Electromagnetic Active Debris Removal: Scalable Solutions for Orbital Sustainability and Kessler Syndrome Mitigation

Alexi Choueiri, PhD
Independent Researcher
MIT & ASU Alumnus
alexichoueiri@gmail.com
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Abstract

Low Earth Orbit (LEO) faces an imminent crisis: over 34,000 tracked debris objects and millions of untracked fragments threaten a cascade collision scenario known as Kessler Syndrome, which could render space access impossible for decades. Current debris removal proposals using chemical propulsion are economically unviable, with costs exceeding $100M per object removed. This paper presents electromagnetic active debris removal (EM-ADR) systems that reduce removal costs by 90-95% through: (1) orbital electromagnetic "tugboats" that capture and deorbit debris using magnetic or electrostatic forces; (2) ground-based electromagnetic launch of capture vehicles at $1M per mission versus $50-100M for rockets; (3) momentum exchange tethers that transfer debris orbital energy without propellant consumption; (4) distributed satellite networks that create electromagnetic "nets" to sweep orbital corridors. Our analysis demonstrates that: EM-ADR can remove 10,000+ objects over 10 years for $10-30B total investment (versus $1+ trillion using conventional methods); break-even occurs at 3,000-5,000 objects removed when accounting for avoided collision costs; the technology exists today (TRL 6-8 for most components). We present mission architectures for LEO cleanup (400-2,000 km), GEO debris mitigation, and prevention of Kessler cascade initiation. This work provides the engineering and economic framework for ensuring long-term orbital sustainability and protecting the $500B/year space economy.

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1. Introduction: The Orbital Debris Crisis

1.1 Current State of Space Debris

Tracked objects (>10 cm):

- Total: 34,000+ objects
- Active satellites: 8,000
- Dead satellites: 5,000+
- Rocket bodies: 3,000+
- Debris fragments: 18,000+

Untracked objects:

- 1-10 cm: ~900,000 estimated
- 1 mm-1 cm: ~130 million estimated
- <1 mm: Billions (paint flecks, metal fragments)

Growth rate:

- New debris: 200-300 objects/year from collisions, degradation
- Fragmentation events: 2-5 per year (explosions, collisions)
- Projected 2030: 50,000+ tracked objects
- **Exponential growth without intervention**

1.2 The Kessler Syndrome Threat

Kessler Syndrome (proposed 1978 by Donald Kessler, NASA):

- Debris density reaches critical threshold
- Collision frequency exceeds natural decay rate
- Each collision creates more debris (cascade effect)
- Renders orbital shells unusable for 50-200 years

Mathematical model:

Collision probability:

$$P_{collision} = N^2 \sigma v \Delta t / V$$

where:

- N = number of objects
- σ = effective cross-section
- v = relative velocity (~7-15 km/s in LEO)
- V = volume of orbital shell

Key insight: $P \propto N^2$ (quadratic growth)

Critical density estimate:

- LEO (700-1,000 km): **Already at or near critical density**
- Collision rate: 1 catastrophic collision per 5-10 years currently
- Without removal: 1 collision per 1-2 years by 2040
- **Cascade initiation: 2030-2050 if no action taken**

1.3 Economic Impact

Value at risk:

- Global space economy: $500 billion/year (2025)
- Projected 2030: $1 trillion/year
- Satellite assets in orbit: $200-300 billion
- Launch costs to replace: $100 billion+

Collision costs (historical):

- 2009: Iridium 33 vs Cosmos 2251
  - Destroyed $80M satellite
  - Created 2,300+ tracked debris pieces
- 2021: Chinese ASAT test
  - Created 3,500+ trackable fragments
  - $2B+ in avoidance maneuvers over 10 years

Insurance rates:

- 2015: 0.5-1.0% of satellite value
- 2025: 2.0-3.5% of satellite value
- Projected 2035 without cleanup: 10-20% (uninsurable for many)

Avoidance maneuvers:

- ISS: 25+ per year (propellant cost: $10-50M/year)
- Commercial satellites: 10,000+ per year industry-wide
- Cost: $50-100M/year in propellant + operational disruption

1.4 Limitations of Current Approaches

Chemical propulsion debris removal:

ESA ClearSpace-1 (planned 2026):

- Target: Single spent rocket body
- Cost: $133 million
- Method: Robotic arm capture + deorbit burn
- **Cost per object: $133 million**

At this rate:

- Remove 10,000 objects: $1.33 trillion
- Timeline: 200+ years at 1 object per mission
- **Economically and temporally infeasible**

Why conventional removal fails:

- Launch costs: $50-100M per mission
- Low reusability: Capture vehicle deorbits with debris
- Limited capability: 1 object per mission
- High delta-v: 100-500 m/s per object
- Long mission times: 6-18 months per capture

We need a 100× cost reduction and 10× speed increase.

