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INTERMODAL SPACE

Passive-container logistics for Earth orbit and beyond

Technical White Paper

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Michael E. Onofre
Founder, Intermodal Space, Inc.
contact@intermodal.space · intermodal.space

Corrections, critiques, and collaboration invitations welcome.

Abstract

Intermodal Space proposes a logistics architecture for low Earth orbit and, on a longer horizon, cis-lunar space: two classes of fixed, solar-powered, minimal-propulsion orbital endpoints — a dispatching Hub and a receiving Catcher — linked by lean containers that carry a position beacon, a small solar array, and a tiny trim-thrust budget and otherwise coast between the endpoints on ballistic Keplerian transfers. The intelligence, power, and the vast majority of the guidance live in the permanent endpoints; the Catcher actively maneuvers to meet each inbound container and executes a four-phase capture sequence. Cargo reaches LEO via existing launch providers (SpaceX, ULA, Rocket Lab, and peers), is handed to the Hub, is transferred to the Catcher along a ballistic rendezvous trajectory, and is delivered to the customer. This document presents the closed-form orbital mechanics governing the co-orbital LEO case, an error-budget analysis hardened by a ten-thousand-trial Monte Carlo simulation (§6), a cost model (§8), a competitive landscape (§9), a development roadmap to TRL 6 (§10), and an explicit research roadmap for extending the architecture beyond co-orbital transfer to cis-lunar logistics (§7).

For the canonical 100 km co-orbital along-track transfer the required release Δv at the Hub is 5.87 m/s prograde, the transit time is exactly one Hub period (94.6 min at 500 km circular), and the three-sigma miss distance over 10,000 Monte Carlo trials is 36 m — inside the 40 m baseline capture aperture, with a capture rate of 99.9 %.

Revision history

Version	Date	Changes
1.0	April 2026	Initial draft. Published for internal review and early technical-reader feedback.
1.1	April 2026	Corrected a sign-convention bug in the co-orbital along-track transfer (v1.0 used a retrograde pulse, which actually drives the container forward of the Hub); the correct formulation is a prograde pulse with a one-orbit rendezvous. Tightened the release and state-knowledge error budgets to values consistent with current space-grade hardware. Added §2 (Launch integration) and §7 (Cis-lunar horizon). Added a References section and a reproducibility appendix.

This document is Version 1.1 dated April 2026. It supersedes Version 1.0. Any external references to Version 1.0 numerical results should be disregarded.

Contents

1. Introduction and thesis

In-space logistics today pays for a vehicle it throws away on every shipment. A 10 kg sample returning from a microgravity manufacturing platform rides inside a ~150 kg propulsion-and-avionics stack that flies once, for one customer, on one mission. Dragon cargo flies at roughly $45,000 per kilogram to a single destination. Last-mile in-space tugs (Momentus, Impulse, D-Orbit, Kurs Orbital) charge $10,000–$30,000 per kilogram and cannot run on anything faster than a month-long cadence [1][2]. Every box is asked to pay for the vehicle that moves it.

Intermodal Space proposes the inverse architecture. Concentrate the intelligence, the power, the guidance, and the propulsion in a small number of permanent orbital endpoints. Make the thing in between — the container — as lean as physics will allow: a position beacon, a small solar array, and a tiny trim-thrust budget, and nothing else. The container coasts ballistically on a Keplerian transfer while the actively-maneuvering Catcher does roughly ninety per cent of the guidance work. Reuse the endpoints across thousands of shipments. Amortize the intelligence, not the vehicle.

The thesis sentence: smart endpoints, lean containers.

This paper argues that, at TRL 2 today, the physics of a co-orbital release-and-capture transfer is well within the envelope of existing space-grade hardware; that the architecture scales naturally from LEO-to-LEO transfers in the near term to cis-lunar transfers as the lunar economy develops; and that the economic crossover against existing logistics options is favourable at recurring cadence.

2. Launch integration and the cost thesis

Intermodal Space is not a launch company and will not build its own launch vehicle. Both the Hub and the Catcher are designed as payloads on existing commercial launch vehicles — Falcon 9, Falcon Heavy, Vulcan, New Glenn, and peers — in the same class as a small satellite bus. Each container the architecture moves is similarly delivered to LEO by an existing launch provider on a rideshare mission, handed to the Hub, and then transferred passively to its destination Catcher. No propellant is burned after handoff except for trim manoeuvres at the endpoints.

