# Active Debris Removal: EDDE, the ElectroDynamic Debris Eliminator

J. Pearson
Star Technology and Research, Inc. USA

J. Carroll
Tether Applications, USA

E. Levin
STAR, Inc., USA

## ABSTRACT

The ElectroDynamic Debris Eliminator (EDDE) is a low-cost solution for LEO space debris removal. EDDE can affordably remove nearly all the 2,465 objects of more than 2 kg that are now in 500-2000 km orbits. That is more than 99% of the total mass, collision area, and debris-generation potential in LEO. EDDE is a propellantless vehicle that reacts against the Earth's magnetic field. EDDE can climb about 200 km/day and change orbit plane at 1.5°/day, even in polar orbit. No other electric vehicle can match these rates, much less sustain them for years. After catching and releasing one object, EDDE can climb and torque its orbit to reach another object within days, while actively avoiding other catalogued objects. Binocular imaging allows accurate relative orbit determination from a distance. Capture uses lightweight expendable nets and real-time man-in-the-loop control. After capture, EDDE drags debris down and releases it and the net into a short-lived orbit safely below ISS, or can take it to a storage/recycling facility. EDDE can also sling debris into controlled reentry, or can include an adjustable drag device with the net before release, to allow later adjustment of payload reentry location. A dozen 100-kg EDDE vehicles could remove nearly all 2166 tons of LEO orbital debris in 7 years. EDDE enables and justifies a shift in focus, from simply reducing the rate of debris growth to active wholesale removal of all large debris objects in LEO.

## INTRODUCTION

Space debris from discarded upper stages, dead satellites, and assorted pieces from staging and tank explosions has been growing since the beginning of the space age. This has increased the risk to active satellites, and the need for avoidance maneuvering. These thousands of pieces of space junk in Earth orbit pose risks to our space assets such as communication and navigation satellites, environmental monitoring satellites, the Hubble Space Telescope and the International Space Station (ISS)[1]. More importantly, they pose a risk to the astronauts who work outside the space station or who repair satellites, as the space shuttle Atlantis astronauts did for Hubble last year. In addition to the Hubble's bad camera and failing gyros, its solar array had a hole in it the size of a .22-caliber bullet. Figure 1 is a depiction of the tracked objects over 2 kg crossing the orbit of a space vehicle in low Earth orbit (LEO).

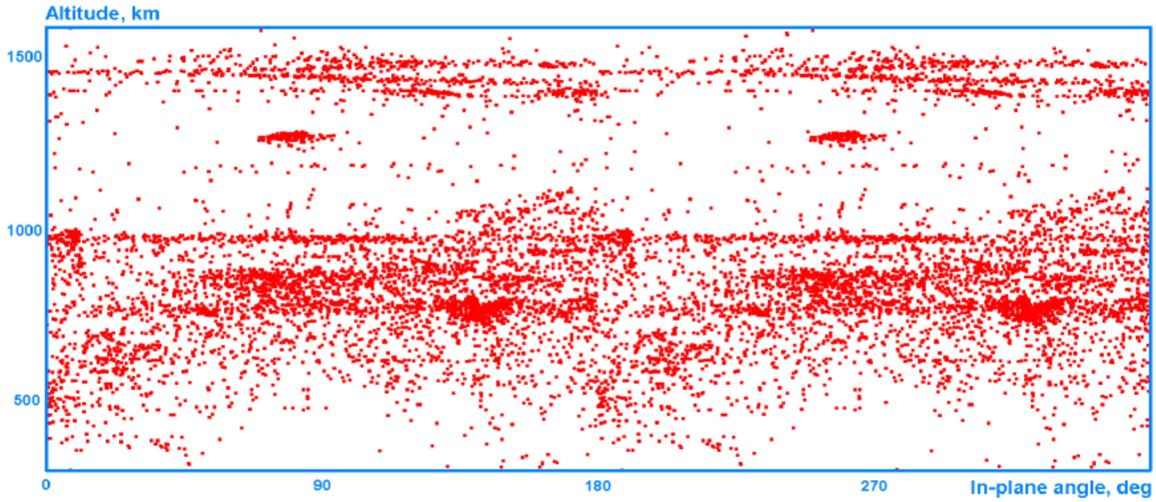


**Figure 1: Tracked Objects Crossing the Orbital Plane of a Spacecraft in LEO**

Up until last year, the dangers of space debris were generally ignored under the "big sky" view that space is very empty. But the loss of the operating Iridium 33 satellite changed that. Since then, there have been Congressional hearings and international conferences discussing the problems of space debris, how to reduce the risks, and whether we can afford it.

