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EDDE SPACECRAFT DEVELOPMENT FOR ACTIVE LEO DEBRIS REMOVAL

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EDDE, the ElectroDynamic Debris Eliminator, is a persistently maneuverable propellantless "taxi" vehicle for low Earth orbit (LEO). EDDE allows affordable wholesale removal of large LEO debris, preventing collisions that is otherwise likely to be the main future source of untracked debris lethal to spacecraft, and the main driver of debris costs. EDDE can also distribute secondary payloads to custom orbits, and deliver service modules to serviceable spacecraft throughout LEO. EDDE consists mostly of a multi-kilometer reinforced aluminum foil tape that collects and conducts electrons, plus solar arrays to drive the current. Hot wires emit electrons back into the ambient plasma, allowing external closure of the current loop. EDDE's maneuver force comes from current in the tape crossing geomagnetic field lines. EDDE slowly rotates to tension and stabilize itself. Adjusting the current around each rotation and each orbit lets EDDE adjust all 6 orbit elements plus rotation axis and rate. Rotation allows persistent directable net thrust even in polar orbit. Accurate control enables capture of large debris in expendable gossamer nets. If EDDE captures ton-class objects at 750-1000 km altitude and releases them below ISS, debris throughput can approach EDDE's own mass per day, or nearly 30 tons/year for an 80 kg EDDE. Two such EDDEs can fit in one ESPA secondary payload slot on any Delta 4, Atlas 5, or Falcon 9 launch with enough payload margin. A full ESPA ring with 12 EDDEs can deorbit most LEO debris mass in <10 years. We matured EDDE design, components, and operating concepts under a recent 2-year contract with the NASA Space Technology Mission Directorate at Langley Research Center. This paper describes EDDE's design and operations, rendezvous and capture concepts, the costs of orbital debris and challenges associated with removing it, and plans for a 12U EDDE flight test. The test can include both payload delivery and imaging of selected US-owned debris, to quantify rendezvous errors.

I. INTRODUCTION

The 2007 Fengyun-1C A-sat test created 3378 cataloged debris fragments, of which 3076 were still in orbit in 2013[1]. Two years later, Cosmos 2251 and Iridium 33 collided. This was the first high-yield accidental collision in 52 years use of low earth orbit. It created another 2201 cataloged fragments, of which 1821 were still in orbit in 2013[1]. These two collisions together created ***over half*** the cataloged fragments in LEO, and probably a larger fraction of a far larger number of untracked cm-class fragments. Impact by such small but lethal "shrapnel" can disable satellites. That rather than tracked debris is the main direct cost of debris. These events have sparked interest in orbital debris, and a search for affordable ways to remove it.

EDDE, the "ElectroDynamic Debris Eliminator," is a leading contender for removal of large debris from LEO, before collisions shred it into more lethal untracked fragments. It may be the only option that allows affordable wholesale debris removal, because EDDE's persistent propellantless maneuverability lets each EDDE remove hundreds of large debris objects.

We proposed orbital debris removal by EDDE in 2002[2], and in more detail at the 2009 NASA/DARPA conference on orbital debris removal[3]. We described removal strategies at the 2010 Prague IAC[4]. A 2012 *Acta Astronautica* paper[5] showed how EDDE can do wholesale removal. A paper at the 2012 Naples IAC described partial removal campaign options[6], and a paper at the 2013 Beijing IAC assessed the long-term cost of debris removal from LEO[7].

Other approaches have also been proposed for active debris removal, including rockets and tethers with nets, harpoons, or robotic grapplers. NASA JSC proposed stabilizing the LEO debris population by removing 5-10 of the most dangerous large objects in LEO each year[8], but doing this with rockets could cost $1B per year and would need to be continued indefinitely[9]. In contrast, EDDE could de-orbit all ~2000 tons of existing large LEO debris in less than a decade, for well under $1B total cost. On 9 May, 2014 it was stated at a US Congress Space Committee hearing that NASA has just one development program focused on active debris removal, and that is EDDE, the ElectroDynamic Debris Eliminator[10].

We recently matured EDDE's design, components, and operating concepts under a 2-year technology maturation contract with the NASA Space Technology Mission Directorate at Langley Research Center. It ended in May 2014. Our main hardware work was on lightweight laminated-film solar arrays using bifacial terrestrial silicon cells, AO-tolerant hot-wire electron emitters, EDDE's conductive tape, a steam resistojet to aid deployment and debris capture, and new options for EDDE packaging and deployment. We also matured strategies for control, navigation, collision avoidance, and rendezvous.

A companion paper[11] in symposium B4 of this IAC shows how EDDE can provide "custom orbit delivery without dedicated launch" to one or more secondary payloads ranging from cubesat to ESPA size.

This paper focuses on aspects of EDDE related to debris. Section II presents key EDDE concepts. Section III covers our maturation of EDDE components; and IV covers control, navigation, and collision avoidance. Section V discusses rendezvous and capture. Section VI discusses the cost of LEO debris and ways to reduce it. Sections VII and VIII discuss how EDDE can do that, by deboosting or collecting debris. Section IX discusses other EDDE uses, and Section X reviews flight test plans.

II. THE EDDE SPACE VEHICLE

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.

This concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test[12]. 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 x conductor length x 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.

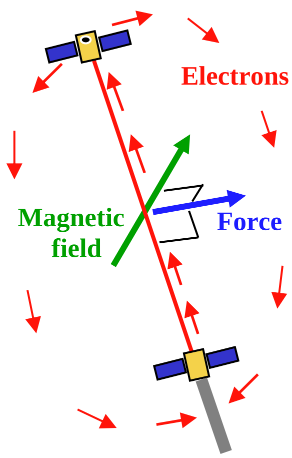

Figure 1. Electrodynamic Propulsion Concept

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 and apparatus for active control, and for the performance benefits of spinning operations[13,14,15].

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.

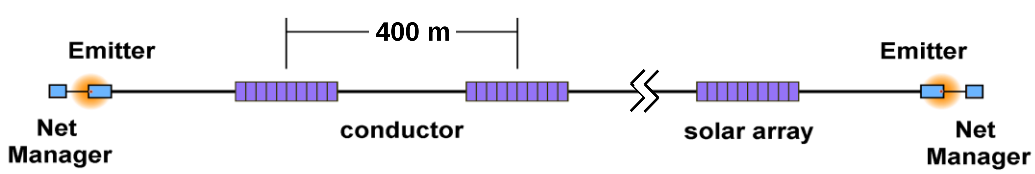

Figure 2: EDDE Vehicle Schematic, Showing Arrays, Conductor, Emitters, and Net Managers

EDDE's design plus its rotation set EDDE apart from previous electrodynamic thruster concepts for LEO. Hanging 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 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.

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^o of polar orbit.

EDDE can be equipped with net managers at each end to deploy large, lightweight nets to capture objects, and/or cubesat-like or other payload carriers to deliver each payload to its own 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[16]. 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 ~400m 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. They 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 20 to 80 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.

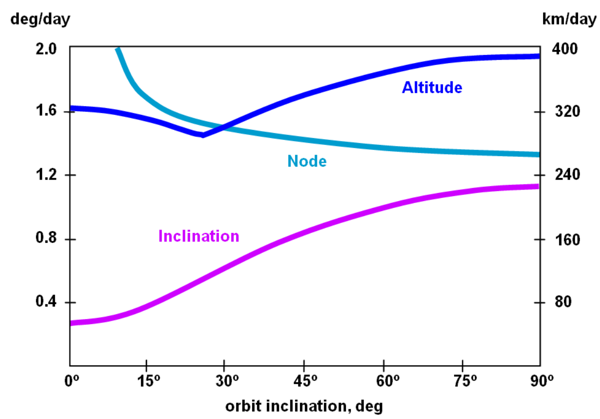

Figure 3. EDDE Orbit Transfer Performance per Ampere Average Current, for an 80 kg EDDE

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 30 tons/year.