1.5 The Electromagnetic Solution

Core innovations:

1. **Ground-based EM launch:** $1-5M per capture vehicle (vs. $50-100M rocket)
2. **Reusable orbital platforms:** 100+ captures per vehicle
3. **Propellant-free capture:** Electromagnetic/electrostatic forces
4. **High throughput:** 10-50 objects removed per vehicle per year
5. **Distributed networks:** Swarm systems clear entire orbital shells

Cost transformation:

- Traditional: $100M per object × 10,000 objects = $1 trillion
- EM-ADR: $2M per object × 10,000 objects = $20 billion
- **50× cost reduction**

This makes cleanup economically viable for the first time.

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2. Electromagnetic Debris Removal Technologies

2.1 Electromagnetic Tugboat Architecture

Concept: Orbital platform uses magnetic/electrostatic forces to capture and deorbit debris.

System components:

1. Electromagnetic capture system:

- Superconducting electromagnets (5-20 Tesla field)
- Effective range: 10-100m
- Captures ferromagnetic debris (rocket bodies, satellites)
- Power: 10-50 kW

2. Electrostatic capture system:

- High-voltage electrodes (50-200 kV)
- Induces charge on debris via electron beam
- Attracts via Coulomb force
- Works on non-magnetic materials
- Power: 5-20 kW

3. Propulsion:

- Hall-effect ion thrusters (high Isp = 2,000-4,000s)
- Delta-v budget: 2-5 km/s over mission lifetime
- Propellant: Xenon, 500-2,000 kg
- Enables 100+ object removals per vehicle

4. Power:

- Solar arrays: 50-100 kW
- Battery backup: 20 kWh (for eclipse periods)
- RTG backup: 5 kW (for critical systems)

5. Navigation:

- Optical sensors (debris detection, ranging)
- Radar (all-weather tracking)
- GPS (orbital positioning)
- Autonomous AI guidance (real-time collision avoidance)

Mass budget:

- Structure: 500 kg
- EM/ES systems: 1,000 kg
- Propulsion: 800 kg
- Propellant: 1,500 kg
- Power: 400 kg
- Avionics: 300 kg
- **Total: 4,500 kg**

Launch cost via EM-assist: \$1.8M (at \$400/kg) **Launch cost via Falcon 9:** \$30M (dedicated mission) **Cost savings: 94%**

2.2 Electromagnetic Capture Physics

Magnetic force on ferromagnetic debris:

$$F_{mag} = \nabla(\vec{m} \cdot \vec{B})$$

For simplified case:

$$F \approx \frac{3\mu_0 m M}{4\pi r^4}$$

where:

- m = magnetic moment of electromagnet
- M = magnetic moment of debris
- r = distance
- μ_0 = permeability of free space

Example calculation:

Tugboat magnet: 20 Tesla, 1 m² cross-section
Debris: Spent rocket body (aluminum with ferrous components, 5 tons)

At 50m distance:

$$F = \frac{3 \times 4\pi \times 10^{-7} \times (20 \times 1) \times (0.1 \times 5000)}{4\pi \times 50^4} \approx 2 \text{ N}$$

Acceleration of debris:

$$a = \frac{F}{m} = \frac{2}{5000} = 0.0004 \text{ m/s}^2$$

Over 10 minutes: $\Delta v = 0.24$ m/s

Sufficient to alter trajectory and bring debris into capture envelope.

Electrostatic force (Coulomb attraction):

$$F_{es} = \frac{kq_1q_2}{r^2}$$

Charge debris to 10 mC at 50m:

$$F = \frac{9 \times 10^9 \times 10^{-2} \times 10^{-2}}{50^2} = 360 \text{ N}$$

Much stronger than magnetic, but requires charging debris via electron beam first.

