EDDE: a Multi-Km Modular Upper Stage for SmallSats

Joseph A. Carroll
Tether Applications, Inc., Chula Vista, CA
619-421-2100; tether@cox.net

Jerome Pearson
STAR Technology and Research, Inc., Mount Pleasant, SC
843-856-3590; jp@star-tech-inc.com

ABSTRACT

"EDDE" (the ElectroDynamic Delivery Express) is a persistently maneuverable modular propellant-less vehicle for low earth orbit (LEO). EDDE has at least 2 major applications: payload delivery and debris removal. Vehicles as light as 20-30 kg can deliver secondary payloads to custom orbits, but 50-100 kg vehicles plus capture hardware are needed to efficiently remove orbital debris above 800 km. EDDE uses a reinforced aluminum foil tape to collect and conduct electrons, and solar arrays distributed along the length to limit peak local voltages. Hot tungsten wires emit electrons back into the ambient plasma. Air drag sets EDDE's minimum altitude of 300-400 km. There is no hard ceiling, but thrust decreases at high altitude, requiring use of longer and heavier vehicles for efficient thrusting. In general, short electrodynamic thrusters do not perform well, since thrust scales with the product of current and length. Large electron collection areas are needed. Making the collector also serve as a long conductor makes it far more effective. This paper describes EDDE's design, components, and operations, and some options for stowing and delivering multiple secondary payloads. The most attractive thing about EDDE to the smallsat world may be the possibility of "custom orbits without dedicated launch."

INTRODUCTION

EDDE is a non-rocket vehicle that propels itself in LEO by reacting against earth's magnetized ionosphere. It does this by driving multi-ampere currents through km of aluminum foil tape, and closing the current loop in the surrounding ionosphere. The tape sees a force normal to the current and local magnetic field. EDDE has a sustained ΔV capability >10X orbit velocity per year.[1] EDDE is like an "infinite mpg car" whose engine gets anemic outside "LEO city limits." Hence EDDE is best suited to repeated maneuvers like debris removal, or distribution of many secondary payloads into widely different orbits.

EDDE is more agile than prior ED vehicle concepts because the conductor spins end over end rather than hanging. This allows far higher currents without inducing instability. It also allows changes in all 6 orbit elements each orbit, by modulating the current as the thrust direction changes. As explained later, spinning also allows fast boost or deboost even in near-polar orbits, where hanging thrusters can change altitude only slowly. Most users of LEO prefer high-inclination orbits, so performance near polar orbit may be critical.

In drag mode, EMFs >350V/km allow peak currents >10A. Orbit-average ED drag on a 70 kg EDDE can exceed 0.5 newton. This allows deboost rates up to 1000 km/day. By using power from its solar arrays, EDDE can also climb up to 200 km/day and change orbit plane at 1-2^{o}/day. When carrying payloads, these maneuver rates must be scaled by the mass ratio of EDDE/(EDDE+payload).

EDDE works best near 400 km altitude, where drag is low enough but ionospheric plasma density and magnetic field strength are both high. Performance drops at higher altitude, but increasing EDDE's length lets it work efficiently down to lower plasma densities. If payload delivery involves one or more large orbit plane changes, most maneuvering can be done near 400 km, and 20-30 kg EDDE vehicles may be adequate.

Initial work on EDDE was done under DoD SBIR and follow-on funding. NASA OCT is now funding EDDE technology maturation. In parallel, the Naval Research Lab is preparing its TetherSat and TEPCE experiments for flight. They will test key aspects of EDDE's plasma interactions and control concepts, including active avoidance of other tracked objects.

The rest of the paper covers these topics:

pg 2 Key EDDE design and ops concepts
6 Key EDDE components
8 Some small-sat delivery scenarios
10 Conclusions and recommendations

KEY EDDE DESIGN AND OPS CONCEPTS

As shown below in Figure 1, electrodynamic thrust uses the electromagnetic force generated by a current through a long conductor in the earth's magnetic field to change the orbit:

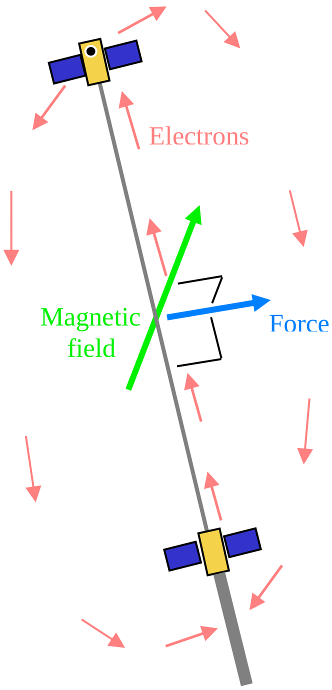

Figure 1: Electrodynamic current loop and force

The bare metal tape at the bottom is positively biased by the adjacent solar array, so it can collect electrons from the surrounding ionospheric plasma. Electrons flow through the long conductor and are emitted back into the ionosphere at the top. The current loop closes externally in the ionosphere. There is a net force on the conductor, and an equal and opposite force on the external return path. Bulk cross-field electron motion involves collision and momentum transfer to neutrals.

If the current flows with the EMF induced by orbit motion through the earth's magnetic field, the current loop can power itself, since the EMF can counter parasitic drops required to collect, conduct, and emit electrons. But the ED force then includes a drag component. Reversing the current direction allows boosting, but requires external power, at a voltage equal to the EMF plus all the parasitic voltage drops.

