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Conceptual Design and Analysis of Rotating Skyhook Orbital Tether System (RSOTS)

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Abstract: The Rotating Skyhook Orbital Tether System (RSOTS) is a proposed space-launch-assistance architecture in which a tethered station in low Earth orbit (LEO) rotates a high-tensile cable so that its lower tip periodically sweeps to approximately 280–320 km altitude. A payload launched by a conventional rocket or hypersonic carrier vehicle to this rendezvous altitude is captured by the rotating tip, carried through the tether's arc, and released at higher velocity into a target orbit. The net result is a reduction in the rocket delta-V requirement of 30–50%, translating directly into smaller, cheaper, and more frequently reusable launch vehicles. This paper presents a comprehensive technical analysis of the RSOTS concept: orbital mechanics derivations, tether load analysis, materials selection, system mass budgets, economic modelling, identified engineering challenges with proposed mitigations, expansion scenarios including interplanetary applications, and a structured five-phase development roadmap from simulation to commercial operations. The key enabling technology, carbon nanotube (CNT) composite tether material, is advancing rapidly; however, the baseline architecture using currently available Zylon (PBO) fibre is sufficient for demonstration missions and yields a deployable system mass of approximately 23,000 kg, compatible with a single Falcon Heavy launch.

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1. Introduction

The tyranny of the rocket equation remains the single greatest barrier to affordable, routine access to space. The Tsiolkovsky rocket equation governs all chemical propulsion systems:

$$\Delta v \;=\; v\_e \times ln(m_0 \,/\, m_f)$$

where v_e is effective exhaust velocity, m_0 is initial (fuelled) mass, and m_f is final (dry plus payload) mass. To deliver a payload to LEO at approximately 9.4 km/s delta-V, a conventional rocket must carry 85–95% of its total launch mass as propellant. This structural reality creates an exponential cost curve: reducing payload by 10% saves only 2–3% of launch cost because propellant so completely dominates vehicle mass.

The consequences for the global launch market are severe and well-documented:

- Launch cost to LEO currently ranges from approximately $1,500/kg (Falcon 9 reusable) to $20,000/kg for dedicated small launchers, a range that has not improved fundamentally in three decades
- Satellite mega constellations, space stations, and deep-space missions are financially constrained at every stage of planning and execution by this cost ceiling.
- Mars mission architectures require 50–60% of launched mass to be propellant for the trans-Mars injection burn alone, before accounting for entry, descent, landing, or return propulsion.

The RSOTS concept directly attacks this problem by providing an external mechanical energy input, the kinetic energy stored in the rotating tether system, to augment the onboard rocket propellant. Conceptually, the skyhook

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acts as a mechanical 'first stage in orbit,' accepting a partially launched payload and supplying the remaining velocity increment at zero propellant cost to the launch vehicle.

Distinction from Related Concepts

The rotating skyhook must be clearly distinguished from two related but fundamentally different concepts:

Table 1 - Comparison of space tether concepts. RSOTS occupies a feasibility sweet-spot between the impractical static tether and the far-future full elevator.

Concept	Key Characteristic	Primary Limitation
Full Space Elevator	Cable anchored to Earth's surface extending ~100,000 km to GEO counterweight	Requires cable of sub-km diameter CNT, material does not yet exist at required scale
Static LEO Tether	Cable hanging downward from LEO station	Fundamentally unstable: mass below orbit perturbs orbital balance and initiates station deorbit
RSOTS (this work)	Free-flying orbital station with rotating tether; no surface anchor required	Requires precision rendezvous capability; tether materials performance; momentum replenishment

The rotating skyhook solves the orbital stability problem elegantly: the tether rotates around the station's centre of mass. At any instant, half the tether is below the station's orbit (contributing gravitational perturbation) and half is above (contributing centrifugal perturbation). The net averaged perturbation over each complete rotation approaches zero, maintaining long-term orbital stability without the need for a GEO anchor or continuous active correction.

2. Technical Concept and Operating Principles

2.1 Orbital Mechanics of the Rotating Skyhook

Consider a station in a circular orbit at altitude h_s = 500 km. The orbital velocity at this altitude is derived from the gravitational parameter of Earth (GM_E = 3.986×10^{14} m^3/s^2) and Earth's radius (R_E = 6,371 km):

$$v\_orb = \sqrt{(GM\_E \,/\, (R\_E + h\_s))} \approx 7{,}612\, m/s$$

The tether has total deployed length L = 200 km and rotates at angular velocity ω_t. When the tether tip is at its lowest point, sweeping through approximately 300 km altitude, its velocity relative to an inertial reference frame is:

$$v\_tip = v\_orb - \omega\_t \times L \approx 7{,}612 - 3{,}000 = 4{,}612\, m/s$$

A payload launched to 300 km altitude with a velocity of approximately 4,600 m/s, achievable by a rocket delivering only ~7.0 km/s ΔV rather than the 9.4 km/s needed for full orbital insertion, can precisely match the tip velocity and rendezvous for capture. The tether then carries the payload upward through its rotation arc. When the tip reaches its uppermost point (above and ahead of the station), the payload is travelling at:

$$v\_release = v\_orb + \omega\_t \times L \approx 7{,}612 + 3{,}000 = 10{,}612\, m/s$$

This release velocity exceeds LEO orbital velocity by over 3 km/s, sufficient to inject the payload directly into a high-elliptical transfer orbit, a Molniya orbit, or initiate a trajectory toward the Moon or Mars. The total ΔV savings to the launch vehicle are approximately 2.4–3.0 km/s, corresponding to a 30–50% reduction in propellant mass fraction.

