An Update on EDDE, the ElectroDynamic Delivery Express

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"EDDE" (the ElectroDynamic Delivery Express) is a new kind of non-rocket space vehicle. It is solar-powered, propellantless, and persistently maneuverable throughout low Earth orbit. EDDE consists mostly of a reinforced aluminum foil tape to collect and conduct electrons, plus solar arrays to drive this current. Hot wires emit electrons back into the ambient plasma. The maneuver force comes from the tape current crossing geomagnetic field lines. The ambient plasma closing the current loop sees an opposite reaction force. EDDE slowly rotates end-over-end to stiffen it. This allows sustained high thrust without dynamic instability. Rotation also improves agility, by allowing a wider range of thrust directions normal to both the EDDE tape and the magnetic field. EDDE is modular and typically weighs 30 to 80 kg for most missions. Air drag sets a minimum altitude near ISS altitude (350-420 km). There is no hard ceiling, but thrust decreases with plasma density at high altitude. EDDE's first major application may be distributing secondary payloads far from the primary's orbit, providing them with "custom orbits without dedicated launch." EDDE's total orbit change capability far exceeds that needed for any single orbit change in LEO. So after distributing payloads, EDDE can inspect failed satellites in multiple orbits, and image impact features and other visible anomalies. With suitable capture interfaces, EDDE might also capture cooperative payloads like satellite service vehicles, so a vehicle can service far more satellites without running out of propellant. Then EDDE becomes a "LEO taxi" that customers can rent rather than buy. EDDE can also rendezvous with and capture ton-class orbital debris in nets. It can then drag it down to short-lived orbits below ISS, or collect it in tethered assemblies at less congested altitudes, for later recycling and/or targeted deorbit. This paper describes EDDE design, components, and operations, the above sequence of increasingly ambitious missions EDDE enables, and our flight test plans.

1. Introduction

EDDE is a non-rocket vehicle that maneuvers in low Earth orbit (LEO) by reacting against the Earth's magnetic field. It does this by driving ampere currents through several kilometers of reinforced aluminum foil tape, and collecting and emitting electrons at opposite ends so the current loop closes in the ambient plasma. The current causes a force normal to both tape current and magnetic field. It scales with the product of current, conductor length, and field strength normal to the tape.

This propulsion concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test.[1] That flowed 0.3 A through a 500 m wire, with a hollow cathode serving as a plasma contactor at each end of the wire. In 1996, NASA MSFC's TSS-1R test flowed 1 A through a 20 km wire. That was enough to provide a ~0.5 newton force.

EDDE is limited to LEO by its dependence on the Earth's magnetic field and ionospheric plasma. But its sustained maneuvering ability vastly exceeds the needs of any now-plausible single LEO operation. If EDDE can capture payloads, it can handle one task after another and can become a zero-fuel "taxi" for use throughout LEO. This will make multi-mission satellite servicing vehicles far more useful in LEO.

This paper provides an overview of EDDE design, components, and operations, and then describes a sequence of 4 increasingly ambitious and valuable missions that EDDE enables. First is distributing secondary payloads to custom orbits throughout LEO. Second is allowing affordable close inspection of many failed satellites and other objects of interest. Third is delivering multi-mission LEO service vehicles to their next assignment and also delivering supplies to them. Fourth is collecting and/or removing from congested altitudes most large debris objects whose occasional collisions are likely to create most future untracked but lethal orbital debris.

2. The EDDE Space Vehicle

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

EDDE uses flexible lightweight solar arrays for power, and rotates slowly to improve stability and performance. Rotation is a key feature that enables high performance. It both stiffens the tether against transverse thrust forces and oscillations, and allows a wider range of long-axis angles to the geomagnetic field and hence a wider range of net thrust directions.

Adequate tension and control require a rotation rate of 6 to 8 turns per orbit. 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.[2, 3, 4]

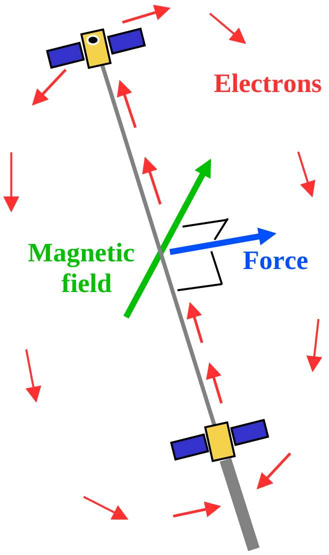

Figure 1. Basic Electrodynamic Propulsion Concept

EDDE's design plus its rotation set EDDE apart from previous LEO electrodynamic thruster concepts. Conventional hanging tethers use the weak gravity gradient force to provide needed tension and stability. For long-term stability, one must limit the average tether current and resulting thrust to a small fraction of the gravity-gradient tension unless the masses at each end are nearly equal. Too much thrust causes a hanging tether to librate chaotically and eventually lose control. By contrast, EDDE's centrifugal stabilization lets EDDE handle currents and thrust levels far higher than feasible with hanging tethers. Rotation also greatly increases the available 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, especially in high-inclination orbits, and even if EDDE carries a heavy payload at one end and nothing at the other end.

Figure 1 shows the basic concept, but Figure 2 is a more accurate view of EDDE. EDDE's solar arrays are distributed along the length of the conductive tape. This lets the solar array controllers divide the tape into separately controllable and isolatable segments. This limits peak local voltages to the plasma. Each tape segment conducts electrons. In addition, all segments biased positive relative to the local plasma also collect electrons, at a rate that scales roughly with plasma density and the square root of the local positive bias.

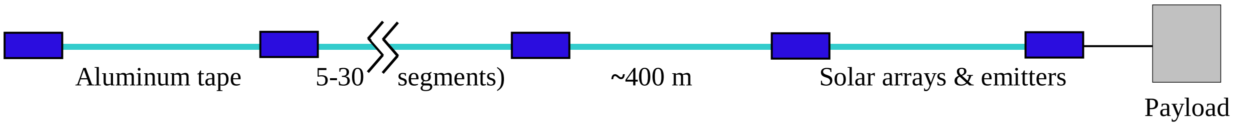

Figure 2. EDDE Layout, with Distributed Control, Power, and Electron Collection and Emission

Figure 3 on the next page shows the directions (normal to the local magnetic field) EDDE can thrust during each ¼ orbit, and which orbit elements that thrust affects most. EDDE's rotation is most useful near polar orbit, particularly for fast altitude changes. The EMF on hanging tethers scales roughly with cos(inclination). In near-polar orbits (which are popular), their thrust is nearly normal to the orbit. So hanging tethers climb and descend far slower than EDDE.

EDDE's modularity lets it be sized to fit a wide range of available secondary payload envelopes, mass limits, and orbit change needs for specific missions, ranging from nanosat delivery to capture and relocation of multi-ton debris objects. We expect most EDDEs to weigh from 30 to 80 kg and have one to several kW of solar array power. The 30 kg size fits a 12U CubeSat envelope, while the 80 kg size fits the inboard 1/4 of an ESPA payload envelope. This leaves the rest of the envelope for payloads EDDE can distribute.

At low inclinations, and when changing orbit plane at high inclinations, and when EDDE's orbit plane is nearly normal to the sun direction, EDDE will usually rotate in the plane of the orbit. At other times EDDE will typically rotate normal to the orbit plane. This increases average EMF, in-plane thrust, and achievable climb or descent rate. The transition between the two spin planes causes the kink in the altitude performance curve in Figure 4 below. Occasional changes between the two orthogonal spin planes should typically take about a day, but longer if EDDE has heavy payloads at both ends.

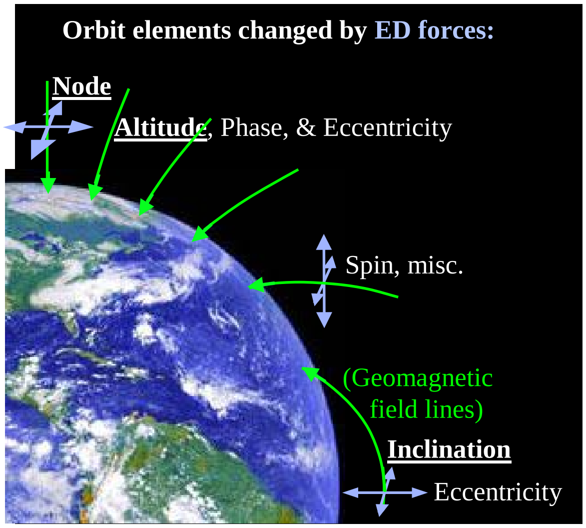

Figure 3. Possible ED Thrust Vectors vs. Latitude

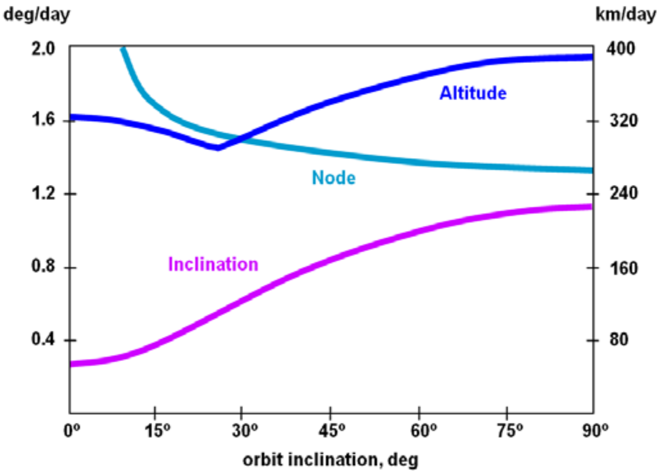

Figure 4. EDDE Orbit Transfer Performance per Ampere Average Current, for an 80 kg EDDE

Orbit-transfer performance is very impressive, as shown in Figure 4 for an 80 kg EDDE. The rates of change in altitude, inclination, and node are shown as functions of the orbit inclination, per amp of orbit-average current. EDDE maneuvers only while in sunlight. It coasts during eclipse, when plasma density is lower. This reduces the required battery mass and improves EDDE's overall agility. Orbit-average currents may be >1 A near 500 km altitude, and <1 A at higher altitudes, especially near solar minimum. These rates are for EDDE moving just its own mass. When EDDE is carrying payloads, the orbit change rate scales with the ratio of EDDE mass to total mass.

3. Maturation of Key EDDE Components

Initial development of EDDE was done under DOD and NASA SBIR funding. Recent technology maturation work was funded by the Game Changing Development Program under the NASA Space Technology Mission Directorate. This matured (but did not complete) the development of EDDE's design, key components, and operating concepts. This section discusses key EDDE components: the conductive tape, solar arrays, hot-wire electron emitters, circuitry to quench high-voltage arcs, and a steam resistojet. Section 4 will discuss packaging and deployment of EDDE, and EDDE operating concepts.

3.1 EDDE Tape Design

EDDE's heaviest component is its conducting tapes. They are nearly half the total mass of a 12U size EDDE, and over half the total for larger EDDEs. Mass-efficient design and compact stowage are both important. Aluminum is nearly twice as good a conductor as copper on a mass basis, but ~70% bulkier. Sodium would be even better on a conductivity/mass basis, but it is far less practical than aluminum.

