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DELIVERY OF SECONDARY PAYLOADS TO CUSTOM ORBITS USING EDDE

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"EDDE" (the ElectroDynamic Delivery Express) is a persistently maneuverable propellantless "taxi" vehicle for low earth orbit (LEO). EDDE has at least 2 major applications: delivery of secondary payloads to custom orbits throughout LEO, and removal of large orbital debris. This paper focuses on payload delivery. A companion paper in session A6.6 focuses on debris removal. 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. The maneuver force comes from current in the tape crossing geomagnetic field lines. Efficient operation requires large electron collection areas and multi-kilometer tape lengths. Air drag sets a minimum altitude near ISS altitude. There is no hard ceiling, but efficient thrust at higher altitude requires longer and heavier EDDEs. EDDE is modular and may typically range from 20 to 80 kg for different missions. Distribution of secondary payloads by EDDE may often start in an orbit near the ISS (51.6^o inclination, 350-420 km altitude) and end with release of payloads at any desired altitudes, nodes, and inclinations, including 97-99^o sun-synch orbits. Large inclination and node changes may best be done 100 km above ISS. Once near the desired orbit plane, EDDE can quickly climb to desired payload release altitudes, up to about 1000 km. Secondary payload delivery times will typically be months. By comparison, waiting for a suitable launch directly to a specific desired orbit may take far longer. The most attractive thing about EDDE to smallsat owners may be "custom orbits without dedicated launch." A payoff to launch service providers is making surplus payload capacity on LEO launches usable to a much wider range of secondary payload customers. We recently matured EDDE design, components, and operating concepts under a 2-year contract with the NASA Space Technology Mission Directorate at Langley Research Center. This paper describes our work maturing components and design, typical nanosat delivery operations, and plans for 3U precursors and a 12U full test.

I. 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 tape sees a force normal to both the current and the local magnetic field. EDDE is limited to LEO by its use of the earth's magnetic field and ionosphere. But it can maneuver indefinitely in LEO. This allows a range of missions that have not previously been feasible. The acronym "EDDE" came from the two major missions we envision for it. It stands for both "ElectroDynamic Debris Eliminator" and also "ElectroDynamic Delivery Express."

We did early work on EDDE under DoD SBIR and follow-on funding. Our most recent work was funded by the Game Changing Development Program under the Space Technology Mission Directorate at NASA Langley Research Center.

A companion paper addresses debris removal[1]. The main focus of this paper is delivery of one or more secondary payloads to custom orbits throughout LEO. Early EDDE applications can stow EDDE plus its payloads together as secondary payload assemblies. This paper focuses mostly on this case, but also mentions later scenarios that can use EDDE vehicles already in orbit to capture and move objects, for repair or to distribute them as needed.

This paper is organized as follows. Section II is an overview of the EDDE vehicle concept and its key features and advantages over other electrodynamic vehicle concepts. Section III reports on our recent NASA-funded technology maturation work on EDDE components. (Two of those components may be of independent utility to nanosat developers: lightweight low-cost solar arrays, and a 10-100 W steam resistojet.) Section IV covers our recent work on EDDE operations. Section V gives examples of EDDE distributing small secondary payloads throughout LEO. Section VI is on flight test plans, and VII presents our conclusions.

II. THE EDDE SPACE VEHICLE

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 the geomagnetic field lines. The current loop closes in the plasma, as shown in Figure 1:

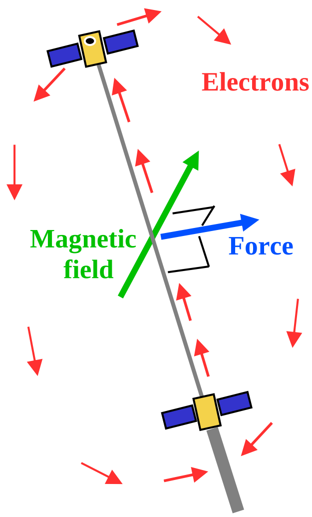

Figure 1. ElectroDynamic Propulsion Concept

This propulsion concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test[2]. 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 achieved 1 A through a 20 km wire. (That is typically 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 assignment. If EDDE can capture payloads, it can handle one task after another and can become a "zero-fuel taxi" for use throughout LEO. One possible use is capture and removal of most of 2500 ton-class orbital debris objects now in LEO.

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 transverse thrust forces and oscillations, and allows a wider range of angles with the geomagnetic field and hence thrust directions. Adequate tension and control require rotation 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 the current collection and emission along the tape length. EDDE is covered by 3 US utility patents, two for the method and apparatus for active control, plus one for the performance benefits of spinning operation in LEO[3, 4, 5].

Figure 1 is a schematic view. Figure 2 shows a more accurate view of EDDE, with the solar arrays distributed along the length of the conductive tape. The arrays and their controls divide the tape into separately controllable and isolatable segments. This lets us limit 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 tape length.