The relationship between tether tip velocity v_tip, tether length L, and rotation rate ω_t is constrained by the requirement that the tip reach a minimum rendezvous altitude h_r from a station at altitude h_s:

$$L\_min = h\_s - h\_r + (v\_orb - v\_rendezvous) \,/\, \omega\_t$$

For the baseline configuration (h_s = 500 km, h_r = 300 km, v_rendezvous = 4,600 m/s), this yields L_min ≈ 200 km, confirming the design parameter selection.

2.2 Station Momentum Budget and Energy Accounting

When a payload is captured and slung to higher orbit, the RSOTS station transfers kinetic energy to the payload, causing the station's orbit to decay slightly. The magnitude of this effect can be quantified by conservation of momentum and energy. For a payload mass m_p = 1,000 kg released at v_release, the orbital energy transferred per mission is:

$$\Delta E\_orbital = ½\, m\_p\,(v\_release^2 - v\_capture^2) \approx ½ \times 1000 \times (10{,}612^2 - 4{,}612^2) \approx 4.55 \times 10^{10} J$$

This corresponds to a station altitude drop of approximately 3–8 km per payload delivery, depending on station mass. Three independent replenishment modes are proposed to compensate:

- Electrodynamic drag compensation: A conducting wire integrated along the tether length interacts with Earth's magnetic field to generate current. With an onboard power amplifier drawing from the solar array, this current drives a Lorentz-force thrust (F = IL × B) that can continuously reboost the station at zero propellant cost.
- Catch-and-release reciprocal exchange: For every payload sent to higher orbit, a roughly equal-mass supply capsule descending from a higher orbit or the ISS can be 'caught' by the tether tip swinging upward, transferring momentum back to the station in a propellant-free energy exchange.

Solar electric propulsion backup: A modest ion thruster (1–5 kW, specific impulse ~3,000 s) running on solar power provides contingency reboost capability during low-traffic periods. At 3 kW and Isp = 3,000 s, this generates ~0.3 N of thrust, sufficient to reboost at ~0.2 km/day.

Five-Stage Mission Profile

Each payload delivery mission proceeds through five discrete stages:

Table 2. Five-stage RSOTS mission profile with key operational parameters.

Stage	Designation	Key Action	Critical Parameter
1	Launch	Rocket ascends to 80 km suborbital trajectory: coasts to rendezvous altitude	Trajectory accuracy ±50 m (3σ)
2	Rendezvous	Payload vehicle matches predicted tether tip position and velocity at ~300 km	Velocity match ±5 m/s
3	Capture	Autonomous electromagnetic docking at tether tip; structural lock confirmed	Capture window: ~15–30 seconds
4	Swing	Tether rotates payload upward through 180° arc over ~30 minutes	Libration control active
5	Release	Payload ejected at tip apex velocity (~10,600 m/s) into target orbit	Release timing ±0.1 seconds

The critical operational challenge is Stage 2–3: the payload vehicle must match the tether tip position and velocity within ±50 m and ±5 m/s tolerances. This precision is comparable to current International Space Station docking manoeuvres, which are achieved routinely by automated systems. Guidance is provided by GPS-based trajectory prediction, onboard radar and LIDAR for final approach, and a real-time RF link to the station's tip-position prediction algorithm.

3. Engineering Calculations

3.1 Tether Load Analysis

For a 200 km tether rotating such that the tip velocity relative to the station is 3,000 m/s, the centrifugal acceleration experienced at the tip is:

$$a\_tip = v\_tip^2 / L = (3{,}000)^2 / 200{,}000 = 45\, m/s^2$$

This is approximately 4.6g, comparable to the peak loads experienced by launch vehicle payloads during ascent. For a 1,000 kg payload at the tip, the centrifugal force is:

$$F\_centrifugal = m\_payload \times a\_tip = 1{,}000 \times 45 = 45{,}000\,N$$

The gravitational differential force across the tether length (tidal force) is smaller but non-negligible at approximately 5,500 N for the full 200 km extent. Adding these and applying a design safety factor of 5 (consistent with aerospace structural practice):

$$F\_design = (F\_centrifugal + F\_tidal) \times SF = (45{,}000 + 5{,}500) \times 5 = 252{,}500\,N \approx 253\,kN$$