Electrodynamic tethers that use round wire conductors can be cut by hypervelocity impactors down to ~1/4 the wire diameter. To prevent this, some tethers use multiple strands with frequent cross-connections, like a ladder.[5] But using small wires with many connections poses fabrication and deployment challenges, and it does not help much if the wires do not stay separated. ED currents can induce skip-rope and other dynamics that may ultimately twist a tether enough to collapse the wires together.

EDDE will use a reinforced aluminum foil tape 1-3 cm wide. Foil allows more electron collection area per unit mass than all but very thin wires. The reinforcement strengthens the tape, prevents propagation of transverse tears, and provides enough exposed area with much higher thermal emittance than bare metal that the tape runs far cooler than bare wires do. Surprisingly, the resulting cooling cuts electrical resistance enough that the electrical conductivity can exceed that of equal-total-mass unreinforced bare foils or wires.

The tape width greatly reduces vulnerability to micrometeoroids and small debris, which becomes dominated by infrequent near-edge-on impacts. EDDE actively avoids all tracked objects to eliminate any chance of impact with them. A danger from untracked debris <10 cm remains but is modest, because the threat of tape severance roughly scales with debris width, and much of the total width of debris that can cut the EDDE tape is thought to be from the large tracked objects.

For "narrow enough" tapes, electron collection from the plasma is expected to scale with tape width. But if the tape width exceeds several times the larger of the plasma Debye length and the gyroradius of ambient thermal electrons, then added tape width apparently has far less benefit.

Limits of this proportional regime have been studied by Sanmartin,[6] but require orbital flight test to verify. Tapes up to 3 cm wide may be in this regime at 700-1000 km altitudes, but tapes 2 cm wide may do almost as well near 500 km altitude, where EDDE may be able to do the fastest orbit plane changes when delivering secondary payloads.

We previously baselined 2 narrow reinforcing strips that interleave on adjacent layers of the double (two-ended) winding. We now plan to use a thinner, full-width reinforcement. This allows use of a ~¼ narrower tape without reducing the reinforcement span and hence significantly increasing the risk of tape cut. Narrower tapes are feasible for brief low-risk missions such as nanosat distribution by 12U-size EDDEs. Such missions will take only months and will spend most of that time changing orbit plane near 500 km, where orbital debris populations are fairly low.

Figure 5 shows the cross-sections of stowed tapes of our old design (30 mm wide) and new design (20 mm wide). The tape width is shown 2.5 times real size, and the relative thickness is exaggerated another 8-fold.

The stowed tape windings are weakly held together by a pressure-sensitive adhesive that peels loose under tension during the born-spinning deployment sequence. The old tape design used a transfer adhesive tape on top of the reinforcing strips. The new design uses a pad adhesive on one side of each winding. This reduces adhesive volume, mass, and peel force.

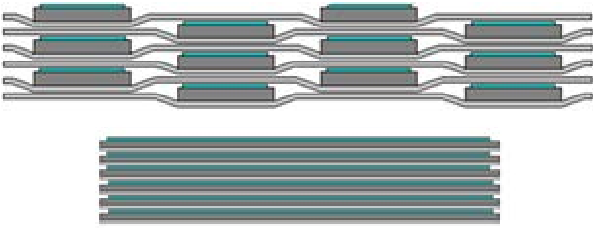

Figure 5. Stowed EDDE Tape Designs, Old and New

3.2 Solar Arrays

After the tapes, EDDE's heaviest component is its solar arrays. EDDE can use as much power as we can provide, but we need to minimize both mass and cost. Early missions should involve only modest total doses of both atomic oxygen and ionizing radiation, so arrays of terrestrial cells may be usable. In addition, average power is more important than end-of-life power, so EDDE can tolerate more solar array degradation than most other spacecraft can.

The best cell type in this fairly benign environment appears to be bifacial silicon cells, because of their low cost and mass and better robustness than space-rated triple-junction cells. The best array design appears to be laminating bifacial cells between layers of clear plastic film, with rigid cross-rails at each end of each array. Each array folds as shown in Figure 6, so both cross-rails are accessible when the array is stowed. This aids stowage, and also lets us daisy-chain the arrays and tapes together so they deploy in the proper sequence.

EDDE's solar arrays are held in tension by EDDE's rotation. This is true even when the arrays first deploy, because EDDE uses "born spinning" deployment to provide tension to deploy all its components.

We initially considered rad-hard triple junction (3J) solar cells. Their high cost led us to consider two-axis tracking, to maximize cell output by keeping the cells normal to the sun. But with EDDE's rotation, this would require strong and rigid solar panels. We could not find a panel design whose added mass could pay for itself compared to an in-line array with one-axis tracking.

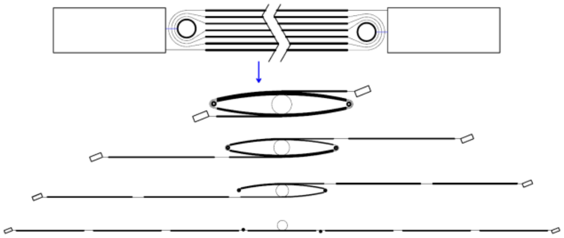

Figure 6. Deployment of Laminated-film Solar Array

But EDDE poses challenges even if the solar arrays track only around EDDE’s long axis, because all we have to torque against to steer the inboard solar arrays is a rotating tensioned tape. We studied adjustable bridles that could shift the array CG. This would let us torque the array using forces provided by transverse bending dynamics. We also studied use of magnetorquing using coils built into the solar arrays, and even reaction wheels usable as CMGs due to EDDE’s rotation. Each approach added mass, parasitic power use, cost, and technical risk.

These problems led us to consider unsteered in-line arrays. This requires solar arrays that generate power from sunlight on either the front or back. We found that there is a terrestrial niche market for high-efficiency bifacial silicon solar cells. The number of bifacial cell suppliers may grow, since a key patent by Sanyo (now Panasonic) recently expired. The cells are thicker than space-rated 3J cells (0.18 vs. 0.14 mm), and only about 60% as efficient, but the germanium substrate of 3J cells is 2.4 times as dense as silicon. On a bare-cell basis, silicon actually has higher power/mass than 3J cells. In addition, silicon cells cost <1% as much as 3J cells and are much less fragile. And based on recent proton dose tests by NRL, they should last for years in medium-inclination orbits.

We compared the performance of space-rated triple-junction single-sided cells vs. lower efficiency bifacial terrestrial cells that were steered in 0, 1, or 2 axes. The comparisons included our estimates of mass and power penalties for steering. The results are shown in Figure 7.

So unsteered arrays seem competitive with steered arrays for system power/mass, and may have lower cost and risk. But if each array has a random angle around EDDE’s long axis, the power and current will be highly variable. We want comparable power at each inboard array along EDDE’s length. This led us to divide each array into 2 sub-arrays. As shown in Figure 8, a 4-line bridle between the sub-arrays holds the sub-arrays at right angles to each other whenever it is under tension. This will limit the power variation from each array pair to about ±20%.

EDDE needs power over a wide range of voltages as the EMF and current change around each spin and along the length. Rather than using DC/DC converters plus radiators, we plan to invest in more array area, and simply switch array strings between series and parallel.

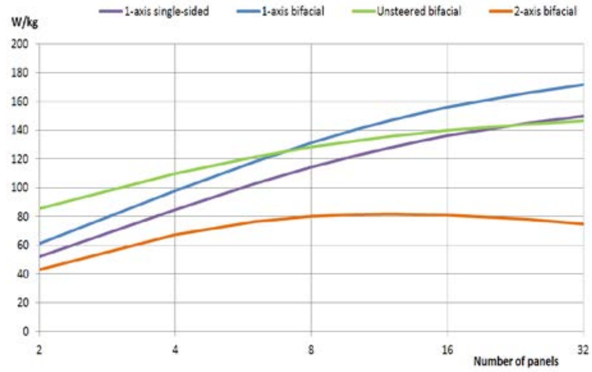

Figure 7. Comparison of Average W/kg for Candidate Solar Arrays and Steering Options

A random orientation of each array pair to the sun requires each sub-array to have two identical strings that can be in either series or parallel. The currents from the two sub-arrays are added in parallel (since the currents from the sub-arrays will generally differ far more than the voltages). Switching losses can be kept low enough that light aluminum cross-rails at each end of the middle bridle should be able to dissipate them.

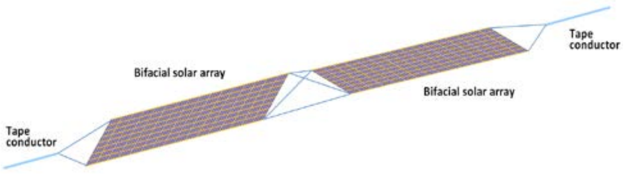

Figure 8. Sub-Arrays Rigged to Stay at Right Angles

Unsteered arrays eliminate the unusual technical challenge of needing to steer arrays around EDDE’s long axis, but our design does let us test long-axis array steering concepts on some arrays.

Structurally, we plan to simply laminate silicon cells between clear plastic films, whereas the more fragile 3J cells need stiffer (even if smaller) support. Complete bifacial silicon arrays may even be mass competitive with 3J arrays, even for spacecraft other than EDDE. EDDE’s complete arrays should provide average power up to 200 W/kg for typical EDDE spin axes, which will usually be within 45° of the sun direction.

A compactly stowable lightweight laminated solar array like this also seems relevant to small satellites that are to be spin-stabilized facing the sun. Spin stabilization not only orients the arrays, but also provides tension so no rigid solar array structure is needed, other than short cross-rails for each array. By the time EDDE needs solar arrays with more tolerance of ionizing radiation, such as for sustained use removing debris from near-polar orbits, rad-hard thin-film arrays using similar laminated designs may be available, for both EDDE and also other spacecraft.

3.3 Electron Emitters

It is easy to collect electrons in plasma: bias bare metal positive, and electrons flow to it. Unfortunately, biasing it negative attracts far fewer ambient ions, since their higher mass reduces their velocity. And biasing a metal surface negative also cannot not make electrons flow from the surface into the plasma, because of a few-volt “work function” needed to move electrons from metal into vacuum. This energy must be supplied over ~1 nanometer, so very high local fields are needed. One option is to provide enough energy thermally to boil some electrons off a hot tungsten wire, or off the inside of a hot hollow cathode. Such cathodes ionize xenon flowing through them. The slow-moving ions allow a far larger electron current to stream out, without creating a large "space charge" region with net negative charge. The space charge requires high electron emission bias voltages in most other emitter concepts.

Our earlier EDDE designs baselined hollow cathodes for electron emission. But they use >1 kg/year of xenon, require bulky tanks, and tend to be both costly and sometimes finicky. Our progress on solar arrays led us to consider thermionic electron emitters as an option. We knew they would take more power per amp emitted, 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.