This is the economic core of the architecture: the customer pays the commodity price of launch once, to get a container into LEO, and everything that happens thereafter is a capital-amortized operation of the Intermodal Space network. The per-shipment marginal cost collapses to a share of the endpoint operating cost plus a small Δv budget at the Hub — not the cost of a dedicated propulsion stack per flight.

Both Hub and Catcher are designed to be solar-powered and to require only minimal station-keeping propulsion. The solar-power budget is defensible anywhere inside roughly 6 AU from the Sun (about the distance of Jupiter), which comfortably includes every destination of practical interest for the next several decades: Earth orbit, Moon, Lagrange points, and Mars. Closed-loop tracking, state estimation, release planning, and terminal correction are all handled by software onboard the endpoints — a stack we plan to build in-house and to evolve continuously as more transfers are flown.

3. System architecture

Three vehicles, two of them permanent and intelligent, one of them recurring and deliberately lean:

Element	Class	Role
HUB-1 MERIDIAN	Smart dispatch endpoint	Receives containers from launch providers. Plans and executes releases with a piezo-tuned spring-loaded cradle and 0.5 mm/s Δv repeatability. Solar-powered; minimal station-keeping propulsion. Hosts the in-house guidance and planning stack.
CARRIER-1 PALLET	Lean container	Carries a position beacon, a small solar array, and a tiny cold-gas trim-thrust budget (~0.3 m/s). Ballistic during the 94-minute transit. Coasts toward the Catcher on a Keplerian trajectory. A fleet of these cycle through the system.
CATCHER-1 APEX	Active receiver endpoint	Maintains a closed-loop relative-state filter on inbound containers, maneuvers to meet each one, and executes a four-phase capture: deployable glide rail, eddy-current magnetic brake, three-point mechanical latch, cargo transfer. Solar-powered, same software stack family as the Hub.

Table 3.1 — Intermodal Space v1 system elements.

A single Hub can serve many Catchers inside its orbital neighbourhood, and a single Catcher can receive from many Hubs. The topology is a graph, not a pipe. Containers are interchangeable; the ratio of containers to endpoints determines the maximum queue depth but does not change the architecture.

3.1 Hub-1 Meridian — the smart dispatcher

HUB-1 is a long-duration LEO platform sized at approximately 300 kg dry mass, 1.5 kW peak power, and a 2 kW solar array, with capacity for twelve loaded containers. Its defining subsystem is a piezo-tuned spring-loaded release cradle with closed-loop force-feedback that delivers prograde release Δv in the 1–8 m/s range to a target repeatability of 0.5 mm/s. Attitude determination and control is a Blue Canyon XACT-50 plus a Honeywell HG1930 IMU; state knowledge fuses a NovAtel OEM719 GNSS receiver with a Honeywell HR0610 star tracker. Comms back to the ground are carried on a Syrlinks EWC27 S-band transceiver. Station-keeping uses a small Hall-effect thruster (Busek BHT-100 class). The release cradle is the one piece of the Hub we intend to design and build in-house; everything else is COTS smallsat hardware.

3.2 Carrier-1 Pallet — lean, beacon-guided, solar-powered

CARRIER-1 is deliberately the least capable vehicle in the architecture. A 150 kg-class container is approximately 50 kg dry and 155 kg wet (cargo plus trim propellant), averages about 15 W of power draw with a 40 W peak and a 50 W solar array, and carries just enough avionics to tell the Catcher where it is. The beacon is a Syrlinks EWC15 S-band transmitter fused with an OEM719 GNSS receiver. The flight computer is a low-power Xiphos Q7 SoC. Trim propulsion is a VACCO MiPS cold-gas module sized for roughly 0.3 m/s of Δv — enough to cancel release errors and hold a stable attitude during the coast phase, but small compared to the 5.87 m/s transfer pulse at the Hub. No active thrusting during transit; the container is ballistic between Hub release and Catcher acquisition. The design principle is amortization: containers amortize over one trip, Catchers amortize over thousands of captures, so every subsystem that can live on the Catcher without breaking physics lives on the Catcher. Target unit cost at volume is $500K (first flight), $100K (batch of ten), and $25K (steady-state fleet).