Having collectors and emitters at both ends allows reversal of the current and force, and bi-directional changes in altitude and orbit plane. Modulating the current as tape orientation and orbit position change allows controlled changes to ***all 6*** orbit elements.

EDDE altitude constraints

As shown in Figure 2, daytime plasma densities vary greatly with altitude and solar cycle. They also vary greatly with time of day and latitude. The plasma is usually much denser near the equator, but values for 60^o latitude are more relevant for near-polar orbits.

Plasma densities <10/mm^3 are low even for EDDE vehicles 10 km long, while densities >100/mm^3 may be enough for EDDE vehicles down to 2-3 km long. Because the plasma varies so much around each orbit, there will generally be enough plasma some of each orbit, but seldom enough around the full orbit. This makes EDDE performance vary somewhat less with altitude and solar cycle than might be inferred from Figure 2. EDDE can pump itself into highly elliptical orbits with low perigee, but that reduces the average thrust and increases vehicle radiation doses.

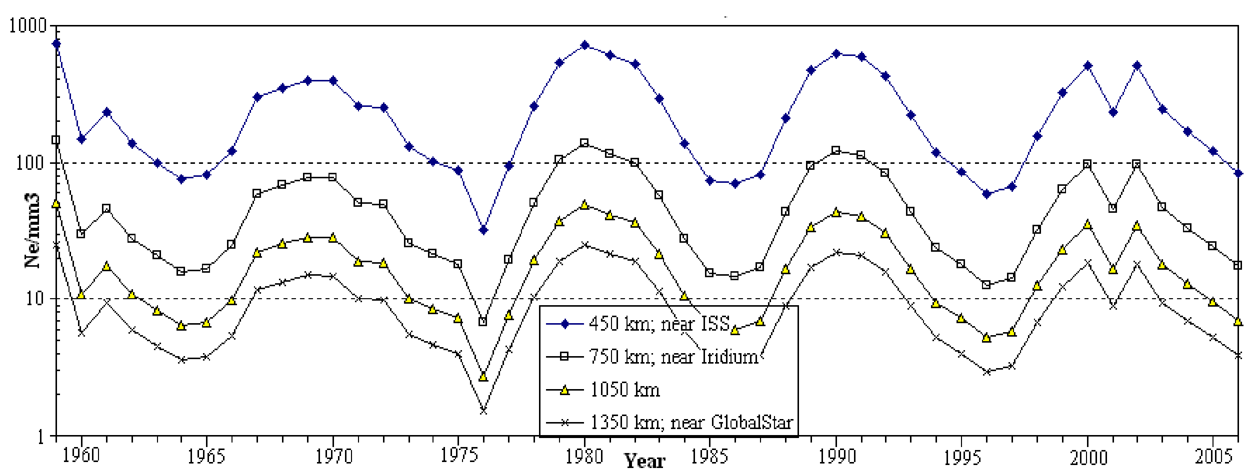

Figure 2: Daytime ionosphere electron densities (IRI-2007, 60^{o}N Lat, 0^o Long, 2pm local, April 1, 1959-2006

Spinning vs hanging ED thrusters

Stability analyses by Levin[2] indicated that it is hard to control ED thruster swinging, bending, and end-mass attitude motion in inclined orbits, if average ED thrust exceeds ~10% of the gravity gradient force. This led him to consider spinning the conductor to stiffen and stabilize it, despite the resulting sacrifice of some of the EMF on a vertical conductor at low latitudes.

But consider peak and average ED drag on vertical and spinning thrusters. A vertical thruster has the highest EMF, current, and drag in equatorial orbit, since it flies normal to the strongest horizontal field there. In 60^o orbit, the EMF and the current it drives each drop by half. This cuts power dissipation and hence drag by 4. In polar orbit, EMF is very low, because the magnetic field lines are in the orbit plane. As a result, a vertical tether gives a side force, not a force along the velocity vector. Hence altitude change rates are very low.

Now consider a spinning tape that is horizontal and broadside to the velocity vector at the poles. The local magnetic field is vertical, and twice as strong as at the equator. This gives 2X the EMF and current of a vertical thruster in equatorial orbit, and hence 4X its power dissipation and drag. Integrated over a full spin, average in-orbit-plane drag drops by half. Integrated over the full orbit, it drops by another factor of ~1.75. But that is still better than the equatorial vertical case.

A spinning conductor is also far more agile than a hanging one, because it can push and pull over a far wider range of angles. This allows changes in other orbit elements when boost or drag are less effective. Figure 3 below allows insight into what latitudes and conductor orientations have the most effect on each orbit element, over ¼ of a near-polar orbit:

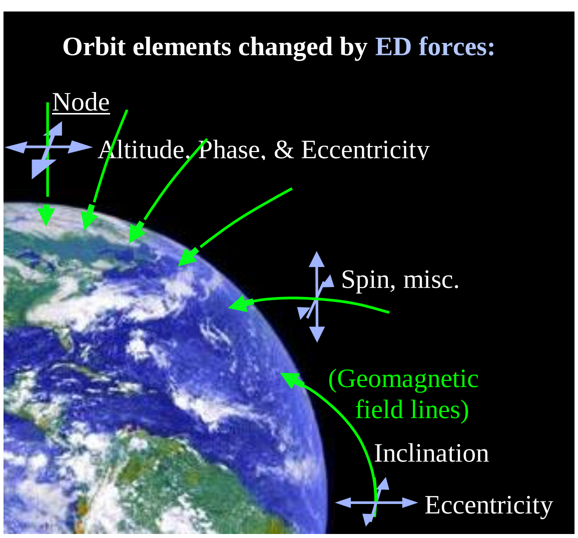

Figure 3: Possible ED thrust vectors vs. latitude

Modifying all 6 orbit parameters

Figure 3 shows how the available force vectors (blue arrows at right angles to the local field) can change all 6 orbit elements (parameters shown in white text), as well as spin rate and plane, each ¼ of a polar orbit:

Inclination:	vertical tape, near equator
Node:	align w/velocity vector, near pole
Altitude:	tape normal to orbit, near pole (or vertical, in low inclination orbit)
Phase:	change altitude; wait; change back
Eccentricity and **Apsides:**	boost and drag once each orbit, or align tape E-W near equator

Effects on each of the 6 orbit elements and 4 spin state parameters vary roughly with the cosine of the spin and orbit phase. Modifying 2 parameters in quadrature often allows changes 71% as large as a change in one, and 4 items can often be changed half as fast as one. Hence it is useful to combine needed orbit and spin changes when feasible.

Besides allowing far higher thrust, spinning also allows simpler and lighter designs. Hanging thrusters develop uncontrollable swinging if driven hard during the day but not at night. To prevent this, they need enough batteries to thrust at night as well as during the day. They also need more electron collection area for the low-density night-time plasma. By contrast, spinning thrusters need not run at night, so they need no heavy batteries. And they work better at high altitude since they need only work in denser daytime plasma.

These benefits of spinning-mode operations were substantial enough that we have obtained patent coverage of spinning LEO ED thrusters, for better system performance, operations, and/or design[3].

Spinning thruster dynamics and control

A spinning tape may be far more stable than a hanging one, but controlling all dynamic modes electrically calls for considerable finesse. We use a very powerful feedback control strategy developed earlier for ED boost of Mir.[4] The algorithm estimates system dynamics from recent observables. With a spinning tape, an orbit's worth of EMF data can indicate spin plane and phase, while MEMS gyros, magnetometers, or sun-sensors can indicate bend and twist dynamics.

After inferring the current state, the algorithm generates a current-modulation plan that damps all observable deviations from the desired dynamics. The algorithm is repeated every minute, so computer errors due to SEUs, etc, will have only brief effects.

Detailed description of feedback damping strategy

Electrodynamic thrusters develop instabilities when energy is pumped into conductor dynamics. This can occur even at constant current, but is usually worse due to current variations driven by the field and/or plasma. Further, the magnetic field is seldom aligned exactly as needed, so modulating current to obtain a desired effect usually also excites undesired modes.

Limiting the undesired dynamics requires persistently draining energy out of the system. Our feedback control strategy starts with an ideal reference frame moving and rotating with the ideal EDDE motion we want (no bending, an ideal spin rate and plane, etc.). We take the state inferred by the estimator, compute its motion relative to the ideal frame, and compute the "error EMF" caused by ***motion*** (not displacement) relative to the ideal frame.

If that error EMF actually drove the current, we would get passive eddy-current damping of all undesired motions. But the actual EMF is not the same as the error EMF, so we must actively mimic the effect of an error EMF. We do this by a control current profile that correlates with the error EMF. Constraints on power and thrust direction limit how much each mode can be driven or damped at each instant, but on timescales >1/4 orbit, all modes are accessible. The main goal is a long-term trend of damping dynamics that are large enough to observe.

All large dynamics are clearly observable, including skip-rope modes. The required control current is usually small. The slow growth of most dynamics and the cumulative nature of damping makes this strategy very tolerant of periods when problems with power availability, data acquisition, or control problems make active stabilizing control temporarily unavailable.

The performance loss due to control currents is often least if current reductions or reversals occur near switching times, when ED forces may be large but the force component in the desired direction is small. We can also damp higher-order modes by adjusting how much of the overall tape ***length*** is used to collect and conduct current. This requires distributed power and distributed emitters. These features also turn out to be useful for several other reasons.

Effects of different spin planes

In near-polar orbit, in-plane spin minimizes the EMF. This seems useful when little change in altitude is desired but large node and/or inclination changes are needed. This might be used to deliver payloads from ISS to sun-synchronous orbit (or eventually to deliver failed sun-synch satellites to ISS for repair).

Spin normal to the orbit allows faster boost or decay, whether the spin is horizontal near the pole or near the equator. The spin plane also affects solar array output: the arrays track only around the tape axis, so spin axes close to the sun can maximize average power. So solar beta angle may often affect spin-plane selection.

EDDE will usually spin close one or the other of these cases, since little torque is needed to maintain a spin axis either near or nearly normal to the orbit plane. By contrast, tilted spins nutate, due to gravity-gradient torques. Tilted spins will occur during shifts between in-plane and normal spins. At spin rates of order 8 revs/orbit, those transitions can be done in hours.

Key EDDE electrical design features

The baseline EDDE electrical design is shown below in Figure 4. Its key features are:

bi-directional current capability

full-length aluminum-tape electron collector

distributed power and control design.