Thermionic emitters require substantial low-voltage power for heating, plus high-voltage power to bias the emitter negative enough to drive electrons through the local space charge region formed by electrons streaming out from the emitter. And their life is limited by slow sublimation of the hot tungsten. And as with most other electron emitters, they are very sensitive to both surface contamination and erosion by ionized atomic oxygen.

As shown in 1923 by Langmuir,[7] thoriated tungsten forms a polarized surface monolayer of thorium atoms on hot tungsten. This greatly reduces the work function and the temperature and power needed for thermionic electron emission. But this enhancement is poisoned by even tiny amounts of oxygen-containing gases, because oxygen reverses this polarization. Adding carbon to the wire re-enables enhancement, by letting surface oxygen escape as CO. But carburizing the wire embrittles it, and protects the wire only until the carbon is used up.

We found that we can coat the wire but delay wire carburization and the resulting embrittlement until after launch and deployment. We can provide enough carbon to enable thorium-enhanced emission with an adequate lifetime at EDDE operating altitudes. Figure 9 shows an emission test in a chamber with enough residual oxygen that enhanced emission occurs only with carburization.

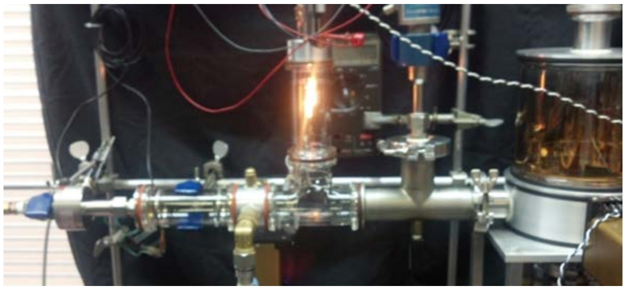

Figure 9. Vacuum Testing of Thermionic Emitter

Surprisingly, one can reduce heating power needs per amp emitted by heating a wire hotter, since emission capability increases 3-4X faster than heating power does. But higher emission from a hot wire of fixed size means a denser stream of electrons and hence a higher space charge. This requires higher emitter bias voltages. With a fixed wire and anode geometry as in vacuum tubes, current that is limited by space charge rather than by thermionic constraints scales with the 1.5 power of the bias voltage. But in plasma, the radius of the space-charge volume out to an "effective plasma anode" is not fixed. The effective plasma anode radius is the radius at which the streaming electron density falls to the ambient ion density. In tenuous plasma like Earth's ionosphere, the effective anode radius should nearly scale with Sqrt(Current). As a result, the current emitted into the plasma should nearly scale with emission bias voltage.

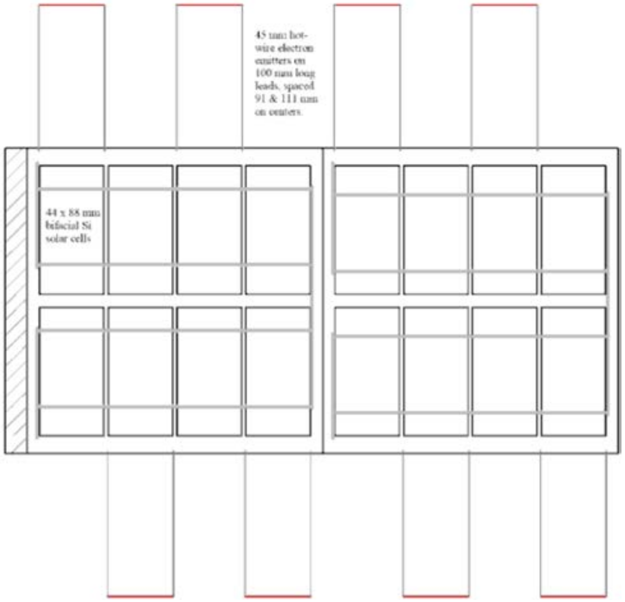

Figure 10. Electron Emitters on Solar Array

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

EDDE's emitters need good exposure to ambient plasma, but each wire also needs 1W of low-voltage heating power. As shown in Figure 10, the emitters and their lead wires fold out from a low-voltage array that directly heats the emitters. The lead wires are long enough to limit how much the array's plasma shadow affects plasma anode density and size, but short enough to stow inside the array. The number of wires heated can vary to fit the available array current as sun angles change, and an adjacent high-voltage solar array can provide the bias to drive emission.

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

3.4 Arc Detection and Quenching

Despite the work function and space charge barriers to electron emission into vacuum or tenuous plasma, there are times when electron emission works 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 started, first from tether to shuttle, and then from tether to space. The arc burned through the tether and ended the experiment.[8] The arc was triggered by a flaw in the tether insulation passing close to grounded metal. Once the arc started, a 3500-V EMF plus 8 m^2 of metal electron collection area on the deployed satellite sustained a 1 A unipolar electron emission arc from tether to ambient plasma. It severed the tether within 10 seconds and kept going at the free end for a minute after that. Then it suddenly stopped, for reasons that do not seem clear to us.

Even if TSS had not had an insulation flaw, a small micrometeoroid or debris impact could create such a flaw, plus a transient cloud of partly-ionized volatiles capable of triggering an arc to the plasma, given the 3500-V EMF over the wire length. Sustained arcs in vacuum apparently create and ionize enough volatiles to keep high currents flowing even at modest voltages, much as in a hollow cathode. Such currents could even be useful, but material ablation rates appear to exceed the xenon mass flows in hollow cathodes.

Each EDDE tape segment has an exposed bare metal area similar to the TSS satellite, and much of the full tape length will often be biased negative enough to the plasma to sustain an arc. Even tiny hypervelocity impacts may trigger such arcs. 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. Solar array plasma arcing tests done at NASA Glenn suggest that sustained arcing to plasma requires currents of order 1 amp; much smaller arcs quench themselves before they do significant damage.[9]

EDDE plans on 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 tape 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.

We also plan for initial EDDE operations to use a spin axis that limits the worst-case combinations of plasma density and EMF until most other mission goals are accomplished. Then we may explore those limits. If necessary, EDDE can also include emergency emitters based on digital solid state propulsion (DSSP) thruster designs.[10] This can give us an on-demand source of partly ionized volatiles that lets us quench a remote arc, by providing a better arc site that lets us "steal" the arc and then turn it off.

Japan's Horyu nanosatellites are also exploring high-voltage spacecraft arcing.[11] They do not have enough collection area to allow unipolar arcing to the plasma, but their data may still be useful. Lab tests of arc trigger and quench thresholds seem worthwhile.

3.5 Steam Resistojet

EDDE requires conventional propulsion to provide a suitable spin axis and spin-up impulse for the "born spinning" deployment scenario described in the next section. The required impulse was equivalent to only a few m/s ΔV, so we had initially assumed use of cold-gas thrusters.

But the growth of secondary payload deployment opportunities from the ISS and interest in EDDE by ISS personnel have led us to consider deployment from ISS. EDDE might drift ~½ orbit forward of ISS, deploy itself there, and then climb to a "cruising altitude" 100 km above ISS. But EDDE's high drag after deployment makes us queasy about trying that on early missions: EDDE could reenter within days if we have problems.

ISS personnel also want EDDE to make a small orbit plane change before full deployment, to reduce chances of re-contact with ISS. A need for more ΔV before full deployment increased our interest in higher thruster performance. We can deploy enough array area for a ~50-W resistojet early in EDDE deployment, so we studied that. But all the commercial resistojets we found that had decent Isp were heavy, and the light ones required flammable and/or high-pressure propellants that raise safety concerns on ISS.

That led us to focus attention on a steam resistojet that stores water at low pressure and pumps it to ~20 atmospheres pressure for use. This eliminates safety concerns about energy stored in pressurant gas, and lets us use unusual tank shapes with low mass penalty. A high pump pressure allows good nozzle efficiency even at power levels <50 W, and makes the hot section small enough to limit radiative heating of nearby components. A pump also lets us vary pressure and flow to fit a wide range of available power. An early concept of the design is shown in Figure 11.

We expect an Isp >160 seconds and a dry mass <100 g, including redundant pumps, a precious-metal hot section, plumbing, an optional 2-axis gimbal, and a controller. This does not include the unpressurized water tank, which may often be application-specific. Tank mass including water acquisition features may be ~10% of water capacity.

We expect this resistojet to be useful to a wide range of small satellites, over at least a 10-50 W power range. We expect a thrust of ~0.3 mN per watt. This is ~10X the thrust available from most concepts for high-Isp electric propulsion now being developed for nanosats. Most development work remains to be done on this resistojet. We plan to publish more details as we mature the design. We invite those who are interested in such a resistojet to contact us and describe their needs, interests, and project schedules.

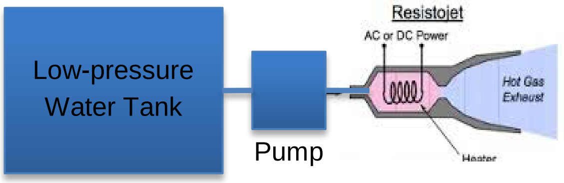

Figure 11. Concept for 10-50 W Steam Resistojet

4. Maturation of EDDE Operating Concepts

Under our recent NASA STMD contract and in work since then we have matured EDDE operational concepts. This includes work on sizing and packaging for launch, our “born spinning” deployment scenario, controls, navigation, and active avoidance of collision with tracked objects. These items are discussed below.

4.1 EDDE Sizing and Packaging

Electrodynamic tethers do not scale down well to small sizes, due to the Earth’s weak geomagnetic field and tenuous ionospheric plasma, because the direct and indirect costs of collecting and emitting electrons cause substantial parasitic loss. If the conductor is very long, most of the vehicle mass and power serve to drive electrons along the conductor. This is what provides the useful ED force. Parasitic losses can then be neglected. But for ED vehicles less than several km long, parasitic losses are usually dominant, and agility drops drastically. One can reduce losses by using a very long thin tether, but it then has a higher risk of cut. One can design an ED tether of any desired mass, but below tens of kilograms mass, both usable ED force and expected life before severance drop faster than mass, so agility and utility both suffer.

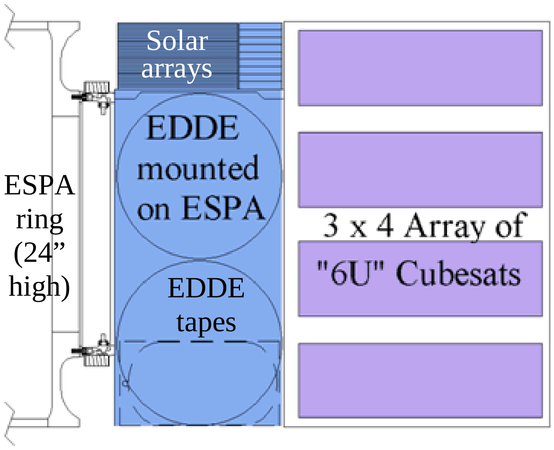

Figure 12. EDDE Sized for ESPA, with CubeSats

Early work on EDDE was in parallel with development of the EELV Secondary Payload Adapter ring or “ESPA ring.” This ring can support 6 payloads each weighing up to 400 lb.[12] Each payload position can carry EDDE plus a collection of EDDE payloads, so we baselined it. EDDE can stow more densely than most secondary payloads, so it makes sense to mount EDDE to the ESPA ring using a lightband, and have EDDE support the payload, as shown in Figure 12.