The U. S. Strategic Command keeps track of about 20,000 catalog debris objects and the 800 active satellites, calculates potential collisions, and issues warnings to satellite operators. Each day they produce 800 "conjunction analyses," about one for every active satellite. Many satellites can maneuver out of the way of debris when a near approach is predicted. However, STRATCOM does not have the resources to predict every potential conjunction, and no warning was issued on the Iridium/Cosmos collision last year.

The NASA Orbital Debris Program Office at the Johnson Space Center in Houston studies space debris and formulates rules to limit debris creation. These rules include eliminating throwaway bolts and latches when spacecraft are placed in orbit, venting fluid tanks to prevent explosions, and requiring that satellites re-enter the atmosphere within 25 years after their missions are completed. But the office director, Nicholas Johnson, says that unless we begin removing existing debris from orbit, the inevitable collisions involving objects like 8-ton rocket bodies and 5-ton dead satellites will create tens of thousands of new pieces of debris, resulting in the "debris runaway" or "Kessler Syndrome" that would make LEO unusable for hundreds of years[2].

## DEBRIS REGIMES AND DANGERS

Space debris can be divided into different orbital regimes and levels of danger to spacecraft and astronauts. Most catalogued debris is in LEO, defined as orbits below 2000 km altitude. In geostationary Earth orbit (GEO), there are many high-value broadcast satellites and environmental satellites, but relatively few debris objects. The debris objects in GEO, such as the Galaxy 15 satellite that is drifting, move at low velocities relative to operational satellites, and do not yet pose the danger of high-velocity collisions that can create tens of thousands of new pieces of debris. In medium Earth orbit (MEO), defined as orbits between 2000 km and GEO, there are fewer satellites and debris objects, and the dangers of collisions are much lower.

The LEO regime represents the more immediate problem. There are more debris objects, the results of collisions can be more catastrophic, and the highest value asset, the International Space Station, is in LEO. For these reasons, active debris removal in LEO should be addressed first.

Table I describes the lethal debris objects in LEO. They can be usefully divided into 3 categories based on their size and the resulting nature of their threat:

| **Type** | Characteristics | Hazard |
|---|---|---|
| **“Bullets”** | Untracked, >1 cm; 98% of lethal objects | Primary direct threat to satellites: too small to track and avoid; too heavy to shield against |
| **“Hubcaps”** | Tracked, <2 kg >10 cm, 2% of lethal objects | Frequent conjunctions, avoidance maneuvers |
| **“Cars”** | Tracked, >2 kg <1% of lethal objects | Primary source of new “bullets”; 99% of collision area and mass |

**Table I: Lethal Debris Objects in LEO**

The bullets are the primary threat to operational satellites, and most new bullets come from car collisions. This means that we must remove the cars to prevent LEO pollution with new bullets.

A December 2009 conference sponsored by NASA and DARPA (the Defense Advanced Research Projects Agency), featured many proposed solutions, including large orbiting shields to catch small debris, ground-based lasers to ablate the front side of debris to deboost it, and active spacecraft to capture large debris items and drag them down to atmospheric entry[3].

## THE EDDE SOLUTION

The most near-term and technically advanced method presented was a roving space vehicle that can capture LEO debris objects in nets and drag them down safely out of the space lanes. EDDE, the ElectroDynamic Debris Eliminator, is the first space vehicle that can remove all the large debris from LEO at reasonable cost[4].

EDDE is a new kind of space vehicle[5]. It is not a rocket that accelerates a payload by throwing propellant mass in the opposite direction. EDDE is an electric motor/generator in space. It maneuvers by reacting against the Earth’s magnetic field, and uses no propellant. This means that it is not limited by the Tsiolkovsky rocket equation. It can produce enormous delta-Vs of hundreds of km/sec over its operational lifetime. An EDDE vehicle equipped with solar panels for power and expendable capture nets could safely remove from orbit its own mass in debris each day on average. The principle of operation of an EDDE vehicle is shown in Figure 2.

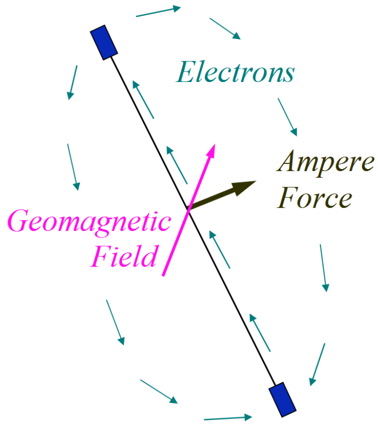


**Figure 2: Propellantless Propulsion**

The vehicle is in low Earth orbit, moving in the Earth's dipole magnetic field and surrounded by the ionized plasma from the solar wind that is trapped in the ionosphere. Solar arrays generate an electric current that is driven through the long conductor; the magnetic field induces a Lorentz force on the conductor that is proportional to its length, the current, and the local strength and direction of the magnetic field. Electrons are collected from the plasma near one end of the bare conductor, and are ejected by an electron emitter at the other end. The current loop is completed through the plasma[6]. This propellantless propulsion was demonstrated in orbit by NASA Johnson on their Plasma Motor Generator experiment. The average thrust going down can be considerably higher than that going up, because energy is being extracted from the orbital motion.

