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SPACE TEST OF LEO DEBRIS REMOVAL

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ABSTRACT

We propose a space test and demonstration of LEO debris removal using the maneuvering spacecraft EDDE (ElectroDynamic Debris Eliminator). EDDE uses solar power to react against the Earth's magnetic field to "sail" in the ionosphere like the clipper ships of yore, with unlimited total delta-V within LEO, and zero propellant usage. EDDE is the most affordable approach to wholesale debris removal from LEO, at a probable cost under $500 per kilogram. Moving debris to safe orbits for storage and later use could cost even less. To quickly demonstrate debris removal without new international agreements, we propose to remove US debris first. Many US companies, such as OneWeb, plan large new constellations of small satellites, and Iridium needs to remove over a dozen apparently dead existing satellites at its constellation altitude, for the safety of Iridium Next. To test debris removal, we would launch EDDE into orbit with a mockup of a small satellite that can be deployed and released. EDDE then uses its orbit transfer capabilities to approach and rendezvous with the target, captures it with its net capture system, and drags it down to a short-lived orbit below the ISS. The small satellite mockup will burn up completely in the atmosphere, and not pose a danger to people or property on the ground. Once EDDE has demonstrated its capability on the mockup, it can then rendezvous with U.S. debris objects in different orbits, and remove about one per week for perhaps 3 years, for a total of up to 150 removals. In all these operations, EDDE performs active avoidance of all operational satellites and all tracked debris, using orbit transfers with flight plans cleared by FAA and DoD, using the current Air Force space object catalog.

1. Introduction

We propose a space test and demonstration of LEO debris removal using the maneuvering spacecraft EDDE (ElectroDynamic Debris Eliminator). EDDE uses solar power to react against the Earth's magnetic field to "sail" in the ionosphere like the clipper ships of yore, with unlimited orbit transfers and delta-V, and zero propellant. EDDE is the most affordable approach to wholesale debris removal from LEO, and it can accomplish the goal at an estimated cost under $500 per kilogram.

There have been multiple proposals for space debris removal from ESA, JAXA, NASA, and several space entrepreneurs. Debra Werner gave an overview of ideas for removing debris and dead satellites in the May 2015 issue of Aerospace America[1]. Most of these ideas suffer from the problem of lack of sufficient delta-V, requiring many launches and high costs.

Darren McKnight reviewed approaches for debris mitigation and alleviation in 2015[2] and was pessimistic about active debris removal. "Active debris removal (ADR) operations will take decades to accrue benefits. NASA studies upon which most of the ADR effectiveness is based indicate it would take 30-50 removals to statistically prevent a single collision. Therefore, by removing five to 10 massive objects per year it would take three to 10 years before a collision is prevented "statistically." The cost of each object removal has not been precisely determined but values range from an optimistic $10 million to a pessimistic $50 million per object. As a result, it may cost $300 million to $2.5 billion for each collision "prevented." The interesting issue remains that the removing of massive derelicts from orbit does not eliminate risk; it merely transforms orbital risk to operational satellites into a re-entry risk to people and structures on the ground. Urgency is also accentuated by the fact that an operational ADR system is likely five to 15 years from being available."

Gen. William Shelton, then Commander, Air Force Space Command (AFSpC), gave the keynote address at the 27th National Space Symposium in 2011, and said "We haven't found a way yet that is affordable and gives us any hope for mitigating space debris."[3]

Several studies have indicated that the debris generation by debris-debris collisions should scale roughly with the square of mass vs altitude, integrated over altitude. To reduce debris creation rates much, wholesale removal of large amounts of mass is required. This typically requires providing a >200 m/s delta-V to a substantial fraction of the ~2000 tons of debris in LEO. If done with conventional chemical stages, this may take >200 tons of stages delivered to these debris masses.

There are in principal at least two alternatives to wholesale removal. One is spreading much of the 2000 tons over a much wider altitude range than it currently occupies. This reduces but does not eliminate risk, and it may require even more propellant than wholesale removal. The other option is collecting much of the debris mass now at congested altitudes at "scrapyards" at several different relatively uncongested altitudes. This may require less propellant mass, but requires eventual deorbit or in-orbit recycling of the collected masses, or some combination of partial recycling and reentry of the remainder.

EDDE can execute any of these 3 strategies: removal, or relocation, or collection for recycling and/or reentry. Our research shows that EDDE can start wholesale debris collection and removal within 5 years, at a cost from one-tenth to one-hundredth of those quoted by McKnight. EDDE is by far the most affordable technology for wholesale LEO debris removal. Key EDDE technologies have been extensively analyzed, developed, and lab tested.