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 altitude rate. The transition between them causes the kink in the altitude performance curve in Figure 3.

III. MATURATION OF EDDE COMPONENTS

This section summarizes the hardware component maturation work done under a two-year contract with the NASA Space Technology Mission Directorate at Langley Research Center that ended in May 2014. It describes our designs for lightweight solar arrays, hot-wire electron emitters, ways to quench high-voltage arcs, refinements of our conductive tape, and concepts for a high-performance steam resistojet to support a "born spinning" deployment scenario. A companion paper[11] in session B4.5 describes that work in more detail, and also use of EDDE for payload delivery.

Solar Arrays

EDDE can use as much power as we can provide, but we need to minimize both mass and cost. What helps this is that early missions involve only modest doses of both AO and ionizing radiation, and average power is more critical than end-of-life power. The best cell type appears to be bifacial silicon terrestrial-type cells because of their low cost and mass and better robustness than space-type triple-junction cells.

The best array design appears to be laminating the bifacial cells between layers of clear plastic film. Array mass should be only ~5 kg/kW.

It also appears that we will get more usable power from the same total mass over the wide range of voltages that we need if we simply switch cell sub-strings between series and parallel, rather than using a heavy DC/DC voltage converter plus heatsink.

Our analysis suggested that mechanisms that would allow one-axis steering about EDDE's long axis might add enough to total solar array mass and technical risk that we would be better off with unsteered bifacial solar arrays. Each array will actually consist of two sub-arrays rigged together by a 4-line bridle that keeps them at right angles to each other when under tension. Such unsteered pairs of bifacial terrestrial cells perform well compared to steered terrestrial or triple-junction ("3J") cells in mass, and extremely well in cost.

Electron Emitters

It is easy to collect electrons in a plasma: simply bias a bare metal surface positive, and electrons will flow to it. It takes much more than negative bias to emit enough electrons to drive ampere-level currents.

Our earlier EDDE designs planned on electron emission using hollow cathodes. But they use >1 kg/year of xenon, require bulky xenon tanks, and tend to be both costly and sometimes finicky. Our recent progress on light solar arrays led us to consider thermionic electron emitters as an alternative. We knew they would take more power, especially to deal with space charge constraints, but with light enough solar arrays, the total mass might be less. Our test work on emitters, plus analyses of space charge in tenuous plasmas, have made hot-wire electron emission seem attractive enough for us to baseline it.

To reduce the total mass needed to emit electrons, including the solar array mass for both heating and space charge, EDDE uses multiple emitters that each emit ~20mA. In high plasma densities, the plasma anodes are close enough to each wire that they don't overlap. But at lower densities, they do overlap. This increases the space charge bias voltage needed for any given current. But at low plasma densities, electron collection along EDDE's tape also drops. So emission into low-density plasmas does not reduce EDDE's current capability as much as collection does.

Based on our emitter work, we now have an AO-tolerant thermionic emitter that requires ~250 watts per amp emitted, for heating plus space charge. Our lightweight solar arrays make this power affordable, and eliminate any need for hollow cathodes or xenon.

If any novel electron emitters like photoelectric emitters, negative electron affinity surfaces, FEACs, or triple-point emitters become practical for LEO, it may be easier to transition to them from thermionic emission than from hollow cathodes, because distributed emission plus the need for power more than mass and volume make their system and packaging implications closer to those of hot wires than hollow cathodes.

Arc Detection and Quenching

Despite work function and space charge barriers to electron emission into a vacuum or a plasma, there are times when emission happens too well. An example was in 1996, after the Tethered Satellite System had deployed 19.7 km of a planned 20 km of insulated wire tether from the space shuttle. An arc was triggered by a flaw in the tether insulation passing close to grounded metal. This burned through the tether within ~10 seconds and severed it[17].

Each EDDE tape segment has similar exposed bare metal area as the TSS satellite, and much of the full tape length will often be biased negative enough to the plasma to sustain an arc. Even a tiny hypervelocity impact may trigger such an arc. The key is to quench arcs before they do much damage, by quickly reducing the EMF and the electron collection area below the thresholds needed to sustain the arc.

EDDE plans solar array spacing of ~400 m. Each 400-m deployed tape length has a winding core at the middle. We plan to put arc detection and isolation circuitry at each solar array and each winding core. That lets us isolate EDDE into 200-m tape lengths when an arc is detected. This reduces both the EMF and the electron collection area available to continue an EMF-driven plasma arc, and should quench the arc.

EDDE Tape Design

EDDE's tape design uses a ribbon of aluminum foil 1-3 cm wide, reinforced with a unidirectional fiber composite layer for strength and tear resistance. This greatly reduces vulnerability to small micrometeoroids and debris. EDDE actively avoids all tracked objects to eliminate any chance of impact with them. A danger from <10 cm untracked debris remains but is modest, because the threat of tape severance roughly scales with debris width, and much of the cumulative width of lethal debris in LEO is due to the large tracked objects.

Reinforced foil tapes are also preferable to wires because they provide more usable electron collection area than wires with the same mass and conductivity. Tapes as wide as 3 cm may collect currents that nearly scale with tape width at typical debris altitudes of 750-1000 km, but tapes 2 cm wide may do almost as well in the denser plasmas near 500 km altitude.

Narrow tapes reduce the risk of arcing, mostly by reducing electron collection area per unit length but also by raising tape resistance. But a narrower tape is more vulnerable to being cut by smaller debris, particularly near-edge-on impacts.

This led us to change the tape reinforcement from two narrow strips that interleave on adjacent layers of the winding, to one thinner full-width reinforcement strip. This allows use of a ~25% narrower tape without increasing the risk of tape cut.

Steam Resistojet

We also did unplanned work on another EDDE component: a high-performance steam resistojet. EDDE requires conventional propulsion to provide a suitable spin axis and spin-up impulse for its "born spinning" deployment. The required impulse was only a few m/s ΔV, so we had assumed use of cold-gas thrusters. But later, we focused our attention on a steam resistojet that could store water at low pressure and pump the water to >20 atmospheres pressure for use. This can eliminate toxicity, stored energy, and other safety concerns, and allows use of unusual tank shapes with low mass penalty. A high pump pressure allows good nozzle efficiency even at power levels <100W, and allows a small enough hot section to limit radiative heating of nearby components. The pump also lets us vary pressure and flow to fit the available power while maintaining a high Isp.

We expect an Isp >150 seconds and a dry mass <100g including plumbing, redundant pumps, a precious-metal hot section, and even an optional 2-axis gimbal. This does not include the unpressurized water tank. Tank mass including water acquisition devices may be ~10% of water capacity. We plan to finish the resistojet for use on the EDDE flight test.

EDDE's "Born Spinning" Deployment Strategy

We plan to start EDDE deployment by deploying a ~50W solar array area to power the resistojet and avionics for one end mass. The resistojet will also put EDDE into a slow spin. This can stabilize the solar array facing the sun, and provide enough tension to drive EDDE component release.

The first phase of full deployment is to pull out all these items in sequence, using the resistojet thrust to maintain spin despite the increasing deployed mass and size. This will weakly pry each component loose.