A schematic of EDDE is shown in Figure 3. It consists of a long conductor, solar arrays, electron collectors and emitters, and net managers at each end to deploy large, lightweight nets to enfold and capture debris objects. The EDDE hardware is shown in Figure 4.

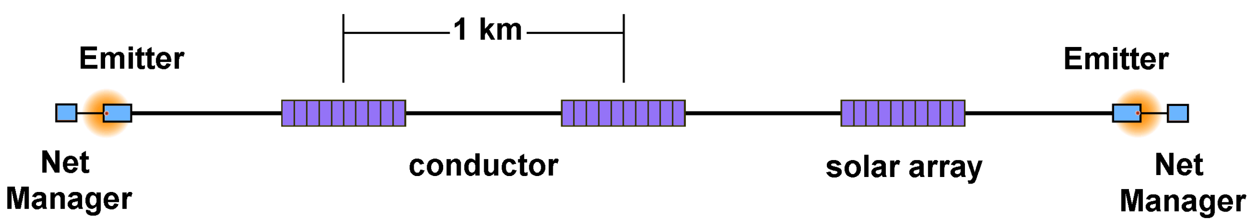


**Figure 3: Representative Sections of the 10-km-Long EDDE Vehicle**

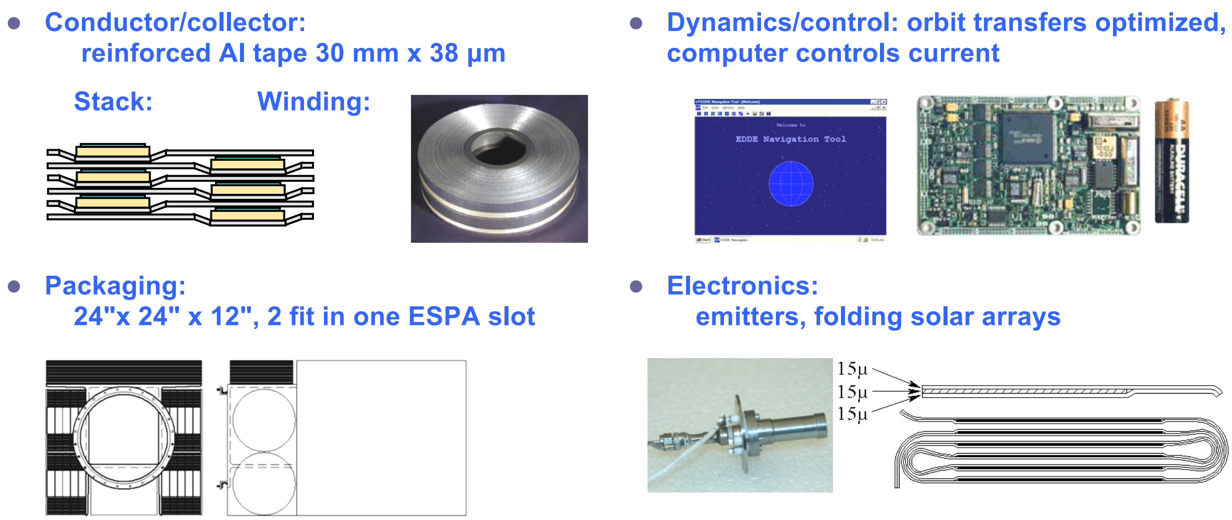


**Figure 4: EDDE Delivered Hardware, Components and Layout**

The EDDE vehicle is a very unusual spacecraft; it is two micro-satellite end bodies connected by multiple 1-km-long segments of reinforced aluminum ribbon conductor just 30 mm wide and 38 microns thick. The aluminum conductor is bare so it can also be an electron collector. Each end body contains an electron emitter. Solar arrays are distributed along the length, and the entire structure rotates slowly end over end to maintain tension and stability, a key patented advance in making its high performance possible[7]. The rotation rate is typically a few revs per orbit, and can be controlled by reversing the currents in different sections of the conductor. The rotation plane is also controlled. Two patents cover the method[8] and apparatus[9] for active control of EDDE.