To design the EDDE net collectors for debris capture, we need information on tumble rates and dimensions of the debris to be removed. That is the object of our companion paper at this conference[4].

2. The ElectroDynamic Debris Eliminator (EDDE)

The ElectroDynamic Debris Eliminator (EDDE) is a space vehicle of a new class: it “sails” through the ionosphere. EDDE uses electric current in a long metal tape to react against the Earth's magnetic field. EDDE collects electrons from the ambient ionospheric plasma near one end of the tape, and ejects them back into the plasma near the other end, using hot-wire electron emitters. EDDE’s thrust comes from the current in the tape crossing geomagnetic field lines. The current loop closes in the plasma, as shown in Figure 1.

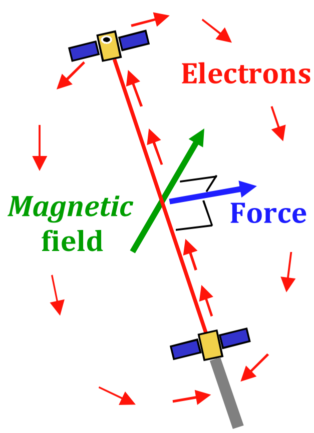

Figure 1. Electrodynamic Propulsion Concept

This concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test[5]. PMG flowed 0.3A through a 500 m wire and used hollow cathodes as plasma contactors at both ends of the wire. In 1996, NASA MSFC’s TSS-1R test achieved 1A through a 20 km wire.

The Ampere force on the conductor induced by the magnetic field scales with current times conductor length times magnetic field strength normal to the conductor, and is normal to both conductor and magnetic field. Average thrust when EDDE descends can be much higher than when it climbs, since energy to help drive the current loop is available from the EMF caused by the orbital motion. This is very advantageous for dragging down large debris objects, such as rocket bodies.

EDDE uses flexible lightweight solar arrays for power, and rotates slowly to improve stability and performance. Rotation is the key feature that enables high performance. It both stiffens the tether against the transverse thrust forces, and allows a wider range of angles with the geomagnetic field and hence thrust directions. We need 6-8 rotations/orbit for adequate tension and control. The rotation rate and plane are controlled by periodically varying the current level and direction. Bending dynamics are damped by varying current collection and emission along the tape length.

EDDE is covered by 3 US utility patents, for the method[6] and apparatus[7] for active control, and for the performance benefits of spinning operations[8]. Its propellantless operation allows it to change orbits repeatedly to match orbits with debris objects, capture them, and drag them down to entry or to collect them in a safe orbit for later use. This allows far better performance than ion rockets.

As shown in Figure 2 below, EDDE's solar arrays are distributed along the length of the conducting tape. The arrays and their controls divide the tape into short separately controllable segments. This lets us limit the peak voltages to the local plasma. Each tape segment both collects and conducts electrons, as a function of the voltage to the local plasma and the voltage gradient along the length of that tape segment.

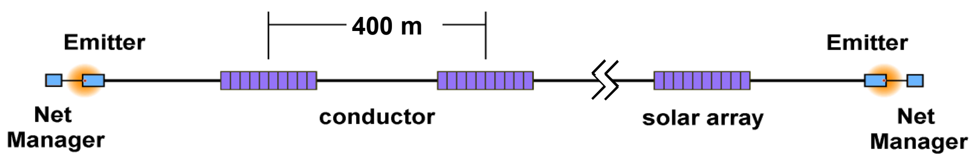

Figure 2. EDDE Vehicle Schematic, Showing Arrays, Conductor, Emitters, and Net Managers

EDDE's design plus its rotation set EDDE apart from previous electrodynamic thruster concepts for LEO. Hanging ED tethers use the weak gravity gradient force to provide needed tension and stability. For long-term stability, one must limit average ED thrust to a small fraction of the gravity-gradient tension. Too much thrust makes hanging tethers librate excessively and eventually causes loss of control. In contrast, because it is stiffened and stabilized by rotation, EDDE can handle currents and thrust much higher than compatible with long-term control of hanging tethers. Rotation also greatly increases the range of conductor angles to the magnetic field. This increases the range of possible average force directions. This in turn greatly increases EDDE's agility compared to hanging tethers, which typically can only thrust roughly east or west.

