SPACE WASTE

TECHNICAL REPORT · SW-TR-002 · REV A · CLASSIFICATION: PUBLIC

The Last Ten Meters

Terminal-Phase Disturbances, Plume Impingement, and Approach Safety Architecture for Rendezvous, Proximity Operations, and Docking

Prepared for: Space Waste — spacewaste.us

Date: June 2026 · Companion report to SW-TR-001 Rev B

Primary sources: Lumpkin, Marichalar & Stewart, "High Fidelity Simulations of Plume Impingement to the International Space Station," NASA-JSC, JANNAF (NTRS 20120017923); International Rendezvous System Interoperability Standards (IRSIS), Baseline, March 2019; RemoveDEBRIS flight results (2018–19); SW-TR-001 Rev B and the field-note literature catalogued in SW-RN-001.

1. Executive Summary

SW-TR-001 established that approach discipline — closure rate against range, lateral alignment, sensor integrity — is what separates a docking from a debris-generating event. This companion report examines the regime where that discipline is hardest to keep: the terminal phase, from corridor entry to contact. Three conclusions organize the material:

- **The corridor is the contract.** The ISS partnership's interoperability standard (IRSIS) shows what mature proximity operations look like: pre-analyzed approach corridors inside a Keep-Out Sphere, defined hold and retreat behaviors, and abort corridors guaranteed safe before anyone flies. A debris target publishes no such contract — the chaser must write one unilaterally, and SW-TR-002 outlines what that self-imposed contract must contain.
- **Plume effects are flight rules, not margins.** Two decades of NASA-JSC practice treats thruster plume impingement as a designed constraint — allowable firing locations, orientations, durations, and timing between firings are written into flight rules and control logic. The same treatment, not padded safety margin, is required when the impinged surface is a derelict rather than a station.
- **Against debris, the plume problem inverts.** ISS analysis protects the station from the visitor. With a 1–3 ton derelict, the larger risk runs the other way: impingement torque can change the target's tumble state during final approach — altering the capture geometry the approach was planned against, at the worst possible moment.

2. Scope and Assumptions

Per SW-EN-001 Principle 01, the simplified world used in this report is stated here, without apology:

- Both vehicles are rigid bodies; flexible appendage dynamics (solar arrays, booms) are noted where they matter but not modeled.
- Relative motion over terminal-phase durations (minutes) is treated as force-free drift plus thrust; orbital curvature terms (Clohessy-Wiltshire) are negligible inside ~100 m for the closure rates considered.
- Plume flow is treated qualitatively through the established NASA-JSC modeling chain (CFD through the nozzle and near field; DSMC in the rarefied far field); no original flow solutions are presented.

- The target is uncontrolled and non-venting. Outgassing or fragment-shedding targets are out of scope.
- All relative states are expressed in target-centered LVLH unless otherwise labeled (Principle 07).

Each assumption fails somewhere. The flexible-body and curvature assumptions degrade for large targets and slow approaches respectively; both edges are flagged in Section 6.

3. The Terminal Phase, Formally Defined

IRSIS — the ISS partnership's interoperability baseline — provides the cleanest published vocabulary for the end-game, and SW-TR-002 adopts it:

IRSIS ELEMENT	DEFINITION AND FUNCTION
Approach Sphere (AS)	Outer control volume around the target; entering it places the visitor under proximity-operations rules
Keep-Out Sphere (KOS)	Inner volume the visitor may enter only on an approach axis, inside a pre-analyzed corridor
Approach corridor	The pre-cleared cone/volume around the approach axis within which the trajectory must remain
Fly-around	Transition between approach axes, or circumnavigation, performed outside or at the edge of the KOS
Hold	Station-keeping at fixed relative position — neither approaching nor retreating
Retreat	Deliberate range increase to a predefined hold point
Free Drift	Both vehicles' translational and rotational control inhibited — initiated at first contact for docking
Abort	Automatic or commanded separation burn placing the visitor on a safe departing trajectory