Because there are many units of each element in the electrical circuit, even if EDDE were cut in two by a meteoroid, each end could still function as an independent satellite, or safely de-orbit itself. For debris removal, each end body is equipped with a net manager that carries about 100 Kevlar nets of 50 g each. To catch a debris object, a net is extended by the rotational force as the EDDE end approaches the target at a few meters per second. The net snares the target, and EDDE actively damps out the dynamics, even if the object is spinning or tumbling up to about 1 rpm. Most debris objects are rotating much slower than this because of the eddy-current damping of their aluminum structure and the tendency of the gravity-gradient force to align them vertically.

A further advantage of the EDDE propellantless spacecraft is that it folds up very compactly. Despite deploying to 10 km long, it folds up into a compact box 60 cm square and 30 cm deep. This allows it to be launched in one of the secondary payload slots of the Boeing Delta 4 or Lockheed Atlas 5 ESPA ring. It can also be launched as a secondary payload on the Orbital Sciences Pegasus air-launched vehicle, and the new SpaceX Falcon 1 and Falcon 9. If there is some payload margin for the launch vehicle, then there is little additional cost to launch EDDE vehicles piggyback. Two EDDE vehicles can fit into each secondary payload slot, or just one EDDE plus several nanosatellites to be carried to custom orbits after the primary payload is released.

For typical values of a few kilowatts of electric power from large, thin-film solar cells, a few amps of current and a 10-kilometer-long conductor, the force is typically half a newton. This is a very small force compared with typical rockets, but its advantage is that it operates continually, orbit after orbit, gradually changing the orbital elements. The result is a low-thrust system that changes orbits slowly, but has very high capability for very large orbit changes. The thrust is several times that of the ion rocket that drove the NASA Deep Space 1 probe to Comet Borrelly in 2001. Reversing the current at the right times around each spin and each orbit allows any desired combination of coordinated changes in all 6 orbit elements. The force can also be used to change the orientation of the conductor by changing the EDDE rotation rate and plane.

## EDDE PERFORMANCE

By using lightweight solar arrays, a reinforced aluminum ribbon conductor, and hollow cathodes at each end to run reversible currents, a typical EDDE spacecraft produces about 7 kW of power and weighs 100 kg, and can make large changes in its orbit in a fairly short time. Figure 5 shows typical rates of change of inclination, node, and altitude of the EDDE orbit[10]. The deboost rate can be much higher than shown, because additional energy is extracted from the orbital motion through the emf.

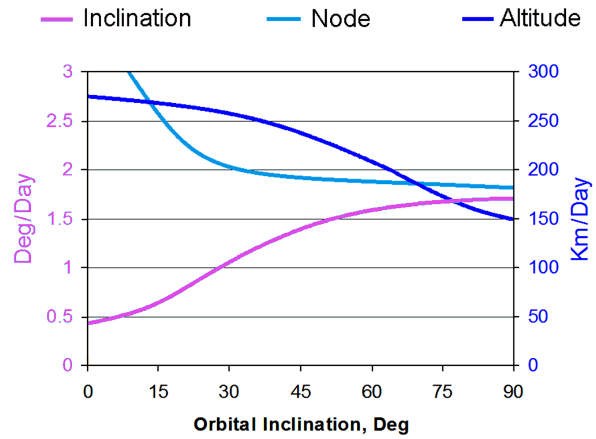


**Figure 5: EDDE Orbit Transfer Performance**

These rates are possible over altitudes of about 300 km to 1000 km, and are reduced at higher altitudes by lower magnetic field strength and plasma density.

A bare EDDE vehicle without a payload could go from the International Space Station 51.6° inclination orbit to 90°-inclination polar orbit in about 3 weeks, a delta-V of nearly 5 km/sec.

Using conventional rockets for space debris removal is extremely difficult. To launch a satellite into low Earth orbit, it must be given a velocity of 7 or 8 km/sec. With chemical propellants, even our best launch vehicles put only about 4% of the total launch mass into orbit. But to change the orbit of a satellite already in orbit can require even higher velocities. For example, to move a satellite from equatorial to polar orbit takes 1.4 times the orbital velocity, or about 10-11 km/sec. It would actually be easier to launch another satellite from the ground than to make this orbit change! Launching a chemical rocket from the ground to remove the debris, each piece in its own orbit, would be extremely expensive.