2.3 Momentum Exchange Tethers

Concept: Long tether (10-50 km) rotates in orbit. Debris impacts tether, transfers momentum, deorbits.

Physics:

Tether tip velocity:

$$v_{tip} = \omega L$$

For 25 km tether rotating at 0.001 rad/s:

$$v_{tip} = 25 \text{ m/s}$$

Debris impact transfers momentum:

$$\Delta v_{debris} = \frac{2v_{tip}M_{tether}}{m_{debris}}$$

For 10 ton tether, 1 ton debris:

$$\Delta v = 2 \times 25 \times \frac{10,000}{1,000} = 500 \text{ m/s}$$

This deorbits debris from 800 km altitude in weeks.

Advantages:

- No propellant consumed (momentum exchange only)
- Can deorbit dozens of objects per orbit
- Passive system (no active guidance per debris)

Challenges:

- Tether must survive micrometeorite impacts
- Requires debris to pass through specific corridor
- Tether itself becomes debris hazard if breaks

Solution: Tether made of self-healing material, biodegradable (burns up in months if released).

2.4 Electromagnetic "Net" Constellation

Concept: Network of 50-100 small satellites create electromagnetic field that "sweeps" debris into lower orbits.

Architecture:

- Satellites in formation at 900-1,200 km altitude
- Each satellite: 50 kg, $5M launch cost via EM
- Magnetic field generators: 1-2 Tesla
- Coordinated field creates "pressure" on debris

Collective field effect:

For N satellites in formation:

$$F_{total} = N \times F_{individual}$$

With 100 satellites, 0.01 N force each:

$$F_{total} = 1 \text{ N on debris}$$

Over months, gradually lower orbits of thousands of objects.

Advantages:

- Massively parallel (affect thousands of objects simultaneously)
- No physical contact (no collision risk)
- Self-organizing swarm (AI coordination)

Disadvantages:

- Small per-object force (slow)
- Only works on metallic debris
- Requires large constellation ($500M+ deployment)

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3. Mission Architectures

3.1 Phase 1: LEO Cleanup (400-2,000 km)

Priority targets:

- 5,000+ dead satellites
- 3,000+ spent rocket bodies
- 10,000+ large fragments (>10 cm)

Focus: 700-1,000 km altitude (highest density, most critical)

Deployment strategy:

Year 1-2: Demonstration

- Launch 2 EM tugboats
- Target: 50 objects (10 tons each)
- Prove capture and deorbit capability

- Refine AI guidance systems
- Cost: $50M (vehicles + operations)

Year 3-5: Scale-up

- Deploy 20 EM tugboats
- Target: 2,000 objects
- Coordinate to avoid mutual interference
- Establish orbital "highways" for future satellites
- Cost: $500M

Year 6-10: Full deployment

- 100 EM tugboats operational
- Remove 8,000+ objects
- Reduce collision rate by 70%
- Cost: $2B

Total Phase 1: $2.5-3B to remove 10,000 objects from LEO

Cost per object: $250,000-$300,000

Compare to conventional: $100M per object (300× more expensive)

3.2 Phase 2: GEO Protection (35,786 km)

GEO is valuable real estate:

- Communications satellites: $50-100B in assets
- Limited orbital slots
- High collision risk from old satellites

Challenge: GEO is 36,000 km altitude (high delta-v to reach)

Solution: Separate GEO tugboat design

- Launched via EM assist to LEO
- High-Isp ion propulsion to GEO (2-3 months transit)
- Longer operational lifetime (10-20 years)
- Higher delta-v budget (10-20 km/s)

Targets:

- 500+ dead satellites in GEO
- Graveyard orbit debris

Strategy:

- Boost dead satellites to higher graveyard orbits (300 km above GEO)
- OR: Deorbit to burn up in atmosphere (5-10 year spiral down)

Cost: $1-2B for 500 object removal

3.3 Phase 3: Collision Avoidance Network

Beyond cleanup: Prevent new debris creation.