But CubeSat ride opportunities to LEO are now far more frequent than ESPA ring rides to LEO, and far cheaper. This led us to develop an EDDE version sized for the 12U CubeSat payload envelope. It will weigh ~30 kg. We think that size is likely to be the smallest and lightest EDDE that has good agility, lifetime, and operational utility for missions like nanosat distribution and satellite inspection. An axial layout for a 12U EDDE is shown in Figure 13.

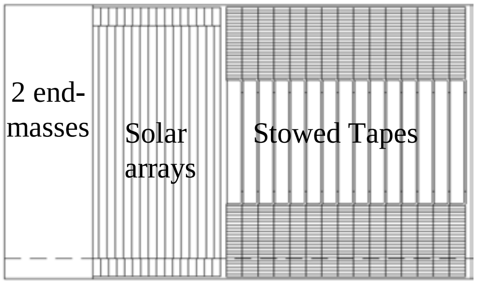

Figure 13. Axial 12U Layout for 6 km EDDE (~30 kg, 16 solar arrays, 15 tapes)

This axial layout allows adjustment for any desired tape width and stowed length, including “fractional U” lengths. If mounted in a longer CubeSat carrier, EDDE payloads can stow and be ejected together with EDDE.

4.2 EDDE’s “Born Spinning” Deployment Scenario

EDDE may need ~60 m/s of conventional ΔV before it deploys itself. We plan to provide that by resistojet, as described in section 3.5. We will start deployment by releasing one endmass and an attached low-voltage solar array that powers the resistojet and avionics. The resistojet will put EDDE into a slow spin. This can stabilize the solar array facing the sun, and can provide enough tension for EDDE component release.

We use “born spinning” deployment as the easiest way to provide tension, manage EDDE’s shape, and drive an orderly deployment of all EDDE components. In addition, transitions either way between hanging and spinning seem to pose far more practical problems than controlling an always-spinning EDDE.

EDDE will use strong Vectran tapes to restrain its stacked components during launch, for both ESPA and CubeSat mounting concepts. Once EDDE and its attached payloads are ejected from the host vehicle, we can release those restraints as needed, by using hot wires to melt the Vectran, as NRL’s TEPCE CubeSat does. Once the flight restraints are released, each EDDE component is restrained only by thin bent wire hooks. Each hook is fairly strong until that component reaches the top of the remaining stack of components. Then there is nothing on top of the hook to help keep it bent, so it becomes far weaker. This lets all components pull free in the proper order, without requiring that EDDE have active mechanisms to release each component in a stack.

A key to controlling EDDE deployment is to limit the relative size of each step increase in moment of inertia as the components deploy. And we must add spin angular momentum to keep tension high enough. We must also wait for dampers built into some EDDE components to help settle out the dynamics. As shown in Figure 6 earlier for a solar array, each stowed array and tape winding is doubled over, so both ends are on the outside of the stowed item. This makes it easy to daisy-chain the wound tapes and folded solar arrays together so they deploy in the right order.

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. The slow spin will weakly pry each component loose. After all components have been released and the dynamics have damped a bit, we will actuate hot-melt wires to let each solar array unfold. After those dynamics settle out, we will further increase the spin and tension to peel the weak adhesive that keeps the tapes from unwinding.

Once enough of the first tape has unwound, EDDE can emit electrons at both ends, and bias the exposed tape positive to collect electrons on it. This can provide useful electrodynamic spin-up torque over part of each orbit, whenever the magnetic field orientation is favorable. This can supplement and then replace resistojet spin-up thrust, to reduce water usage. We expect full “born-spinning” deployment to take <1 day, even with payloads at one or both ends. But on the first mission, we may take several days for full deployment, so we can study all the diagnostic data collected during deployment. The tapes have 80% of the drag area of the fully deployed EDDE, so we can do useful tests with only one or a few tapes deployed, without risking a prompt reentry due to high drag at low altitude.

4.3 Controlling EDDE

EDDE has batteries for power to run its avionics and communications at night but does not thrust then, since substantial night-time thrust requires heavier batteries. Their added mass reduces EDDE’s overall maneuver rates. And night-time maneuvering is less productive anyway due to lower plasma densities at night. So EDDE maneuvers in the sun and coasts when in eclipse. If batteries or ultracapacitors improve enough more in performance than solar arrays do, then we may be able to justify at least partial-spin energy storage (day/night is harder to justify), but right now the best power management strategy seems to be “use it or lose it.”

In the sun, we estimate EDDE attitude and bending using sun sensors, magnetometers, and GPS. The solar array long axes follow the local tape direction closely. Combined with GPS data from the end-bodies, this determines vehicle mechanical state. A recent history of this data plus onboard models of the magnetic field and ionosphere let us determine EDDE’s dynamic state and identify and damp differences between the actual and preferred state. We do this by adjusting the times at which we switch the solar array voltage and polarity, to cause electron collection and emission as desired.[2,3,4]

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.

4.4 Navigation and Active Collision Avoidance

The main challenge for EDDE navigation is reliably avoiding all tracked objects whose orbit altitudes overlap EDDE's. These objects include 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.[13] We will uplink the time, position, and uncertainty of all predicted penetrations of this volume, to define "keep-out zones" within it.

Figures 14 and 15 illustrate this with a reference trajectory, maneuver volume around it, plus two keep-out zones created by objects predicted to pass through the moving maneuver volume. The zones are ellipsoids in a phase space of time, arc length along the reference trajectory, and altitude offset from the trajectory.

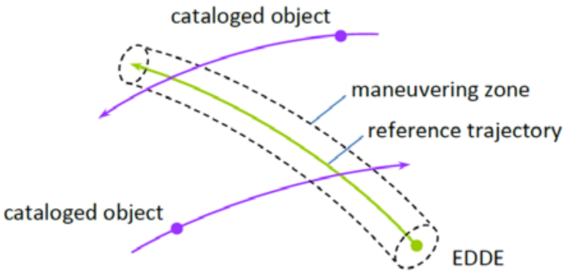

Figure 14. EDDE in a Defined Maneuver Volume

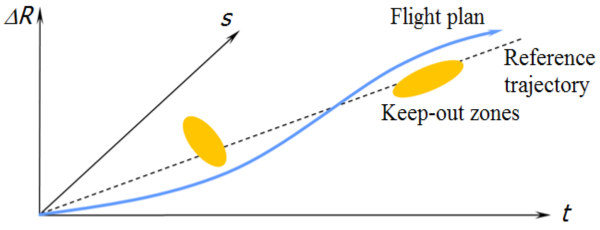

Figure 15. EDDE Maneuvering Around Conjunctions

Figure 16 shows the expected rates that objects in the 2011 catalog would penetrate a 30 km diameter, 200 km long EDDE maneuver volume, for an EDDE in medium inclination orbit. The volume could be far smaller than 30 x 200 km, but a large volume eases autonomous avoidance despite plasma density and other variations. The simplest maneuver may usually be a small change in along-track position or spin phase. Even at the most congested altitudes, active maneuvers should be needed only a few times/day. 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 enough miss distance. With proper flight planning and execution, EDDE can actively and affordably avoid collision with all catalog objects. EDDE doesn't use fuel to maneuver, so it can continue active collision avoidance as long as it stays in service, at a very minor penalty in throughput.

The risk of tether cut by small untracked debris seems low enough for EDDE missions that distribute multiple nanosat secondary payloads to individual orbits. That should take months, spent mostly near 500 km altitude. Wholesale LEO debris removal will take years, mostly >600 km. Debris removal EDDEs can be heavier and can use wider or redundant tapes. We can afford to lose a few such EDDEs to cuts by small untracked debris. Even after an EDDE is severed, each half can actively avoid all operating satellites while it autonomously spirals down to a prompt reentry. EDDE tapes weigh <4 grams/meter. Impact by small debris may sever an EDDE tape, but should not create much new debris massive enough to be lethal to typical satellites.

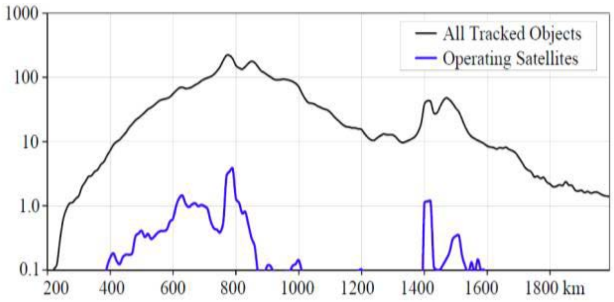

Figure 16. Typical Penetrations/Day of a 30 x 200 km Maneuver Volume, vs. EDDE Altitude

4.5 Tracking and Communication

As part of our STMD-funded work, the Naval Research Laboratory developed methods to track maneuvering multi-kilometer vehicles like EDDE. The main issue is that ***all*** ED tethers are large fuzzy glinting radar targets, whose "center of brightness" may be kilometers from the center of mass and may move very erratically. Inferring the actual trajectory from such data requires care. Even compact but persistently-maneuvering vehicles like ion-engine vehicles can pose problems, if conjunction predictions assume that all tracked objects have been coasting since the most recent observation.

We also studied comm. issues. It seems useful to get status data at least once/orbit. We also need low-latency video downlink plus low-rate uplink during rendezvous, inspection, and capture passes, on missions that involve those tasks. We can use existing commercial stations, mostly in the Arctic, for high-rate data for rendezvous, inspection, and capture. Globalstar may allow status downlinks, if it is approved for LEO-Globalstar-ground services. (It now provides only ground-Globalstar-ground services, and doesn't even have cross-links.)

5. Secondary Payload Distribution by EDDE

EDDE will reach fullest use as a "LEO taxi," doing payload deliveries one after another throughout LEO. But that requires rendezvous plus payload capture. Many useful early missions do not require either. The simplest and probably most useful early mission is likely to be distributing payloads launched with EDDE.

Payload distribution by EDDE is most relevant to secondary payloads, since primary payloads can be launched directly to any desired orbit. EDDE's ability to deliver secondary payloads far from a primary's orbit means that EDDE can make surplus capacity on any LEO launch more valuable: that capacity is no longer limited to use by secondary payloads that are satisfied with orbits near the orbit of the primary payload or its booster stage.

EDDE can deliver individual secondary payloads ranging from 12U to at least ESPA size. EDDE can also distribute multiple secondary payloads to substantially different orbits. As shown earlier in Figure 12, we initially sized EDDE for launch with payloads on the ESPA ring.