EDDE's design plus its rotation set EDDE apart from previous LEO electrodynamic thruster concepts. 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. Too much thrust causes a hanging tether to librate excessively and eventually causes loss of control. By contrast, because it is stabilized by rotation, EDDE can handle currents and thrust 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.

Figure 3 on the next page shows the directions (all normal to the local magnetic field) that EDDE is able to thrust during each ¼ orbit, and what orbit elements each thrust direction can change. EDDE's rotation is most useful near polar orbit, particularly for altitude changes. The EMF on hanging tethers is low, scaling roughly with Cos(Inclination). As a result, the thrust is nearly normal to the orbit. This gives very slow altitude changes. EDDE can spin normal to the orbit plane. This greatly increases both peak and average EMF, and achievable climb and descent rates in near-polar orbits.

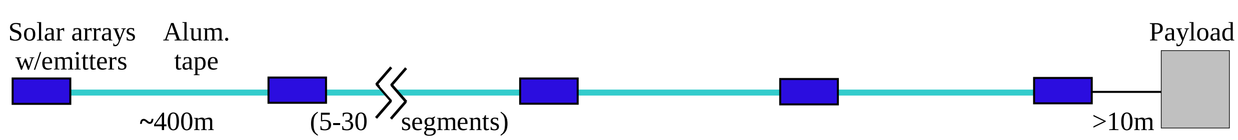

Figure 2: EDDE Layout, with Distributed Control, Power, and Electron Collection and Emission

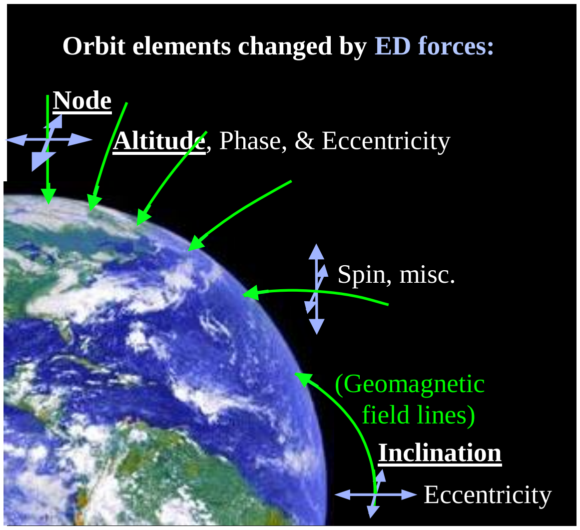

Figure 3: Possible ED Thrust Vectors vs. Latitude

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 to weigh from 20 to 80 kg and have one to several kilowatts of power.

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 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.

These rates are for EDDE maneuvering just its own mass. When EDDE carries payloads or debris, the orbit change rate scales down with the ratio of EDDE mass 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 be up to EDDE's own mass per day, or 30 tons/year.

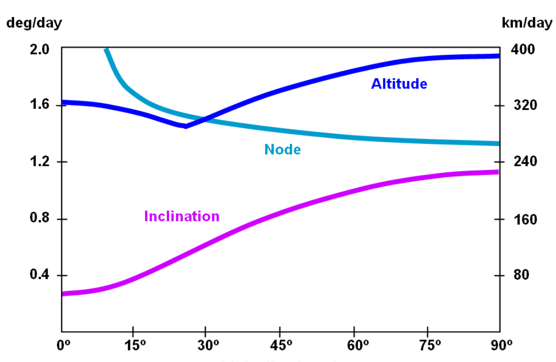

Figure 4 EDDE Orbit Transfer Performance per Ampere Average Current, for an 80 kg EDDE

At low inclinations, and when changing orbit plane at higher inclinations, EDDE will usually rotate in the plane of the orbit, but at higher inclinations it will rotate normal to the orbit plane to maximize altitude rate. The transition between them causes the kink in the altitude performance curve in Figure 4.

III. MATURATION OF EDDE COMPONENTS

We recently matured EDDE's overall design, key components, and operating concepts under a two-year contract with the NASA Space Technology Mission Directorate at Langley Research Center that ended in May 2014. This section of the paper discusses the component maturation work done under that contract. 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 that is not only very useful to EDDE but may also be of independent interest to nanosat designers.

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.

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 the tension for deployment. Array deployment is shown below in Figure 5:

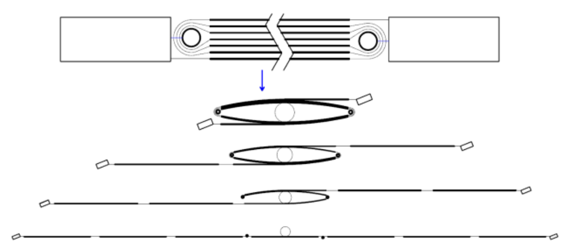

Figure 5. Deployment of Laminated-film Solar Array

It also appears that we will get more usable power from the same total power system 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.