EDDE must reverse the current direction 2X/spin to provide a net translational force. This means it must collect and emit electrons at both ends of the tape. (Hanging thrusters also need bi-directional current capability if they want bi-directional altitude or plane changes.) Rather than using short collectors at each end, with an insulated wire between them, EDDE's full conductor length also serves as electron collector. The larger collection area allows higher thrust at high altitude, by allowing adequate current collection down to much lower plasma densities.

In drag mode, the EMF automatically leads to preferential electron collection at the end far from the emitter. The collection length adjusts itself to EMF and plasma density, so a simple bare-tape collector can work well in drag mode.

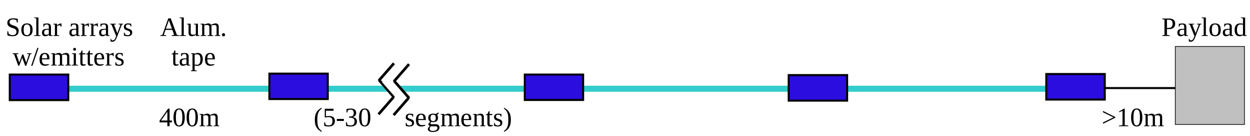

Figure 4: EDDE electrical layout, with distributed power, collection, and emission

When climbing, EDDE must use solar power to drive current against the EMF. Then electron collection by a bare tape is preferentially near the emitter. This could drastically cut working tape length and ED thrust. But EDDE's distributed power lets it "pump" electrons along the conducting tape. This actively biases tape segments near the emitter negative, so collection occurs further away. Collection on each tape segment is still preferentially at the end nearest the emitter, but if the near segments are biased negative and the far ones positive, collection will occur only on far segments, and the current will flow through most of the tape length.

"Use it or lose it" power management

EDDE can get by with very small batteries sized mostly for the avionics, if it immediately uses power from its solar arrays or the EMF. The idea is to "commutate" the current, or drive it one way for half a spin, and the other way for the next half-spin. The average force is nearly in the direction of the force at the middle of each half-spin. Varying switch phasing over time allows adjustment of thrust vector as the magnetic field and desired thrust direction slowly vary around each orbit.

Changing the duty cycle away from 50/50 affects the spin rate and plane. Varying where electrons are collected or emitted also affects spin (and bending dynamics). Each time current is reversed (16X/orbit, for an 8 rev/orbit spin) there can be a brief quiescent period, to allow accurate measurement of the EMF and undisturbed ambient plasma properties.

Performance and control may both improve if we store energy near switching times or when solar array voltages are off-optimum, for use at other times. This may require only a few % as much storage as day/night storage. But >1E5 storage cycles may be required. This may make ultracaps more suitable than batteries. Faster spin can reduce intra-spin storage needs but raises tape reinforcement requirements. It is not clear whether such "intra-spin" energy storage is justified.

Arc detection and suppression

Peak EDDE EMFs can exceed 3kV. Periodic impacts by small debris or micrometeoroids will create transient partly-ionized clouds of volatiles. This can trigger sustained arcing similar to the flaw-triggered arc on TSS-1R in 1996. Once triggered, >1A arcs from negatively biased surfaces to a plasma may sustain themselves until actively quenched. Putting the solar arrays every ~400m lets EDDE limit local voltages. We will also put isolation switches and arcing sensors at both the solar arrays and the winding cores mid-way between arrays. The switches enable active quenching of any sustained arcs, by letting us greatly reduce the collection area and EMF available to sustain an arc.

"Born spinning" deployment

Changing between hanging and spinning modes using only electrodynamic forces is difficult, so we plan to spin EDDE up at the start of deployment and use ED torques to control spin thereafter. Spin-up can start before or after release by the host vehicle, and can use small cold-gas thrusters or any other available option.

Releasing the solar arrays and undeployed tapes in sequence slows the spin but lets us start ED torquing as soon as tape starts to deploy. Torquing spins the system and unwinds more tape. Depending on how much gas we use to start spin-up, full deployment may take hours to days. If EDDE does not work properly, it will remain <1% of its full deployed length. This minimizes its contribution to orbital debris problems. EDDE is not designed for either de-spin or tape retraction: payload release and even capture will be done at the end of a slowly spinning EDDE.

Controlling spin plane and rate

We plan 6-8 rev/orbit spin after deployment. This is enough for centrifugal stabilization, but does not require much tape reinforcement. Faster spin may be justified with little or no payload, since tape tension is less then, and faster spin gets more value out of any intra-spin energy storage.

There are two ways to apply electrodynamic torque to adjust the spin plane or rate. One is to collect electrons in the middle and drive them to emitters at both ends. This causes little force but a large torque. The torque direction varies with spin and orbit phase, allowing arbitrary changes over time. (Torque can be reversed without having to reverse the current, by waiting ~1/4 orbit until the magnetic field direction reverses.)

The other way to apply torque is for use when EDDE has a heavy payload at one end, so its CM is far from the middle. Then any current along the full tape imposes a net torque. Then DC current has a secular effect on spin, while reversing the current twice/spin imposes little net torque but large net translation forces. Here too, one can vary the current around the orbit, to get any desired net spin torque by combining spin torques as desired.