The enormous advantage that the propellantless EDDE vehicle has over conventional rockets is shown in Table II, which compares different propulsion systems in performing the task of removing the 2465 objects in LEO weighing over 2 kg.

| Propulsion System | Isp, sec | Number of Vehicles | Total Mass in Orbit |
|---|---|---|---|
| Bipropellant | 300 | 900 | 800 tons |
| $NH_3$ Arcjet | 800 | 300 | 250 tons |
| Ion Rocket | 3,000 | 120 | 65 tons |
| VASIMR | 10,000 | 30 | 25 tons |
| **EDDE** | **---** | **12** | **1 ton** |

**Table II: Propulsion System Requirements for Debris Removal**

A typical bipropellant chemical rocket might have specific impulse of 300 seconds, and the table shows that this task would require 900 vehicles weighing 800 tons. Higher-Isp systems include arc jets, ion rockets, and the recently-tested Variable Specific Impulse Magneto-plasma Rocket (VASIMR) championed by former NASA astronaut Franklin Chang-Diaz of Ad Astra[11]. These systems also require higher power.

But even VASIMR would require 25 tons in orbit to remove all the debris, more than 20 times the mass of 12 EDDEs, a little over 1 ton. Twelve EDDEs could remove all 2465 objects, a total of 2166 tons, in less than 7 years.

## EDDE OPERATIONS

The total LEO debris mass of the 2465 largest objects is 2166 tons. Many are in orbits of 81°-83° or 70°-74° inclination. There are also many old satellites in "sun-synchronous" orbits that allow them to pass over the same spot on the Earth at the same time each day; these are typically 400-800 km in altitude and 97°-99° in inclination, slightly retrograde. The EDDE performance in doing this task of removing all the large debris from LEO has been analyzed in detail by Star Technology and Research, and Tether Applications, the two small companies who developed the EDDE concept and vehicle[12,13]. Within 100 km, EDDE can take advantage of its 10-km length and use binocular imaging and ranging. Suitable target lighting and target and star views are available if we approach from a target's sunlit side, and do captures near the terminator rather than with the sun overhead.

Rendezvous trajectories

We plan successively closer passes before capture. The main challenge is that we want a close approach not of EDDE's center of mass (CM) but its spinning tip[10,12]. We also want a free return each orbit, so we must match orbit periods. To obtain both these features, capture must be done when the tip spin is normal to the orbit velocity vector. Lighting and binocular ranging are both better if EDDE is in a flat spin during the pass, rather than an in-plane spin. Figure 6 is a perspective view of EDDE and target trajectories near the North Pole:

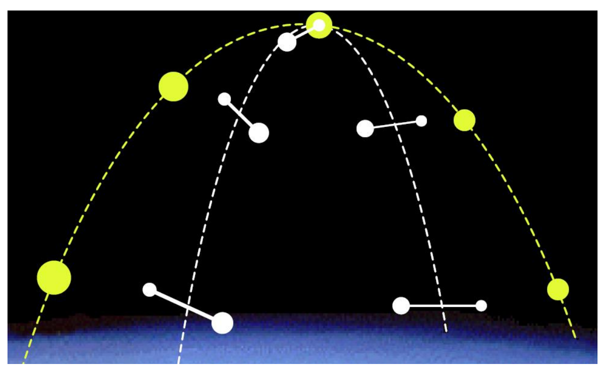

**Figure 6: Rendezvous by EDDE tip in flat spin.**

EDDE may be able to capture high-resolution images of targets from several angles during the pre-capture and capture passes. Since the targets all have known altitude histories, this could greatly improve data on the extent of observable impact damage by small impactors vs. altitude and time.

Capture operations and dynamics

As shown earlier in Figure 3, the "net manager" hangs outboard of the emitter, at the end of a 100-m tether that can be reeled in or out to abort the capture, compensate for trajectory errors, and pull the net up around a target. The rendezvous strategy allows free returns each orbit, so the operator can "be choosy" and attempt capture only when success appears likely.

Reeling tether in and out allows easy late error corrections in one axis. Reeling in and out earlier also allows minor spin-phase correction, using Coriolis effects. Figure 7 shows 3 frames from a spin-up test of a hanging net, as seen by the net manager, which itself spins while spinning up the net. To allow testing in air, the net was made of heavy bead-chain material, so inertia and weight are dominant over air-drag. The intended payload trajectory, shown as an arrowed dashed line, is curved in the rotating reference frame of the net and net manager. This test was done in 2002 as part of a Phase I NIAC project.[13]