After all components are released and dynamics have time to damp out, we will actuate hot-melt wires to let each solar array unfold. After those dynamics settle out, then we further increase the spin and tension to overcome a weak adhesive that keeps the tapes from unwinding. Once enough of one tape has unwound, EDDE can supplement and then replace the resistojet thrust with electrodynamic torque, to cut water usage.

IV. CONTROL, NAVIGATION, AND COLLISION AVOIDANCE

EDDE has batteries to run the avionics and communications at night but does not thrust then, because substantial night-time thrust requires heavy batteries that reduce overall EDDE maneuver rates. So EDDE maneuvers in the sun and coasts at night. If batteries or ultracaps improve enough more than solar arrays do in performance, we may be able to justify at least partial-spin energy storage, but right now the best power strategy seem to be "use it or lose it."

In the sun, we estimate EDDE attitude motion and bending using sun sensors, magnetometers, rate-gyros, and GPS. Solar array long axes follow the local tape direction very closely. Combined with GPS data from the end-bodies, this determines the vehicle mechanical state. A recent history of this data plus onboard models of the magnetic field and ionosphere let us plan and control EDDE rotation and oscillation. We do this by switching the solar array output voltages that drive electron collection by each tape segment and emission by each emitter array.

The main challenge for EDDE navigation is reliably avoiding all tracked objects near EDDE's altitude. This includes debris, operating satellites (maneuverable or not), and satellites without accurate posted orbit data, which may also maneuver without notifying the EDDE operator.

Our plan for dealing with these uncertainties is to propose several trajectory options to the JSpOC, select and publicly post an approved one, and have EDDE actively maneuver around other objects while staying within a defined maneuver volume centered on the posted trajectory[18]. We will uplink the time, position, and uncertainty of all predicted penetrations of this volume, to define "keep-out zones" within it. Active avoidance of the keep-out zones within the maneuver volume should require adjusting spin phase or position only a few times/day, since the maneuver volume can be far larger than EDDE.

Figure 4 illustrates this with a reference trajectory and 2 keep-out zones. The zones are ellipsoids in a phase space of time, arc length along the reference trajectory, and altitude offset from the trajectory:

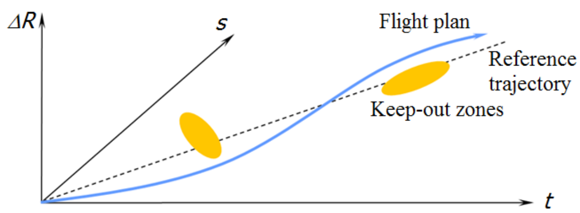

Figure 4. EDDE Maneuvering Around Conjunctions

Figure 5 below shows the typical expected rates of penetration of a 30 km diameter 200 km long EDDE maneuver volume, as a function of EDDE altitude in a medium inclination orbit:

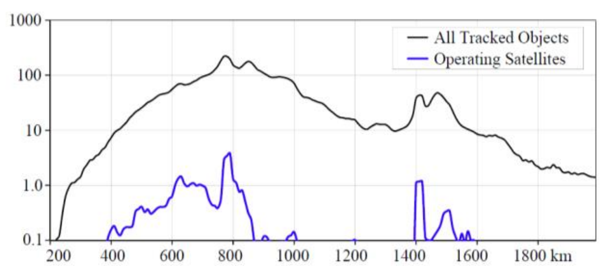

Figure 5. Typical Penetrations/Day of 30 x 200 km Maneuver Volume, vs EDDE Altitude

The size of the keep-out zone around each object can vary with object type. EDDE can arrange to miss operating satellites by far more than EDDE's radius, but debris can be allowed to penetrate an EDDE-radius sphere if needed, as long as rotation is phased to ensure an adequate miss distance.

With proper flight planning and execution, EDDE collision risks can be comparable to conventional spacecraft, even if EDDE is 10 kilometers long. EDDE never runs out of fuel so it can continue active collision avoidance maneuvering as long as it stays in service, at a very minor penalty in throughput.

As noted earlier, a danger from <10 cm untracked debris does remain. But it is modest, because the threat of tape severance roughly scales with debris width, and much of the cumulative width of lethal debris in LEO is due to the large tracked objects. Even if EDDE is severed, each half can maintain active avoidance of all operating satellites while it autonomously spirals down to a prompt reentry.

The risk of a tether cut by small untracked shrapnel seems low enough for EDDE missions that distribute multiple small secondary payloads. They should take months, mostly near 500 km. Wholesale LEO debris removal will take years, mostly above 600 km. We can afford to lose a few such EDDEs to cuts by small untracked shrapnel.

Note that EDDE's tapes and solar arrays both weigh <1 kg/m^2. Impact by small untracked shrapnel may sever an EDDE tape, but should not create much new lethal-mass shrapnel.

As part of our recent work, the Naval Research Laboratory developed methods to track maneuvering multi-kilometer vehicles like EDDE. The main challenge is that EDDE is a large fuzzy glinting radar target. Its center of brightness may be kilometers from its center of mass and can move erratically. Inferring EDDE's actual trajectory from such data requires care.

We also studied comm issues. It seems useful to get status data at least once/orbit, and we need low-latency video downlink plus low-rate uplink during rendezvous, inspection, and capture passes. Boeing suggested that we use existing commercial stations, mostly in the Arctic, for low-latency video. Globalstar seems more relevant for status downlinks, if it gets approval to provide LEO-Globalstar-ground comm services. (It is now licensed only to provide ground-Globalstar-ground services.)

V. RENDEZVOUS AND CAPTURE

EDDE is limited to LEO by its dependence on the earth's magnetic field and ionosphere. But its sustained maneuvering ability vastly exceeds the needs of any currently plausible single assignment. So one can view EDDE as a "zero-fuel taxi" for LEO, that can handle one task after another. But such tasking requires EDDE to be able to rendezvous with and capture its payloads.

Capture of large, uncooperative, tumbling debris poses several challenges. Capturing it at the tip of a flexible multi-kilometer EDDE rotating with a tip speed of ~30 m/s relative to EDDE's center of mass poses even more challenges. But debris capture does have one advantage: there need be no paranoia about fouling on or damaging an object while capturing it.

This section of the paper covers capture of large debris objects first. Then it briefly discusses concepts that could allow safe capture of other targets, such as failed satellites in orbits far from the ISS, that could benefit from capture and delivery to ISS for repair.

Our plan is to match orbits with a target except for a half-EDDE-length along-track offset, and transverse EDDE CM motion that nearly cancels out the tip rotational velocity. This allows very low relative velocities between EDDE's tip and a target, and also allows a free-return trajectory each orbit. This EDDE orbit plus an integer number of EDDE rotations per orbit lets us use free-return successive approximation approaches once each orbit.

Figure 6 shows typical free-return trajectories of the tether end-points A and B (solid lines) and the center of mass of the tether system (dashed lines) relative to an LVLH frame centered on the target, for an 8 km long EDDE rotating in a local-horizontal plane at the time of capture. At the time of closest approach, EDDE is oriented along the orbit, the relative velocity of the net to the target is very low, and soft capture is feasible despite EDDE's rotation.