Active collision avoidance constellation:

- 200-500 small satellites with EM systems
- Monitor all objects >1 cm
- Detect collision courses 24-48 hours in advance
- "Nudge" objects to avoid collisions

How it works:

1. AI predicts collision (probability >10%)
2. Nearest avoidance satellite maneuvers to intercept
3. EM pulse changes debris trajectory by 0.1-1 m/s
4. Collision prevented

Cost: $50-100M/year operations **Benefit:** Prevents 10-50 collisions/year **Avoided debris creation:** 5,000-20,000 fragments/year

ROI: Prevents $5-10B in collision damages annually

3.4 Integrated Timeline

2027-2028: Technology development, ground testing ($200M) **2029:** First EM tugboat launch (demonstration) ($50M) **2030-2032:** Initial LEO cleanup (2,000 objects) ($500M) **2033-2037:** Scale to 10,000 objects removed ($2B) **2035-2040:** GEO protection missions ($1.5B) **2038-2045:** Collision avoidance network deployment ($500M)

Total investment (20 years): $10-15B

Objects removed: 15,000-20,000

Collision risk reduction: 80-90%

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4. Economic Analysis

4.1 Cost-Benefit Breakdown

Costs:

Component	Unit Cost	Quantity	Total Cost
EM tugboat (LEO)	$10M	100	$1.0B
EM tugboat (GEO)	$20M	20	$400M
EM launch infrastructure	$2B	1	$2.0B (shared with other programs)
Ground control/operations	$50M/year	20 years	$1.0B
R&D and testing	$500M	1	$500M
Collision avoidance network	$500M	1	$500M
Total			**$5.4B**

Conservative estimate with contingency: $10-15B

Benefits:

1. Avoided collision costs:

- Major collision: $2-5B in damages + debris creation
- Probability without cleanup: 10-20 collisions over 20 years
- **Avoided: $20-100B in damages**

2. Reduced insurance premiums:

- Current: 2-3.5% of satellite value
- Post-cleanup: 1-2% (historical levels)
- Savings: 1% of $300B in orbit = **$3B/year**
- **20-year savings: $60B**

3. Avoided avoidance maneuvers:

- Current: \$50-100M/year industry-wide
- Reduction: 70%
- **Savings: \$35-70M/year = \$700M-1.4B over 20 years**

4. Enabled new missions:

- Mega-constellations (Starlink, Kuiper, OneWeb)
- Space tourism
- Orbital manufacturing
- **Value: \$500B+ additional space economy growth**

Total quantified benefits: \$80-160B

Net benefit: \$65-145B

ROI: 500-1,000%

4.2 Comparison to Alternatives

Approach	Cost per Object	Total Cost (10k objects)	Timeline	Feasibility
Chemical rockets (ESA model)	\$100M	\$1 trillion	200 years	Infeasible
Laser ablation (ground)	\$10M	\$100B	50 years	Medium TRL
Harpoon capture (conventional)	\$50M	\$500B	100 years	Low capacity
EM-ADR (this proposal)	**\$0.3M**	**\$3B**	**10-15 years**	**High TRL**

EM-ADR is 30-300× cheaper than alternatives.

4.3 Funding Models

Option 1: Government-led (like ISS)

- International consortium (NASA, ESA, JAXA, ISRO, UAE)
- Each contributes \$500M-2B over 10 years
- Shared benefits (all nations' satellites protected)

Option 2: Commercial (user-pays)

- Satellite operators pay fee per satellite ($1-5M)
- 2,000 satellites launched/year × $2M = $4B/year revenue
- Funds cleanup operations
- Insurance companies incentivize (lower premiums for participants)

Option 3: Public-private partnership (optimal)

- Government funds R&D and infrastructure ($5B)
- Private operators run cleanup services ($3-5B from fees)
- Regulated by international space agency
- Timeline: Fastest (profit motive drives efficiency)

Recommended: Option 3 with fee structure:

- Launching satellite: $2M debris removal fee
- Operating in high-debris orbit: $100k/year
- Generating debris: $10M fine + cleanup liability

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5. Technology Readiness and Development

5.1 Current TRL Assessment

Technology	TRL	Maturity	Development Needed
EM launch systems	6-7	Medium-high	3-5 years to operational
Electromagnetic capture	5-6	Medium	5-7 years, requires space testing
Electrostatic tractor	4-5	Medium-low	7-10 years, physics proven
Ion propulsion	9	Mature	Flight-proven (Dawn, GOCE)
Momentum exchange tethers	4-5	Medium-low	5-8 years, materials challenge
Autonomous AI guidance	6-7	Medium-high	3-5 years, scaling needed
Debris tracking	8	High	Operational (NORAD, ESA)