We were led to this array design by the following issues. First, EDDE poses rather unusual challenges on solar array control, because of its rotation, its axial tension, and the lack of any rigid massive primary structure to torque against to steer solar arrays. We considered two-axis solar array tracking, but this seems to require rigid solar panels, given EDDE's rotation and tension. We could not find a rigid panel design concept whose added mass paid for itself compared to an in-line array with one-axis tracking.

But even one-axis tracking is a challenge with EDDE, because all we have to torque against to steer the arrays is a rotating tensioned tape with bending dynamics. We investigated adjustable bridles that could shift the array CG. This would let us torque the array by using EDDE's transverse bending dynamics. We also analyzed magnetorquing using coils built into the arrays, and even reaction wheels that we could use as CMGs due to EDDE's rotation. Each approach added mass, parasitic power use, cost, and/or technical risk.

These problems led us to also consider unsteered in-line arrays. We quickly realized that we needed arrays that generated power from sunlight on either the front or back. We learned that there is a modest niche market for high-efficiency terrestrial bifacial silicon solar cells. The number of suppliers may grow, since a key patent by Sanyo (now Panasonic) recently expired. 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 estimated masses and power penalties for steering. The results are shown in Figure 6:

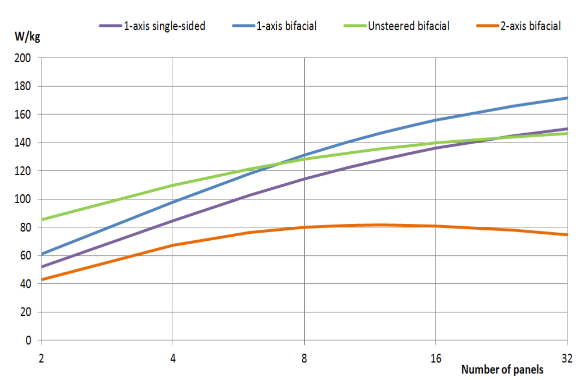

Figure 6. Comparison of Average W/kg for Candidate Solar Arrays and Steering Options

This analysis suggested that mechanisms that allow 1-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. But if each array can have a random angle around EDDE's long axis, the power and current available at each array will be highly variable. This in turn led us to have each array actually consist of two sub-arrays. As Figure 7 shows, those two sub-arrays are rigged together by a 4-line bridle that keeps them at right angles to each other when under tension.

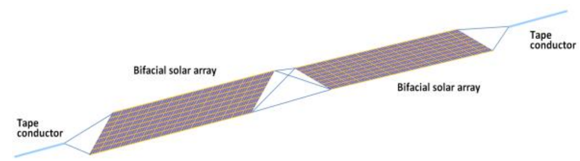

Figure 7. Sub-Arrays Rigged to Stay at Right Angles

Each sub-array has two identical strings that can be put in series or parallel; then the currents from both sub-arrays are added in parallel (since the currents will generally differ far more than the voltages). Switching losses can be kept small enough that rigid aluminum cross-pieces at each end of the middle bridle can dissipate them.

Such unsteered pairs of bifacial terrestrial cells appear to compare favorably with steered terrestrial or triple-junction ("3J") cells in both mass and cost. They also eliminate the novel technical risks of steering the arrays around EDDE's long axis, but do let us test different steering concepts on some of the arrays.

On a cell weight basis, bifacial silicon cells have higher power/weight than even moderately thinner 3J cells having 70% higher efficiency, because 3J cells use a germanium substrate that is 2.4 times as dense as the silicon substrate of bifacial cells.

Silicon cells are also much less brittle than 3J cells. Simple lamination of the silicon cells between clear plastic films seems adequate, whereas 3J cells seem to need heavier (even if smaller) support. Hence bifacial silicon arrays may even be competitive based on array mass, even for spacecraft other than EDDE. They are also radically cheaper—just 1% the cost of 3J cells.

EDDE's complete arrays should provide average power levels of up to 200 W/kg for typical EDDE spin axes, which will usually be within 45^o of the sun direction. The cells are not very radiation resistant, but early EDDE missions will spend most of their time near 500 km, where moderate radiation levels will allow acceptable power system lifetimes.

Our compactly-stowable lightweight laminated solar array design may be particularly relevant to smallsats that are spin-stabilized facing the sun. This not only orients the arrays, but provides tension so no rigid array structure is needed. By the time EDDE needs solar arrays with higher radiation tolerance, for sustained use removing debris from high altitude near-polar orbits, rad-hard thin-film arrays that use similar laminated designs may be feasible, both for EDDE and for other spacecraft.

Electron Emitters

It is easy to collect electrons in a plasma: bias bare metal positive, and electrons flow to it. Unfortunately, biasing it negative attracts far fewer ambient ions: their higher mass reduces their velocity. And biasing a metal surface negative also does not make electrons flow away, because of a few-volt "work function" needed to move electrons from metal into vacuum. This energy must be supplied over ~1 nanometer, so high fields are required.

One can also 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 effect requires high electron emission bias voltages in most other emitter concepts.