Rotation is particularly useful in near-polar orbit, particularly for altitude changes, which dominate the time needed for wholesale removal of large debris. The EMF on hanging tethers is low, since it nearly scales with Cos(Inclination). Thrust is nearly normal to the orbit, so altitude changes are slow. EDDE can spin normal to the orbit. This greatly increases both peak and average EMF, and climb and descent rates in near-polar orbits. Performance in such orbits is critical for wholesale debris removal, since >60% of the 2200 tons of LEO mass other than ISS is within 10° of polar orbit.

EDDE can be equipped with net managers at each end to deploy house-sized nets weighing ~50 grams each to capture objects, and/or CubeSat or other payload carriers to distribute multiple payloads to any desired low Earth orbit.

EDDE's tape design greatly reduces the risks of cut by hypervelocity impacts. Electrodynamic tethers that use small diameter wires can be cut by impactors down to ~1/3 the wire diameter. To overcome this, some electrodynamic tethers use multiple strands with cross-members, like a ladder[9]. But small wires with many connections pose fabrication and deployment challenges, including keeping the thin strands apart. EDDE's conductor design is simple but effective. It is a ribbon of aluminum foil 1-3 cm wide, reinforced with a full-width unidirectional fiber composite layer for strength and tear resistance. This greatly reduces vulnerability to small micrometeoroids and debris.

EDDE's power is provided and controlled by solar arrays at ~400 m intervals along EDDE's length. This allows control of current and hence force along the length, and eases detection and quenching of arcs to the plasma. Such arcs can be triggered by meteoroid or debris impact on parts of EDDE that are biased negatively to the local plasma. Those arcs can be quenched by isolating the tape segments. This reduces the bare tape electron collection area and EMF that drive the arc. Control of current along the length and over time allows control of rotation plane and rate and bending dynamics, as well as changes in all 6 orbit elements.

EDDE's distributed control also allows control after component failures, including tape severance by debris or micrometeoroid impact. Segmented design plus distributed control let EDDE become a highly redundant vehicle controllable from either end. Each segment has power and control of electron collection, conduction, and emission, and each end can control overall maneuvers. If EDDE is cut by a meteoroid or debris, each half can still thrust and control itself, and can either continue a mission more slowly, or deorbit itself promptly, to prevent danger to other spacecraft that could arise after another tape severance.

EDDE's modularity lets it be sized to fit the available envelope, payload, and orbit change needs of specific missions, ranging from nanosat delivery to capture and relocation of multi-ton debris objects. We expect most EDDEs will weigh from 30 to 160 kg and have one to several kilowatts of power.

Orbit-transfer performance is very impressive, as shown in Figure 3 for an 80 kg EDDE. The rates of change in altitude, inclination, and node are shown as functions of the orbit inclination, per ampere orbit-average current. Currents are likely to average more than 1 A near 500 km altitude, and less than 1A at much higher altitudes, especially near solar minimum. Heavy EDDE vehicles (80-160 kg) can use longer and wider tapes, so their performance is degraded less by low plasma density, so they can climb higher with less loss of agility than 30 kg EDDEs.

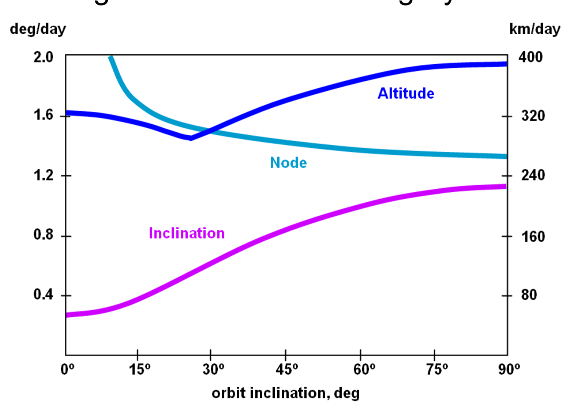

Figure 3. EDDE Orbit Transfer Performance per Ampere Average Current, for an 80 kg EDDE

The above maneuver rates are for EDDE by itself. When EDDE carries payloads or debris, the orbit change rate scales down with the ratio of EDDE to total mass. If EDDE captures ton-class debris at 750-1000 km altitude and releases it into short-lived orbits below ISS, average throughput can approach EDDE's own mass per day, or nearly 60 tons/year for a 160 kg EDDE.