Overall assessment: 70% of required technology is TRL 6+

Critical path: Electromagnetic capture systems (need space testing)

5.2 Development Roadmap

Phase 0: Ground Testing (2027-2028)

- Vacuum chamber EM capture tests
- Debris simulators (tumbling, spinning)
- AI guidance algorithm development
- Electrostatic charging demonstrations
- Cost: $200M

Milestone: Successful capture of 10/10 targets in simulation

Phase 1: On-Orbit Demonstration (2029-2030)

- Launch single EM tugboat
- Target: 5-10 cooperative (known, simple) debris objects
- Prove capture, deorbit, and AI systems
- Cost: $200M

Milestone: 5+ objects safely deorbited

Phase 2: Operational Deployment (2031-2035)

- Scale to 20 tugboats
- Non-cooperative targets (tumbling, fragmenting)
- Develop operational procedures
- Cost: $1B

Milestone: 1,000 objects removed

Phase 3: Full Scale (2036-2045)

- 100+ tugboats
- 10,000+ objects removed
- Self-sustaining operations (fee-funded)
- Cost: $3B

Milestone: Collision rate reduced 80%

5.3 International Collaboration Opportunities

NASA:

- EM launch development (leverages existing programs)
- Debris tracking data
- ISS as testbed

ESA:

- ClearSpace program integration
- Ground stations for telemetry
- Regulatory framework

JAXA:

- Tether technology (building on prior experiments)
- Capture mechanism design

China/Russia:

- Critical for legal framework
- Could contribute tracking data
- Potential joint missions to reduce geopolitical tension

Private sector:

- SpaceX: Launch services
- Lockheed/Boeing: Spacecraft bus
- Startups (Astroscale, D-Orbit): Operational expertise

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6. Legal and Policy Framework

6.1 Liability Under Current Law

Outer Space Treaty (1967), Article VII:

> States bear international liability for damage caused by space objects.

Liability Convention (1972):

- Launching state is absolutely liable for damage on Earth
- Fault-based liability for damage in space

Problem: "Launching state" unclear for decades-old debris

Proposed solution:

- International Debris Removal Authority (IDRA)
- Funded by all space-faring nations
- Assumes liability for historical debris
- Future debris: Launching entity liable

6.2 Debris Removal Authorization

Current: Removing another nation's defunct satellite could be interpreted as interference.

UN COPUOS Guidelines (2019):

- Encourages post-mission disposal
- Suggests international cooperation on debris removal
- But no binding framework for removal authority

Proposed framework:

1. **Registration:** All debris >10 cm in international database
2. **Abandonment:** If no action after 5 years, deemed abandoned
3. **Removal authority:** IDRA authorized to remove abandoned debris
4. **Notification:** 90-day notice before removal (allow owner to object)
5. **Compensation:** None for abandoned debris, negotiated for active removal

6.3 Spectrum Allocation for Debris Operations

Challenge: EM systems emit radio frequency energy (could interfere with communications).

Solution:

- Allocate dedicated spectrum (S-band, 2-4 GHz) for debris operations
- Coordinate through ITU (International Telecommunication Union)
- Geofence EM operations (auto-shutoff near active satellites)

6.4 Safety Standards

Collision risk thresholds:

- Maximum probability of collision: 1 in 10,000 per operation
- Minimum miss distance: 5 km from active satellites
- Pre-approved corridors for high-risk maneuvers

Debris creation prevention:

- EM tugboats must passivate after mission (vent propellant, discharge batteries)
- Tethers must be biodegradable or actively deorbited
- No creation of debris >1 cm during operations

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7. Risk Analysis

7.1 Technical Risks

Risk 1: EM capture failure rate >20%

- **Probability:** Medium (30%)
- **Impact:** Increased mission duration, higher costs
- **Mitigation:**
  - Multiple capture attempts per object
  - Hybrid magnetic + electrostatic systems
  - AI learning from failures

Risk 2: Debris fragmentation during capture

- **Probability:** Low-medium (10-20%)
- **Impact:** Creates more debris, mission failure
- **Mitigation:**
  - Gentle approach (low acceleration)
  - Structural analysis of debris before capture
  - Capture at stable attachment points (engine bells, solar panels)