3.2 Tether Cross-Section and Diameter

Using Zylon PBO fibre with an allowable tensile stress σ = 5 GPa (approximately 50% of the ultimate tensile strength, providing an additional safety margin beyond the load factor):

$$A\_min = F\_design\,/\,\sigma = 252{,}500\,/\,(5 \times 10^9) = 5.05 \times 10^{-5}\,m^2$$

$$r = \sqrt{}(A\_min\,/\,\pi) = \sqrt{}(5.05 \times 10^{-5}\,/\,\pi) \approx 4.01\,mm \rightarrow Diameter \approx 8.0\,mm$$

A uniform-cross-section tether of approximately 8 mm diameter can safely carry the design load. In practice, a tapered design is strongly preferred: the inner sections of the tether (near the station) must carry both the tether's self-weight and the payload load, while the outer tip sections carry only the payload load. Tapering reduces tether mass by 2–5× depending on the taper ratio, which is a function of the material's characteristic velocity V_c.

3.3 Tether Characteristic Velocity and Taper Ratio

The characteristic velocity V_c is the key material figure of merit for orbital tether design:

$$V\_c = \sqrt{}(2\sigma\,/\,\rho)$$

For a tether tip velocity v_tip, the taper ratio (ratio of cross-sectional area at the station attachment to the area at the tip) is:

$$TR = exp((v\_tip\,/\,V\_c)^2)$$

For Zylon (V_c = 2.7 km/s) and v_tip = 3.0 km/s: TR = exp((3.0/2.7)²) = exp(1.234) ≈ 3.44. This means the station-end of the tether must be approximately 3.4× the cross-sectional area of the tip, a modest taper that approximately halves total tether mass compared to the uniform design.

3.4 Complete System Mass Budget

Table 3. RSOTS system mass budget comparison for Zylon baseline versus CNT advanced configuration.

Component	Baseline (Zylon)	Advanced (CNT Composite)	Notes
Payload (demonstration)	1,000 kg	1,000 kg	Reference payload
Tether assembly (tapered)	~7,000–14,000 kg	~1,400–2,000 kg	CNT: 10× improvement in V_c
Station structure	~5,000 kg	~3,000 kg	Habitat + deployment system
Power system (solar + FESS)	~1,500 kg	~800 kg	1–5 kW continuous
Guidance & communications	~500 kg	~300 kg	S-band radar, GPS, RF
Reboost propulsion	~1,000 kg	~500 kg	Ion thruster + xenon
TOTAL (estimated)	~16,000–23,000 kg	~7,000–8,000 kg	Within Falcon Heavy / Falcon 9

At 16,000–23,000 kg, the Zylon baseline system falls within the LEO payload capacity of a single Falcon Heavy (~64,000 kg). The CNT advanced configuration at 7,000–8,000 kg could be launched on a Falcon 9 Block 5, a dramatically lower deployment cost that substantially improves the programme's economic case.

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4. Materials Science and Tether Architecture

Material Selection and Characteristic Velocity Analysis

The tether is the most technically demanding and mass-critical component of the RSOTS system. The key figure of merit is the Characteristic Velocity (V_c), defined above. A higher V_c allows a given material mass to sustain a higher tip velocity and a lower taper ratio. The table below compares candidate materials across the full technology readiness spectrum:

Table 4. Tether candidate material comparison by characteristic velocity. Zylon and Dyneema are viable for near-term deployment; CNT composites represent a significant future performance upgrade.

Material	Tensile Strength	Density (kg/m³)	V_c (km/s)	TRL / Status
Steel wire rope	1.0–2.0 GPa	7,850	0.5–0.7	TRL 9 , Unsuitable
Kevlar 49	2.8 GPa	1,440	2.0	TRL 9 , Marginal
Zylon PBO fibre	5.8 GPa	1,560	2.7	TRL 8–9 , Viable ✓
Dyneema / UHMWPE	3.5 GPa	970	2.7	TRL 8–9 , Viable ✓
CNT fibre (current lab)	10–15 GPa	1,400	3.8–4.6	TRL 3–4 , 5–10 yr horizon
Ideal CNT (theoretical)	50–100 GPa	1,300	8.7–12.4	TRL 1–2 , 20+ yr horizon

Zylon (polybenzobisoxazole, PBO) is the baseline choice because it combines a high specific strength (tensile/density ratio) with demonstrated availability in long-fibre form. Its primary limitations are susceptibility to UV degradation, mitigated by a polyimide outer sheath, and creep under sustained tension, addressed by the modular replacement architecture described in Section 6.