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.

Thermionic emitters require substantial power for heating, and added power to bias the emitter negative enough to drive currents through the negative 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 types of electron emitters, they are very sensitive to both surface contamination and erosion from atomic oxygen (AO).

As shown in 1923 by Langmuir[6], thoriated tungsten can form a polarized surface mono-layer of thorium atoms on tungsten. This greatly reduces the work function and hence the temperature and power needed for thermionic electron emission. But this enhancement is poisoned by even tiny amounts of oxygen-containing gases, whose oxygen reverses this polarization. Adding carbon to the wire re-enables the 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 8 shows an emission test in a chamber with enough residual oxygen that enhanced emission occurs only with carburization.

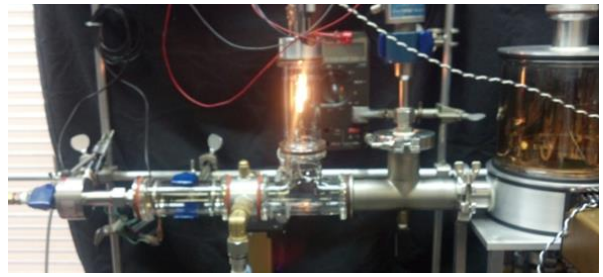

Figure 8. Vacuum Testing of Thermionic Emitters

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 emission bias voltages. With a fixed wire and anode geometry as in vacuum tubes, current that is limited by space charge rather than thermionic constraints scales with the 1.5 power of the bias voltage. But in a plasma, the space-charge radius out to an "effective plasma anode" is not fixed. That radius is the distance at which the streaming electron density falls to the ambient ion density. In a tenuous plasma like earth's ionosphere, the effective anode radius changes with the current emitted so the emitted current should nearly scale with emission bias voltage.

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 ~20 mA. 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.

EDDE's emitters need good exposure to ambient plasma, but each wire also needs 1 W of low-voltage heating power. As shown in Figure 9 on the next page, EDDE uses nearby solar cells to directly heat emitter wires that fold out from each side of the array. 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. Since solar array output varies, each wire's heating current can be switched on and off. This lets us use the available power to heat the maximum number of nearby wires that have the best spacing and the best exposure to the plasma.

Based on this 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.

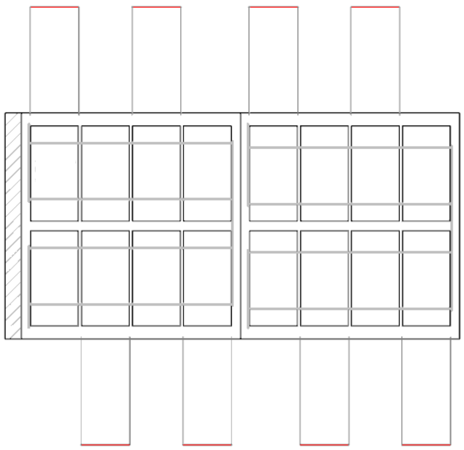

Figure 9. Emitters Heated by Low-voltage Cell Strings

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 tenuous 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 started, first between the tether and the shuttle, and then from the tether to space. It severed the tether and ended the experiment[7]. The arc was triggered by a flaw in the tether insulation passing close to grounded metal. Once the arc started, the EMF plus 8 m^2 of bare metal electron collection area on the satellite were able to sustain a 1A unipolar arc to the ambient plasma. It severed the tether within 10 seconds and kept going at the free wire end for about a minute after that.

Even if TSS had not had an insulation flaw, any hypervelocity impact by micrometeroids or debris on the deployed tether could have created such a flaw, plus a transient cloud of partly-ionized volatiles capable of triggering an arc to the plasma, especially with an EMF of 3500 V over the tether length. Sustained vacuum arcs apparently create and ionize enough volatiles to keep high currents flowing even at modest voltages, much as in a hollow cathode. Such currents could actually be useful, except that the material ablation rates appear to exceed xenon mass flows in hollow cathodes.

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. Solar array plasma arcing tests done at NASA Glenn suggest that sustained arcing to a plasma requires currents of order 1 A; much smaller arcs quench themselves before they do significant damage[8].

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 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 DSSP thruster designs[9]. 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[10]. They do not have enough electron collection area to allow unipolar arcing to the plasma, but their data may still be useful to EDDE.

EDDE Tape Design

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 about 1/3 the wire diameter. To overcome this, some electrodynamic tethers use multiple strands with cross-members, like a ladder[11]. But small wires with many connections pose fabrication and deployment challenges, including keeping the thin strands apart.

EDDE’s tape design is simple but effective—an aluminum-foil ribbon 1-3 cm wide, with unidirectional fiber composite reinforcement for strength and to stop tear propagation. 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 untracked debris under 10 cm 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.