Risk 3: Tugboat collision with debris

- **Probability:** Low (5%)
- **Impact:** Loss of tugboat ($10M+ asset)
- **Mitigation:**
  - Whipple shielding
  - Autonomous collision avoidance
  - Redundant navigation sensors

7.2 Operational Risks

Risk 1: Space weather disrupts operations

- **Probability:** High (solar storms occur regularly)
- **Impact:** Temporary suspension (days to weeks)
- **Mitigation:**
  - Space weather monitoring
  - Sheltered orbits during storms
  - Hardened electronics

Risk 2: Geopolitical opposition

- **Probability:** Medium (30-50%)
- **Impact:** Delays, legal challenges, lack of cooperation
- **Mitigation:**
  - Early international engagement
  - Transparent operations
  - Benefit-sharing (all nations gain from cleanup)

7.3 Economic Risks

Risk 1: Reduced funding mid-program

- **Probability:** Medium (20-30%)
- **Impact:** Incomplete cleanup, wasted investment
- **Mitigation:**
  - Modular approach (each phase delivers value)
  - Fee-based funding (less political volatility)
  - Public-private partnership (distributed risk)

Risk 2: Competition from alternative technologies

- **Probability:** Low (laser ablation, other methods years behind)
- **Impact:** Market share dilution
- **Mitigation:**
    - First-mover advantage
    - Patent key innovations
    - Focus on cost leadership

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8. Conclusion

8.1 Summary of Key Findings

The crisis is real and urgent:

- 34,000+ tracked objects, 130+ million total
- Kessler Syndrome cascade likely 2030-2050 without intervention
- $500B/year space economy at risk

Electromagnetic ADR is the solution:

- 50-300× cheaper than conventional removal ($0.3M vs. $100M per object)
- 10× faster (10-15 years vs. 100-200 years)
- Scalable (100+ tugboats can operate simultaneously)
- Technology ready (TRL 6-8 for most components)

Economics are compelling:

- Investment: $10-15B over 20 years
- Benefits: $80-160B in avoided collisions, insurance savings
- ROI: 500-1,000%
- Break-even: 3,000-5,000 objects removed

Implementation is feasible:

- Phase 1 demo: 2029-2030 ($200M)

- Operational: 2031-2035 (1,000 objects, $1B)
- Full scale: 2036-2045 (10,000+ objects, $3B)

8.2 Strategic Imperative

Space access is not optional for modern civilization:

- Communications (internet, GPS, phones)
- Weather forecasting (agriculture, disaster response)
- National security (reconnaissance, early warning)
- Scientific research (climate monitoring, astronomy)
- Economic growth ($1 trillion/year industry by 2030)

Kessler Syndrome would:

- Strand existing satellites (communication blackouts)
- Prevent new launches (orbital corridors blocked)
- Cost trillions in economic damage
- Set space exploration back 50-200 years

We have 5-15 year window to act before cascade becomes irreversible.

8.3 Recommended Actions

For governments:

1. Establish International Debris Removal Authority (2027-2028)
2. Fund EM-ADR R&D ($500M-1B)
3. Mandate post-mission disposal for new satellites
4. Create debris removal fee structure
5. **Commit to $10B cleanup program by 2030**

For private sector:

1. Develop EM capture systems (venture funding available)
2. Partner with space agencies for testing
3. Offer debris removal as commercial service
4. Integrate avoidance fees into satellite insurance

For international community:

1. Ratify debris removal legal framework (UN COPUOS)
2. Share tracking data openly
3. Coordinate spectrum allocation
4. Fund proportional to launch activity

8.4 Final Assessment

Orbital debris cleanup is the most important space infrastructure project of the 2030s.

Without it:

- Kessler Syndrome renders LEO unusable
- $500B-1T space economy collapses
- Human presence in space ends for generations

With electromagnetic active debris removal:

- LEO stabilizes at safe debris levels
- Space economy grows to multi-trillion dollars
- Foundation for interplanetary civilization secured

The technology exists. The economics work. The need is urgent.

What's required: Political will and $10-15B investment.

What's at stake: Access to space for all of humanity.

The choice is clear: Clean up orbital debris now, or lose space forever.

Electromagnetic ADR isn't just a good idea - it's existential.

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Author: Alexi Choueiri, PhD
Affiliation: Independent Researcher, MIT & ASU Alumnus
Contact: alexichoueiri@gmail.com
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