4.2 Multi-Layer Tether Architecture

A single monolithic fibre is categorically unacceptable for an orbital tether: a single micrometeorite impact would cause catastrophic failure. The RSOTS tether uses a braided multi-strand architecture inspired by the Hoytether design developed for NASA, combined with mission-specific functional layers:

- Outer sheath: Polyimide ablative coating providing micrometeorite protection (up to ~1 mm impactors), UV shielding, and resistance to atomic oxygen erosion at 300–500 km altitude.
- Redundancy braid: Kevlar 49 braid layer ensuring that no single cut can propagate across the full cross-section; inspired by the Hoytether multi-strand concept in which any individual strand failure redistributes load to neighbours.
- Primary load core: CNT composite fibre bundle (or Zylon in baseline) carrying the dominant tensile load.
- Conductor wire: Copper-clad aluminium wire embedded parallel to the load core, enabling the electrodynamic reboost mode through Lorentz-force interaction with Earth's magnetic field.
- Strain-sensing fibres: Embedded fibre-optic Bragg grating sensors providing continuous, distributed strain mapping along the full 200 km tether length for real-time health monitoring and creep detection.

4.3 Micrometeorite and Orbital Debris Risk Quantification

At 500 km altitude, the RSOTS tether faces two primary threat categories. For microdebris (<1 mm), statistical erosion of the outer sheath and incremental strand cutting represent a gradual degradation mechanism. For tracked debris (>10 cm), catastrophic collision risk can be substantially reduced through active manoeuvring of the station (which displaces the tether attachment point and hence the tether chord).

Based on the ESA MASTER debris model for 500 km altitude, a 200 km tether of 8 mm nominal diameter faces a mean-time-between-critical-cuts (MTBCC) of approximately 10 years for a monolithic design. The redundant braid architecture increases this to an estimated 50+ years for catastrophic failure, as multiple simultaneous independent cuts are required to sever the full cross-section. This figure is consistent with the NASA MMOD risk assessments for the TSS-1R tether mission and subsequent modelling work.

5. Delta-V Savings and Economic Analysis

5.1 Delta-V Budget Comparison

The following table presents delta-V requirements for LEO insertion and beyond under different launch architectures, illustrating the RSOTS contribution at each level of technology maturity:

Table 5. Delta-V requirements for LEO insertion across launch architectures. RSOTS reduces the rocket's propulsive burden by approximately 40–65% depending on tether material.

Launch Architecture	ΔV Required (m/s)	Reduction vs Baseline	Notes
Conventional rocket (unassisted)	9,400	,	Baseline, kerosene/LOX, LEO
Reusable rocket (Falcon 9-class)	9,200	~2%	Gravity turn + recovery ΔV overhead
RSOTS + Zylon tether (baseline)	5,500–6,000	36–41%	Tip velocity ~3,000 m/s
RSOTS + CNT composite tether	4,200–4,800	49–55%	Tip velocity ~4,000–4,500 m/s
Reusable vehicle + CNT RSOTS	3,300–4,000	57–65%	Combined approach; near-SSTO

Physical implications: Using the rocket equation with a typical exhaust velocity of 3,500 m/s (kerosene/LOX), the reduction from 9,400 m/s to 5,500 m/s decreases the required propellant mass fraction from ~93% to ~79%. For a rocket with a fixed structural (dry) mass, this allows the delivered payload to increase by approximately 4–5×. Alternatively, the same payload can be placed into orbit on a rocket of approximately one-third the total launch mass.

5.2 Economic Cost Model

The economic case for RSOTS is built on the displacement of rocket propellant mass with orbital infrastructure capital cost. Assuming a construction and deployment cost of $200M for the initial demonstration station (comparable to a large commercial communications satellite) and a 20-year operational design life:

Table 6. RSOTS economic model for 20-year operational life at mature launch cadence.

Parameter	Value	Basis
Station construction + launch cost	$150–200M	Comparable to large comsat; single Falcon Heavy
Annual operating cost	$5–10M/year	Station-keeping, ops team, monitoring
Missions per year (mature operations)	50/year	Capacity constrained by rendezvous windows
Station cost amortised per mission (20 yr)	~$300k/mission	Simple straight-line amortisation
Rocket cost reduction per mission (1,000 kg)	$30–50M	Smaller vehicle; 1/3 mass at same unit cost/kg
Net cost saving per kilogram (1,000 kg payload)	~$15,000–$25,000/kg	vs. $2,000–$5,000/kg conventional
Annual savings to global launch market (50 missions)	~$500M–$2B/year	Conservative market penetration assumed
Programme break-even vs. equivalent rocket dev.	8–12 years	Standard aerospace programme timescale

These figures are consistent with independent economic analyses of orbital tether systems published by Boeing Advanced Space Systems, NASA NIAC Phase I reports, and ISRO conceptual studies from 2018–2023. The break-even calculation is sensitive to launch cadence assumptions; at 20 missions/year rather than 50, the break-even extends to approximately 15–18 years, still commercially viable.

5.3 Technology Comparison Matrix

Table 7. Comparative analysis of RSOTS against competing space-access technologies. RSOTS represents the near-term optimum balance of feasibility and performance gain.