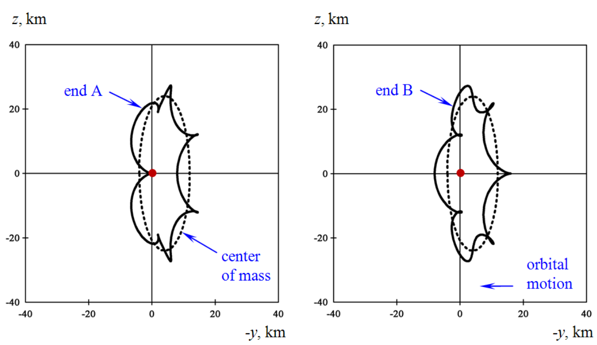

Figure 6. Free-Return EDDE Rendezvous Trajectories

The above trajectories are mapped onto the local horizontal plane, which has one inertial rotation in pitch per orbit. Hence if the sun is to the left as both tips approach and image the target from the left, they will also be sunward of the target a half orbit later, when the target is again visible against the starfield.

Visual Targeting and Inspection

Once we get within ~100 km of a typical sunlit intact debris target, it will be brighter than Venus and easy to find as it slowly moves across the starfield. The same is true even for large fragments, once we get within ~20 km. Cameras at each end of EDDE allow binocular viewing of the target against the starfield. This allows accurate ranging many times per orbit. This is our main guidance tool. Our free-return trajectory relative to the target lets us reduce our residual errors by successive approximation.

Binocular ranging is only feasible when a target is sunlit, and it is far simpler if the target is imaged in front of a starfield instead of a sunlit earth. We can time close approaches so EDDE and the target are both in the sun, with EDDE approaching the sunlit side of the target, and stars rather than a sunlit earth behind the target. Binocular range errors scale nearly with range squared. They should approach 1 m as EDDE approaches. Eventually targets will get bright enough for their glare to wash out the starfield. But then co-mounted cameras looking in other directions can provide an adequate stellar pointing reference.

An iterative "successive approximation" approach strategy allows multiple sunlit inspection passes. This lets us verify the target tumble rate, and ensure that a target has no unexpected features that may complicate capture. We also plan to use the same approach on early EDDE test missions that do inspection but not capture. Note that unlike typical free-fall rendezvous approaches, we are only close to the target once per orbit. That will always occur in the sun, with good lighting angles and good communication links.

The main targeting errors requiring detection and correction are likely to be due to EDDE itself, not its target, because of EDDE's drag area, bending modes, and small EMF-driven parasitic plasma current loops involving each tape segment. So occasional binocular fixes from GPS-equipped EDDE endmasses can determine a target's orbit accurately on each pass. This lets EDDE focus on gradually "quieting" its dynamics to allow closer and closer safe approaches. If EDDE takes an average of 2 weeks to move typical large debris, then spending an extra half-day on each final approach costs only 3% of EDDE's throughput. If each return lets us cut errors by half, then 7 orbits let us reduce targeting errors by a factor of >100.

Debris Capture

EDDE can do imaging inspection passes using only electrodynamic forces, but capture needs higher accuracy. The capture hardware can maneuver during each final approach. We can iteratively estimate the errors in approach range from target image size, and null errors out by reeling the capture hardware in or out. We can estimate errors in the 2 other axes far more precisely, from target position errors against the stars. We plan to use a steam resistojet to null those errors. Water use should be a few grams per pass.

To capture large debris, each EDDE end body can have a net manager that holds ~100 square house-sized expendable Spectra nets weighing ~50 g each. To catch a debris object, EDDE extends one of the nets and its support lines, using the ~0.027 gee centrifugal acceleration at each end of EDDE.

The net manager then slowly spins itself and the net up to ~2 rpm around EDDE's long axis. Gyroscopic effects will cause a slight displacement of the center of the net from EDDE's long axis, but this is predictable so we can compensate for it. Deployment and spin-up of the net can be done a half orbit or longer before the first planned capture attempt.

Capture is done by arranging for the target to pass between 2 net support lines at a few meters/sec, as shown below in Figure 7. This shows 2 video frames from a 2002 test of an early version of our capture concept[2]. The curved dashed yellow line represents the target path relative to a rotating net and camera.

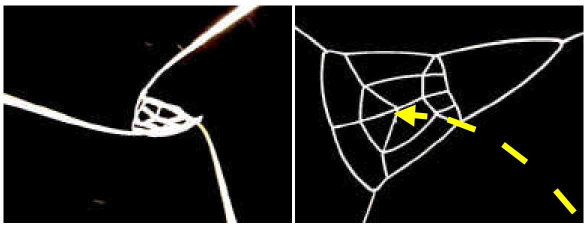

Figure 7. Net Spin-up and Capture Target Trajectory

This technique requires suitable phasing of the net's rotation before capture. As the target passes over the center of the net, the net manager quickly retracts the lines to pull the net up around the target.

Peak capture snatch loads are limited by EDDE's mass, not the target's larger mass. Peak loads can be limited to near a ~20 newton post-capture equilibrium tension if the net manager pays out line between itself and EDDE. Target tumbling about an axis normal to EDDE's tape provides spin kinetic energy a target can use to climb out of a net. With 20 newton tension and a ~5m climb, targets need ~100J of kinetic energy to escape. This requires tumble rates >2 rpm for 1.4 ton rocket bodies, and >1/2 rpm for 8 ton Zenit bodies, both relative to EDDE's own ~0.08 rpm rotation.

Most large debris objects include significant amounts of aluminum alloys. Eddy-current damping in the earth's magnetic field tends to slowly de-spin them. Ground-based photometric studies can estimate tumble rates before target selection is finalized, and EDDE's inspection passes can verify those estimates before EDDE attempts capture.

For debris objects in near-polar inclination (which includes most LEO debris), repeating close passes by EDDE can occur over the arctic, within line of sight of commercial ground stations having low-latency internet connections. This allows real-time downlink of compressible imagery like that in Figure 7. This allows real-time man-in-the-loop control from any EDDE control facility with low-latency connections.

An average capture rate of 1 object/day is enough to capture the 2500 largest LEO debris objects within 7 years. Hence "capture operator" may be a part-time job for a few people who can acquire the right video-game-like skills. By contrast, developing automated capture may require far more effort, due to the large number of different kinds of objects needing capture, mostly satellites with deployed appendages.

If video imagery provided during final approach to the target suggests problems, there are at least two options for late abort: retract the net early, or don't retract it at all, and let the target escape. In either case, another capture attempt can be made one orbit later, using the same net.

If pulsed-laser ablation turns out to be viable for removing small debris, similar precisely-aimed pulses should be able to de-tumble large debris that tumbles too fast for EDDE, so EDDE can safely capture it.

Pulsed-laser ablation may also allow occasional small along-track nudging of large debris, to prevent predicted debris collisions. This could greatly reduce the growth of lethal shrapnel in LEO, as discussed in a paper for the poster session of symposium A6 of this congress[19]. But laser nudging by itself is not a viable long-term solution to the LEO debris problem since it would have to continue indefinitely, or at least until EDDE or something else can remove or relocate most of the large debris.