Active avoidance of other objects

The collision cross-sectional area of a tether with another object is roughly the tether length times the other-object width. This can be ~1000X larger than typical collision cross-sections. Hence it is prudent for EDDE (and other tethers) to actively avoid other objects, especially working spacecraft. EDDE's persistent maneuverability makes this a challenge.

But avoidance of all other tracked objects need not be a serious computational challenge if EDDE can stay inside a defined zone around its nominal maneuver trajectory, and we uplink the predicted time, position, and uncertainty of all predicted zone penetrations. If this zone is 30 km dia by 200 km long, tracked debris may penetrate it ~5X/orbit, and working satellites ~3X/day. Active avoidance should require adjusting spin phase or position only a few times per day, and EDDE's agility should make this fairly easy.

Contingency operations after tape cut or other failure

If an EDDE tape is cut, each half still has a comm link plus solar arrays, emitters, and controls. The halves are less agile, but they can maintain control and can still actively de-orbit within a few days. EDDE may even be able to safely complete its payload delivery. In addition, both halves can still maneuver to actively avoid ISS while de-orbiting themselves, as long as they have recent ISS ephemerides. EDDE's high modularity should let it quickly deorbit itself after most other failures, if the control architecture is robust and enough of the components still work properly.

KEY EDDE COMPONENTS

The above overview of EDDE provides context for a more detailed discussion of key EDDE components:

- the conducting tape
- solar arrays (design, stowage, & tracking)
- power switching
- electron emitters & avionics
- capture nets and net dispenser

The conducting tape: why 30mm of aluminum foil?

ED current and thrust is limited by the ~30Ω/km tape electrical resistance. Pure aluminum has the highest conductivity/weight ratio of practical metals: nearly 2X that of copper. The 1000 series alloys have the highest conductivity and thinnest surface oxides (which can affect collection). So 1000-series aluminum alloys seem like an easy decision.

The argument for a 30mm wide foil strip is more complex. Positively biased objects in a magnetized plasma can attract electrons across magnetic field lines only within a few Debye lengths and electron gyro radii of the object. Within that regime, current should scale with the square root of the collection voltage, but at larger distances, electrons are not attracted as much. As a result, wires and narrow tapes may collect far more electrons than equal areas of larger spherical or "window shade" collectors.[5, 6, 7]

At low plasma densities, where EDDE performance is most limited, the Debye length and gyro radius are both of order 30 mm. Wide tapes allow EDDE to be shorter, but limits for "narrow tape collection" cannot be accurately determined by analysis, ground test, or even sounding rockets: orbit velocity is needed.

NRL's TetherSat/TEPCE experiments may allow such tests next year. These 3U cubesats use 30mm x 5m collectors and hot-wire emitters at each end of a 1km exposed conducting tether. Properly biasing the collectors, tether, and emitters allows measurement of collector performance over a range of plasma densities and field strengths. Proper analysis should let us infer electron collection rates by tapes moderately wider or narrower than 30mm over a useful range of conditions.

NRL flight data will let us refine our design, but for now we baseline a 30mm wide tape. It is 38 microns thick, because this is the thinnest that we could easily reinforce, wind, and deploy without tearing.

EDDE's foil tape is reinforced against tearing by an 8 mm wide composite tape bonded to one side. This tape consists of quartz fiber in a cyanate ester resin. The reinforcement also has high thermal emittance. This reduces the temperature and electrical resistance of the bare aluminum foil tape. The quartz fiber is an oxide, so atomic oxygen will erode only exposed resin.

The tape is assembled from lengths 200 m long. Two tapes are wound together on a stackable flangeless core, with the reinforcing strips offset. The free tape ends are both at the outside of the double winding. This lets us daisy chain the tapes together with the solar arrays to allow 400m in-line spacing of the solar arrays.

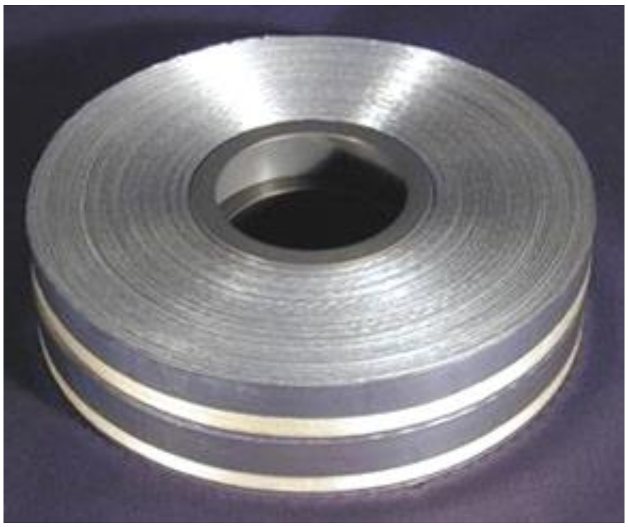

Figure 5: Two stacked dual-200m tapes

To ensure controlled deployment, we wind the tapes with a weak adhesive. It requires a modest peel force that varies little with temperature. In addition, the peel force rises significantly with unwinding rate. This gives passive viscous damping of deployment. The windings are baked out in vacuum after winding. This artificially ages the adhesive bond and reduces later outgassing.

Figure 6 shows a cross-section of layers of wound tape, including the adhesive, reinforcement, and foil. It is 2.5X scale horizontally, with 15X vertical exaggeration. The bends in the wound tape are due to competition for the neutral-stress plane between the foil and quartz. Winding under modest tension is enough to make the winding solid enough to handle launch vibrations.

