1st IAA Conference on Space Situational Awareness (ICSSA)
Orlando, FL, USA, 13-15 November 2017

# CLOSE-UP SURVEY OF LEO DEBRIS OBJECTS

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***Keywords:*** *Orbital debris characterization, orbit transfer vehicles, electric propulsion, electrodynamic tethers, space situational awareness*

## ABSTRACT

The aerospace community needs to improve space situational awareness (SSA) of the growing number of debris and other objects cluttering LEO. The larger ones are tracked, and sometimes we can estimate tumbling rates, but we need close-up images to assess structural integrity and surface condition so they can be removed. This paper describes a way to obtain high-resolution close-up imagery of dozens of large and small LEO debris objects in one mission. EDDE (ElectroDynamic Debris Eliminator) is an affordable approach to SSA and wholesale removal of debris from LEO. EDDE can rendezvous and provide close-up imagery of about 75 tracked debris objects per year, and improve our space situational awareness. It is an agile spacecraft capable of roaming all over LEO without propellant and with practically unlimited delta-V. It uses solar power to drive electric current in a long conductor, react against the Earth's magnetic field, and "sail" in the ionosphere like the clipper ships of yore. EDDE can change altitude by up to 300 kilometers per day and inclination by up to 1 degree per day. It can be launched as a secondary payload without a dedicated launch vehicle. After deployment, EDDE can approach rocket bodies, selected dead satellites, and large debris fragments and take pictures from 1-10 km away, with resolutions of about 1-10 cm. This will provide vital information on the mechanical and dynamic state of the debris objects that could be considered for removal in the future. We describe the spacecraft design and operation in a typical debris survey campaign. EDDE has been developed under funding from Air Force, DARPA, and NASA. It has undergone ground testing of relevant components, and the Naval Research Lab plans to fly the EDDE precursor TEPCE on the second Falcon Heavy launch.

# 1. Introduction

There is a growing need for improved space situational awareness (SSA) of objects in low Earth orbit (LEO). With the number of debris objects and the risk of collisions both increasing, we need to improve characterization of LEO objects at the most useful altitudes in terms of their sizes, tumble axes and rates, protuberances, and surface conditions. This will enable us to design capture hardware and operations for debris collection or removal, as described in our companion paper in this conference[1].

The Air Force Space Command set up a Space Situational Awareness Integration Office at Peterson AFB, Colorado[2] in 2002. The US Strategic Command provides conjunction predictions for LEO up to 7 days in advance[3]. The Air Force Research Laboratory has been developing improved methods for SSA, and the Air Force Space Command has recognized the danger to critical space assets from space debris such as upper stages, dead satellites, and collision fragments. Space based SSA for LEO could discover and warn against such threats.

Current SSA efforts have focused on GEO, which is far easier than LEO. All GEO satellites are in the same orbital altitude and inclination. This makes it easier to move from one satellite to another for observations and servicing, and even for moving dead satellites to a disposal orbit 300 km above GEO. The Air Force has a program for GEO space situational awareness called GSSAP[4]. Two satellites were launched in 2014, and two replacement satellites were launched in 2016.

But performing observations, servicing, and removal in LEO is far more difficult, because of the much higher delta-V required to move from one object to the next. Because LEO objects can be moving in opposite directions in their orbits, the relative velocities and required delta-Vs can be up to 15 km/sec. The best rockets for this are ion rockets such as Hall thrusters, which can have specific impulse, Isp, of up to 3500 seconds. And with the use of solid iodine rather than gaseous xenon as the propellant, they can dispense with pressurized tanks. This reduces mass and allows higher total mission delta-V. Busek has developed and tested an iodine Hall thruster[5], and NASA Marshall based their iSAT[6] on this thruster.

A 12U CubeSat version of the iSAT can achieve 1 km/s of delta-V on 1.5 kg of iodine propellant, but this is far less than the delta-V required to perform broad surveys of LEO object populations. A propulsion system with very high delta-V capability is required for a roving space vehicle to perform close-up surveys of multiple objects in LEO. We have developed a non-rocket propellantless propulsion system for a roving space vehicle that we call EDDE, the ElectroDynamic Debris Eliminator. EDDE and its capabilities for LEO SSA are described in this paper.