Capture of Cooperative Targets

Compared to capture of tumbling debris, capture of cooperative targets like multi-use satellite servicing vehicles can be far easier. They have attitude control and can have suitable capture features and targeting aids, including GPS, strobe lights, and retroreflectors. Centrifugal acceleration of EDDE's end masses means that a rigidizable capture interface is not needed: some kind of releasable "hook and loop" interface should be enough. Our "two dog capture" concept shown below in Figure 8 even lets a passive object like a failed satellite be captured cooperatively:

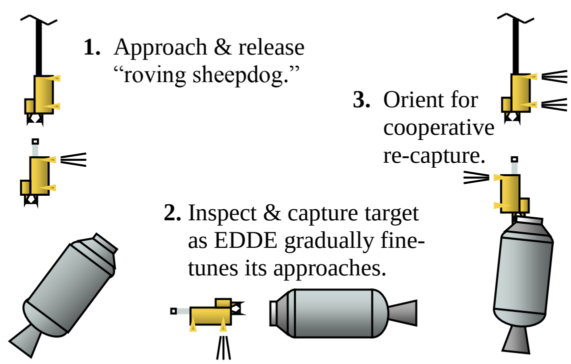

Figure 8. "Two-Dog Capture" Without Nets

This scenario decouples capture of a passive target from capture by EDDE. This lets EDDE plus minimal "sheepdog" assistants capture failed satellites so they can be delivered to ISS or another facility for repair, without needing a net. Once delivered to the repair facility, EDDE can release the satellite and attached sheepdog so they slowly and safely drift towards the repair facility. After repair, that process can be reversed to return the satellite to its operational orbit.

VI. THE COST OF DEBRIS IN LEO, AND WAYS TO REDUCE IT

As Ailor argued at the 2010 IAC[20], the direct cost of orbital debris is mostly due to "cm-class shrapnel" that occasionally hits and disables expensive satellites. LEO shrapnel this size is far below current tracking thresholds but often has enough impact energy to fully disable even large high-value assets.

Levin and Carroll[21] developed a statistical model and estimated the cost of future collisions between intact objects in LEO. The analysis showed that most of the damage will be delayed by years and will occur when pieces of shrapnel generated in the collision hit valuable assets. Very conservatively, the delayed damage is estimated to be on the order of $200M, but in the light of the latest impact testing[22], it is likely to be several times higher[7].

Carroll[23] analyzed the cost of LEO debris in detail and developed a spreadsheet to estimate the average statistically expected damage from shrapnel impacts. Based on this analysis, the present cost of discounted total damage over the next 20 years could be as high as $2B. Readers are encouraged to download the paper and spreadsheet[23] and experiment with the inputs.

Most shrapnel created by accident in LEO in this century seems likely to come from collisions of two ton-class intact objects at congested altitudes. Two such collisions, in 2007 and 2009, created over half the LEO fragments tracked in 2013, and probably a higher fraction of smaller but still lethal shrapnel.

Intact/intact collisions will usually involve large enough CG offsets to limit the directly involved mass to 1-10% of the total mass, especially if the collision directly involves only appendages on one or both objects. But this can still involve 10-100X the involved mass and energy of fragment/intact collisions, to shred 2X as much mass. Direct hypervelocity impact creates fine particles that splash out at speeds similar to the initial impact speed. Such a "hypervelocity hailstorm" may shred much of the rest of each object into shrapnel, without spreading its trajectories out very much.

In LEO, most debris >10 cm is tracked and can be avoided. That visible debris gets all the attention, but it is only a few % of the problem. The direct $ cost of debris is from impacts that disable working satellites, disproportionately large high-cost long-lived satellites at congested altitudes. Nearly all such losses are from cm-class shrapnel. That is far below current tracking thresholds so it cannot now be actively avoided. Most losses may not even be definitely ascribed to impact, so the direct cost of debris may not be easy to quantify even for possible past losses. An example of such an analysis is available for a likely impact on BLITS[24].

Until recently, the main concern about collisional debris creation was a slow cascade of fragment/intact collisions. But radar cross-section and orbit decay data for fragments from Fengyun/A-sat and Cosmos/Iridium indicate that few fragments have enough mass and hence impact energy (~40j/g) to propagate a collision cascade with the ton-class intact objects having most of the target area and mass. So collisions of intact ton-class objects like Cosmos and Iridium seem likely to be the main future source of lethal cm-class shrapnel.

Most cm-class shrapnel may be near the original thickness of the source material. This may explain why tracked Iridium fragments are decaying 2.5-3X faster than Fengyun and Cosmos fragments in similar orbits. The best basis for estimating shrapnel A/M and lifetime may be the bills of materials (including thickness) of the two source objects. This may lead to higher estimates of small but lethal and long-lived shrapnel, especially from rocket bodies. On the average, rocket bodies may be made of heavier sheet materials than satellites are.

It is plausible for tracked debris to be lighter than expected but cm-class shrapnel heavier, because the NASA Standard Breakup Model predicts a 5.6X rise in mean A/M as characteristic size L_c drops from 56 to 18 mm, but much slower A/M slopes for all larger and smaller sizes. This relation may fit data from the SOCIT 4 impact test on a Transit satellite, which had an unusually high mass fraction of circuit boards. But it may not be relevant to most intact/intact collisions. NASA recently did more representative tests[25], but detailed reports are not expected for another ~3 years.

Figure 9 shows an estimated mean creation rate of >1 gram shrapnel at different altitudes due to a ~6%/year chance of collision of objects $\geq$1 kg. The average total colliding mass is estimated at 2855 kg. This is 21% higher than the total source mass of the tracked Fengyun plus Cosmos/Iridium fragments.

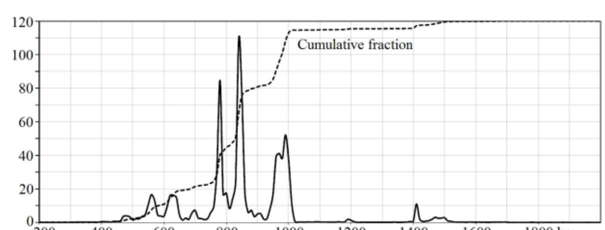

Figure 9. Inferred Mean Creation of >1 gram Shrapnel by Collision of $\geq$1 kg Objects, #/year per km alt.

The altitude range at risk from shrapnel is far wider than in Figure 9. It is even wider than the top curve in Figure 5, since shrapnel should have a similar source altitude distribution as tracked fragments, but should be dispersed much more energetically on average.

The curve of cumulative distribution suggests that little LEO shrapnel will be created <500 km or >1010 km. Shrapnel created at low altitude will have fairly short orbit life, so most of the long-term problem will be from shrapnel created between ~750 and 1010 km. So the best objects to remove are large objects at ~750-1010 km altitude.

There are many ways to reduce future direct debris costs by interfering with different stages of the "shrapnel life cycle," as discussed in a paper for the poster session of symposium A6 of this congress[19]. If we list these stages in the order of the shrapnel life-cycle, our options for interfering include:

1. Reduce mass additions to congested altitudes
2. Continue to reduce future explosions & breakups
3. Remove or collect large shrapnel source objects
4. Laser-nudge large debris to prevent collisions
5. Find and remove lethal shrapnel from LEO
6. Find, track, and actively avoid lethal shrapnel
7. Put new satellites in lower orbits and reboost more
8. Make new satellites cheaper and/or more robust

These options are complementary, not mutually exclusive. The last 3 options above are open to each satellite operator, but the others require collective action, ranging from tracking shrapnel to deorbiting foreign objects. Careful study may show some options to be more cost-effective than others, but the rankings will change as new technologies are developed.

A practical goal may be maximum ***net*** reduction in debris cost per $ spent. One concept is to pay bounties for actual net reductions in debris costs. This can level the playing field for a very wide range of competing concepts. It is also a natural way to cap bounties: don't pay more than the current value of calculated future reductions in debris cost.

Economic solutions to the debris problem may involve collecting "parking fees" for the user additions to debris cost. Current rules for LEO are equivalent to "25 years free parking after your mission ends." In crowded cities, parking fees start when you arrive, and vary with location, congestion, and vehicle size. Why not manage congestion in LEO the same way? This is discussed in more detail in companion paper ref. 19.