At low inclinations, and when changing orbit plane at higher inclinations, EDDE will usually rotate in the plane of the orbit, but at higher inclinations it will rotate normal to the orbit plane to maximize climb and descent rates. The transition between these altitudes causes the kink in the altitude performance curve in Figure 3.

The current status of the EDDE technology and key components is given in our publication at the international tether conference in 2016[10].

3. EDDE Capabilities for Wholesale LEO Debris Removal

Because the revolutionary EDDE spacecraft is completely propellantless, can roam all over LEO with essentially unlimited range and orbit transfer capabilities, and can remove roughly its own weight of large debris objects from LEO each day, it is the only known system that requires little enough launched mass to be affordable for wholesale mass removal from LEO. EDDE capabilities can be illustrated by describing 4 examples of debris removal: clearing dead Iridium satellites from the constellation; doing the same for OneWeb as some of its ten-times larger numbe of satellites fail in situ; clearing sun-synchronous orbits of U.S. and allied objects; and wholesale debris removal from LEO.

An immediate problem is ensuring safety of existing and planned satellite constellations such as Iridium and OneWeb. Iridium is in the process of replacing its original satellites with the Iridium Next constellation in its nominal orbit of 780 km and 86.4° inclination in 6 planes of 11 860-kg satellites each, spaced 30° apart.

According to Rod Sladen[11], of the original 66 Iridium satellites, 12 have failed and are tumbling, and another 6 have communication failures but are not tumbling. They weigh ~689 kg each. EDDE vehicles can remove all the original Iridium satellites to make the orbit safe for Iridium Next, and its large nets plus centrifugal stabilization can handle Iridium satellites tumbling at up to several rpm.

Operations and a timetable for removal of the 12 dead Iridium satellites near 765 km altitude, slightly below the main Iridium constellation are shown in Table 1, taken from our 2014 IAC paper[12]. This assumes that EDDE will drag them down to ~350 km, below ISS, for quick re-entry. The total time needed is about 4 months for the 12 tumbling satellites with one EDDE, and about 6 months to remove all 66 existing satellites with 4 EDDEs.

Operation	Days	Typical Parameters
Phase to next target	**0.4**	380 to 765 km, ½ orbit average phasing
Climb and tune orbit	**1.9**	380 to 765 km at 300 km/day, +50% for plane change
Approach and capture	**0.5**	7 orbits at 765 km Iridium altitude
Deboost and release	**7.7**	765-350 km, +10% , at -600 km/day*80/(80+689)
Days per Iridium	**10.5**	765 to 350 km, with 689 kg dead Iridium

Table 1: EDDE Removal Times for Original Iridium Satellites

The second example is OneWeb[13] is planning a constellation of 648 satellites of 150 kg each, at 1200 km altitude and 18 polar planes of 36 each. This may be augmented by an additional 1972 satellites later. The satellites are planned to de-orbit themselves after 5 years, but as with Iridium, some fraction will fail at the constellation altitude. This creates a need for active removal of perhaps 30-130 satellites, or 5-20 tons. The time required for removing 30 satellites with one EDDE is 9 months, and for removing 130 satellites with 4 EDDEs is 10 months. The OneWeb constellation could keep one EDDE busy constantly to keep the orbit clear and safe.

A larger project that could be undertaken without additional international agreements with Russia and China is to clear sun-synchronous orbits of US and allied country dead satellites and upper stages. In the inclination range of 96-102°, there are 55 U.S. upper stages totaling 22 tons and about 34 tons and 80 Allied upper stages. In addition, there are perhaps 40 tons in 80 U.S. dead satellites and 60 tons in 120 Allied dead satellites. The altitudes average perhaps 900 km.

To remove these approximately 335 items of about 156 tons from 900 km near-polar orbits would take a little over 3 years for a fleet of 4 EDDE vehicles, allowing extra time for moving over the expected large differences in orbital nodes.

The largest task by far for EDDE is wholesale removal of most of the thousands of objects over 1 kg in mass from LEO. (Lighter debris objects can disable satellites by impact, but they are unlikely to shred the ton-class intact debris objects that have most of the target area and mass in LEO. It is better to remove large and massive objects, but fragments >1 kg are also useful “targets of opportunity.”)

There are about 2600 intact LEO debris objects totaling ~2200 tons, not counting active satellites. Removing nearly all of them would eliminate the danger of the Kessler Syndrome, and vastly reduce the danger to operational satellites of catastrophic collisions such as the Kosmos-Iridium collision of 2009.