In this layout, EDDE plus its lightband can use the inboard 12" of the 38" deep payload envelope and nearly half the payload mass allowance. It can support its payloads outboard. ESPA payloads are limited to 400 lb with a CG 20" outboard of the mounting plane. But EDDE's dense inboard packaging may allow a somewhat higher total payload mass since it reduces peak cantilever loads. The standard ESPA ring can hold up to 6 payloads. A single EDDE can distribute not just payloads mounted on it, but if desired, two more full ESPA payloads mounted in adjacent ESPA slots and tethered to EDDE. Sequenced release of the lightbands, plus suitable variations in separation spring energy, could even start EDDE's born-spinning deployment.

ESPA launches have been infrequent and costs per ESPA slot high. For cheaper and more frequent launch of smaller secondary payloads, we scaled EDDE down to 12U size, as shown earlier in Figure 13. Nanoracks has developed and already used a 1x1x6U carrier. We have checked with two suppliers of 12U (i.e., 2x2x3U) carriers. They say that they can be stretched to at least 2x2x6U. This lets them carry 12U each of EDDE plus EDDE payloads. Both these carriers clamp the payloads transversely as well as axially, so there is no need for EDDE to handle launch loads of the CubeSats stowed with it.

We do need a severable tie between EDDE and any payloads mounted with EDDE in one carrier, so EDDE can hold them while delivering them to the final orbits. We plan to use Vectran tapes and hot-wire cutters as used on the Naval Research Lab's TEPCE CubeSat, to secure both EDDE's payloads and its stacks of stowed components.

Two ESPA-sized EDDEs packaged with payloads as in shown Figure 12 could deploy a complete 6-plane constellation of 24 6U CubeSats for Earth observations. Each CubeSat could include a 90-mm Maksutov telescope using a University of Washington design.[14] Figure 17 shows the satellite and orbit configuration:

The EDDEs and their payloads can launch together, and then separate and head in opposite directions in node to populate the 6 orbit planes. The full constellation could be deployed within 94 days.

Most US launch vehicles do not have a good way to carry multiple secondary payloads larger than CubeSats but smaller than washing-machine size ESPA payloads. If this gap is filled, we can easily also size an EDDE for it, to allow delivery of intermediate-size payloads throughout LEO.

After distributing their payloads, ESPA-size EDDEs might capture and remove ton-class debris, while 12U-size EDDEs do inspections and possibly capture and deorbit debris objects under ~100 kg.

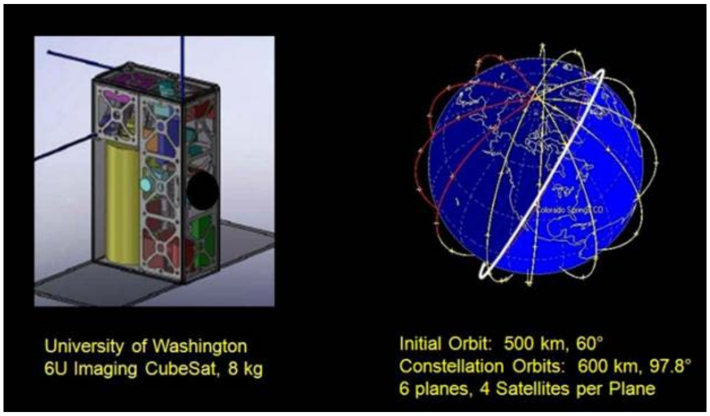

Figure 17. A 6-Plane Constellation of 24 6U Imaging CubeSats

5.1 Payload Distribution Times Using EDDE

Table 1 below shows typical times EDDE will need to deliver or distribute payloads to other orbits. It assumes an 8 km, 60 kg EDDE delivering 180 kg of secondary payloads: either a single max-mass ESPA payload mounted in an adjacent ESPA slot, or many P-Pods, or any other desired combination with 3 times EDDE's mass. For other payload masses, delivery times scale with M_{total}/M_{EDDE}. Delivery times of 49-170 days to different orbit planes may seem long, but the typical alternative for secondary payloads is to wait for a more suitable launch. That usually imposes much longer delays.

Table 1. EDDE Nanosat Distribution Times

Operation	Days	Notes: (M_p/M_{EDDE}=3)
400 km circ. boost	8	Power-limited climb
400 km circ.deboost	2	If plasma dense enough
51.6° to 70° orbit	49	Departure day sets node
51.6° to 98° orbit	124	Departure day sets node
Same+ 90° node shift	150	Combined maneuver
Same+180° node shift	170	Combined maneuver

A particularly useful EDDE mission is delivering CubeSats and other smallsats to sun-synchronous orbit from the International Space Station. EDDE can make any orbit in LEO accessible to secondary payloads, such as the CubeSats launched from the NanoRacks deployer on the ISS. Currently CubeSats are released into the ISS orbit and decay within a few months. EDDE's ability to both change planes and also reach higher altitudes lets each satellite's orbit life be matched to its mission.

Surrey Satellite Technology US LLC has asked us to provide EDDE as an upper stage for their FeatherCraft-SS 50-kg spacecraft, which will be carried and released by a new NanoRacks deployer. This is a complete spacecraft bus, with 100 watts power and room for 20 kg of payload, as shown in Figure 18.

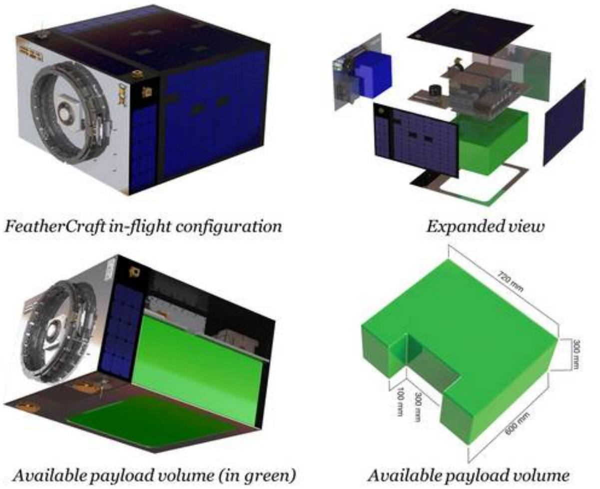

Figure 18. Surrey FeatherCraft-SS

Surrey wants its FeatherCraft-SS to go from ISS to sun-synchronous orbit (SS), at 400 km altitude and 97° orbit inclination. We compared the performance of a 24-kg Mini-EDDE with a Busek BHT-200 Hall thruster of the same total mass. EDDE takes the payload to S-S in 168 days (a plane change delta-V of 5919 m/s).

When EDDE reaches 97°, the equal-mass Hall is at only 70.5° inclination. It runs out of fuel by the time it reaches 78° inclination, after providing only 58% of the desired ΔV, in 230 days. The Hall stage cannot reach sun-synch without more fuel, and that mass will further slow it down. This comparison is shown in Figure 19.

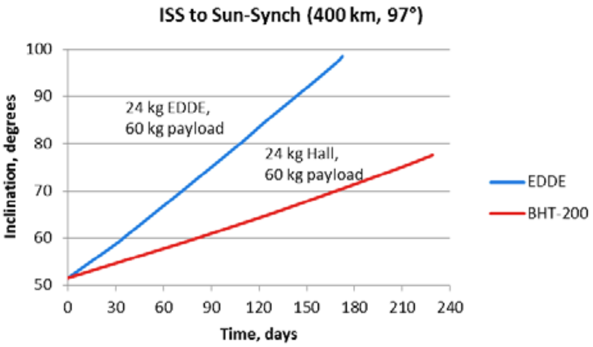

Figure 19. ISS to Sun-Synch Orbit (12U EDDE)

We also compared an ESPA-sized EDDE with the best Hall thruster, the Busek BHT-1500. Each weighed 80 kg and was to deliver 100 kg of payload through a very large inclination change, from 28.5° to 97°, both at 400 km. EDDE completes this mission in less than 60 days, but the equal-mass Hall thruster stage runs out of propellant after 105 days, after providing 69% of the desired delta-V. This case is shown in Figure 20.

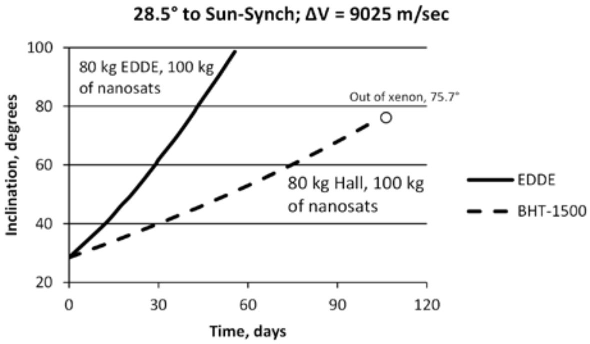

Figure 20. 28.5° to Sun-Synch Orbit, ESPA class

6. Inspections by EDDE

Initial EDDE missions may involve just payload distribution, but EDDE will become far more useful once it can also make safe close approaches to objects, to inspect or even capture them. And a series of accurately guided inspections will be a key step in qualifying EDDE for capture operations.

In the past, close imaging has required a dedicated inspector launch to the orbit of each inspection target. The cost of a dedicated launch to the target's orbit makes inspection operations expensive enough that they are done very seldom. EDDE can change that, because its sustained agility allows rendezvous with a series of objects even in quite different orbits. EDDE can either do close inspections itself, or it can enable sustained close inspections by dropping off a dedicated low-deltaV picosat or nanosat inspector near each of a series of inspection targets.

Close imaging inspections may serve multiple goals. Many spacecraft fail in ways that are not conclusively established on the ground. Close inspection may resolve some of those cases, and may change the accepted cause for others. For example, battery explosion is a common failure mode, but we don't know whether many such failures may have been due to impact by untracked cm-class debris that damaged the battery or shorted out the power bus.

Close imaging of old rocket bodies to find "bullet holes" may be useful in establishing impact rates by cm-class untracked debris. This is a new kind of space situational awareness (SSA) that can shed light on the past and likely future costs of debris in LEO. Adding hyperspectral imagers could let us characterize degradation of solar array, thermal control, and other surfaces, complementing what is known from the LDEF and ISS-based MISSE experiments done at lower altitudes. Early inspections should be of US-owned objects. We should start with non-functional objects, to avoid any risk of possibly damaging operating satellites.

6.1 EDDE Inspection Trajectories

Due to its slow rotation (~8 revs/orbit), if EDDE hovers near an object it will eventually wrap around it. And for both inspection and capture, what we really want is for cameras on an endmass to approach such objects, rather than the middle of EDDE. But EDDE's endmasses are not in free fall, so conventional approaches will not work.

EDDE can use an orbit with the same orbit period as the target but small differences in other parameters. This allows repeated free-return cusp-like approaches of one endmass to the sunlit side of a target, at the same point in each orbit. EDDE can do this using either in-plane or out-of-plane spin. Out-of-plane spin lets EDDE stay closer to the target all around the orbit. This allows more precise binocular ranging to the target between approaches. An out-of-plane approach of a spinning tether to a target is shown in Figure 21.

Figure 22 shows 3 orthogonal views of an EDDE endmass inspection trajectory relative to the sunlit side of a Delta stage. If the stage slowly tumbles or librates, each pass can image different parts of the stage.