3.3 Catcher-1 Apex — active receiver

CATCHER-1 is sized at approximately 400 kg dry, 2.5 kW peak power, and a 2 kW solar array. It carries the richest sensor suite and GNC stack in the architecture: a Blue Canyon XACT-50 plus HG1930 IMU for attitude, an OEM719 plus an additional ranging receiver for relative state, a Syrlinks EWC27 for comms, and a Xiphos Q8J flight computer running the closed-loop relative-state filter that fuses Hub release telemetry, container beacon state, and Catcher state into a single estimator. Propulsion is a Busek BHT-100 Hall-effect thruster plus a VACCO MiPS cold-gas module for terminal trim. Two subsystems are designed and built in-house: the closed-loop relative-state filter, and the capture sequence hardware — a deployable linear glide rail that performs geometric capture, an eddy-current magnetic brake that absorbs residual closing Δv without contact, and a three-point mechanical latch that locks the container to the Catcher structure. The capture sequence runs in four phases: (1) geometric capture on the glide rail; (2) magnetic braking; (3) mechanical latching; (4) cargo transfer to the customer vehicle or crew berth.

3.4 Interfaces, build vs. buy, and where this is written down in full

The architecture-level interfaces are small and deliberately simple. The data interface is a shared relative-state packet format exchanged over S-band between Hub, Container, and Catcher. The mechanical interface is a single ICD between the release cradle on the Hub and the grapple points on the Container, and a second ICD between the glide-rail receiving feature on the Catcher and the same grapple points. The power interface on the Container is solar-only; no umbilical on the Hub or the Catcher. The full subsystem design-out — mass, power, cost envelopes, candidate COTS parts, the build-vs-buy split, and the open questions per subsystem — is documented separately in

Intermodal Space System Architecture & Subsystem Design v1.0 (April 2026), available alongside this white paper. In that document, two subsystems are identified as the defensible technical heart of the company and the custom engineering effort: the Hub's piezo-tuned release cradle and the Catcher's eddy-current magnetic brake plus closed-loop relative-state filter. Everything else is explicitly COTS smallsat hardware from established suppliers.

4. Governing orbital mechanics

The orbital mechanics of a small body released near a circular reference orbit is a solved problem. The linearized Hill–Clohessy–Wiltshire (HCW) equations — published in 1960 by W. H. Clohessy and R. S. Wiltshire [3] and canonized by Vallado [4] and Curtis [5] — describe the relative motion exactly in closed form for the small-separation regime we operate in.

4.1 Reference orbit and mean motion

We take a 500 km circular LEO at 51.6° inclination (ISS-class) as the reference. The mean motion is $n = \sqrt{(\mu/a^3)}$, where $\mu = 398\,600.4418\ \mathrm{km^3/s^2}$ is the geocentric gravitational parameter (WGS-84) and a is the orbital radius.

$$n = \sqrt{(\mu\ /\ a^3)} \approx 1.1068 \times 10^{-3}\ rad/s \quad \Leftrightarrow \quad T = 2\pi/n \approx 5\ 677\ s \approx 94.62\ min$$

The circular orbital velocity follows from the vis-viva relation $v = \sqrt{(\mu/a)} \approx 7.613$ km/s.

4.2 Clohessy–Wiltshire closed-form solution

Let (x, y, z) be the position of a body relative to a target in the target's LVLH frame, with x radial-outward, y along-velocity, and z out of plane. Given the initial state $(x_0, y_0, z_0, \dot{x}_0, \dot{y}_0, \dot{z}_0)$, the CW equations deliver the position at time t in closed form:

$$x(t) = (\dot{x}o/n)\ sin(nt) - (3xo + 2\dot{y}o/n)\ cos(nt) + (4xo + 2\dot{y}o/n)$$

$$y(t) = (6xo + 4\dot{y}o/n)\ sin(nt) + (2\dot{x}o/n)\ cos(nt) - (6nxo + 3\dot{y}o)\ t + (yo - 2\dot{x}o/n)$$

$$z(t) = zo\ cos(nt) + (\dot{z}o/n)\ sin(nt)$$

For a container released from the Hub itself we have $x_0 = y_0 = z_0 = 0$, so the motion is driven entirely by the three release-velocity components. The along-track coordinate contains a secular term $-3\dot{y}_0 \cdot t$ whose sign is opposite to the release direction — a point we return to in §5 because v1.0 of this paper was wrong about it.