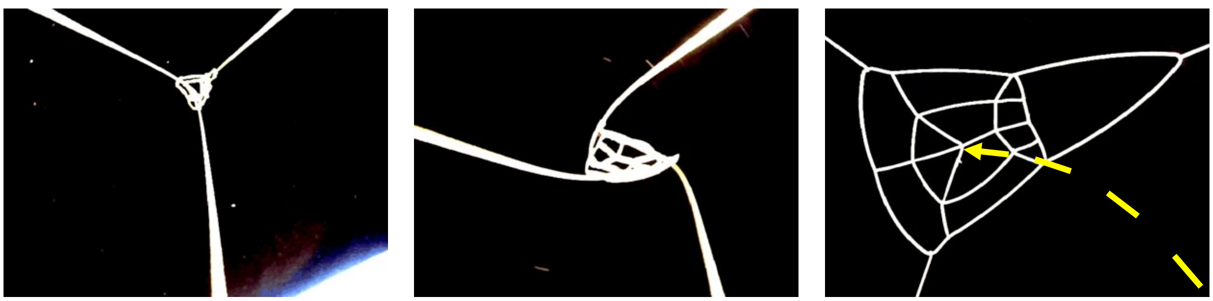

**Figure 7: Net spin-up as viewed from the net manager, with desired payload trajectory shown in frame 3**

Table III shows the typical removal operations that the EDDE vehicles would perform in dragging each LEO debris object down to an altitude of about 330 km, reducing its orbit life to a few months. It takes 10 days to remove an average debris object of 1000 kg from an average altitude of 800 km, which means that on average each 100-kg EDDE vehicle can remove its own mass in debris every day. EDDE could also provide targeted re-entry by using a ballast mass of another piece of debris to throw the debris into the southern Pacific Ocean[13].

| Operation | Days | Typical Parameters |
|---|---|---|
| Phase to next target | 0.4 | 400 km Δaltitude, ½ orbit average |
| Climb and tune orbit | 2.9 | 200 km/day, +20% for plane change |
| Approach and capture | 0.5 | 6-8 orbits at 800 km average altitude |
| Deboost and release | 6.2 | 90 km/day, +20% margin |
| **Total per target** | **10** | **1000 kg object, 800 km To 330 km altitude** |

**Table III: Typical EDDE Timelines with 1-Ton Objects**

A simulation of LEO debris removal using 12 EDDE vehicles for 6.7 years is available on-line at: www.star-tech-inc.com/id121.html. This simulation shows the history of the space debris buildup from 1959 to 2010, and snapshots of its removal by EDDE. The full simulation is shown in a link on the same web page. The page also has links to presentations given at the DARPA/NASA International debris removal conference in December 2009.

There are other methods for debris removal using electrodynamic tethers, but they are far less effective and far more risky than EDDE. It has been suggested that rockets could be used in a single orbit inclination to attach drag devices such as balloons or passive electrodynamic tethers to drag the debris down.

Debris removal using chemical rockets will be much more expensive by itself, but there is also another problem. These devices do not actively control the debris for collision avoidance during de-orbit, have much larger collision cross-sections than the debris, and add to the collision risk during their longer de-orbit times. Using passive electrodynamic tethers, for example, would require having multi-kilometer tethers on hundreds of objects over years as they slowly spiral down to re-entry. This would result in a huge additional collision risk, especially to ISS. By contrast, EDDE removes debris objects quickly, each object within days, and actively avoids all tracked objects while dragging debris to disposal.

Many operational issues need to be resolved for EDDE to perform its debris collection function, including agreements to capture debris objects, space object registration transfer or some other arrangement before handling any foreign-owned objects, if required, insurance for EDDE operator and debris owner, agreement on disposal or recycling methods, safety requirements on debris capture and removal.

## SPACE TRAFFIC MANAGEMENT

EDDE is the first example of a new class of space vehicles that can move all over LEO doing jobs like removing orbital debris and delivering payloads. But to perform its functions and move freely among other objects in LEO, constantly changing its orbital elements, EDDE needs a way to coordinate its flight plans with the plans of other spacecraft operators. A centralized flight coordination service such as offered by Center for Space Standards and Innovation (CSSI) can support EDDE operations in the future[14].

Additional work is needed on tracking. EDDE has an unusual radar signature with multiple from objects in non-Keplerian trajectories. New tracking algorithms need to be developed to calculate the orbit of the center of mass of the EDDE vehicle, and to predict future positions by keeping track of the changing orbit from the continuous electrodynamic thrusting[15].

## TETHER TECHNOLOGY MATURATION

Several successful spaceflights have demonstrated tether deployment and operation in orbit. The SEDS-1 and SEDS-2 flights by NASA Marshall deployed 20-km-long braided Spectra tethers, and SEDS-1 sent a 26-kg end-mass into a controlled entry.

The PMG (Plasma Motor Generator) flight by NASA Johnson demonstrated motor/generator operation with a 500-m copper wire and a hollow cathode, which is enabling for EDDE. The TiPS (Tether Physics and Survivability Experiment) by the Naval Research Laboratory demonstrated a long lifetime for a 2-mm by 4-km tether between two end masses. The tethers and deployers for SEDS-1, SEDS-2, PMG, and TiPS were all designed and fabricated by STAR subcontractor Joe Carroll of TAI (www.tetherapplications.com).