Figure 4 shows the comparative cost per kg of wholesale removal using EDDE propellantless propulsion vehicles, compared with chemical and ion rockets. It also shows the reduction in potential of debris generation from collisions between the large debris objects as the debris is removed.

It is groundbreaking that the unit cost of debris removal can be a small fraction of typical launch costs. For rockets, estimated unit costs of debris removal are comparable with the original launch costs. This is prohibitive. It is hard to justify debris removal if it costs as much per kg as launch. The service must be much cheaper than launch to make economic sense to satellite operators.

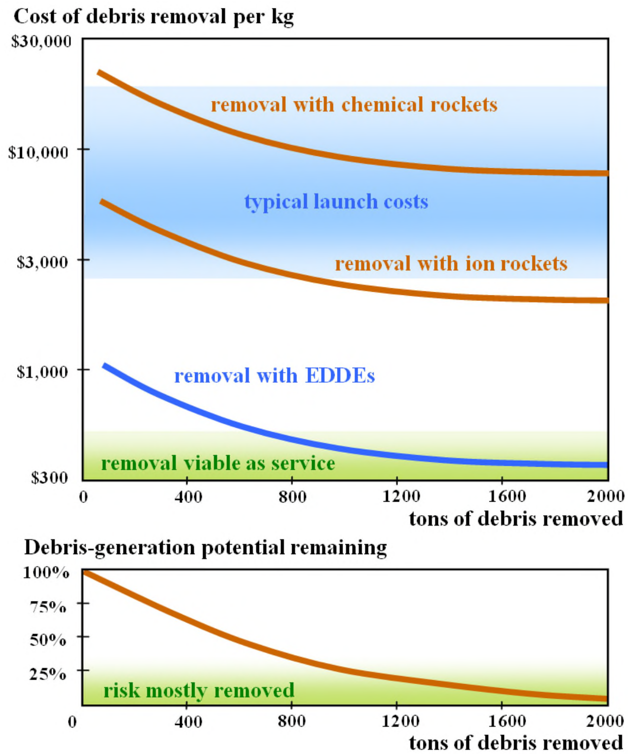

Figure 4. Wholesale Debris Removal Costs

Participation of the 12 members of the Inter-Agency Space Debris Coordination Committee can create an international regime supporting wholesale debris removal. Debris removal might be a commercial activity funded and regulated by an appropriate regulatory agency in each participating country, such as the FAA in the US. The most efficient payment mechanism to commercial operators like EDDE may be bounties for actual removal of debris, with the bounty payment proportional to the reduction in expected long-term debris risk. Bounty concepts are discussed in more detail in a 2014 IAC paper[14].

4. Debris Collection Compared with Debris Removal

The simplest technique for removing debris is to have EDDE capture it, drag it down to perhaps 350 km altitude (below ISS), and release it. Entry will usually occur within a few months, but this is an untargeted entry. Large or dense objects will likely survive entry and endanger people or objects on the ground. Targeted entry would be safer.

EDDE could perhaps attach a small rocket package to each object before releasing it. If the rocket could provide about 20 m/s delta-V, the object could be targeted for entry in, say, the unpopulated southeastern Pacific Ocean. But carrying a rocket package to each object would greatly increase the cost of removal.

Another method would be for EDDE to capture two objects, one on each end, and then release one near 350 km perigee from the lower end of the rotating EDDE, causing it to enter and EDDE to rebound up to catch the next object. But slinging large objects to entry would result in large loads on the EDDE conductor, making it much heavier, and carrying a large object back to altitude to capture another would drastically slow EDDE down, reducing throughput and raising costs.

A better solution could be collecting the large debris rather than removing it from orbit. EDDE could take such debris to a safe storage orbit at an uncluttered altitude between 660 and 730 km. Since the debris mass is concentrated in narrow inclination bands, we could create “tethered scrapyards” near these inclinations to be controlled by EDDE propulsion to actively avoid collisions, effectively removing the danger of collisions from the objects.

Collection requires matching all orbit elements, including the node. But if a scrapyard is lower than the debris that is brought to it, nodal regression will be faster, so one can wait until nodal coincidence to capture an object and bring it to the scrapyard. For the most crowded inclinations, several scrapyards at different nodes allow faster collection. Tethered scrapyards can be stabilized vertically, and can maneuver electrodynamically to avoid other **>**1 kg tracked objects at their altitude. (A few EDDEs can capture and deorbit most **>**1 kg tracked fragments near scrapyard altitudes. Nearly all such fragments should burn up during reentry.)