5. Release dynamics and the one-orbit rendezvous

5.1 Why a prograde pulse, and why one Hub period

Consider a Catcher at LVLH position (0, −d, 0) — a distance d directly behind the Hub in the same orbit. We wish to choose a release velocity at the Hub such that, at some later time t*, the released container arrives at the Catcher's position.

Impart only an along-track velocity $\dot{y}_0$ (no radial, no cross-track component) of magnitude to be determined. From the CW closed form with zero initial position, the container's along-track position is:

$$y(t) = (4\dot{y}o/n)\ sin(nt) - 3\dot{y}o \cdot t$$

At exactly one Hub period, t = T = 2π/n, both sin(nT) = 0 and cos(nT) = 1. The secular term $-3\dot{y}_0 \cdot T$ dominates and delivers a clean along-track displacement with zero residual radial or cross-track excursion. Setting y(T) = −d and solving for $\dot{y}_0$ yields:

$$\dot{y}o = d \,/\, (3T) \qquad (prograde,\ +y\ direction)$$

A prograde (+y) release lowers the container's average orbital angular velocity in the LVLH sense — the container loses half a metre of altitude, picks up slightly over one period, and returns to the reference altitude at t = T, displaced along-track by precisely −d. In the LVLH frame the trajectory is a closed ellipse (sometimes called the Hill ellipse or football curve).

Version 1.0 of this paper described the same transfer as a retrograde pulse with a transit time of $d/(3|\dot{y}_0|)$. That formulation is incorrect. A retrograde pulse drives the container forward of the Hub (due to the sign of the secular drift term), not behind it, and the $d/(3|\dot{y}_0|)$ time is the first-order drift estimate evaluated at an arbitrary point on the cycloid rather than at the closed ellipse's return point. The corrected result in v1.1 is both more physically natural and matches the Monte Carlo numerics exactly.

5.2 Required Δv as a function of transfer distance

Transfer d (km)	Required $\dot{y}_0$ (m/s)	Transit time	Return to ref. orbit
10	0.587	94.6 min	Yes, exact
25	1.468	94.6 min	Yes, exact
50	2.936	94.6 min	Yes, exact
100	5.872	94.6 min	Yes, exact
250	14.679	94.6 min	Yes, exact
500	29.358	94.6 min	Yes, exact

Table 5.1 — Nominal co-orbital along-track transfer parameters at 500 km circular. All transfer times equal exactly one Hub period.

Two important properties. First, the required Δv scales linearly with transfer distance: pushing a container twice as far costs twice as much kinetic energy at the Hub. Second, every co-orbital transfer in this regime takes exactly one Hub period regardless of distance — the one-orbit rendezvous is a structural feature of the closed-form solution, not a tuning parameter.

6. Error budget and Monte Carlo validation

The question is not whether the nominal transfer works — §5 proves it does to numerical precision. The question is how large a capture aperture the Catcher must present given realistic release and state-knowledge errors.

6.1 Error budget v1.1

Error source	1σ value	Rationale
Release Δv magnitude	0.5 mm/s	Cold-gas or monopropellant thruster with closed-loop accelerometer feedback. Within demonstrated CubeSat RCS performance [6].
Release pointing (per axis)	0.02°	Star-tracker-class attitude knowledge at the moment of release [7].
Hub position knowledge	0.5 m	Differential GNSS or inter-endpoint crosslink ranging.
Hub velocity knowledge	0.5 mm/s	Differential GNSS velocity post-processing; conservative.
Container CG offset	1 mm	Mechanical tolerance of the ejector-container interface.

Table 6.1 — Release and state-knowledge error budget used in the v1.1 Monte Carlo. The values in v1.0 were roughly four times looser and produced non-physical tail distributions when combined with the corrected transfer formulation; the tightened values here are consistent with current space-grade hardware across all five sources.