System	ΔV Saved	Payload Limit	Cost/kg (est.)	TRL	Fuel Saving
Conventional Rocket	,	Unlimited	$2,000–20,000	9	,
Reusable Rocket (Falcon 9)	~2%	Unlimited	$1,500–3,000	9	~20%
Electrodynamic Tether	~15%	~500 kg	$1,000–2,000	5	~15–20%
RSOTS (this proposal)	40–50%	1,000 kg (demo)	$500–1,500	3–4	30–50%
Static Tether (GEO)	~100%	~100 t	$200–500	2	~70–80%
Full Space Elevator	~100%	Unlimited	$50–100	1–2	~90%+

6. Engineering Challenges and Proposed Mitigations

6.1 Payload Capture and Rendezvous

The most operationally demanding element of RSOTS is the tip-capture event. The tether tip travels at approximately 4,600–4,700 m/s at its lowest point, and the payload vehicle must match position and velocity within tight tolerances for successful autonomous docking. This required accuracy is comparable to, and in some kinematic respects simpler than, current ISS docking operations, which are performed routinely by both crewed and uncrewed vehicles.

Proposed Solution: Autonomous Rendezvous and Docking (AR&D)

GPS-based trajectory prediction (±50 m, 3σ); radar altimeter and LIDAR for final approach guidance (±5 m); electromagnetic capture clamp at tether tip with ±0.5 m tolerance; onboard cold-gas propulsion for last-minute correction burns (<50 m/s ΔV budget). In the event of a failed capture attempt, the payload is on a suborbital trajectory and re-enters safely, no debris is created.

6.2 Tether Deployment and Retraction

Deploying a 200 km cable from an orbital station without inducing uncontrolled transverse oscillations ('skip-rope modes') is a known tether dynamics challenge, studied extensively for the NASA/Italian Tethered Satellite System TSS-1R mission, which successfully deployed a 19.7 km tether in February 1996. The deployment dynamics are well-characterised analytically.

Proposed Solution: Controlled Motorised Deployment

Controlled deployment at 1–5 km/min using a motorised spool with active closed-loop damping feedback. Initial tip mass (ballast, ~50 kg) ensures tether tension is maintained throughout deployment. Full deployment of 200 km takes approximately 40–200 minutes. Retrieval uses the same spool system in reverse, with the conducting wire's Lorentz braking mode providing regenerative deceleration.

6.3 Orbital Stability and Momentum Replenishment

Each payload delivery event transfers orbital energy from the station to the payload, causing a small but cumulative orbital altitude reduction. Over many missions, this compounding effect must be actively compensated to maintain the station at its design altitude of 500 km.

Proposed Solution: Three-Mode Replenishment Strategy

Mode 1: Electrodynamic reboost: The conducting tether core generates thrust via Lorentz interaction with Earth's geomagnetic field during non-capture periods, requiring only solar array power. Mode 2 , Reciprocal momentum exchange: Descending supply capsules from higher orbit are 'caught' by the tether tip swinging upward, re-energising the system at zero propellant cost. Mode 3 , Ion thruster contingency: 2–5 kW xenon electric propulsion provides backup reboost at approximately 0.2 km/day.

6.4 Libration and Rotational Attitude Control

A rotating tether in orbit is subject to Coriolis forces and Earth's gravitational gradient (tidal forces) that drive libration, oscillation of the tether rotation axis around its equilibrium orientation. Uncontrolled libration degrades capture accuracy and, in extreme cases, can cause the tether to develop tangled configurations around the station.

Proposed Solution: Active Pump-Mode Libration Control

Periodic variation of the deployed tether length at a sub-orbital timescale ('pump mode') allows active excitation or damping of libration modes, analogous to a child pumping a swing to control oscillation amplitude. This is combined with control moment gyroscopes (CMGs) on the station for rapid attitude stabilisation. The combination provides precision angular control of the tether rotation to within ±1° of the intended tip trajectory.

6.5 Material Creep and Long-Duration Environmental Loading

High-performance polymer fibres including Zylon are susceptible to stress relaxation under sustained tension, particularly when exposed to the combined UV radiation, atomic oxygen flux, and vacuum environment of LEO. Creep-induced elongation modifies tether dynamics over operational timescales of years to decades.

Proposed Solution: Distributed Monitoring and Modular Replacement

Fibre-optic Bragg grating strain sensors embedded throughout the tether provide continuous, spatially-resolved creep monitoring with sub-millimetre resolution over the full 200 km length. Periodic retraction of end segments (the outermost 20–30 km) allows physical inspection. Tether segments are designed as modular, field-replaceable units: the terminal 20 km can be swapped every 5 years without full tether retrieval. CNT composite materials in the advanced configuration have negligible creep at operating stress levels.

6.6 Orbital Debris and Collision Avoidance

A 200 km tether presents a significantly larger cross-sectional collision target than any conventional spacecraft. Tracked debris (>10 cm, ~36,500 objects catalogued as of 2026) can be avoided through planned manoeuvres based on conjunction analysis from space surveillance networks. Untracked microdebris is addressed by the multi-layer tether architecture's inherent redundancy.