Some of the debris can be separated and delivered by EDDE vehicles to customers anywhere in LEO. The largest debris collections will be mostly 1.4 ton Kosmos-3M stages near 83° inclination, and 8-ton Zenit stages at 71°. Tanks can be cut into shingles to serve as impact and radiation shielding, or convenient feedstock for other processes. Cutting tank skins also ventilates objects so they burn up more during reentry. This may even make untargeted reentry acceptable. Figure 5 shows one scenario. Small adjustments of inclination, node, and other orbit elements are needed to get debris to a scrapyard. They can be done efficiently while EDDE descends. EDDE throughput can be high since the required altitude changes are far less than if EDDE has to drag debris down to 350 km.

Figure 5 shows how a scrapyard might accumulate rockets delivered by EDDE (steps 1-2). Step 3 adds processing equipment, to cut the rockets up into shingles (steps 3-4) that can then be delivered by EDDE vehicle to customers in ISS orbit or elsewhere (step 5). The shingles can serve as shielding, or become feedstock for various additive manufacturing processes. Cutting up rockets and satellites also ventilates any remaining mass so it will burn up more during reentry. This may make its untargeted reentry acceptable. The most common rocket body types tend to be used at different inclinations, so each scrapyard need only catch and process one type of rocket. That should simplify design of the processing equipment.

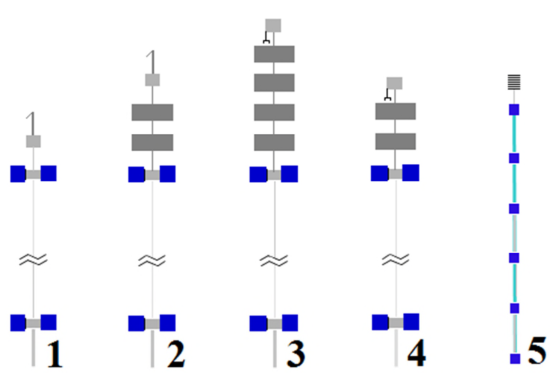

Figure 5. Collection, Shingle Cutting, EDDE Delivery

If recycling technologies can be developed to use upper stage aluminum to build large space structures in LEO, then the ~1000 tons of upper stage tanks could become very valuable. At current launch costs of $1000/kg, it could be worth $10B in orbit; if SpaceX succeeds in reducing launch costs to $2000/kg, it is still worth $1B, even if the recycling costs of construction in space are $1000/kg.

5. Comparison of Debris Removal Approaches

NASA scientist Donald Kessler warned of the dangers of space debris accumulation in 1978[15], and since then there have been many proposals for active debris removal to prevent the "Kessler Syndrome." Because most space debris mass belongs to Russia, international agreements and funding will be required to remove all LEO debris. About 78% of the debris mass in LEO is owned by Russia (67%) and China (11%). The U.S. owns 13% and all othe countries 11% combined. We can make a start by removing the 20% of the debris owned by the U.S. and its allies, but the rest will depend mainly on Russian cooperation.

Active debris removal consists of two parts— the debris grappling and de-tumbling method, and the propulsion required to take the removal device to the debris and to de-orbit it. The grappling devices explored have included capture nets, harpoons and adhesive tethers, as well as non-contact methods such as laser ablation and ion beam shepherds. The propulsion methods are based on chemical rockets, ion rockets, and the EDDE rotating electrodynamic tether. All devices depend on chemical rockets to get into orbit, but ion rockets and tethers are proposed for the main delta-V requirements to rendezvous with the thousands of debris objects in different orbits and to drag the debris to storage orbits or down to entry.

The NASA debris office at Johnson Space Center has assessed the debris environment in LEO, and J.-C. Liou[16] proposed that removing just 5 large objects per year would stabilize debris population. (But these numbers appear to depend on large Zenit and other Russian stages being removed first.) The debris office expects to see about one major collision every 5 years. ESA has studied debris extensively, and has their Clean Space program and the e.deorbit system based on rockets and thrown nets[17]. They propose a test of the system on a single debris object in 2023, launching a 1600-kg spacecraft on a Vega rocket into a polar orbit at an altitude of 800–1,000 kilometers. Once on orbit, the spacecraft will rendezvous with a derelict satellite and capture in with robotic arms or nets. The spacecraft will then deorbit itself.