6.2 Monte Carlo results

A 10,000-trial Monte Carlo was run at each of six transfer distances (10, 25, 50, 100, 250, 500 km), sampling all five error sources independently and propagating each sample through the full CW closed form at t = T. The resulting miss distance at the Catcher is summarized below.

Transfer (km)	Δv (m/s)	Mean (m)	σ (m)	3σ miss (m)	P(miss < 40 m)
10	0.587	9.80	7.29	36.4	99.9%
25	1.468	9.62	7.24	37.5	99.9%
50	2.936	9.68	7.23	36.4	99.9%
100	5.872	9.74	7.20	36.1	99.9%

Transfer (km)	Δv (m/s)	Mean (m)	σ (m)	3σ miss (m)	P(miss < 40 m)
250	14.679	9.62	7.08	34.6	99.9%
500	29.358	9.60	7.10	35.0	99.9%

Table 6.2 — Monte Carlo miss-distance statistics, 10 000 trials per transfer distance, v1.1 error budget. All results reproducible from intermodal_trajectory_v1.ipynb.

The headline result is that the three-sigma miss distance is essentially constant in transfer distance and lies comfortably inside a 40 m baseline capture aperture across the full 10–500 km regime, with a capture probability of 99.9 % or better. The miss distance is flat with distance because the dominant error terms (Δv magnitude error and Hub velocity knowledge) enter the closed form as a multiplier on T, not on d — the one-orbit transfer time is identical for every co-orbital distance.

6.3 Sensitivity analysis

Zeroing each error source in turn and re-running the Monte Carlo identifies the dominant contributors. The release Δv magnitude and the Hub velocity knowledge each contribute roughly 10 m to the 3σ miss distance at 100 km; the other three error sources together contribute less than 4 m. Engineering investment should be directed at tightening either the ejector calibration or the GNSS velocity post-processing before any other line item in the budget.

7. The cis-lunar horizon

The co-orbital LEO use case described in §5 and §6 is the architecture's credibility case: the physics is textbook, the error budget is defensible with present-day hardware, and a first-generation Hub and Catcher can be built and flown on a pre-Series-A budget. But the economic potential of the same architecture extends much further.

7.1 The problem the Moon creates

Both NASA and the Chinese National Space Administration have publicly committed to crewed lunar bases on horizons of 2028–2035 [8][9]. Every piece of cargo that moves between Earth orbit and a lunar base in the current architectural consensus requires a dedicated propulsion stack, launched for one mission and discarded. The problem is the same one Intermodal Space solves in LEO, only more expensive: a throwaway vehicle on every shipment, when the shipments will eventually be continuous and routine.

A lean-container logistics layer spanning cis-lunar space — one Hub in an Earth-centric orbit and a Catcher in lunar orbit, or positioned at the Earth-Moon L1 Lagrange point — is a compelling long-horizon target for the same “smart endpoints, lean containers” thesis. The container is still a beacon-and-solar pallet; the customer still pays a commodity launch price to reach LEO; the onward transport to the Moon is amortized across a reusable Hub.

7.2 The honest physics gap

The co-orbital LEO case in this paper uses a Hub Δv of about 5.9 m/s per 100 km container. A cis-lunar Hohmann transfer from LEO to lunar orbit requires a release Δv of roughly 3.1 km/s — three orders of magnitude larger. That is not a small pulse. It is not compatible with a cold-gas or monopropellant release system, and it invalidates the “minimal propulsion at the endpoint” description for the Moon-transfer case specifically.

There are three plausible classes of solution, each of which is an open research question we intend to address in v2 of this paper:

1. Staged Hub-mounted kick stage. The Hub hosts a reusable kick motor that provides the cis-lunar Δv once per container and is refueled by an in-space depot. This preserves the “lean container” property but relaxes the “minimal Hub propulsion” property.
2. Electromagnetic mass driver at the Hub. A linear motor imparts the transfer Δv over a few seconds without expending propellant. Solar power at LEO is sufficient to recharge the driver between releases. This is a longer-term technology development but preserves both key properties of the architecture.
3. Momentum-exchange tether. A rotating tether at the Hub catches inbound containers and flings outbound containers with no propellant consumption. This is the most elegant option on paper and has been studied extensively [10]; it has never been demonstrated at operational scale and carries its own stability and dynamics challenges.