US debris will be far from dominant in creating shrapnel. The US did set a precedent of putting objects into long-lived orbits: 97 of the 100 oldest objects in LEO are US-owned. But >70% of the mass in LEO is now Russian, and most of that mass is rocket bodies. Not only is the Russian mass dominant, but it is also highly clustered. That clustering creates most of the peaks in shrapnel-creation rate vs altitude in Figure 9. Figure 10 shows ownership of the LEO mass that will create >90% of the shrapnel shown earlier in Figure 9.

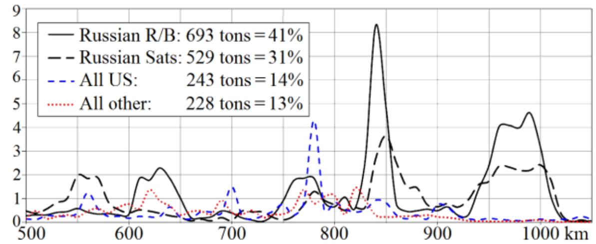

Figure 10. LEO Mass Ownership, Tons/Km Altitude

Removing all non-Russian mass from LEO should reduce shrapnel creation by ~48%, while removing ***only*** Russian mass from LEO should reduce shrapnel creation by ~88%. Even removing only Russian rocket bodies should reduce shrapnel creation by ~62%. Any comprehensive LEO cleanup scenario has to address the dominance of Russian debris mass.

Congress may not let the US accept liability for foreign debris and may not pay for its removal. But removal should start with US debris anyway, even if the debris cost reduction per object removed is less. By the time most US debris has been removed, there will be a far better grasp of value, cost, liability, and other issues. This can guide international negotiations.

VII. WHOLESALE DEBRIS REMOVAL BY EDDE

Debris removal by EDDE might start at altitudes near the bottom of the 750-1010 km congested region, with objects of modest mass that may mostly burn up during reentry. Early targets might be USG-owned. Then EDDE might remove 12 dead Iridium satellites near 765 km altitude, slightly below the main Iridium constellation. EDDE could drag them down to ~330 km, below ISS. A rough timeline is below in Table 1:

Operation	Days	Typical Parameters
Phase to next target	**0.4**	380 vs 765 km, ½ orbit avg 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	**6.3**	765-330 km, +10% , at -600 km/day*80/(80+550)
Days per Iridium	**9.1**	765 to 330 km, with 550 kg dead Iridium

Table 1: EDDE Timelines with Dead Iridium Satellites

Much of the non-Russian mass is in sun-synchronous orbit, which is also nearly polar (97-99°, vs 86.4° for Iridium). It may be useful for EDDE to shift among several crowded inclinations. This allows productive use of time needed for nodal regression between orbits that differ far more in node than in inclination.

As shown below in Figure 11, EDDE seems to be the only known LEO debris removal option whose costs are just a few % of the original launch costs[6]. Even with learning curves, ion rockets seem ~6X as costly as EDDE, and chemical rockets ~20X as costly.

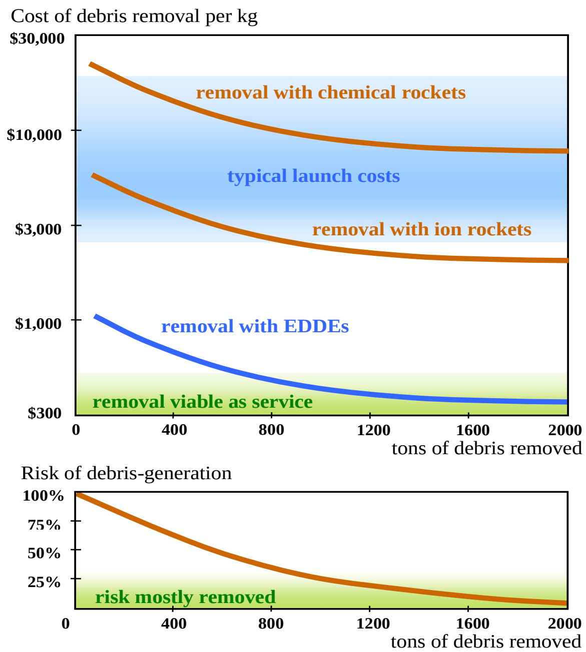

Figure 11. EDDE for Wholesale Debris Removal

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. Our analysis shows[6] that 16 EDDE vehicles launched as secondary payloads on ESPA can affordably remove 2,000 tons of large debris from LEO in about 9 years. That would reduce future collisional shrapnel production in LEO by more than 97%. It would take only 10 vehicles and 7 years to remove 1,000 tons of upper stages, reducing the future collision shrapnel production by 79%.

VIII. DEBRIS COLLECTION BY EDDE

EDDE cannot drag objects far heavier than itself low enough to target reentry: ~330 km may be as low as feasible. This problem does not affect just EDDE: the low thrust of ion rockets also results in untargeted reentries. The problem is less obvious there because ion rocket throughput ambitions are far lower. Reentry from 330 km will occur within a few months. Even if a dozen EDDEs all deliver objects to 330 km, fast decay will limit the local congestion to <2 tons/km, far lower than the peaks in Figure 10. When releasing objects, EDDE can sling itself into a 330 x 430 km orbit with daytime apogee. Then EDDE can quickly raise its perigee above ISS.

There are several ways to avoid untargeted reentry, with both EDDE and ion rockets. One is to attach a small rocket package to each object before releasing it. It can use changing eclipse timing to infer impending reentry. It can then orient the object and provide a ~20 m/s ΔV to target a shallow reentry, perhaps over the SE Pacific. This rocket plus controls might weigh ~1% as much as the debris. But that 1% of the mass could be ~20X EDDE's mass, so it should only be done for objects that really need targeted reentry. Otherwise the rocket costs will dominate total costs.

There is another way to eliminate most untargeted reentries, for both EDDE and ion rockets: move mass at ~500-1000 km altitudes to "tethered scrapyards" at several less congested altitudes, perhaps at 660 to 730 km. This is feasible since most such mass is in narrow inclination bands, as shown below in Figure 12. (The 60-100^o inclination range shown includes >95% of the mass at 500-1000 km altitude.)

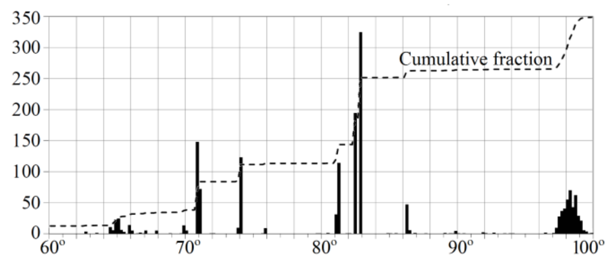

Figure 12. Tons at 500-1000 km, per 0.2^o Inclination Bin

If not collected, this mass will create >90% of the collisional shrapnel created above 500 km. As shown in Figure 10, the main source is Russian rocket bodies.

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. Since shrapnel creation scales with the square of potentially colliding mass, shrapnel creation can be cut in half by the time 30% of the mass at congested altitudes is collected.

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.)

Once much of the debris mass is collected, there are at least two options available. One is to use a large deorbit stage ~1% as massive as the scrapyard. It can induce a targeted reentry once the scrapyard decays to its last few orbits, many decades from now. Hence one need not develop such a rocket immediately.