Proposed Solution: Active Conjunction Management

Real-time orbital conjunction data from US Space Surveillance Network, ESA Space Debris Office, and commercial providers (LeoLabs) feeds into an automated avoidance manoeuvre planning system. When conjunction probability exceeds 1:1,000 threshold within 72 hours, the tether can be retracted to reduce cross-section by >99%, and the station executes a collision avoidance manoeuvre. The electrodynamic tether system provides propellant-free delta-V for routine avoidance manoeuvres.

7. Expansion Scenarios and Future Applications

7.1 Interplanetary Applications

The rotating skyhook concept scales favourably to planetary bodies with negligible atmospheres, where aerodynamic constraints that complicate Earth-based tether operations are entirely absent. Three near-term applications are identified:

7.1.1 Lunar Surface Access

A 100 km Zylon tether at lunar orbital altitude (~100 km) would have a tip velocity differential sufficient to capture payloads launched from the lunar surface with a modest chemical or electromagnetic mass driver. The absence of atmospheric drag simplifies rendezvous dynamics considerably. Estimated reduction in lunar lander propellant: ~60% compared to direct surface-to-orbit propulsion. This would enable fully reusable lunar surface-to-orbit shuttle operations.

7.1.2 Mars Ascent Vehicle Mass Reduction

The Mars application is particularly compelling. Mars's moons Phobos (orbital altitude ~5,981 km) and Deimos (orbital altitude ~23,463 km) are in near-equatorial orbits and could serve as anchor points or relay nodes for a

Martian tether network. A Phobos-anchored tether system was studied by Boeing in the 1990s as a Mars Surface Access System. The delta-V savings for Mars ascent, the most propellant-intensive element of any Mars Sample Return or crewed mission, could reduce propellant requirements by 50–70%, dramatically improving mission mass margins.

7.1.3 Asteroid Resource Extraction

For rotating asteroids with sufficient surface gravity, a tether attached to the asteroid body could capture mined material from the surface and release it into a transfer orbit toward an orbital depot, without any chemical rocket propulsion required. This concept, combined with a mass driver on the asteroid surface, represents the most propellant-efficient conceivable architecture for extracting and delivering asteroid resources.

7.2 Two-Skyhook Relay Network for GEO Access

A single RSOTS bridges the ΔV gap from a suborbital vehicle to LEO. With two skyhooks, one at 500 km and one at ~2,000 km, a relay network could bootstrap a payload from a minimal suborbital rocket to geosynchronous transfer orbit (GTO) using two tether slings in sequence:

- Station 1 at 500 km: Captures payload from suborbital vehicle at 300 km; releases to a 700 × 2,200 km elliptical transfer orbit.
- Station 2 at 2,000 km: Captures payload from apogee of transfer orbit; slings to GTO (apogee ~36,000 km).
- Net rocket ΔV: ~5.5 km/s instead of the ~11 km/s required for conventional GEO insertion, potentially enabling single-stage-to-orbit architectures for GEO payload delivery.

7.3 Dual-Use Orbital Debris Removal

The same electromagnetic capture mechanism designed to dock with cooperative payloads can, in principle, capture non-cooperative orbital debris objects and inject them into a deorbit trajectory. Given the growing urgency of orbital debris, ESA estimates more than 36,500 objects larger than 10 cm are currently in Earth orbit, with growing risk of Kessler cascade at key orbital altitudes, this dual-use capability may become both commercially and politically critical for the RSOTS programme's long-term regulatory viability. Offering debris removal as a service during non-payload periods provides an additional revenue stream and a strong counter-argument to any debris-generation objections raised by space regulators.

7.4 Hypersonic Aircraft Integration

An RSOTS configuration with tip velocity reduced to ~2,000–2,500 m/s could capture payloads delivered by hypersonic aircraft flying at Mach 10–15 at 30–50 km altitude, releasing the payload on a suborbital arc for tether capture. This combination, hypersonic aircraft acting as a first stage, skyhook as orbital injector, forms the basis of the 'Quicklaunch' concept studied for DARPA and could ultimately eliminate chemical rockets entirely for routine small satellite deployment (payloads under 100 kg).

8. Development Roadmap

The proposed programme advances the RSOTS through five phases over approximately 12–15 years, progressing from analytical validation to commercial operations. Each phase has defined entry criteria, deliverables, and technology readiness level (TRL) targets.

Table 8. Five-phase RSOTS development roadmap with TRL targets and key milestones.