The Busek company has developed Hall thruster ion rockets using iodine fuel, and have proposed their ODER active removal system[18]. JAXA is developing an electrodynamic tether and nets for de-orbiting debris, and did a space test this year of an 800-m tether[19]. In the U.S. TUI has proposed their electrodynamic tether Rustler[20], and ESA has proposed a bare ED tether for removal[21].

Table 2 compares the three propulsion approaches in terms of development cost, launch cost, total cost, and cost/kg to remove all large LEO debris objects larger than 1 kg (2600 objects, 2200 MT).

Propulsion	Example	Cost to Develop	Launch Mass, MT	Program Cost	Cost/kg
Chemical Rocket	ESA	Existing	3500	$57B	$26,000
Ion Rocket	Busek	$80M	52	$4.4B	$2,000
EDDE Tether	STAR, Inc.	$18M	1	$770M	$350

Table 2. Debris Removal of 2200 Tons (2600 Objects>2 kg) from LEO

EDDE is the only affordable method, costing only one-fifth as much as ion rockets and one-fiftieth as much as chemical rockets. And EDDE does not just stabilize the debris, but removes all large LEO debris objects in less than 10 years.

6. NRL Flight Test of EDDE Components and Operations

The Naval Research Laboratory is now readying a 3U CubeSat that will serve as a precursor flight test for EDDE. It is named "TEPCE," for the "Tethered Electrodynamic Propulsion CubeSat Experiment." TEPCE is shown in Figure 6. It uses a stacer spring to energetically push the outer cubes apart. This drives deployment of a 1 km long tether stowed around the stacer.

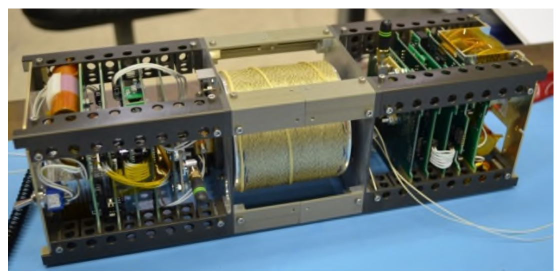

Figure 6. NRL TEPCE CubeSat

TEPCE can switch its high-voltage electronics to collect electrons on the EDDE-like bare metal tapes that deploy outboard of the end masses (they are stowed at bottom left and top right in Figure 6). TEPCE uses EDDE-like hot wire emitters at each end mass to emit electrons. TEPCE's body-mounted solar cells limit the probable orbit change rate to ~1 km/day.

NRL has tested tether deployment both in vacuum chambers and by free fall experiments in air. The satellites were repeatedly dropped from three stories to test the spring deployer called a stacer that will push the end masses apart at 4 meters/second. NRL also also tested the high voltage electronics that will use power from solar arrays and batteries to push a 0.01 amp current along the tether.

It is planned to eject TEPCE into an elliptical orbit on the second Falcon Heavy launch. Orbit life will be limited by a 1.3 m^2 average drag area including tether and tapes. NRL could perform several tests on EDDE operational capabilities. The USAF Space Test Program is funding the TEPCE launch.

7. Space Test of EDDE Operations

We propose a low-cost space test of a complete 80-kg EDDE with auxiliary payloads in an ESPA (EELV Secondary Payload Adapter) slot or on a small dedicated launcher. The total mass of the mockup and the small satellite payloads can be up to 120 kg in the current ESPA design. Such a space test could achieve several significant goals—demonstration of the critical basic functions of deployment, control, orbit changes and active collision avoidance that each EDDE must perform; payload delivery, capture, and de-orbit of a simulated satellite; approach, survey, capture and de-orbit selected in-space debris objects; space situational awareness by high-resolution observations of multiple selected objects in LEO, such as U.S. rocket bodies; and additional deployments such as drag spheres. The space test could be open-ended, consisting of increasingly demanding performance of the EDDE vehicle.

Primary payload operators want to see accurate insertion into their desired orbit, but secondary payload operators never had this luxury. To break this mold, EDDE can demonstrate accurate insertion into a pre-selected orbit different from the orbit of the primary payload. EDDE might get a ride to a 9 am 600 km sun-sync orbit with a mockup payload. We can then select a 10 am 800 km sun-sync orbit before the launch and show that EDDE can indeed perform accurate insertion into this orbit that is quite different from the primary payload orbit (in this example, it will require changing altitude, inclination, node, and phasing). Accurate orbit insertion from a rotating tethered vehicle is an interesting and challenging task by itself, and a demonstration of this capability will be important and impressive.