Two observations matter for debris missions. First, every element above is *pre-analyzed*: the corridors and abort trajectories are certified safe before flight, against a target whose geometry, attitude, and keep-out requirements are published by its owner. Second, the free-drift convention — both vehicles passive at contact — exists precisely because thruster firings during the contact instant are the most dangerous firings of all. A derelict satisfies the second condition trivially (it is always passive) and the first condition never: there is no owner, no published keep-out volume, and no agreed corridor. The chaser must therefore generate the corridor itself, from its own characterization of the target's geometry and tumble — which is why SW-TR-001 §8 argued that target characterization is a capture-phase deliverable, not a nice-to-have.

4. Plume Impingement: The Established Practice

4.1 The NASA-JSC Modeling Chain

The reference treatment is the NASA-JSC Applied Aeroscience and CFD Branch capability documented by Lumpkin, Marichalar and Stewart. A reaction-control thruster plume spans many orders of magnitude in density between combustion chamber and orbital vacuum; no single method covers the span. The JSC chain couples computational fluid dynamics through the nozzle and continuum near field with Direct Simulation Monte Carlo (DSMC) in the rarefied far field, capturing the nonequilibrium effects and boundary physics that continuum methods miss at near-vacuum densities.

Equally instructive is how the high-fidelity capability is used. The vast majority of impingement assessments — dozens to hundreds of firings per trajectory, across nominal and off-nominal cases — run through fast engineering math models. High-fidelity CFD/DSMC is reserved for developing those models, anchoring them, and supplementing them where their assumptions break down. This is SW-EN-001 Principle 03 (model tiers, always labeled) operating at institutional scale, two decades running, from Shuttle-Mir through current ISS operations.

4.2 What Plumes Do to the Impinged Vehicle

- **Structural loads** — impingement pressure on large surfaces (arrays, radiators) drives transient loads assessed by the ISS loads team against allowables.
- **Heating** — impingement heat rates and integrated loads on thermally sensitive hardware.
- **Contamination and erosion** — propellant byproducts deposit on optics and surfaces; sustained exposure erodes them.
- **Electrical effects** — plume plasma conditions can enable Paschen discharge across charged hardware.

The institutional response is not margin but constraint: allowable firing locations and orientations relative to the station, allowable firing durations, and required timing between successive firings are written into flight rules and embedded in the visiting vehicle's control logic. The plume problem is solved at the level of what the vehicle is permitted to do, verified by analysis beforehand.

5. The Debris Inversion

Against an uncooperative target, the ISS framing inverts in three ways:

- **The protected party swaps.** ISS analysis protects a 400-ton crewed station from a small visitor. In ADR, the chaser is the valuable asset and the target is expendable hardware — but the target's *state* is not expendable. A braking burn directed at a 3-ton derelict imparts torque on whatever surface it strikes; a lightweight rocket-body shell with large area-to-mass responds. The approach plan's central input — the target's tumble state — is perturbed by the act of approaching.
- **No flight rules arrive with the target.** Allowable firing geometry must be derived from the chaser's own target characterization: surface geometry from inspection imagery, attitude motion from the tracking filter. This couples the plume problem to the pose-estimation problem (SW-TR-001 agenda) — corridor and firing constraints can be no better than the target model they are computed against.
- **Plume-induced tumble change compounds at the worst time.** Impingement disturbance grows as range shrinks (flux scales steeply with distance), peaking exactly where capture-envelope margins are thinnest. The wind-shear lesson from the legacy flight-test literature (SW-RN-001) applies directly: the disturbances of the final seconds deserve the modeling effort, because that is where the mission dies.