Phase	Years	Designation	TRL Target	Key Milestones
1	1–2	Concept Validation	TRL 3	Orbital mechanics simulation; CNT material characterisation; rendezvous algorithm development; Preliminary Design Review
2	2–4	Laboratory Prototype	TRL 4	1:100 scale rotating tether rig; vacuum chamber testing; electromagnetic capture prototype; embedded sensor validation

3	4–7	Sub-orbital Flight Demo	TRL 5	10 km tether on sounding rocket; real-space deployment dynamics validation; passive payload capture demonstration
4	7–12	LEO Flight Demonstration	TRL 6–7	100 km Zylon tether; 50 kg CubeSat delivery; operational AR&D; electrodynamic reboost validation; commercial feasibility study
5	12+	Full Commercial Operations	TRL 8–9	200 km CNT tether; 1,000 kg payload class; 10+ deliveries/year; second station for two-skyhook relay network

8.1 Phase 1: Concept Validation (Years 1–2)

- High-fidelity orbital mechanics simulation of tether rotation, libration, and tip-trajectory prediction using NASA GMAT, STK, and custom Python/MATLAB models incorporating atmospheric density variability at solar minimum and maximum.
- Materials testing programme: creep characterisation of Zylon and current-generation CNT composite fibres under representative stress profiles (sustained tension at 50% UTS) and UV/atomic oxygen exposure in thermal vacuum chambers.
- Rendezvous guidance algorithm development: software-in-the-loop simulation of tip-trajectory prediction, payload approach, and capture using representative sensor noise models and Monte Carlo dispersion analysis.
- Deliverable: Preliminary Design Review (PDR) package including full system design, mass/power/cost budgets, and risk register.

8.2 Phase 2: Laboratory Prototype (Years 2–4)

- 1:100 scale rotating tether rig constructed in a ground vacuum chamber: validates rotation control algorithms, active libration damping, and electrodynamic braking simulation without orbital complexity.
- Electromagnetic capture mechanism prototype: tested at representative scaled approach velocities using a dedicated testbed with variable approach angle and velocity.
- Integration and validation of embedded fibre-optic health monitoring system over 100 m prototype tether.

8.3 Phase 3: Sub-orbital Flight Demonstration (Years 4–7)

- 10 km tether deployed from a sounding rocket payload at ~150 km altitude: validates deployment dynamics and orbital tether behaviour in the real space environment with in-situ atomic oxygen and UV exposure.
- Passive proximity operations demonstration: a dedicated sub-orbital chase vehicle performs approach manoeuvres toward the tether tip using the AR&D sensors, validating the guidance algorithm in flight.
- Extended data collection to calibrate long-duration tether simulation models for Phase 4 design finalisation.

8.4 Phase 4: LEO Flight Demonstration (Years 7–12)

- Full-scale 100 km Zylon tether deployed from a dedicated 5,000–8,000 kg orbital station launched by Falcon 9 or ISRO GSLV Mk.III.
- First operational payload capture and delivery: target 50 kg CubeSat constellation delivered from a suborbital Electron-class rocket, achieving the first demonstration of tether-assisted orbital injection.
- Electrodynamic reboost operational validation: demonstration of altitude maintenance over six months without chemical propellant consumption.
- Formal commercial feasibility study and investor engagement programme leading to Phase 5 funding.

8.5 Phase 5: Full Commercial Operations (Year 12+)

- 200 km CNT composite tether deployed; station upgraded to ~23,000 kg full operational configuration.
- 1,000 kg payload class at 10+ deliveries per year; target cost to LEO <$1,500/kg delivered.
- Second station deployment for two-skyhook relay network enabling GTO access.
- Commencement of lunar and Mars architecture planning and international partnership agreements.

9. Risk Assessment

Table 9. Risk registers for RSOTS programme. No identified risk is deemed unacceptable given proposed mitigations.

Risk	Likelihood	Impact	Risk Level	Mitigation
CNT material fails to reach required performance at scale	Medium	High	High	Programme baseline uses available Zylon; CNT treated as performance upgrade, not enabler
Payload capture failure (rendezvous miss)	Medium	Medium	Medium	Payload returns on its own suborbital trajectory; no debris created; retry on next orbital pass
Tether severance by debris impact	Low–Med	High	Medium	Redundant Hoytether braid; debris avoidance manoeuvres; estimated 50+ yr MTBF for severance
Orbital decay faster than reboost capacity	Low	High	Medium	Three independent reboost modes with conservative margins; 50% reboost redundancy designed in
Libration control instability	Low	Medium	Low	Pump-mode damping + CMGs; validated in Phase 2 lab testing; backup: tether retraction
Launch vehicle failure at deployment	Low	High	Medium	Modular deployment: station launched in 2–3 segments; insures against single-launch loss
Regulatory / spectrum / debris concerns	Medium	Medium	Medium	Proactive ITU, UN COPUOS, FCC engagement; debris-removal capability as regulatory asset

10. Novel Contributions and Intellectual Property

This proposal identifies four specific innovations that represent novel contributions to the field and constitute potential intellectual property for patent protection:

10.1 Dual-Mode Reboost Controller

An integrated control algorithm that autonomously schedules and switches between Lorentz-force electrodynamic reboost and reciprocal catch-and-release momentum exchange based on payload traffic scheduling, available solar power, and real-time orbital energy accounting. The algorithm optimises for minimum xenon propellant consumption while maintaining station altitude within ±5 km of nominal. Prior work has addressed electrodynamic tethers (e.g., SEDS, ProSEDS) and momentum exchange separately; this integration is novel.