## 2. The ElectroDynamic Debris Eliminator (EDDE)

The ElectroDynamic Debris Eliminator (EDDE) is a space vehicle of a new class: it "sails" through the ionosphere without propellant, and with unlimited delta-V. EDDE uses electric current in a long metal tape to react against the Earth's magnetic field. EDDE collects electrons from the ambient ionospheric plasma near one end of the tape, and ejects them back into the plasma near the other end, using hot-wire electron emitters. EDDE's thrust comes from the current in the tape crossing geomagnetic field lines. The current loop closes in the plasma, as shown in Figure 1.

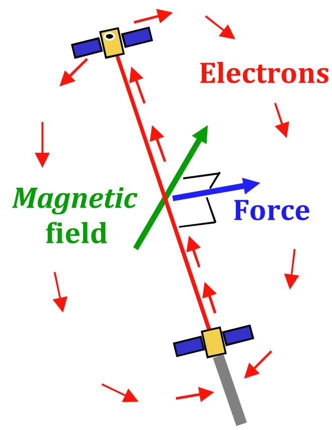


**Figure 1. Electrodynamic Propulsion Concept**

This concept was tested by NASA JSC on the 1993 Plasma Motor-Generator (PMG) flight test[7]. PMG flowed 0.3 A through a 500-m wire and used hollow cathodes as plasma contactors at both ends of the wire. In 1996, the NASA MSFC TSS-1R test achieved 1A through a 20-km wire.

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

EDDE uses flexible lightweight solar arrays for power, and rotates slowly to improve stability and performance. Rotation is the key feature that enables high performance. It both stiffens the tether against the transverse thrust forces, and allows a wider range of angles with the geomagnetic field and hence thrust directions. We need 6-8 rotations/orbit for adequate tension and control. The rotation rate and plane are controlled by periodically varying the current level and direction. Bending dynamics are inferred from endmass GPS measurements, and actively damped by varying current collection and emission along the tape length. EDDE is covered by three US utility patents, for the method[8,] and apparatus[9] for active control, and for the performance benefits of spinning operations[10].

EDDE's solar arrays, shown in Figure 2, are distributed along the length of the conducting tape. The arrays consist of unsteered bifacial cells in paired sub-arrays to eliminate any need for steering the arrays around the long axis. The arrays and their controls divide the tape into short separately controllable segments. This lets us limit the peak voltages to the local plasma. Each tape segment both collects and conducts electrons, as a function of the voltage to the local plasma and the voltage gradient along the length of that tape segment. Payloads can be added to either or both ends, and for the survey mission each end will include cameras for detection, binocular ranging, and imaging of target objects.

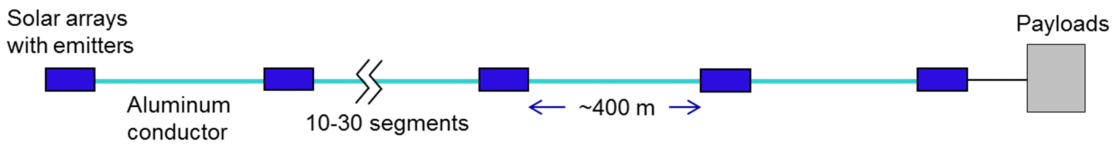


**Figure 2: EDDE Vehicle Schematic, Showing Arrays, Conductor, Emitters, and Payloads**

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

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

EDDE can be equipped with net managers at each end to deploy large, lightweight nets to capture objects, and/or CubeSat-like or other payload carriers to deliver each payload to its own orbit.