For "narrow enough" tapes, collection is expected to scale with tape width. But if the tape width greatly exceeds both the Debye length and the gyroradius of ambient thermal electrons, added width has far less benefit. The limits of the proportional regime have been estimated by Sanmartin[12]**,** but require orbital flight test to verify. Tapes as wide as 3 cm may be in this regime at typical debris altitudes of 750-1000 km, 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.

Early in our recent technology maturation contract we decided not to work on refining EDDE's tape design, since efforts in the other areas discussed above promised higher payoff. But late in the contract we faced the fact that the most frequent ride opportunities for a flight test were CubeSat-class. We wanted such an EDDE to use the same packaging and deployment scenario as longer operationally useful EDDEs. 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. Much larger decreases in width are feasible for brief low-risk missions such as nanosat distribution using 12U-size EDDEs. Such missions will take only months and will spend most of that time changing orbit plane near 500 km, where debris populations are fairly low.

A cross-section of stowed tapes of the old design (30 mm wide) and new design (20 mm wide) are below in Figure 10. Tape thickness is exaggerated 8-fold.

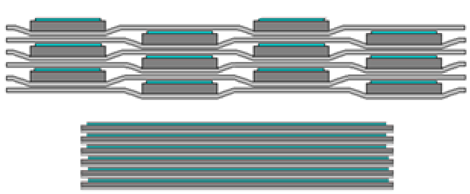

Figure 10. Stowed EDDE Tape Designs, Old and New

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 the "born spinning" deployment scenario described in the next section. The required impulse was only a few m/s ΔV, so we had assumed use of cold-gas thrusters.

But the growth of secondary payload deployment opportunities from the ISS plus interest in EDDE by ISS personnel have led us to consider deployment from ISS. After EDDE has been flight tested, we may have EDDE phase 1/2 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 a few days if we have problems during or after deployment.

ISS personnel also suggested that EDDE make a small plane change before full deployment, to reduce any chance of re-contact with ISS. A need for more maneuvering before full deployment increased our interest in higher thruster performance. We can easily deploy enough solar array area for a ~50-W resistojet before deploying the rest of EDDE, so we studied that. We became less interested as we learned about commercially available options: the ones with decent Isp were heavy, and light ones used flammable and/or high-pressure propellants that could raise safety concerns if EDDE has to pass through ISS.

That led us to focus attention on a steam resistojet that stores the water at low pressure and pumps it to >20 atmospheres pressure for use. This can eliminate toxicity, stored energy, and other safety concerns, and allows use of unusual tank shapes with very low mass penalty. A high pump pressure allows good nozzle efficiency even at power levels <100 W, 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 a wide range of available power levels. An early concept of the design is shown below in Figure 11:

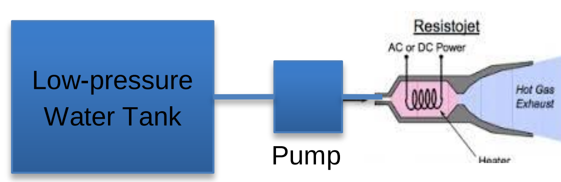

Figure 11. Concept for 10-100 W Steam Resistojet

Most of the development work remains to be done on this resistojet. We expect it to be useful to a wide range of small satellites, over at least a 10-100 W power range. We expect an Isp >150 seconds and a dry mass <100 g, including redundant pumps, plumbing, a small precious-metal hot section, and even an optional 2-axis gimbal. This does not include the unpressurized water tank. The tank mass including zero-gee water acquisition devices may be ~10% of the water capacity. We plan to publish additional details as we mature the design. We invite potential users to contact us and describe their needs, interests, and project schedules.

IV. MATURATION OF EDDE OPS CONCEPTS

This part of the paper describes our recent NASA-funded work on maturing EDDE operational concepts. It discusses our "born spinning" deployment scenario, controls, navigation, and active avoidance of collision with all tracked objects.

EDDE's "Born Spinning" Deployment Scenario

As indicated earlier, EDDE may need ~60 m/s of conventional propulsive ΔV before it deploys itself. We plan to provide that by resistojet. We will start EDDE deployment by deploying a 50 W solar array 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 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 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 in NRL's TEPCE CubeSat.

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 overlying it helping to keep the hook bent, so the hook becomes far weaker. This helps all of the components pull free in the proper order, without requiring that EDDE have active mechanisms for each component in a stack.

The key to controlling EDDE's deployment is to limit the relative size of each step increase in EDDE's moment of inertia as components deploy. At the same time, we must keep adding spin angular momentum, to keep tension high enough for that stage of deployment. We must also wait for dampers built into some EDDE components to help settle out the dynamics.

As shown in Figure 5 earlier for a solar array, each stowed solar 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. 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 forces, to minimize water usage.

We expect full "born-spinning" deployment to take only hours, even if EDDE has payloads at one or both ends. But on the first mission, we may take a day or more to do the full "born-spinning" deployment, so we have time to study diagnostic data collected earlier in the deployment sequence. The tapes have 80% of the drag area of the fully deployed EDDE, so we can do useful tests with only some of the tapes deployed, without risking prompt reentry due to very high drag.