The trajectory in Figure 22 includes an 8 m sunward offset of the EDDE endmass from the target. This offset can be much larger during the first few imaging passes. The offset may have to remain large if a target has appendages or erratic attitude motion, or if rendezvous is at a low enough altitude that EDDE's air-drag uncertainty degrades the free-return accuracy.

The pass includes a ~0.2 m/s tangential velocity so the approach and departure paths of the endmass differ enough to provide complementary views of the target, and even stereo imaging of much of it. Dozens of such passes plus suitable attitude motion of the target may be required to fully inspect some targets.

Figure 23 shows another perspective on the out-of-plane free-return trajectories in Figures 21 and 22. It shows trajectories of tether end-points A and B (solid lines) and tether center of mass (dashes) relative to an LVLH frame centered on the target, for an 8 km long EDDE rotating in the local-horizontal plane at the time of closest approach. At that time, EDDE is oriented along the orbit, the relative velocity of endmass A to the target is very low, and EDDE's cameras should be able to get good inspection images of the target.

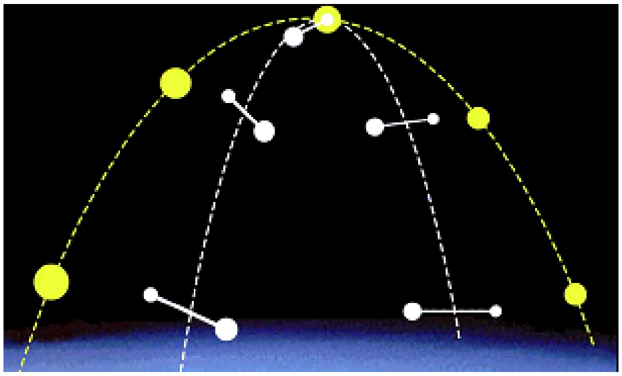

Figure 21. Free-return Out-of-plane Rendezvous

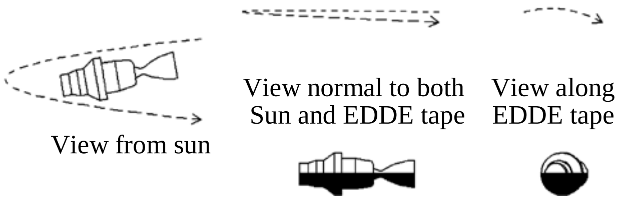

Figure 22. 3 Views of an Inspection Pass by EDDE

Centrifugal acceleration at each end of an 8 km EDDE rotating at 8 revs/orbit is ~0.26 m/s^2. This means that each close imaging pass will last about 20 seconds, during which the endmass will move past the target at up to ~2.6 m/s. The sunlit targets should allow exposures well under a millisecond. Even with limited image motion compensation, image resolution well under 1 mm should be feasible for key features such as impact craters on the target.

Figure 23 maps the trajectories onto a 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.

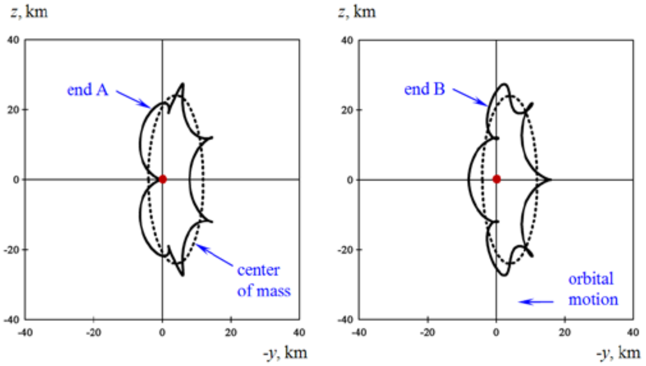

Figure 23. Free-Return EDDE Rendezvous Trajectories

6.2 Visual Guidance for Rendezvous

EDDE will be given an initial “waypoint orbit” with a safe standoff from the desired inspection target. It will use its GPS receivers for guidance to maneuver to that orbit. But once EDDE gets within 100 km of a typical sunlit intact target, the target should be brighter than all celestial objects other than the sun, moon and Venus. The target will be easy to find as it slowly moves across the starfield. Even large debris fragments will be very bright, once EDDE gets within ~10 km range.

Cameras plus GPS receivers in each EDDE endmass allow precise binocular ranging to the target against the starfield. Ranging sensitivity is shown at right in Figure 24.

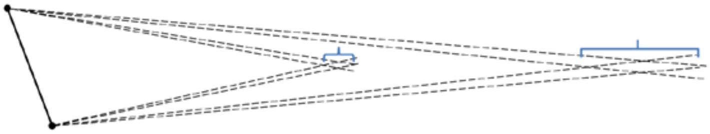

Figure 24. Angle-based Ranging Errors Scale as ~Range^2

EDDE can range to the target multiple times every half-orbit, when the target is both sunlit and in front of the starfield. Range errors scale with range squared, and should drop to meters by the time EDDE approaches to within a few EDDE lengths of the target. This plus the even more precise transverse target direction data in the images provide our best targeting data. We can use that targeting data to fine-tune EDDE’s free-return trajectory by successive approximation over multiple orbits.

The main targeting errors needing to be detected and corrected are likely to be due to EDDE itself, not its target. EDDE’s large tape plus solar array areas gives it roughly 30X the area/mass (A/M) ratio of typical intact LEO objects. The dominant issues may be EDDE’s drag area, bending modes, and small EMF-driven parasitic current loops involving electron and ion collection on each tape segment. GPS fixes at each endmass can limit EDDE’s absolute errors, and occasional binocular fixes can update estimates of errors relative to the target. Once EDDE gets close to the target, it can mostly coast. This lets it gradually “quiet” its dynamics to allow closer and closer safe approaches.

When EDDE gets close enough, glare from the sunlit target will preclude detection of stars in the same frame. Then we will use cameras on the same optical bench but facing other directions to provide orientation references. Transfer errors will reduce ranging accuracy a bit, but at short range those errors will be too small to cause problems.

Each time an EDDE endmass makes its closest approach to a target, EDDE is end-on to it, so it briefly loses binocular ranging capability. But the size and location of the target in the close images allow precise evaluation of close-approach errors for each pass.

Typical targets may tumble slowly enough that on each pass EDDE can image only a part of the sunlit area. Many passes may be needed to get good images of all sides, preferably with several lighting angles. But if EDDE takes a week to match orbits with a target, spending another day to get ~14 imaging passes should not be a problem. In some cases, study of images from early passes may lead operators to increase the number of passes to ensure the best possible lighting angles and images of specific areas on the target.

After EDDE does enough inspections, its positional errors in rendezvous should become reliably small enough to allow consideration of EDDE operations requiring capture, of cooperative targets first, and then passive targets. That enables a wider range of EDDE missions. The next two sections of the paper discuss capture of cooperative and passive targets.

7. EDDE Support of Satellite Servicing in LEO

Satellite servicing initiatives are essentially a bet that one can cost-effectively extend the useful lifetimes of at least some satellites by launching robotic service vehicles to refuel, repair, and/or upgrade them, somewhat as done by shuttle crews on the Hubble space telescope. EDDE can actually play two useful robotic satellite servicing support roles even before it masters the art of capture. One is taking a service vehicle launched as a secondary payload from the primary-payload orbit to the needed orbit. The other is delivering supplies or new modules to a service vehicle already in orbit, for it to capture and use. Both are simply delivery missions.

But once EDDE masters capture, it can do far more to support robotic satellite servicing. Those roles may make the difference between extensive LEO satellite servicing becoming viable or not.

DARPA and NRL are applying Orbital Express, SUMO, and FREND concepts to satellite servicing.[15] DARPA and NASA tested ASTRO with NextSat in the Orbital Express flight test, as shown in Figure 25. Recently GSFC tested robotic refueling on ISS, to prepare for a GEO robotic servicing vehicle, with a 100- kg servicing module.

The current focus for satellite servicing is mostly on GEO, because operating GEO satellites are actively kept in the same equatorial orbit plane. Once you get a service vehicle to GEO, it takes little delta-V to visit a series of GEO satellites. Comm links do have a small delay, but "comm passes" last forever, and lighting angles change far more slowly than in LEO.

In contrast, maneuver delta-Vs from one LEO satellite to another are radically larger, except for a few LEO satellites that are actively kept in one orbit plane, like NASA's "A-train" constellation. So large-scale satellite servicing in LEO will require a high-delta-V maneuver capability to deliver the service vehicle from one client satellite to the next.

EDDE can provide the required series of large maneuvers. Once a service vehicle finishes servicing a satellite, it can drift away from it. Once it is far enough away, EDDE can approach and capture it, deliver it to its next target, and release it so it slowly drifts towards its new target. Having a rotating EDDE reliably capture a service vehicle is a novelty and a challenge.

Figure 25. Orbital Express and NextSat Docking

7.1 EDDE Capture of Cooperative Objects

Multi-use satellite servicing vehicles can easily be very cooperative. They need good attitude control to provide servicing, and they can have suitable capture features and targeting aids such as strobe lights and retroreflectors. Centrifugal acceleration of EDDE's ends means that a rigidizable capture interface is not needed: some kind of releasable "hook and loop" interface should be adequate.

EDDE can probably do imaging inspection passes using only electrodynamic forces, but capture by an EDDE end-effector needs far closer approaches with reliably high accuracy. The endmass making the approach can actively maneuver during each approach. We can iteratively estimate errors in approach range by short-range RF or laser ranging to the target, and we can null out predicted errors in apex range by reeling the capture hardware in or out.

We can precisely estimate errors normal to EDDE's long axis using trends in target position errors relative to the stars. Steam resistojet thrust of ~0.01 newton should be enough to control those errors. We estimate water use of ~1 gram for each active maneuver pass.

Capture will begin with gradually closer inspection passes. Actual capture attempts can be scheduled for times that allow a low-latency video downlink plus command uplink. Ground operations can either directly control maneuvers, or might be limited to commanding an abort if a current automated approach may be unsafe.

7.2 "Two-Dog Captures" of Passive Objects

A satellite may sometimes be found to need more service than the service vehicle can provide. EDDE can help here as well. The service vehicle can attach itself to a suitable strongpoint on the satellite, and then orient itself and the satellite for capture by EDDE. Once it is captured, EDDE can deliver the service vehicle and its payload to the ISS or some future commercial facility. Such a capture might be tested first with a spent stage rather than an actual satellite. An example is shown in Figure 26 on the next page.

This scenario decouples capture of the passive target from capture by EDDE. EDDE can release the service vehicle and satellite near the repair facility. After repair, the delivery process can be reversed to return the repaired satellite to its operational orbit. Depending on the relative size of EDDE and the satellite, the round-trip plus repair (which may involve launch of new hardware) may take far less time than building and launching a new satellite to replace a failed but repairable one.

Two-dog capture does require that a target be tumbling slowly enough to allow the first capture by the untethered sheepdog. Most space objects have enough aluminum alloys in them that rotation in the Earth’s magnetic field generates eddy currents in the body. That slowly damps rotation, on a timescale of months to years in LEO.