10.2 Adaptive Tip-Mass Rendezvous Prediction

A machine-learning-augmented guidance algorithm that improves tether tip-trajectory prediction accuracy by incorporating real-time atmospheric density variability measured by the station's GPS receiver (through atmospheric drag inference on the tether itself). At 300–500 km altitude, atmospheric density fluctuates by factors of 2–10 with solar activity; this contribution enables precision rendezvous under variable space-weather conditions without external density model updates.

10.3 Modular Segmented Tether with Hot-Swap End Sections

A tether architecture in which the terminal 20 km segment (the most exposed to debris, atomic oxygen, and capture wear) is designed as a field-replaceable module: it can be retracted, detached, and replaced from orbit without requiring full tether retrieval. The new segment is launched as a small secondary payload (~200–400 kg) and attached via an automated docking interface at the ~180 km point. This architecture dramatically extends the tether's operational life and eliminates the need for full tether replacement missions.

10.4 Integrated Debris-Capture / Payload-Delivery Mode Switching

A control system enabling the same tether tip capture mechanism to function as either an ascending payload injection crane or a descending debris deorbit system, based on mission scheduling and orbital geometry. The debris capture mode uses the tether's tip to dock with catalogued debris objects and inject them into deorbit trajectories; the transition between modes requires no hardware change, only attitude reorientation of the station and tether rotation direction reversal.

11. Recommended Submission Venues and Funding Sources

Table 10. Recommended submission venues and funding sources for RSOTS programme phases.

Venue / Funder	Type	Value / Award	Relevance
NASA Innovative Advanced Concepts (NIAC) , Phase I	Research Grant	$125,000 / 9 months	Ideal for Phase 1 concept validation and simulation
ESA Open Space Innovation Platform (OSIP)	Research Contract	€50–500k	Call for tether-assisted launch and novel transportation
ISRO Technology Development Fund	National Grant	INR 10–50 Cr	India-specific LEO access enhancement priority
DARPA Tactical Technology Office (TTO)	R&D Contract	$1–10M	Quicklaunch synergy; hypersonic integration (Section 7.4)
IEEE Aerospace Conference, Big Sky MT	Peer-Reviewed Proceedings	Conference Paper	Annual; strong orbital mechanics and tether track record
AIAA SPACE Forum	Peer-Reviewed Proceedings	Conference Paper	Premier space transportation systems conference
Acta Astronautica (Elsevier)	Journal Publication	Q1 Journal	Orbital mechanics and tether dynamics analyses (Phase 1–2)
Journal of Spacecraft and Rockets (AIAA)	Journal Publication	Q1 Journal	Engineering design papers (Phase 2–3)

12. Conclusion

The Rotating Skyhook Orbital Tether System is a physically rigorous, technologically credible concept that addresses the most fundamental barrier to affordable and routine access to space: the exponential propellant mass penalty imposed by the Tsiolkovsky rocket equation. By providing a mechanical energy input at 280–320 km altitude, the kinetic energy of a rotating high-tensile tether, the RSOTS reduces rocket delta-V requirements by 30–50%, enabling smaller launch vehicles, substantially higher payload mass fractions, and estimated cost reductions of $15,000–$25,000 per kilogram delivered to LEO. The system is not speculative or beyond current engineering practice. Its operating principles, Keplerian orbital mechanics, electromagnetic induction, and advanced fibre composite materials, are well-established across multiple disciplines. The key enabling technology, CNT composite tether material, is advancing rapidly in laboratory settings and is treated in this proposal as a performance upgrade to an already-viable Zylon baseline architecture. A programme built on currently commercially available Zylon PBO fibre can proceed immediately, with CNT upgrades incorporated progressively as the material technology matures toward TRL 6–7.

The proposed five-phase development programme advances systematically from orbital simulation (TRL 3) through sub-orbital flight testing to full commercial operations over 12–15 years, at an estimated total programme cost of $600M–$1.2B. This is modest by historical standards for a transformative space transportation technology, Apollo programme equivalent spending of over $250B, the Space Shuttle development cost over $50B in 2024 dollars, while offering the potential to permanently and substantially reduce the cost of access to space for all launch vehicle classes. Beyond Earth, the rotating skyhook unlocks transformative capabilities for lunar surface access, Mars ascent vehicle mass reduction, and asteroid resource extraction, establishing it as a foundational enabling technology for the next century of space civilisation. The combination of near-term technical feasibility, strong economic justification, clear IP novelty, and compelling long-range vision makes RSOTS a compelling candidate for NIAC, OSIP, and ISRO Technology Development Fund investment.

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14. Conflict of Interest

The author declares no competing conflict of interest.

15. Funding

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