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 much heavier batteries. Their added mass reduces EDDE's overall maneuver rates. In addition, 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 strategy seems to be "use it or lose it."

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.

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 plan and control EDDE rotation and oscillation. We do this by switching the solar array voltages that drive electron collection by each tape segment and emission by each emitter array.

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. 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 12 illustrates this with a reference trajectory and two 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.

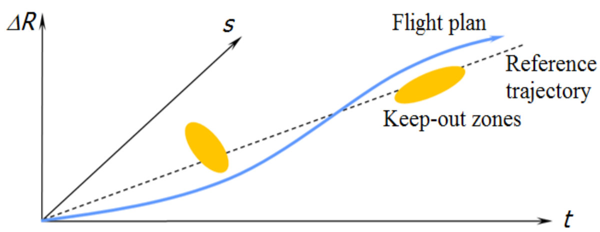

Figure 12. EDDE Maneuvering Around Conjunctions

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.

Even if EDDE is severed, each half can keep actively avoiding all operating satellites while it autonomously spirals down to a prompt reentry.

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, mostly near 500 km. Wholesale LEO debris removal will take years, mostly >600 km. We can afford to lose a few such EDDEs to cuts by small untracked debris.

Note that EDDE's tapes and solar arrays each weigh less than 1 kg/m^2. Impact by small debris may sever an EDDE tape, but should not create much new debris massive enough to be lethal to typical satellites.

As part of our recent work, the Naval Research Laboratory developed methods to track maneuvering multi-kilometer vehicles like EDDE. The main issue is that EDDE is a large fuzzy glinting radar target, whose center of brightness may be kilometers from its center of mass and can move very erratically. Inferring the actual EDDE 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 uplinks during rendezvous, inspection, and capture passes, on missions that involve those tasks.

Boeing suggested that we use existing commercial stations, mostly in the Arctic, for high-rate data for rendezvous, inspection, and capture. Globalstar seems more relevant for status downlinks, if it is approved to provide LEO-Globalstar-ground comm services. (It is now licensed only to provide ground-Globalstar-ground comm services.)

V. EDDE PAYLOAD DELIVERY CAPABILITIES

EDDE will reach fullest use as a "LEO taxi," doing one delivery after another throughout LEO. But that requires payload capture capabilities. Many useful early missions do not require capture. They include distributing payloads launched with EDDE, and close inspection of US-owned objects to assist in diagnosing failures.

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 the primary's orbit means that EDDE can make surplus capacity on any LEO launch more valuable, since that surplus capacity is no longer limited to use by secondary payloads that are satisfied with orbits near the primary payload's orbit.

Mounting EDDE with its Payloads for Launch

EDDE can deliver individual secondary payloads ranging from 12U to ESPA size, and EDDE can also distribute multiple secondary payloads to substantially different orbits.

In all our earlier work on EDDE, we sized EDDE for the EELV Secondary Payload Adapter (ESPA) ring, for launch on Atlas V or Delta IV. Figure 13 on the next page shows that layout:

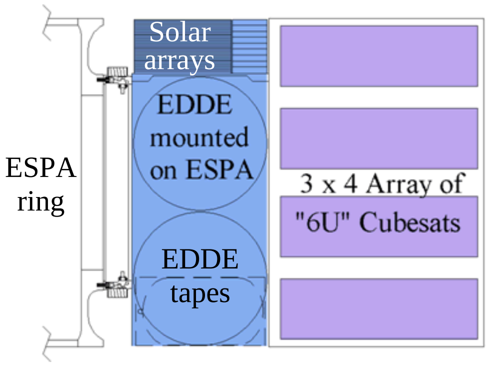

Figure 13. EDDE Sized for ESPA, with CubeSats

In this layout, EDDE uses the inboard 1/3 of the 38" deep payload envelope and about half the payload mass allowance, and can support either another EDDE or other payloads outboard. ESPA payloads are listed as limited to 400 lb with a CG 20" from the mounting plane[14], but EDDE's dense inboard packaging may allow a somewhat higher total payload mass since it reduces peak cantilever loads.

But ESPA launches have been infrequent and the costs per ESPA slot have been high. To allow use of CubeSat launch opportunities that are both cheaper and far more frequent, we scaled EDDE down to a smaller 12U-size. A full-scale model is shown in Figure 14.

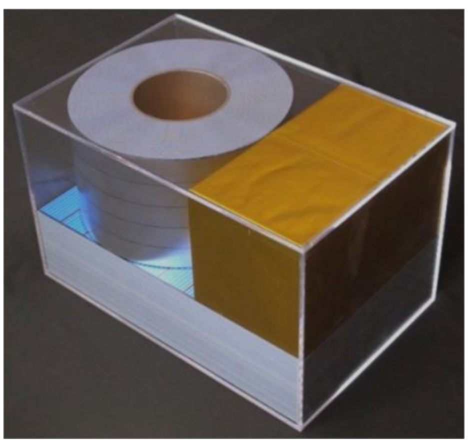

Figure 14. Full-scale Model of a 12U EDDE (9x9x14")

When EDDE is to deliver CubeSat-class payloads to orbits far from the host-launcher orbit, we can mount EDDE's payloads end-to-end with EDDE in a "stretch" of the 2x2x3U=12U carrier.