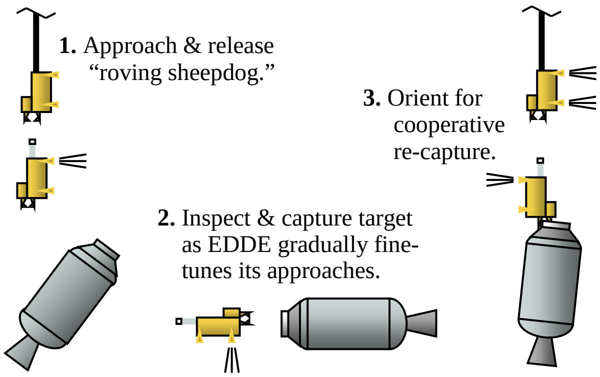

Figure 26. “Two-Dog Capture” (no net needed)

Besides two-dog captures, EDDE can also do captures using slowly spinning nets that hang outward from the endmass. This seems most likely to be useful in capturing orbital debris, so it is discussed in section 8.

8. Orbital Debris Clearing or Collection

Most current concern about orbital debris focuses on a continuing increase in the number of tracked >10 cm objects. But that problem is mostly just an annoyance. A far less visible problem is likely to be far more expensive.

8.1 The Expensive Orbital Debris Problem

Untracked cm-class debris or “shrapnel” is far less visible than tracked fragments, but far more numerous. And since it is not tracked, it cannot be avoided. It can disable even large satellites without creating clear observables. Lethal shrapnel may outnumber tracked fragments ~100-fold, and has probably already disabled many LEO satellites.

Most industry practices are improving, so propellant and battery explosions should become less frequent. Most future shrapnel seems likely to come not from such causes, but rather from infrequent accidental collisions of two intact ton-class satellites or rocket bodies. (The chance of such collisions is now ~7%/year.) Already an intentional 2007 A-sat test plus the accidental 2009 Cosmos/Iridium collision have created 44% of the 8800 cataloged fragments now in LEO, and probably a larger fraction of the untracked cm-class shrapnel. High-power pulsed laser ablation may be able to nudge tracked debris to prevent predicted debris collisions,[16,17] but the practicality and cost are unknown, and laser nudging would have to be continued until the most congested altitudes are cleared out.

Figure 27 is our estimate of the mean creation of >1 gram shrapnel from accidental collisions of >1 kg objects in LEO. It is based on the objects in LEO on April 27, 2016, and a refined version of the analysis in ref. 18. Shrapnel creation scales roughly with the square of the mass at congested altitudes. That inventory has increased 9% in the last 5 years and the expected shrapnel creation rate has increased by >20%. The problem will continue to get worse until we start removing material from congested altitudes, or use lasers or other means to prevent debris collisions.

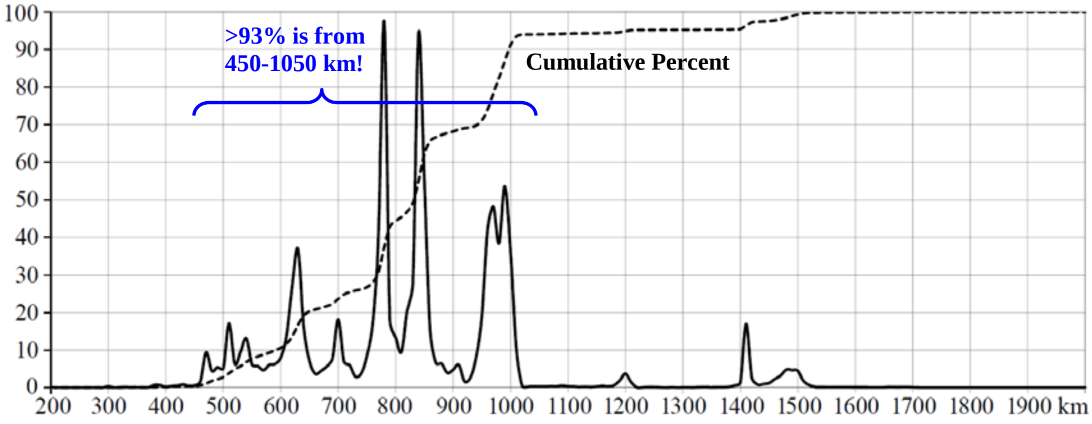

Figure 27. Expected Mean Creation of >1 gram Shrapnel by Collision of ≥1 kg Objects, #/year/km

The cumulative percent curve in Figure 27 shows that the 450-1050 km altitude range should be responsible for >93% of the future LEO shrapnel created by unintentional collisions of >1 kg objects, based on the current mass in LEO. Figure 28 shows how mass and its ownership are distributed over that altitude range in April 2016:

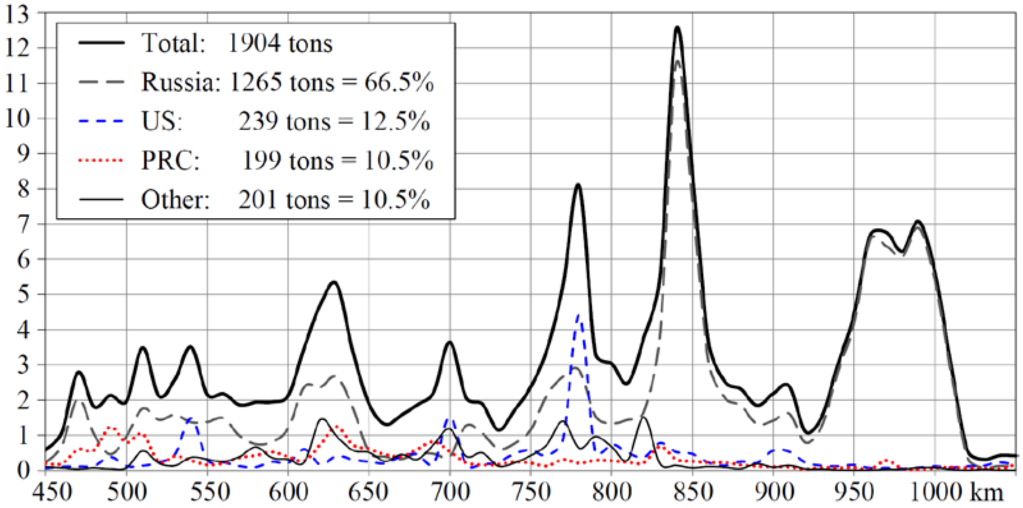

Figure 28. Ownership of Mass at Congested Altitudes in LEO, Tons/Km Altitude

The Russian mass is not only highly dominant, but also tightly clustered at altitudes with long orbit life. Russian rocket bodies are 36% of the total mass at 450-1050 km (vs. 34% for ***all*** non-Russian mass). Removing just Russian rocket bodies will do more to reduce future shrapnel-creating collisions than removing all non-Russian mass.

Excluding ISS, ~55% of the total mass in LEO is in objects weighing 1-3 tons, with the rest split nearly evenly between objects >3 tons or <1 ton. It will take long and heavy EDDE vehicles to efficiently remove or relocate the ton-class debris objects from the long-lived 750-1050 km orbit altitudes where ~2/3 of the shrapnel will be created. Such EDDEs might be up to 10 km long, with much wider tapes than in Figure 5 above, both for impact tolerance and also for better electron collection in the tenuous plasmas at 750-1050 km altitude. Such EDDEs might launch on ESPA as shown in Figure 12. But rather than carrying CubeSats outboard, a second set of EDDE components can mount there and attach to the inboard EDDE. EDDE's orbit-change agility allows launch on any LEO mission: the altitude, orbit inclination, and ascending node are not important. Any EELV-class mission with 800-1400 kg payload margin could carry an ESPA ring with 3-6 such EDDE vehicles.

Figure 29. Thrown-Net Capture of Dead Satellite

8.2 Debris Capture by a Spinning EDDE

An artist's concept of EDDE capturing a debris object in a net is shown in Figure 29. This is from the DVD of the movie "Gravity," from Warner Brothers in 2013.[19]

A 2002 orbital debris study for NIAC considered a range of capture concepts for large orbital debris.[20] We considered thrown nets first, but they seemed likely to be less reliable and more likely to cause fouling on the EDDE endmass, compared to capture in a slowly spinning net hanging outward from an EDDE endmass.

To capture large debris, each EDDE end body can have a net manager that holds ~100 house-sized square expendable Spectra nets weighing ~50 g each. To catch an object, the net manager pays out one of the nets and its support lines, using the 0.26 m/s^2 centrifugal acceleration available at each end of EDDE.

Figure 30. Net Spin-up & Debris Path to Capture

Video frames from a spin-up test of an early net design are shown in Figure 30. The planned free-fall trajectory of a target relative to the spinning net is shown in yellow. This concept allows relatively late aborts, either by retracting the net support lines before the payload reaches the net, or by letting the target continue its path without pulling the net up around the target. Peak capture snatch loads can be kept below ~50 newtons if the net manager pays out line to cushion the capture. Typical intact debris objects far outweigh EDDE, so snatch loads will be constrained by EDDE's finite mass rather than the much larger payload mass.

Target tumbling about either axis normal to EDDE's tape provides spin kinetic energy that a target can use to try to climb out of a net. This limits allowable tumble rates to <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 photometry can estimate tumble rates before target selection is finalized. Before EDDE attempts capture, it can use its inspection passes to verify the target spin rate and axis and check for any unexpected appendages.

Most debris is in near-polar orbits. EDDE can make repeated close passes by such objects while in contact with commercial arctic ground stations having low-latency internet links. This allows real-time video downlink and real-time man-in-the-loop control from any EDDE control facility that also has a low-latency internet link.

8.3 Debris *Collection* by EDDE

Besides dragging large objects down to short-lived orbits below ISS, there is another way EDDE can reduce collision rates. EDDE can move some objects now at congested altitudes to "tethered scrapyards" at less congested altitudes, which Figures 27 and 28 show are at 660, 730, 925, and 1020-1180 km. This is feasible because most LEO mass is in narrow inclination bands, as shown in Figure 31. The 60-100^{o} range shown includes >95% of the mass at 500-1000 km altitude.

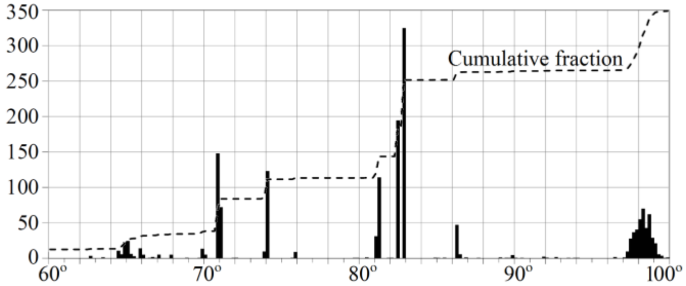

Figure 31. Tons at 500-1000 km in 2011, per 0.2^{o} Inclination Bin

One can start by using EDDE to clear most tracked objects from the planned scrapyard altitudes, particularly the lighter objects that are likely to burn up during reentry. Tethered scrapyards can be stabilized vertically, each at a different altitude. They can be occasionally maneuvered to avoid remaining objects passing through their altitude.