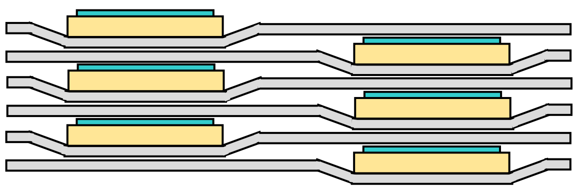

Figure 6: Wound tape cross-section (thickness X15)

Operational versions may want to use two distinct reinforcing strips ~5 mm wide with a ~9mm gap between them. We did not do this on our prototype windings. We could not figure out how to determine whether one of two strips was cut, to assess cut risks, so we decided to let the tape fail if a full reinforcing strip was cut, and use that datapoint to estimate the much longer MTBF of an operational version with two narrower but separated reinforcing strips.

Solar array design and stowage options

We can use either conventional crystalline solar cells or thin-film cells. The added solar array area needed with low-efficiency thin-film arrays is not an issue here. The aluminum foil tape has ~10X larger drag area, so a low-efficiency thin-film array just increases the minimum operating altitude a few km. The flexibility of thin-film arrays is also not a problem, since centrifugal force due to EDDE's spin can keep the array tensioned. But rigid cross-members are needed at the ends of each array.

A thin-film solar array can laminate the solar cells and interconnects between thin polymer films. For stowage, we can fold the array like a doubled-over folded "bolt" of cloth, as shown in Figure 7. This eliminates any need for the tight creases that occur with zigzag folding. Tight creases could crack thin AO-protection coatings on the film. This concept requires variable gaps at the hinges. Very long arrays can be made without requiring large gaps, by joining and stacking several shorter "bolts."

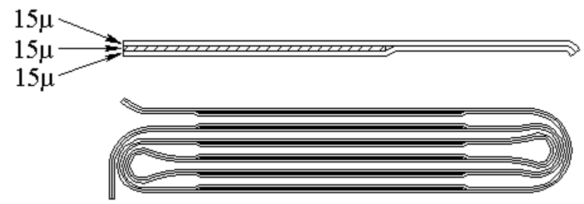

Figure 7: Stowed laminated thin-film solar cells

The continued low maturity of thin-film arrays for use in space has led us to baseline flexible arrays using crystalline cells, as shown in Figure 8 below. The "coverglass" (thick film or thin glass) must be thick enough to reduce ionizing radiation to levels crystalline cell junctions can tolerate. The thick front cover need not cross hinge lines, but cell interconnects across the hinges do need insulation to limit solar array arcing opportunities. This array concept can use either the "bolt of cloth" fold shown above in Figure 7, or the zig-zag fold shown below in Figure 8:

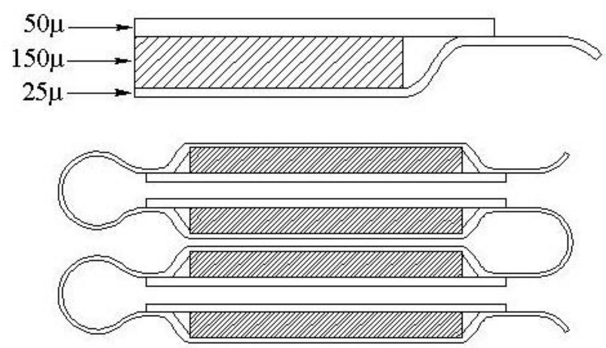

Figure 8: Stowed laminated crystalline solar cells

The detailed design of the array requires attention to issues such as materials selection to minimize arcing problems, keeping cells at widely different potentials far enough apart and eliminating trapped gas and arcing paths between them, protection against atomic oxygen, and ensuring that sustained flexing and thermal cycling (~150-350K) do not fatigue the films, interconnects, or cell/interconnect bonds. For guidance on film materials and techniques, we are studying MISSE test results, with a particular interest in polymer "coverglass" tests.

One-axis solar-array tracking

To ease solar array design and reduce mass, we plan to use only one-axis solar array tracking, around the tape axis. (Our performance estimates include losses from 1-axis tracking.) The main perturbation torque affecting sun tracking may be a flexible-array "snap-through" response to tape skip-rope dynamics. This and tape torsional effects are hard to quantify but can be useful, since they actually give us something to react against.

Switchable-voltage solar arrays

Power to pump electrons along the tether is required over a wide range of voltages. Peak EMF-driven ~10A currents don’t need the solar arrays. In solar-powered modes, currents of ~1-4A are desired, typically in the 50-200V range. Our earliest plans (based on work on ED reboost of Mir) used wide-range DC/DC converters between the solar arrays and the conducting tape. But DC/DC converters can actually outweigh lightweight solar arrays, especially if one includes the radiator mass needed to spread out and reject converter heat loads.

Our first step away from that was series-parallel switching of 4 equal sub-arrays. This has recently changed to a more efficient switching topology. Each solar array has 8 panels, each with 24 27cm^2 triple-junction cells. They can be connected with 2, 3, 4, 6, or 8 cell strings in parallel. This allows ~1-4A currents at ~50-200V. Appropriate switching should allow an average array efficiency >90% that of peak-power efficiency. This is comparable to good wide-range DC/DC converters, at much lower mass and cost.