Nanoracks has developed and already used a 6U-long 1x1x6U carrier. We have checked with two suppliers of 12U (i.e., 2x2x3U) carriers and verified that they can also be stretched to 2x2x6U. This would let them carry 12U each of EDDE plus EDDE payloads. Both these carrier designs clamp the CubeSat payloads transversely as well as axially, so there is no need for EDDE to handle the launch loads of the CubeSats.

We do need a severable tie between EDDE and any payloads co-mounted with EDDE in one carrier, so EDDE hold onto them while delivering them to their final orbits. We plan to use Vectran tapes and hot-wire cutters like those used on the Naval Research Lab's TEPCE CubeSat, to restrain both EDDE's payloads and the stowed EDDE.

Figure 15 shows an alternative axial 12U layout, that also uses much longer and narrower tapes. The volume on the left is for EDDE's end masses. Both layouts are sized for 12U CubeSat carriers, but an axial layout allows easy adjustment to any desired stowed length, including "fractional U" lengths. Both options can stow together with CubeSats that EDDE can deliver.

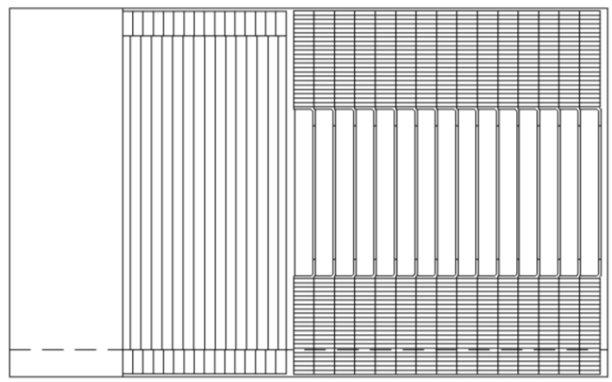

Figure 15. Layout for a 6 km long 12U EDDE (24 kg, 15 tapes, 16 solar arrays, 1.5 kW)

For removal of large debris, EDDE may be up to 10 km long, with much wider tapes than in Figure 15 above. Such EDDEs might launch on ESPA as shown in Figure 13, but with a second EDDE where the CubeSats are.

Two ESPA-sized EDDEs packaged with payloads as in Figure 13 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[15]. Figure 16 shows the satellite and orbit configurations.

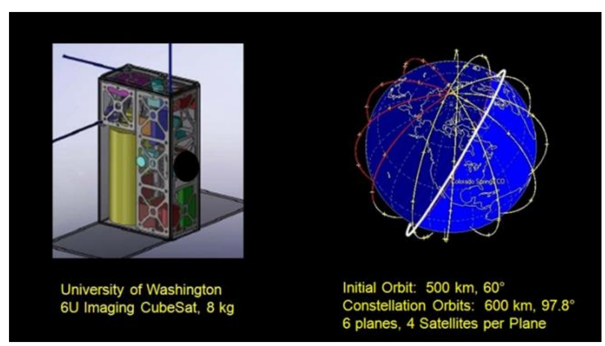

Figure 16. Constellation of 24 6U Imaging CubeSats

The EDDEs and their payloads could be launched together, then separate and head in opposite directions in node to populate the 6 planes. The full constellation might be complete in 94 days.

After completing payload deliveries, ESPA-size EDDEs might capture and remove ton-class debris, while 12U-size EDDEs do inspections and possibly capture and remove debris objects under ~100 kg.

Payload Distribution Times Using EDDE

A key question is how long it will take EDDE to deliver or distribute payloads to other orbits. Several cases of interest are shown in Table 1.

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

Table 1: EDDE Nanosat Distribution Timeline

For specificity, Table 1 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 having 3 times EDDE's mass. Other payload masses are feasible. 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 will usually impose far longer delays.

EDDE-Enabled Satellite Servicing Throughout LEO

To extend satellite lifetimes, there are concepts for service modules to refuel satellites or replace electronics modules. DARPA and NRL are applying Orbital Express, SUMO, and FREND concepts to satellite servicing[16]. DARPA and NASA tested ASTRO with NextSat in the Orbital Express flight test, as shown in Figure 17.

Recently GSFC tested robotic refueling on ISS, to prepare for a GEO robotic servicing vehicle, with a 100-kg servicing module. One can mount EDDE and that module together in an ESPA slot, on any LEO launch with enough margin. EDDE can then deliver it to any satellite anywhere in LEO that needs servicing.

Another option is to use a capture concept like that shown in Figure 18, which separates capture of a passive object from capture by EDDE. It lets EDDE safely capture failed satellites and deliver them to ISS. This lets the crew can do more complex repairs than can be done robotically.