Joe Carroll also designed and fabricated electrodynamic tethers and deployers for ProSEDS (Propulsive Small Expendable Deployer System) and METS (Mir Electrodynamic Tether System). ProSEDS was built by NASA Marshall to demonstrate de-orbiting of Delta II upper stage using a 5 km electrodynamic tether. It was scheduled for launch but canceled after the Columbia accident. METS was built to keep Mir in orbit without fuel re-supply using a 7.5 km electrodynamic tether. It was scheduled for launch in early 2001, but canceled due to the decision to de-orbit Mir. Despite their not flying, these projects greatly advanced technologies crucial for electrodynamic tethers.

A new electrodynamic tether system, TEPCE (Tether Electrodynamics Propulsion CubeSat Experiment), shown in Figure 8, is being developed by NRL. TEPCE is a 3-unit CubeSat demonstration of emission, collection, and electrodynamic propulsion[16] planned for 2011. The two end pieces are connected by a 1-km conducting tether stowed in the center cube. The conductive tether design and stacer-driven deployment technique were proposed by Joe Carroll.

Following the TEPCE flight and a possible follow-on, the EDDE program is aimed at a Mini-EDDE spaceflight of a scaled-down 50-kg vehicle 2-3 km long that will demonstrate large orbit changes and rendezvous. This will be followed by a mission-capable EDDE that can fly piggyback on any flight with a 100-kg payload margin. It will demonstrate the capture and de-orbiting of an inactive US object using a deployable net, such as a Pegasus upper stage of 176 kg mass that is 1.3 m long.

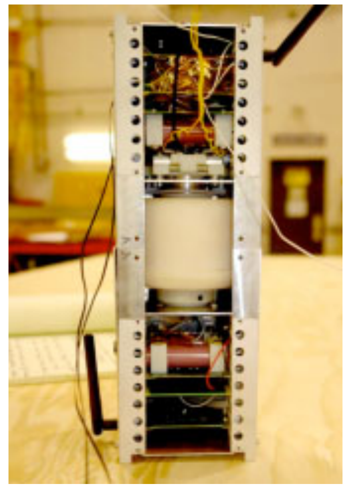

**Figure 8: TEPCE Hardware for Deployment Test**

## EDDE APPLICATIONS

EDDE can be used for a variety of useful purposes other than debris removal. To limit the dangers from re-entry, EDDE can deliver debris objects to a space processing facility that uses the aluminum in large upper stages as raw material for space processing and space manufacturing.

EDDE can deliver payloads to custom orbits, deliver fuel to operational satellites, deliver service modules to satellites, move satellites to new orbits, inspect failed satellites, and monitor space weather all over LEO. Multiple EDDE vehicles in different orbits could provide real-time maps of the ionosphere, keeping track of "space weather," which affects satellite communication, and could also record the effects of solar flares and proton events on the Sun, which are dangerous to satellites and crew.

Perhaps more importantly, after there is enough confidence in EDDE operations including capture, EDDE can deliver aged or failed satellites to ISS for repair, even from sun-synch orbit. This will want to use capture without nets, probably using the two-stage capture concept shown on page 23 of ref. 13. After capture, EDDE needs to torque the orbit plane to bring the satellite to ISS and release it. During the transfer, replacement parts can be sent to ISS. After delivery and repair, EDDE can take the satellite back to its original orbit or a new one, for continued operation. There have been billion-dollar satellites that failed soon after launch. Such on-orbit repair operations could be a very valuable part of full-scale ISS operations.

## CONCLUSIONS AND ECOMMENDATIONS

The immediate danger of LEO debris is now being recognized, as the urgency to prevent debris runaway. EDDE, for the first time, makes it feasible to remove all LEO debris over 2 kg at reasonable cost.

The EDDE vehicle is based largely on concepts already proven in flight, mostly on projects in which EDDE team members played key roles. Some of EDDE's novel aspects are planned for test as part of NRL's TEPCE experiment next year, and others are being considered for a potential TEPCE-II test. We plan to mature all other novel aspects of EDDE under current SBIR and follow-on funding. We hope to be ready for an integrated 50-kg, 3-km "Mini-EDDE" flight test within 4 years. This test would use full-scale EDDE components, but fewer of them than in a full 10 km EDDE.

Starting with next year's TEPCE test, this sequence of flight tests will validate EDDE's persistent maneuvering capability and allow extensive testing and refinement of EDDE components and software. Iterative refinement of software for control, rendezvous, and active avoidance of other tracked objects will also allow TEPCE and EDDE to assist the testing of upgraded space tracking and traffic management capabilities.