Each solar array controller includes an “H-bridge” so the array can drive current in either direction in the tape. Turning the bridge off isolates tape segments and array from each other, to help quench arcs on either. The bridge also includes a shunt switch so current can bypass a solar array. This lets EDDE operate despite failed power switches or mis-aimed solar arrays. It also allows EMF-driven “drag-mode” operation at night. The switches are soft-switching solid-state devices.

EDDE’s overall energy efficiency is modest, mostly because of parasitic electron collection, conduction, and emission costs, but also because of the “use it or lose it” power strategy, one-axis array tracking losses, and off-optimum solar array voltages. These features reduce efficiency, but they reduce mass and cost far more, so they improve both power/weight and cost-effectiveness.

Electron emitters

One can usefully distinguish 3 classes of candidate electron emitters:

- Ion collecting areas
- Hollow cathodes
- All others (hot wires, FEACs, electrides)

Effective ion collection requires areas far larger than the already large electron collection areas, and hence seems unlikely to make sense. Our baseline was hollow cathodes until recently, since their power requirements for heating and electron emission voltage are low. But they do emit xenon, and over a potentially useful maneuver life of months to years the xenon budget becomes a problem. By contrast, hot wires take more power, both to heat the wires and to overcome emission space-charge limits. But hot wires plus the added solar array area they require appear to both weigh and cost less than hollow cathodes plus their xenon tanks.

FEACs may be usable if they can tolerate sustained sputtering by ionized atomic oxygen. There are also more exotic options such as C12A7 electride, which may serve as a low-work-function emitter. Most “unconventional” alternatives to hot wires may be easy to substitute for hot wires, if they prove workable.

Avionics

Distributed emitters and avionics can be incorporated into each deployable solar array. Small modules at each end can also include cameras, GPS receivers, other sensors, antennas and comm hardware, and small batteries. Whichever end is emitting can serve as “master” controller of the distributed solar arrays. Each end can assume master control of its half, if the tape is severed. Inter-module communication can be by conventional wireless (if the tape itself does not cause excessive fading), or by modulation of tape currents.

Control requires on-board state-estimation using models of the dynamics and earth’s magnetic field and ionosphere. This requires extensive calculations, but they need only be done every few minutes, so a slow computer appears adequate.

SOME SMALL-SAT DELIVERY SCENARIOS

EDDE is highly modular. An initial test vehicle might be only 1-3 km long. Such a “Mini-EDDE” might launch as a secondary payload on any launch to >400 km with >20 kg margin. As shown below in Figure 9, an EDDE vehicle up to at least 8 km and ~60 kg can fit in the inner ~12” of a single EELV ESPA payload position. This lets it support secondary payloads and deliver them to orbits far different from that of the EELV. Most launches with enough mass margin to carry secondaries plus EDDE and room for secondaries are likely to also have enough room to stow EDDE.

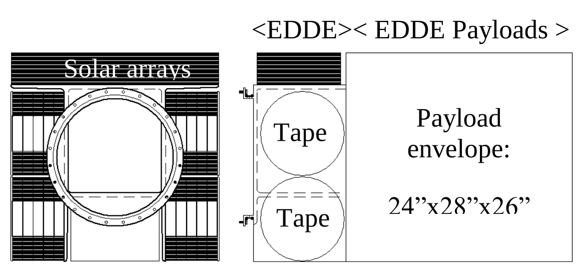

Figure 9: Two views of EDDE in ESPA Envelope

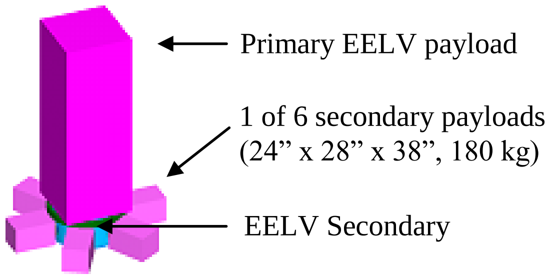

Figure 10: EELV payloads mounted on ESPA

Falcon/Dragon Mission Options

An alternative to mounting secondary payloads on an ESPA ring on EELV launches is to use any margin on DragonLab missions, or even on Dragon cargo missions to ISS. Secondary payloads carried in the Dragon’s aft “trunk” can be mounted on the Falcon 9 standard 1575mm payload adapter, which is unused on Dragon missions. As shown below in Figure 11, one might mount a large plate on that adapter, and put up to 12 ESPA-size payloads plus P-PODS on that plate, on missions with enough margin for such payloads. Soft-ride dampers under this plate can improve the ride not just for secondary payloads, but even for Dragon itself.

Attaching secondary payloads to Falcon rather than the Dragon trunk reduces constraints on Dragon operations, and lets the Falcon boost the secondary payloads above ISS if it has enough remaining margin. Many mission scenarios are possible, with or without EDDE. One is to stow EDDE vehicles in unused corners, and attach them to secondary payloads needing custom altitude and/or plane changes. Once Falcon reaches 400 km or more, the EDDE vehicles and payloads can be released.

Figure 11 below shows a side view of this opportunity. The ESPA payloads are shown with 18.25” rather than 15” clampbands, but either are usable. Tight payload spacing is needed only if the Falcon’s payload margin is enough to carry 12 ESPA-size payloads. One can increase payload separation clearances using Coriolis effects, if Falcon spins slowly during payload releases.