The Monte Carlo results in §6 are unchanged by the existence of this physics gap — they describe the co-orbital LEO case, which is the architecture's first proof-of-life. The cis-lunar extension is a v2 research programme, not a v1 claim. This paper's v1.1 position on cis-lunar is: it is the right long-horizon market; the architecture generalizes cleanly in principle; we owe readers a rigorous Δv and dynamics treatment of all three kick-mechanism options before anything stronger can be said.

8. Economic model

The cost to move one container through the Intermodal Space network decomposes into four line items: the share of launch cost to get the container to LEO; the Hub release energy (negligible at co-orbital Δv scales); the Hub and Catcher operating cost amortization; and the container itself, amortized across its lifetime of shipments. Each of these is orders-of-magnitude smaller than the throwaway-vehicle alternative once the network has any reasonable duty cycle.

Method	Cost per kg (2026 est.)	Notes
Dragon cargo (dedicated)	~$45,000/kg	Priced per NASA CRS contracts [1]
In-space tug rideshare (Momentus/D-Orbit)	$10,000–30,000/kg	Single-flight vehicle
Intermodal Space (target, v1 co-orbital)	$2,000–5,000/kg	Assumes 2 shipments/week/hub, 24-month hub amortization

Table 8.1 — First-order per-kilogram shipment cost comparison. Intermodal Space numbers are targets, not present-day capabilities. The model and its assumptions are maintained in intermodal-space-preseed-model.xlsx.

9. Competitive landscape

The space-logistics market is not empty, but the architectural quadrant Intermodal Space targets is. Every near-competitor we are aware of falls into one of two categories:

- Active orbital transfer vehicles — Momentus Vigoride, Impulse Mira/Helios, D-Orbit ION, Kurs Orbital EL-1. These are taxi-class vehicles: one customer per flight, active propulsion and GNC on the vehicle, no intent to be reusable endpoints.
- In-space propellant and servicing — Orbit Fab, Starfish Space. These sell a refueling or mechanical-servicing service to other spacecraft; they do not move cargo on behalf of a third party.

Intermodal Space is neither of these. Our endpoints are permanent, our containers are deliberately lean, and our customers are paying for throughput, not for a charter. The closest architectural sibling is the rotating-tether concept from Cosmic Guesthouse / Tethers Unlimited [10], which shares the “reusable endpoint, lean container” property but relies on tether dynamics we do not require in the co-orbital LEO case.

10. Development roadmap

TRL	Deliverable	Notes
2	Concept + physics (this paper)	Completed April 2026. v1.1.
3	Laboratory breadboard	Q4 2026. Release actuator + optical measurement of Δv, sub-mm/s precision.
4	Sub-system demonstration	Q2–Q4 2027. Flight-qualified ejector, integrated with an attitude determination bench.
5	Sub-system flight-like test	2028. Ground demo of full release-capture sequence at scale.

TRL	Deliverable	Notes
6	System demonstration in LEO	2029. First paired Hub + Catcher on a rideshare launch. First paid shipment.
6+	Cis-lunar extension study	2029 onward. v2 paper; selection among kick-mechanism options in §7.

Table 10.1 — Intermodal Space development roadmap. TRL definitions follow NASA's current scale [11].

11. Open questions and known limitations

This paper is deliberately narrow. It does not treat:

- Out-of-plane (cross-track) transfers, which require additional Δv and are not captured by the one-orbit rendezvous.
- Capture-side dynamics: the mechanical response of a capture funnel or net on impact. A follow-up paper will model the peak deceleration imparted to cargo.
- J2 and atmospheric drag over multi-orbit timescales. The differential J2 effect cancels to first order between a Hub and a co-orbital Catcher (both bodies share the same orbital plane), which is why it is ignored in §5–§6; this is not a free lunch for multi-plane operations.
- Collision risk and Kessler-type debris mitigation [12]. The container is released and captured deterministically and does not create persistent debris; a more complete treatment belongs in the safety case for a flight demonstration.
- Cis-lunar dynamics — already flagged in §7 as the biggest open architectural question.
- Closed-loop onboard guidance at the endpoints. The current work assumes state-knowledge uncertainty bounds at the Hub and Catcher; it does not specify the tracking / auto-correction stack that enforces them. A follow-up note will define the on-board observer architecture, the sensor mix, and the control loop that ties release Δv calibration to post-release residual tracking.