After these test missions, EDDE should be ready to begin removing debris from LEO, for U.S. and foreign customers, government and commercial, and to perform commercial operations of delivering and recovering satellites. It is unlikely that plausible improvements in alternative concepts can make any of them competitive with EDDE, because the wholesale debris removal that requires about 1 ton of EDDE vehicles would require 25 to 800 tons of vehicles using rockets.

We recommend that the international debris community immediately begin planning on removing debris with EDDE vehicles, which can be done more cheaply than current concepts for simply maintaining the status quo and not adding new debris. Planning should begin now for this removal, addressing the legal, diplomatic, treaty, and insurance implications of wholesale debris removal.

EDDE makes it possible to shift from reducing the rate of growth (the current policy and near-term plans involving selective removal) to wholesale cleanup. This has many implications that are not appreciated. EDDE is low cost, versatile, robust, and able to actively avoid all tracked objects. It is the logical solution to LEO debris removal, and should be implemented immediately.

## REFERENCES


[1] Liou, J.-C., and Johnson, N. L., "Risks in Space from Orbiting Debris," *Science* Vol.311, pp. 340-341, 20 January 2006.

[2] Kessler, D. J., and Cour-Palais, B. G., "Kessler Syndrome Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," *Journal of Geophysical Research*, Vol. 83, No. A6, 1978, pp. 2637-2646.

[3] Klinkrad, Heiner, and Johnson, Nicholas, "Space Debris Environment Remediation Concepts," NASA-DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 8-10 December 2009.

[4] Pearson, J., J. Carroll, E. Levin and J. Oldson, "EDDE: ElectroDynamic Debris Eliminator for Active Debris Removal," NASA-DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 8-10 December 2009. http://www.star-tech-inc.com/papers/EDDE_for_Debris_Conference.pdf

[5] Pearson, J, J. Carroll, E. Levin, J. Oldson, & P. Hausgen, "Overview of the ElectroDynamic Delivery Express (EDDE)," paper AIAA2003-4790 at 39th Joint Propulsion Conference, Huntsville, July 2003. www.star-tech-inc.com/papers/edde/edde_2003.pdf

[6] Pearson, J., E. Levin, J. Carroll, and J. Oldson, "The Spinning Electrodynamic Thruster (SET): An Order Of Magnitude Improvement over Ion Rockets," IAC-04-IAF-S.P.07, Vancouver, Canada, October 2004.

[7] Levin, E. and J. Carroll, "Method and Apparatus for Propulsion and Power Generation Using Spinning Electrodynamic Tethers," US patent 6,942,186, Sept 2005.

[8] Levin, E. and J. Carroll, "Method for Observing and Stabilizing Electrodynamic Tethers," US Patent 6,755,377, June 2004.

[9] Levin, E. and J. Carroll, "Apparatus for Observing and Stabilizing Electrodynamic Tethers," US patent 6,758,433, July 2004.

[10] Levin, E., *Dynamic Analysis of Space Tether Missions*, Vol. 126 in *Advances in the Astronautical Sciences*, American Astronautical Society, San Diego, CA, 2007.

[11] Cassady, L., et al., "VASIMR Technological Advances and First Stage Performance Results," AIAA Paper 2009-5362, 45th Joint Propulsion Conference, Denver, CO, 2-5 August 2009. www.adastrarocket.com/aarc/Publications

[12] Levin, E. M., J. Pearson, and J. C. Oldson, *Dynamics Simulation Model for Space Tethers*, NASA Contractor Report NASA/CR—2006–214432, June 2006.

[13] Carroll, J. A., "Space Transport Development Using Orbital Debris," NIAC Phase I presentation and final report, Oct/Nov 2002. www.niac.usra.edu/studies/800Carroll.html

[14] Pearson, J., E. Levin, J. Oldson, and J. Carroll, "EDDE: ElectroDynamic Debris Eliminator For Safe Commercial Space Operations," 13th Annual FAA/AIAA Commercial Space Transportation

Conference, Arlington, VA, 10-11 February 2010.

[15] Pearson, J., E. Levin, J. Carroll, and J. Oldson, "ElectroDynamic Debris Eliminator (EDDE) Opens New Frontiers in Space Traffic Management," 4th IAASS Conference, Huntsville, AL, 19-21 May 2010.

[16] Coffey, S., B. Kelm, A. Hoskins, J. Carroll, and E. Levin, "Tethered Electrodynamic Propulsion CubeSat Experiment (TEPCE)," Air Force Orbital Resources Ionosphere Conference, Dayton, Ohio, 12-14 January 2010.