6. A Terminal-Phase Disturbance Budget

Following the fire-control architecture of SW-EN-001 Principle 06 — a clean baseline plus separately validated correction terms — the terminal-phase guidance budget decomposes as:

TERM	CHARACTER AND TREATMENT
Baseline relative motion	Drift + commanded thrust in target-centered LVLH; the reference trajectory the corridor is built around
Plume reaction on chaser	Deterministic; embedded in the thrust model
Plume impingement on target	Modeled disturbance: torque/force from firing geometry versus target surfaces; constrained by self-imposed firing rules; verified against the EMPIRE-class engineering-model approach
Target tumble evolution	Propagated from the tracking filter; updated continuously; capture window recomputed when the estimate shifts
Sensor multipath near the target	Ghost returns off large reflective surfaces (SW-RN-001, ground-wave analogy); handled in measurement gating, validated against reflective mockups
Flexible-body response	Edge-of-model term (Section 2): target array/boom flexing under impingement; bounded analytically, flagged for high-fidelity simulation
Navigation and execution error	Stochastic; sized by the filter covariance and thruster minimum-impulse quantization

Each term is testable in isolation — by analysis, mockup, or air-bearing experiment — and auditable independently, which is precisely the property procurement reviewers and safety boards require.

7. Application to South Star PROX-M18

SW-TR-002 DRIVER	DESIGN RESPONSE
Self-generated corridor (IRSIS without an owner)	Characterization products (geometry model, tumble state, surface map) are formal exit criteria of the inspection phase; the corridor and abort trajectories are computed from them and re-validated when estimates move
Firing rules against the target	Thruster selection logic excludes target-pointing firings inside a range threshold; braking authority biased to canted thrusters; firing-duration and spacing limits carried as flight rules
Plume-tumble coupling	Impingement torque model runs in the guidance loop; predicted tumble perturbation folded into the capture-window computation
Abort architecture	Passively safe abort per SW-TR-001 (NESC R-1): the abort burn is pre-computed for every corridor point and is itself plume-checked
Model tiers	Engineering plume model in the loop; high-fidelity CFD/DSMC reserved for anchoring and for cases flagged at the assumption edges (Section 2)
Public demonstrator	The RPODU Simulator at spacewaste.us implements the corridor, closure-rate rule, and abort discipline of this report in simplified form — Tier 1 of the model hierarchy, labeled as such

PROX-M18 is a development program at TRL 3–4. The mappings above are design intent validated against published practice, not flight-qualified capability.

8. Conclusions

Mature proximity operations encode their safety in pre-analyzed structure: corridors, holds, aborts, and firing rules certified before flight. Debris removal must reproduce that structure without a counterparty — the chaser carries the entire contract. The published ISS practice supplies the architecture and the modeling methodology; the debris case adds the inversion this report centers on: the act of approaching disturbs the thing being approached. Treating plume impingement on the target as a guidance-loop input, rather than a margin, is the single largest methodological change ADR requires of the inherited practice — and it binds the terminal phase to target characterization, which SW-TR-001 already identified as the program's connective tissue.

9. References

- Lumpkin, F. E., Marichalar, J. J., and Stewart, B. D., "High Fidelity Simulations of Plume Impingement to the International Space Station," 33rd JANNAF Exhaust Plume and Signatures Subcommittee Meeting, NASA-JSC. NTRS 20120017923.
- International Rendezvous System Interoperability Standards (IRSIS), Baseline, March 2019. International Space Station partnership / International Deep Space Standards.
- "Plume Impingement Heating on the International Space Station," NTRS 20160009502.
- Forshaw et al., RemoveDEBRIS mission flight results (net capture demonstration, 2018).
- Space Waste, SW-TR-001 Rev B, "Rendezvous, Proximity Operations, and Docking: An Engineering Assessment," June 2026.
- Space Waste, SW-RN-001, "Field Notes — Legacy Flight-Test Literature," June 2026 (wind-shear terminal-disturbance lesson; artillery correction-stack architecture; ground-wave multipath analogy).
- Dennehy & Carpenter, NASA/TM-2011-217088 (NESC abort-architecture recommendations cited via SW-TR-001).