A second option is to separate some of the mass and use EDDE to deliver it to customers anywhere in LEO. The largest debris collections will be mostly 1.4 ton Kosmos-3M stages near 83^o inclination, and 8-ton Zenit stages at 71^o. 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 13 below shows one scenario:

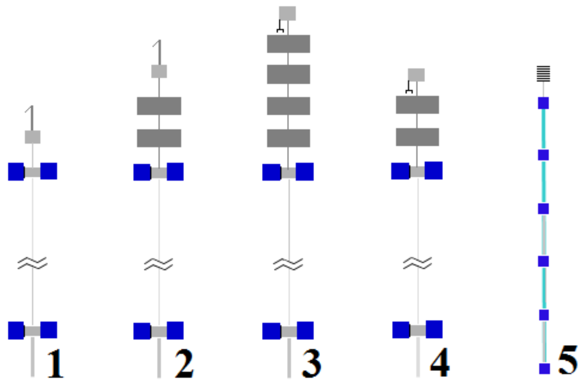

Figure 13. Collection, Shingle Cutting, EDDE Delivery

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. Handoff from EDDE to a scrapyard can use an error-tolerant "crossed-tether" technique. EDDE throughput can be high since the required altitude changes are far less than if EDDE has to drag debris down to 330 km.

The key issue with collection is whether it can pay for itself. Several startup companies want to refine, deliver, and sell asteroidal materials, but we have not yet found anyone who wants the ~2000 tons of well-characterized aerospace materials already in LEO. Even if the only salable product is shielding and the only customer is Bigelow, EDDE's ability to deliver debris to a scrapyard and shingles to ISS or other "marketplace orbits" seems to merit serious study.

If such study suggests that recycling might pay for itself, it may be in the interest of both Russia and the US for the US to collect much of the Russian debris for free, with the US assuming ownership and full liability for some debris collections and Russia keeping ownership and full liability for the rest.

In particular, consider the 18 Zenit stages in 71^o orbit, mostly near 850 km altitude. Their total mass is 150 tons. A collision involving them has <1% chance per year, but could more than triple the count and cost of shrapnel throughout LEO. Collecting those stages is clearly very useful. Selectively recycling them and bringing shingles to ISS or another orbit can stimulate interest in the other massive debris. Half of the rest is also spent stages, mostly Russian. Stimulating the market for them should hence be useful to Russia as well as the US. Any reentry liability for a scrapyard should clearly remain with the country that launched the mass collected there, since assembling that mass clearly enhances debris value rather than damaging it.

A final benefit of debris collection is that it can quickly and greatly reduce shrapnel creation rates, while also buying decades more time for developing recycling technologies and/or a large deorbit stage.

IX. OTHER EDDE APPLICATIONS

EDDE will reach fullest use as a "LEO taxi" that can handle one job after another throughout LEO. But that requires payload capture. Early tasks don't; they include distribution of payloads launched with EDDE, and close inspection of US-owned objects to assist in failure diagnosis and even to count small craters.

Payload distribution by EDDE is most relevant to secondary payloads, since primary payloads can be launched directly to any desired orbit. This in turn means that EDDE can make surplus capacity on any LEO launch more valuable, since that surplus is no longer limited to use by secondary payloads that are satisfied with orbits near the primary payload's orbit.

EDDE can deliver individual secondary payloads, and it can also distribute multiple secondary payloads to substantially different orbits. For example, EDDE can be packaged with several payloads that it can distribute and insert into different orbits for rapid creation of multi-plane satellite constellations.

To extend satellite lifetimes, there are concepts for service modules that can refuel satellites or even replace electronics modules. DARPA and NRL have applied Orbital Express, SUMO, and FREND concepts to satellite servicing[26]. DARPA and NASA tested ASTRO with NextSat in the Orbital Express flight test, as shown in Figure 14.

Figure 14. Orbital Express and NextSat

Recently GSFC tested robotic refueling on ISS, to prepare for a GEO robotic servicing vehicle. The service module is ~100 kg. One can mount EDDE and that module together in an ESPA slot, on any LEO launch with enough margin. EDDE can then take it to any satellite anywhere in LEO that needs servicing. The "two dog capture" shown in Figure 8 can let EDDE capture failed satellites for delivery to ISS, to allow more complex repairs than can be done robotically.

A companion paper in symposium B4 discusses custom orbit delivery by EDDE in more detail [11].

X. EDDE FLIGHT TESTING

The Naval Research Laboratory has a 3U cubesat precursor test for EDDE scheduled to deploy from ISS in 2015. It is the Tethered Electrodynamic Propulsion Cubesat Experiment, TEPCE. It is shown in Figure 15:

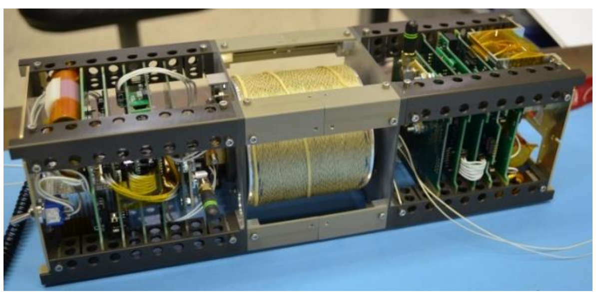

Figure 15. NRL's "TEPCE" Cubesat

TEPCE uses a stacer spring to energetically push the ends apart, to pay out a 1 km conductive tether stowed around the stacer. It can use either the tether or 5m EDDE-like metal tapes at each end to collect electrons from the plasma, and EDDE-like hot wire emitters at each end to emit electrons into the plasma.

Each endmass has isolated high voltage supplies, magnetorquers, GPS, a camera, and plasma sensors. TEPCE has too little power to counteract drag near ISS altitude, and will reenter within a few days after tether deployment. But that is enough to test hardware operation and measure plasma interactions.

In 2016, TEPCE-2 is scheduled to deploy near 720 km. It will remain in orbit for months. This provides time to climb and descend, stimulate and then damp libration, iteratively test revised flight code, do active avoidance, and thoroughly evaluate TEPCE's sensors.

The next step beyond this is to test actual EDDE hardware and deployment concepts. A 12U format cubesat is the smallest operationally useful size for EDDE, because smaller sizes require a tape that is too narrow (with high risk of cut) or so short that the power needed for electron collection and emission exceeds the productive power used to push electrons along the tape. One layout is shown in Figure 16:

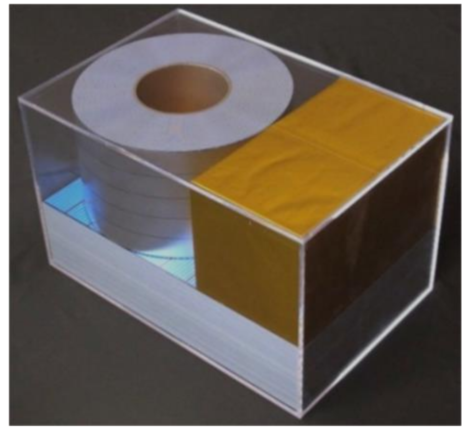

Figure 16. Full-size Model of a 2 km 12U EDDE Format

Figure 17 shows an axial 12U layout, with much longer and narrower tapes. Both layouts are sized for 12U cubesat carriers, but an axial layout allows easy adjustment to any desired stowed length. Both options can stow end-to-end with cubesats EDDE can deliver. Both 12U cubesat carriers we have studied can be stretched to 24U, and both clamp payloads transversely so EDDE need not support them against launch loads.