The EDDE space test would begin with a launch on a flight into polar orbit with the mockup satellite and several additional payloads. Upon release in the initial orbit, EDDE will demonstrate "born spinning" deployment of its components, and complete functioning and dynamic control of all its systems. EDDE will spread its magnetic "sails" and begin navigating through LEO, to demonstrate orbit changes and collision avoidance.

It will first file a set of proposed flight plans with the appropriate agency, FAA or DOD, to take the smallsat mockup to a different orbit and release it for later rendezvous and capture. The U.S. Strategic Command, through its Joint Space Operations Center (JSpOC), will approve a flight plan that does not come close to any operational satellites. During the orbit transfers to deliver the smallsat mockup, EDDE will by modify its path to actively avoid all tracked objects by safe distances.

After dropping off the smallsat mockup, EDDE can then demonstrate satellite delivery by taking the additional small satellite payloads into their desired orbits, perhaps creating a smallsat constellation for Earth observations. During and after these deliveries, EDDE can approach other objects for close-up observations for space situational awareness, again with an approved flight plan. This will complete the tests of satellite delivery and space object observations.

The next test requires that EDDE be equipped with net managers at each end containing multiple lightweight capture nets. EDDE will return to the smallsat mockup, rendezvous and match orbits with it, and then deploy a net to capture it, using its rotation to swing the net to envelop the target. Once it is captured, EDDE will thrust to lower its orbit to well below the International Space Station (ISS), where it will release the smallsat mockup into a short-lived orbit for re-entry. EDDE obtains a slight boost from the release, then thrusts to safely climb above the ISS to continue other operations for space situational awareness. Since EDDE does not use propellant, it will be able to rendezvous with and observe multiple objects close-up. These space observations would need to comply with planned NOAA requirements for space imaging.

Using its multiple nets at each end, EDDE can then approach and rendezvous with several space debris objects in different orbits. These might include some fragments from the Iridium 33 that was destroyed by the collision with the dead Cosmos satellite in 2009. EDDE could approach, rendezvous with, capture and de-orbit several of these fragments. With nets at each end, EDDE could even test targeted entry of selected objects, using one object to be released from one end, and another at the other end for ballast[22]. These tests would remove dangerous debris objects and start clearing the Iridium constellation altitude as well as demonstrating EDDE capabilities. Later flights can use larger nets and capture larger objects.

The space test or later flights could also include capturing and recovering historically significant satellites[23], such as the Vanguard I, the oldest satellite in Earth orbit. To return Vanguard I to Earth, EDDE could place it in the ISS orbit for return on a Dragon or other capsule, or could take it to the Air Force X-37B for return in its cargo bay.

The EDDE space test might also include among its payloads for distribution multiple drag spheres for atmospheric drag measurements at different altitudes and inclinations. They might be about the size and mass of ping-pong balls (4 cm, 3 grams). They might be polished hollow aluminum balls. They can be easily detected and tracked by either telescopes or the new S-band radar. They would have a high enough area/mass to quickly and clearly show the effects of atmospheric density changes, and low enough mass to not shred ton-class intact objects.

Successfully completing these space tests will demonstrate all the required EDDE activities for payload delivery, space situational awareness by close-up observations, and debris removal. These demonstrations will clear the way for EDDE to begin performing its full range of capabilities.

8. Conclusions

The EDDE roving spacecraft for LEO is the most affordable approach to wholesale debris collection or removal. EDDE can clear orbits for safety, including the OneWeb planned constellation and the Iridium constellation. Once international agreements are in place and funding is available for wholesale debris removal, a fleet of a dozen EDDE vehicles launched as secondary payloads of low cost could remove every debris object of over one kilogram mass from LEO in about 10 years.

A space test of EDDE could demonstrate its capability to remove a mockup satellite from orbit that EDDE carries with it on the launch. Then the test EDDE, equipped with multiple disposable nets at each end could remove perhaps 150 U.S. debris objects from LEO in about 3 years. These could include historically significant satellites such as Vanguard I, the oldest satellite in orbit, which could be recovered and returned to Earth through the NASA ISS Dragon capsules or the Air Force X-37B spaceplane.

This space test will demonstrate the EDDE operations, speed of removals, and the cost per kilogram of objects removed, paving the way for wholesale LEO debris collection and removal. If international agreements are in place, EDDE could recover 1000 tons of upper-stage aluminum, which could be worth $1B after recycling costs, and this would more than pay for the entire EDDE debris removal cost.

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