Figure 17. Orbital Express and NextSat Docking

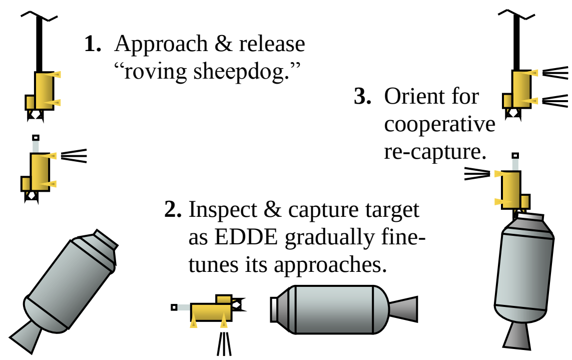

Figure 18. "Two Dog Capture" of Passive Objects

VI. FLIGHT TEST PLANS

The Naval Research Laboratory is readying an EDDE precursor test for deployment from the ISS in 2015: the Tethered Electrodynamic Propulsion CubeSat Experiment or "TEPCE." It is shown in Figure 19.

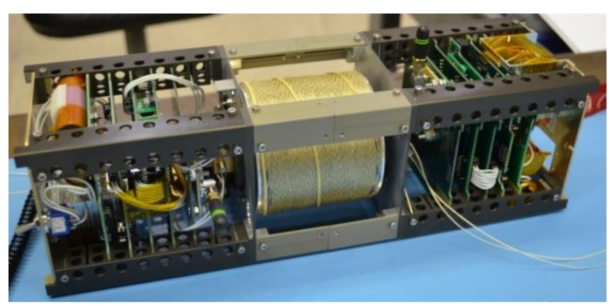

Figure 19. NRL's "TEPCE" CubeSat

TEPCE uses a stacer spring to energetically push the ends apart at 4 m/s. This drives deployment of a 1-km conductive Aracon/Kevlar flat-braid tether that stows around the stacer, shown in the middle of Figure 19. TEPCE can collect electrons on either the Aracon or 0.025 x 5m EDDE-like tapes that deploy from each endmass. It uses EDDE-like hot wire emitters at each end to emit electrons. TEPCE's body-mounted solar cells and hot-wire emitters limit its orbit change rate to ~1 km/day.

Each endmass has isolated high voltage supplies, magnetorquers, GPS, a camera, and plasma sensors. TEPCE has far too little power to counteract the drag of its 1 m^2 deployed tether area near ISS altitude, so it will reenter within a few days after tether deployment. But that is enough to test hardware operation and measure electron collection and emission voltages vs. current.

In 2016, TEPCE-2 is scheduled to deploy at 720 km altitude, where it will remain in orbit for years. This gives time to stimulate and damp libration, climb and descend, uplink and test revised code, and test active avoidance. Launch of both TEPCEs is provided by the Air Force Space Test Program.

The next step beyond TEPCE-2 is to test actual EDDE hardware and deployment concepts. 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 power needed for electron collection and emission will greatly exceed the productive power used to drive electrons along the tape.

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.

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 check out EDDE's controls, deploy one solar array for power, and when we get far enough from ISS, do a small plane change and climb using resistojet thrust. Once EDDE gets 100 km above ISS and phases far enough back from it, EDDE will release all of its daisy-chained components, unfold its solar arrays, spin up more to unwind the tapes, and verify control and performance. 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.

VII. CONCLUSIONS

EDDE enables many LEO missions that are either impossible or unaffordable with any other known form of propulsion. Examples include affordable removal or collection of most large orbital debris now in LEO, and distribution of secondary payloads to orbits far from the primary mission orbit. This is "custom orbit delivery without dedicated launch." Eventually EDDE will even be able to capture failed polar-orbit satellites, move them to ISS orbit for repair, and return them to polar orbit.

Overall, EDDE's sustained maneuver capability in LEO is an unexpected and precious gift. TEPCE and TEPCE-2 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 stowage and deployment concepts, determine its payload delivery performance and lifetime, and verify its utility for satellite servicing and debris removal throughout LEO.

We have done considerable technology maturation and testing over the last 2 years. More such work is still needed, particularly on the solar arrays and the steam resistojet. Fortunately, these are the 2 items most likely to have value independent of EDDE itself. The planned NRL TEPCE experiments will support the maturation effort and planned definition of a 12U EDDE flight test.

EDDE propellantless upper stages can deploy from the ISS with CubeSat payloads, and can provide safe propulsion for departure from ISS orbit. EDDE can use the NanoRacks deployer or the new NASA Cyclops satellite deployer, both of which use Japan's Kibo airlock on ISS. Eventually EDDE will even be able to capture and remove old CubeSats from higher orbits.

For more information, potential EDDE users are encouraged to contact the authors of this paper, using the contact information on page 1.

VIII. ACKNOWLEDGEMENTS

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