Collection requires matching all orbit elements, including ascending node. This can require large plane changes. But if a scrapyard is at the same inclination but a different altitude than the debris that is brought to it, nodal regression rates will differ, so one can wait for nodal coincidence with each object before capturing it and bringing it to the scrapyard. Required small adjustments of inclination, node, and other orbit elements can be done efficiently while EDDE descends. Handoff from EDDE to a scrapyard can use an error-tolerant "crossed-tether" technique. EDDE throughput should be high since the altitude change is much less than if EDDE had to drag debris down below ISS.

For the most crowded inclinations, several scrapyards at different nodes can be used to speed collection. It may still take decades to collect most of the massive debris. But shrapnel creation scales with the square of potentially colliding mass, so shrapnel creation can be cut in half by the time 30% of the mass is collected.

Once much of the debris mass at a given inclination has been collected, at least two options are 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 low altitude, as was done to deorbit Mir. Such deorbit stages would not be needed for decades.

A second option is to separate "usable mass" and use EDDE to deliver it to customers in LEO. Figure 32 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 2 most massive debris clusters are all Russian: 204 tons of 1.4 ton Kosmos-3M stages at 83^{o} and 900-1000 km, and 150 tons of 8-ton Zenit stages at 71^{o} and 815-860 km. Each scrapyard need only catch and process one type of rocket. That should simplify their design.

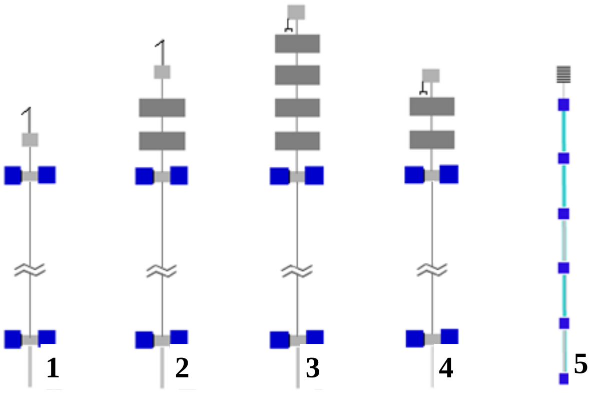

Figure 32. Collection, Processing, & Delivery by EDDE

8.4 Can Orbital Debris Be Profitably Recycled?

The key question about collecting and recycling debris is whether it can pay for itself. Several startup companies want to find, mine, refine, sell, and deliver asteroid materials, but nobody seems interested in ~2000 tons of debris already available in low earth orbit, and consisting of well-characterized aerospace materials. Even if the only customer is Bigelow and the only salable product is shingles to shield against impact and radiation, an ability to collect massive debris objects at scrapyards and deliver 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. Scrapyard reentry liability might remain with the country that launched the mass collected there, since assembling that mass seems to enhance rather than damage debris value. Or the US might acquire ownership and full liability for some debris collections with Russia retaining ownership and full liability for the rest. In particular, consider the 18 Zenit stages in 71° orbit, mostly near 850 km altitude. Their total mass is 150 tons. A collision involving them with each other or other objects has <0.1% chance per year, but it could more than triple the count and cost of untracked but lethal shrapnel throughout LEO. Collecting those stages is clearly very useful. Learning how to convert shingles into 3D printing feedstock could stimulate the market for shingles. About half the non-ISS mass in LEO is spent stages, and they may be easier to recycle than satellites.

In the long run, sustainable expansion of human activities beyond Earth may be enabled far more by thorough recycling than by asteroid and comet mining. What is mined, refined, and delivered to customers once is likely to be recycled many times. Thorough recycling seems like the main key to sustainability, both on and off planet Earth.

8.5 Diplomatic Challenges Relating to Debris

The US has more invested in LEO than any other country, so it made sense for it to take a lead on debris issues. But if most future LEO shrapnel will come from Russian objects, then LEO debris is largely a US/Russia bilateral issue. Under the 1967 UN Outer Space Treaty,[21] the location and condition of space objects do not affect ownership, and under the 1972 UN Convention for Liability of Space Objects,[22] launching states have unlimited strict liability for damage caused by reentry of their space objects, and liability for damage caused in space if they are at fault (which is not defined!). The liability convention also says that if state A's object damages state B's object, A can acquire a share in the liability for any later damage caused by B's object. The convention lets a state suffering a loss sue any of the involved states for the full loss. But it also lets states agree on indemnification for different liability cases like launch failures or satellite reentry. No new UN treaties may be needed to allow handling of another state's debris, just the owner's permission plus a liability indemnification agreement with the launching states.

The actual risk of damage from reentry seems low, based on uncontrolled reentries to date, but it may complicate debris negotiations. Congress may not let the US accept any liability for foreign debris, and may not even allow direct or indirect US payment for its removal. But US debris removal or collection should start with US debris anyway, even if the benefit per object is less. By the time much of the US debris has been removed or collected, there will be a far better grasp of value, cost, liability, and other issues. This can guide debris negotiations.

8.6 What Agency Should Lead US Debris Removal Efforts?

Under current US National Space Policy,[23] NASA and DOD are tasked to:

> Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment;

This does not task either DOD or NASA to remove debris, but to do R&D, which can inform future policy choices. Neither agency seems interested in removing debris, perhaps because it may not come with enough funding, and will be a distraction from existing roles. Also, a DOD lead will raise foreign concerns about new A-sat concepts, and US worries about stimulating efforts by potential adversaries. NASA will see a need for "9s" of reliability. It is possible that no USG agency should get the lead role. Bounty payments to appropriately regulated commercial entities may be the best option, and one that can also encourage other countries to participate. The USG lead would have to be a regulatory agency like the FAA, not DOD or NASA. Debris bounties are discussed in more detail on page 10 of ref. 15.

The US and many other countries now allow "25 years free parking" in LEO after a mission ends. But in crowded cities, parking fees start when you arrive, and vary with congestion and vehicle size. In return for providing general funds to clean up LEO, Congress could require US users of LEO to pay parking fees that pay for enough bounties to compensate for net new debris costs LEO users add. Coordinated foreign bounty programs and parking fees could soon follow, especially if they are needed to get new foreign launch business. A key early step here will be to quantify the economic impact of debris and the best options for dealing with it, to set suitable bounty and parking fee levels.

9. Flight Test Plans

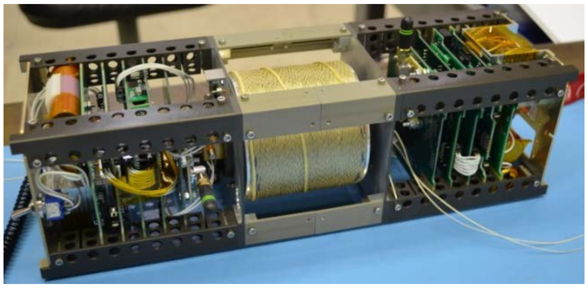
Figure 33. NRL's TEPCE CubeSat with 1 km tether

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 33. It uses a stacer spring to energetically push the outer cubes apart at 4 m/s. This drives deployment of a 1 km long tether stowed around the stacer. The tether is a 9-strand flat braid, ~0.25x1.6 mm in cross-section, with 0.4 g/m mass. It uses 6 strands of Kevlar plus 3 strands of "Aracon" conductive metal-coated Kevlar. Its electrical resistance is 1.6 ohms/meter at room temperature.

TEPCE can switch its high-voltage electronics to collect electrons on either the bare Aracon, or on one or both 0.025 x 5 m EDDE-like bare metal tapes that deploy outboard of the endmasses (they are stowed at bottom left and top right in Figure 33). TEPCE uses EDDE-like hot wire emitters at each endmass to emit electrons. The power supplies and recessed emitters limit the emitted current to ~8 mA at each end, and the body-mounted solar cells limit the orbit change rate to ~1 km/day. Each end mass also has magnetorquers, GPS, a camera, and plasma sensors.

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 plans to drive and damp libration, climb and descend, uplink and test revised code, and test active avoidance. The USAF Space Test Program is funding TEPCE's launch.

EDDE's proposed packaging, born-spinning deployment, and operating concepts are unusual enough that the next relevant flight test beyond TEPCE is really to test the full hardware, packaging, deployment, and operating concepts. Any test short of that requires temporary solutions that introduce unrepresentative failure modes. A 12U CubeSat is the smallest size that we think operationally useful for EDDE, because smaller sizes require a tape that is too narrow (with high risk of cut) or so short that the "parasitic" power needed for electron collection and emission will exceed the productive power that drives electrons along the tape. So we envision a 12U EDDE flight test as the next flight test beyond TEPCE. (But there will be substantial added ground development and testing preceding that flight test.)

A 12U test might deploy from ISS using a NanoRacks CubeSat deployer. If that deployer is >3U long, it can also hold some CubeSats for EDDE to distribute. EDDE will drift back, down, and then forward. We will then check out EDDE, deploy one solar array for power, and when we get far enough from ISS, do a small plane change and climb with resistojet thrust. Once EDDE gets ~100 km above ISS, EDDE can release its daisy-chained components, unfold its other solar arrays, spin up more to unwind the tapes, and verify control and performance. Then EDDE can distribute its payloads to several orbits, while actively avoiding all tracked objects in LEO. EDDE can then approach and inspect selected US debris. This may let us learn more about how crater and hole counts vary with size, altitude, and age.

10. Conclusions and Recommendations

EDDE's sustained maneuver capability in LEO is an unexpected and precious gift. EDDE enables a sequence of 4 novel and increasingly challenging missions that are now either impossible or unaffordable with any other form of propulsion. The first mission is distributing multiple secondary payloads to orbits far from a primary's orbit, providing "custom orbit delivery without dedicated launch." Inspections are likely to follow, both by EDDE itself and by picosat inspectors that EDDE makes feasible. Support of LEO satellite servicing should follow. EDDE can even capture failed satellites in sun-synch orbit, move them to ISS orbit for repair, and return them to sun-synch. Finally, EDDE can also remove or collect most debris mass now in LEO, and enable useful recycling of much of that debris mass.

TEPCE should answer open questions about electron collection and emitter performance and lifetime in LEO. A good 12U EDDE flight test can validate EDDE's novel deployment concepts, verify payload delivery performance and lifetime, and test EDDE's capabilities to support inspection, satellite servicing, and orbit clearing throughout LEO.

We have recently matured and tested many EDDE components and operating concepts. More work is needed on packaging and deployment, and on tension-stabilized bifacial solar arrays, the steam resistojet, and net capture of debris. The bifacial solar arrays and resistojet both have uses independent of EDDE that may justify direct funding. There is a growing need for EDDE's unique capabilities. To provide them, we must finish EDDE development and test EDDE in orbit. For more information about EDDE, please contact the authors at the email addresses on page 1.

Acknowledgments

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