission duration, loss of objectives	Shuttle MCC immediately called Orbiter back to "auto" attitude hold Nominal approach and dock

4.2. Flight Experience Lessons Learned – ISS Anomalies, Contingencies & Close calls:

The Shuttle/ISS flight experience was beset by ten "off-nominal" events during the thirty-seven missions cited in the following table.

Acronyms: FGB (functional cargo block), CCTV (closed circuit television), P6 (ISS truss port 6) , EVA (extravehicular activity), FDIR (fault detection isolation recovery), PCT (post contact thrust), FPS (feet per second), VRCS (vernier reaction control system), PRCS (primary reaction control system), DEMO (demonstration), RS (Russian segment), SEP (separation).

STS/ISS	Operation	Incident	Shuttle Risk	ISS Risk	Possible Effect	Outcome
STS-88 L-4 week no sensor certificate In-flight incident	FGB to Node 1 berthing using Space Vision System	SVS shutdown - dynamic lighting; Orbiter CCTV nominal; close call	FGB Node 1 docking failure	Collision (Shuttle & FGB)	Loss of mission and ISS (FGB)	Nominal docking without SVS Orbiter CCTVs & monitor overlays
STS-92 In-flight/PROX OPS incident	RNDZ terminal phase	Orbiter RNDZ Radar failure; excess braking higher plume impingement; close call	Trajectory & attitude error requires breakout; prop margin loss (loss of 2nd RNDZ)	Excess plume loads; loss of mission & objectives	Shorter mission duration, loss of objectives	Nominal transition to proximity operations and approach to docking; benign ISS plume loads
STS-97 In-flight/PVA deploy contingency	"Passive" Orbiter zero-plume separation	P6 US PVA deploy failure; PVA EVA repaired; close call	Contingency undock untested "hands off" separation flight OPS design; Collision ISS	Failed P6 PVA plume loads mast-blanket failure; ISS damage; Collision Orbiter	Loss of Orbiter crew and both vehicles	EVA contingency procedure recovered P6 PVA Nominal separation and end of mission
STS-108 In-flight/PROX OPS incident	Final approach 2 –X PRCS thrusters deselected; single –X jet configuration	Unknown single – X thruster failed off; FDIR trip master alarm inside 3 feet range; very close call	No –X translation for inside range < 30' Collision ISS	Collision Orbiter	Loss of both crews and vehicles	Range < 30' –X firings (3) commanded inside 3 ft; even with master alarm, CDR fired PCT on time for nominal docking
STS-112 In-flight/PROX OPS incident	Final 30 ft approach	7 factors drove high docking velocity (+6 sigma); very close call	Collision ISS	Collision Orbiter	Loss of both crews and vehicles	Contact velocity at 0.21 fps; target is 0.1 fps; APAS limit at 0.20 fps; nominal PCT & capture with highest ever ISS docking loads
STS-126 In-flight/PROX OPS incident	Orbiter approach & separation	Low Z loss with VRCS & 2 PRCS jet failures; very close call	Collision ISS	Collision Orbiter	Loss of both crews and vehicles	Low Z fail for 2nd PRCS jet failure procedures in place; nominal separation (2nd) PRCS down firing jet failed during entry hot fire
STS-130 In-flight/PROX OPS incident	Post docking capture; APAS retract to structural hooks, ISS hard dock	APAS no fixers, pitch error and lockup; no contingency sep; very close call	Collision ISS	Collision Orbiter	Loss of crews and vehicles	Nominal but protracted delay in APAS hard mate in ISS attitude free drift
STS-133 In-flight/PROX OPS incident	Post docking capture; APAS retract to structural hooks, ISS hard dock	APAS no fixers, pitch error and lockup; no contingency sep; very close call	Collision ISS	Collision Orbiter	Loss of crews and vehicles	Nominal but protracted delay in APAS hard mate in ISS attitude free drift
STS-134 Detailed flight test objective	Dual Docked Operation DEMO; RS Soyuz undock fly-around with Orbiter docked	Soyuz trajectory error; Orbiter plume sensitive hardware; near miss	Soyuz Collision, loss of both crews; loss of Orbiter vehicle flight safety hardware	Soyuz – Orbiter and ISS collisions	Loss of both crews and vehicles	Dual docked OPS soyuz fly-around demo successful
STS-135 In-flight/PROX OPS incident	Final Shuttle mission; Orbiter fly-around	Orbiter trajectory error; pilot error; near miss	Unprecedented breakout; prop margin loss	Excess US PVA plume loads;	Loss of ISS crew and vehicle; ISS emergency separation	Orbiter attitude snap & hold delay; separation burn outside of ISS attitude limits

5. CONCLUSION

Space Shuttle, Mir and ISS flight experience should be considered as pathfinders to foster Lunar mission success - given safe, risk mitigated and robust engineered human-in-the-loop (manual) spacecraft proximity operations (approach, separation and fly-around and docking/undocking).

Human-in-the-loop operations must be foremost to ensure flight safety and accommodated to drive mission certification. Safe and "flexible" Shuttle/space station operations preserved mission success despite the

impacts from highly likely but unanticipated contingencies.

It cannot be overstated that, despite the unforeseen contingencies and cascading failures, the integrated teams (flight crews, engineers/operators) performed beyond expectations and effectively "saved the day" on every flight.

All forty-seven Shuttle Mir/ISS missions demonstrated that, in the end, their operations were executed safely.

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