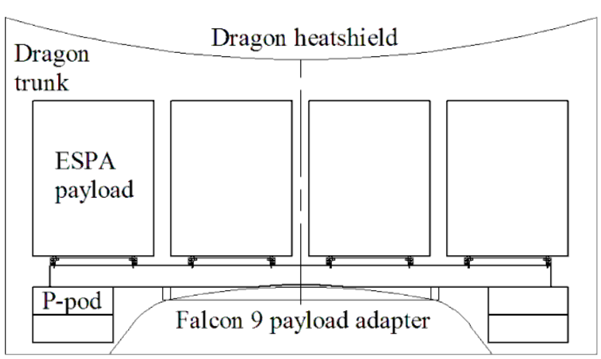

Figure 11: Dragon trunk w/ESPA payloads & P-pods

EDDE delivery times with secondary payloads

However EDDE and a collection of secondary payloads are delivered to an altitude of at least 400 km, the key question is really how long it will take EDDE to deliver or distribute those payloads to other orbits. Several cases of interest are shown below. For specificity we assume an 8km 60 kg EDDE delivering 3X its own mass of secondary payloads: either a single max-weight ESPA payload, or many P-pods, or any other desired combination having 3X EDDE’s own mass.

Table 1. Times for typical EDDE deliveries

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

Delivery times of 49-170 days to different orbit planes may seem undesirably long, but in the small-sat world, the usual alternative may be to wait for a more suitable launch opportunity. That may often take far longer.

We are in the process of revising EDDE performance estimates based on our recent design changes. At the time of the presentation we should have more accurate estimates for the above and other interesting cases, including creating a multi-plane small-sat constellation from one launch.

An Overview of Current Work on EDDE

In February 2012 we started work on a 2-year $1.9M SBIR Phase III NASA OCT contract with NASA Langley, to mature EDDE technologies. This contract includes the following 7 tasks:

1. Selection and/or development of key components
2. Customization, packaging, and deployment
3. Control strategies, including solar array steering
4. Tracking, navigation, and collision avoidance
5. Rendezvous strategies, including binocular vision
6. Conceptual design of a Mini-EDDE flight test
7. Identify and evaluate high-payoff applications.

The goal of the current contract is to mature EDDE enough for the final review to serve as a productive Preliminary Design Review for an EDDE flight test. That mission is not planned to include capture, but it may include repeated “kiss” passes of EDDE’s spinning ends by passive targets.

CONCLUSIONS AND RECOMMENDATIONS

EDDE enables many missions that are either impossible or impossibly expensive with other forms of propulsion. Examples include wholesale removal or relocation of large orbital debris in LEO, and distributing secondary payloads to orbits far from the primary mission orbit: "custom orbit delivery without dedicated launch." Eventually EDDE may even be able to safely capture failed polar satellites, move them to ISS orbit for repair, and then return them to polar orbit.

Considerable ground-development and testing work are needed and underway on key EDDE components and operating strategies. In parallel with this work, NRL's planned TetherSat and TEPCE cubesat experiments may be able to resolve key questions about EDDE plasma interactions and controls, in time to support the current maturation effort and its planned definition of a "Mini-EDDE" flight test.

Potential EDDE users are encouraged to contact either author of this paper, using the contact info on page 1.

ACKNOWLEDGEMENTS

EDDE vehicle development work was funded initially by the AFRL Space Vehicles Directorate under SBIR Phase I and II contracts, with some SBIR and follow-on funding from NASA MSFC. DARPA/TTO funded work on orbit transfers and an SBIR Phase I on space debris removal, and NIAC funded work on debris removal by EDDE. Current work is an SBIR Phase III funded by NASA OCT through NASA Langley.

REFERENCES

[1] Pearson, J, J. Carroll, E. Levin, J. Oldson, & P. Hausgen, "Overview of the ElectroDynamic Delivery Express (EDDE)," paper AIAA2003-4790 at 39th Joint Propulsion Conference, Huntsville, July, 2003.

[2] Levin, E., *Dynamic Analysis of Space Tether Missions*, Vol. 126 in Advances in the Astronautical Sciences, AAS, 2007. Ch 3 is on Mir; 4 on spinning ED tethers; 5 on tether capture.

[3] Levin, E. and J. Carroll, "Method and Apparatus for Propul-sion and Power Generation Using Spinning Electrodynamic Tethers," US patent 6942186, Sept 2005.

[4] Levin, E. and J. Carroll, "Apparatus for Observing and Stabil-izing Electrodynamic Tethers," and "Method for Observing and Stabilizing Electrodynamic Tethers," US patents 6755377, June 2004, and 6758433, July 2004.

[5] Sanmartin, J., M. Martinez-Sanchez, and E. Ahedo, "Bare Wire Anodes for Electrodynamic Tethers," *Journal of Propulsion and Power*, Vol. 9, No. 3, pp. 353–360, 1993.

[6] Onishi, T., and M. Martinez-Sanchez, "Computation of Current to a Moving Bare Tether," 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-2000-1578, 2000.

[7] Van Noord, J. L., B. West, and B. Gilchrist, "Electrodyna-mic Tape Tether Performance with Varying Tether Widths at Low Earth Altitudes," AIAA-2001-1141, 39th Aerospace Sciences Meeting, Reno, NV, Jan. 2001.