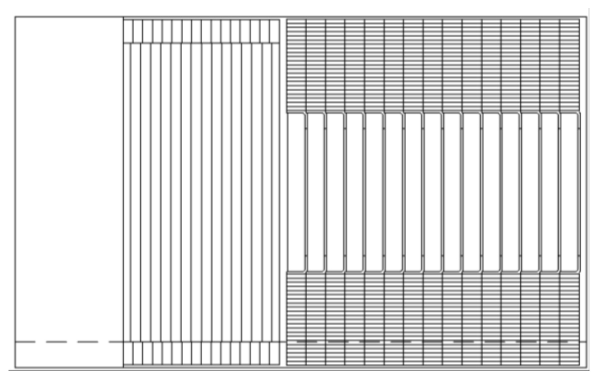

Figure 17. Axial Layout for a 6 km 12U 24 kg EDDE

EDDE launch from ISS involves safety issues generic to all propulsive vehicles, plus issues specific to long tethers. To meet ISS safety constraints, EDDE must separate from ISS in altitude and/or orbit plane before it fully deploys. Those maneuvers must not use pressurized, flammable, or toxic propellants.

To provide these initial orbit changes and also to spin EDDE to drive a "born spinning" full deployment, we plan to use a ~50W steam resistojet. It uses pumps to allow unpressurized water storage in light tanks of arbitrary shape. We expect an Isp >150 seconds and a total dry mass <100g for redundant pumps, plumbing, an optional 2-axis gimbal, and a precious metal hot section. We expect an ISS separation ΔV of ~60 m/s. The resistojet ΔV for born-spinning deployment can be smaller, since most of the spin-up can be done electrodynamically, after EDDE deploys some tape.

A NanoRacks deployer will eject EDDE together with any co-mounted payloads. EDDE will drift back, down, and then forward below ISS. We will then test EDDE's controls, deploy one solar array to power the resistojet, and when we get far enough from ISS, use the resistojet for a combined plane change and climb. Once EDDE gets ~100 km above ISS and phases far enough back from it, EDDE will release all its daisy-chained components, unfold its solar arrays, spin up more to unwind the tapes, and verify controllability. Then EDDE can distribute payloads to several orbits, while actively avoiding satellites and tracked debris. EDDE can then rendezvous with and inspect selected US debris. Some images may include visible impact craters. This may let us learn more about how crater and hole counts vary with size, altitude, and age.

XI. CONCLUSIONS

Overall, EDDE's sustained maneuver capability in LEO is an unexpected and precious gift. It enables removal of large LEO debris on a scale not currently affordable by any other means. It will be hard for competing concepts to be anywhere near as cost-effective as EDDE because of the radical difference in required launch mass for similar effect.

TEPCE and TEPCE-2 should answer questions about plasma interactions, emitter performance, and electrodynamic thrust, and a good 12U EDDE flight test can determine whether EDDE will actually allow affordable debris removal or collection.

One of the most effective ways to interfere with the shrapnel life cycle and its costs is to remove or collect most of the mass now at congested altitudes (~600-1010 km), before it collides and shreds itself into lethal shrapnel. A fleet of 10 to 16 EDDE vehicles can do this job at a cost comparable to the statistically anticipated reduction in damages from impacts of the shrapnel produced in future collisions over the next two decades.

A challenge to most concepts for wholesale debris removal is that >70% of the mass in LEO is owned by Russia. This need not be an immediate problem, since US efforts should start with US debris anyway. But Russia must eventually be a part of any effective long-term program. The Russian mass is clustered in both altitude and inclination. The altitude clustering raises the chances of collision, but inclination clustering can ease debris collection at "tethered scrapyards."

Readers with questions about EDDE, or an interest in future progress on EDDE, are invited to contact us at the email addresses on page 1.

XII. ACKNOWLEDGEMENTS

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XIII. REFERENCES

1 Orbital Debris Quarterly News, NASA, Volume 17, Issue 1, January 2013.

2 Carroll, J., "Space Transport Development Using Orbital Debris," final report and presentations on NIAC Phase I Research Grant 07600-087; see www.niac.usra.edu/studies/800Carroll.html.

3 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.

4 Pearson, J., J. Carroll, and E. Levin, "Active Debris Removal: EDDE, the ElectroDynamic Debris Eliminator," Paper IAC10-A6.4.9, Prague, 2010.

5 Levin, E., J. Pearson, and J. Carroll, "Wholesale Debris Removal From LEO," *Acta Astronautica*, v. 73, pp. 100-108, April-May 2012.

6 Pearson, J., E. Levin, and J. Carroll, "Affordable Debris Removal and Collection in LEO," Paper IAC-12-A6.6.7, Naples, Italy, 2012.

7 Levin, E., Carroll, J., and Pearson, J., "The Long-Term Cost of Debris Removal from LEO," Paper IAC-13-A6.8.9, Beijing, China, 2013.

8 Liou, J.-C., An active debris removal parametric study for LEO environment remediation, *Advances in Space Research*, Vol. 47, pp. 1865-1876, 2011.

9 McKnight, D., "Collision Point" interview on the DVD of the movie *Gravity*, October 2013.

10 Weeden, B., "Space Traffic Management: Preventing a Real-Life 'Gravity,'" testimony before House Committee on Science, Space and Technology, 9 May 2014.

11 Carroll, J., E. Levin, and J. Pearson, "Delivery of Secondary Payloads to Custom Orbits Using EDDE," Paper IAC14,B4,5.13x24695, Toronto, 2014.

12 McCoy, J. E. et al., "Plasma Motor Generator (PMG) Flight Experiment Results," 4th International Conference on Tethers in Space, Smithsonian Institution, 10-14 April 1995.

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

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

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

16 Forward, R. L., Hoyt, R. P.,"Failsafe Multiline Hoytether Lifetimes", AIAA paper 95-28903, 1st AIAA/SAE/ASME/ASEE Joint Propulsion Conf., San Diego, CA, USA, July 1995.

17 Tethered Satellite System 1 Reflight (TSS-1R) Failure, NASA, http://llis.nasa.gov/lesson/0566

18 Levin, E. M., "Conjunctions and Collision Avoidance with Electrodynamic Tethers," AMOS Conf., Maui, Hawaii, September 10-13, 2013.

19 Carroll, J., "Can Pulsed Laser Ablation Prevent Most Debris Creation?" Paper IAC-14,A6.P,52x24670, Toronto, 2014.

20 Ailor, W., "Effects of Space Debris on the Cost of Space Operation," IAC-10.A6.2.10, Prague, 2010.

21 Levin, E. M. and Carroll, J. A., "The Cost of Future Collisions in LEO," White Paper, Feb. 28, 2012, http://electrodynamictechnologies.com/PDF/WhitePaper-2012.pdf

22 Bensoussan, D., "Spacecraft Vulnerability to Space Debris is not an Option," 6th IAASS Conference, Montreal, Canada, May 21-23, 2013.

23 Carroll, J., "Potential Future Costs of Orbital Debris in Low Earth Orbit," Subcontract Report to Lockheed Martin, January 2014, http://www.star-tech-inc.com/id27.html. The paper also serves as a guide to the spreadsheet. To download that as well, click on "spreadsheet" below the link to the paper.

24 Kelso, T.S. et al, "What Happened to BLITS? An Analysis of the 2013 Jan 22 Event," 2013 AMOS Conf., www.amostech.com/TechnicalPapers/2013.cfm

25 NASA Orbital Debris Quarterly News, July 2014, p 3-5. http://orbitaldebris.jsc.nasa.gov/newsletter/newsletter.html

26 Kelm, B. E., et al., "FREND: Pushing the Envelope of Space Robotics," 2008 NRL Review, pp. 239-241, Naval Research Laboratory, 2008.