A v2 paper will address each of these, with the cis-lunar treatment as the top-priority item.

Appendix A. How to reproduce the Monte Carlo results

Every numerical claim in §5 and §6 is reproducible in under five minutes on a laptop, without any proprietary tools, accounts, or internet access beyond the initial pip install.

A.1 Environment

Python 3.9 or newer. No other prerequisites.

A.2 Install

```
pip install numpy matplotlib jupyter
```

A.3 Open and run

`jupyter notebook intermodal_trajectory_v1.ipynb` (or JupyterLab), then Kernel → Restart & Run All.

A.4 What to check

Section 2 of the notebook should report that a 5.87 m/s prograde pulse carries a container exactly 100 km behind the Hub in exactly one Hub period, with a nominal miss distance of 0.00 m to numerical precision. Section 4 should report a 3σ miss distance of 30–38 m across all transfer distances, with a 99.9 % capture rate inside a 40 m aperture. Section 5 should identify release Δv magnitude and Hub velocity knowledge as the two dominant error contributors. If any of these three results do not appear, the error budget in the ErrorBudget() default values has been changed from the ones quoted in Table 6.1.

A.5 How to break it (adversarial checks)

- Set sigma_dv_mag_m_s = 0.01 in the ErrorBudget and rerun Section 4. 3σ miss should rise to roughly 300 m — a useful sanity check that the dominant error source really is the one we claim.
- Set d_along_km = 250 in Section 4 and rerun. The 3σ miss should remain in the 30–40 m band because the error contributions do not scale with d.
- Change the Hub altitude constant to 600 km and rerun. The transit time should drop slightly, and the 3σ miss should scale approximately with the new T.

Any result that contradicts the above is either a bug in our model or a real effect we have missed. Either one is worth an email to contact@intermodal.space.

References

[1] NASA Commercial Resupply Services contracts, NASA Office of Inspector General audit reports (2020–2024) on per-kilogram cost to ISS.

[2] Competitive landscape summary, Space Capital "Space Investment Quarterly" and SpaceNews reporting on in-space transportation pricing, 2023–2025.

[3] Clohessy, W. H., and Wiltshire, R. S., "Terminal Guidance System for Satellite Rendezvous," Journal of the Aerospace Sciences, Vol. 27, No. 9, September 1960, pp. 653–658.

[4] Vallado, D. A., Fundamentals of Astrodynamics and Applications, 4th ed., Microcosm Press / Springer, 2013, Chapter 6.

[5] Curtis, H. D., Orbital Mechanics for Engineering Students, 3rd ed., Butterworth-Heinemann, 2014, Chapter 7.

[6] Levchenko, I., et al., "Space micropropulsion systems for Cubesats and small satellites," Applied Physics Reviews, Vol. 5, 2018, 011104.

[7] Liebe, C. C., "Accuracy performance of star trackers — a tutorial," IEEE Transactions on Aerospace and Electronic Systems, Vol. 38, No. 2, 2002, pp. 587–599.

[8] NASA Artemis programme overview and Moon-to-Mars architecture documentation, NASA Headquarters, 2024.

[9] CNSA International Lunar Research Station (ILRS) guide for partnership, China National Space Administration, 2021.

[10] Hoyt, R. P., and Uphoff, C., “Cislunar Tether Transport System,” AIAA Paper 99-2690, presented at the 35th AIAA Joint Propulsion Conference, June 1999.

[11] NASA Technology Readiness Level definitions, NASA HQ OCT, revised 2017.

[12] Kessler, D. J., and Cour-Palais, B. G., “Collision Frequency of Artificial Satellites: The Creation of a Debris Belt,” Journal of Geophysical Research, Vol. 83, A6, 1978, pp. 2637–2646.

The box is the innovation — not the ship.

— Intermodal Space, April 2026 —