EDDE's tape design greatly reduces the risks of cut by hypervelocity impacts. Electrodynamic tethers that use small diameter wires can be cut by impactors down to ~1/3 the wire diameter. To overcome this, some electrodynamic tethers use multiple strands with cross-members, like a ladder[11]. But small wires with many connections pose fabrication and deployment challenges, including keeping the thin strands apart. EDDE's conductive tape design is simple but effective. It is a ribbon of aluminum foil 1-3 cm wide, reinforced with a full-width unidirectional fiber composite layer for strength and tear resistance. This greatly reduces vulnerability to small micrometeoroids and debris.

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

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

EDDE's modularity lets it be sized to fit the available envelope, payload, and orbit change needs of specific missions, ranging from nanosat delivery to capture and relocation of multi-ton debris objects. We expect most EDDEs will weigh from 28 to 100 kg and have one to several kilowatts of power.

Orbit-transfer performance is very impressive, as shown in Figure 3 for an 80 kg EDDE. The rates of change in altitude, inclination, and node are shown as functions of the orbit inclination, per ampere orbit-average current. Currents are likely to average more than 1 A near 500 km altitude, and less than 1 A at much higher altitudes, especially near solar minimum.

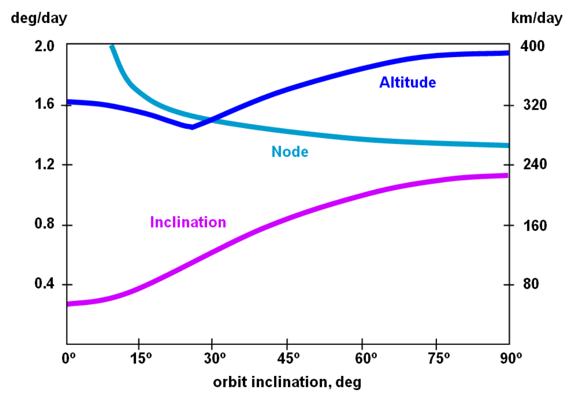


**Figure 3. 80 kg EDDE Orbit Transfer Rates per Ampere Average Current**

The above maneuver rates are for EDDE by itself, and apply to the debris survey mission, which will entail a total delta-V of about 50 km/s. When EDDE carries payloads or debris, the orbit change rate scales down with the ratio of EDDE to total mass. If EDDE captures ton-class debris at 750-1000 km altitude and releases it into short-lived orbits below ISS, average throughput can approach EDDE's own mass per day, or nearly 30 tons/year.

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

## 3. EDDE High-Resolution Survey of LEO Debris Objects

The revolutionary performance of the propellantless EDDE roving spacecraft will enable the collection or removal of LEO space debris at an affordable cost. The wholesale removal of debris from many countries will require international agreements, but we need not wait for such agreements to begin the process of preparing for LEO debris removal. The EDDE vehicle can be used in a low-cost mission to survey large numbers of debris objects in LEO, and during this mission it will demonstrate its capability for large delta-V and orbit changes that will show that active debris removal is feasible and affordable.

For example, a single EDDE vehicle can survey in 2 years the population of more than 150 rocket bodies in the most congested altitude range between 900 and 1000 km of the cluster at 82-83° inclination. The survey will provide information on the attitude motion, structural integrity, and surface condition of the debris objects necessary to properly prepare for their removal. EDDE can also survey rocket bodies in the 71-74° and sun-synchronous clusters at rates of up to 40 objects per year.

Each survey will involve a full 360° orbital node sweep of the cluster and will require an enormous delta-V of approximately 50 km/s. This cannot be done with today's fuel-burning spacecraft because of the limitations imposed by the Tsiolkovsky rocket equation, but it can be achieved with the EDDE spacecraft, which is truly propellantless, unlike conventional electrodynamic propulsion using hollow cathodes. Hollow cathodes require expenditure of xenon for electron emission. EDDE uses hot-wire emitters as cathodes, which require power, but not xenon.

To begin the mission, EDDE will be launched into any convenient orbit, preferable near 82° inclination, but no matter what initial orbit EDDE is delivered to, it can change its inclination to the required orbit and its altitude to perhaps 950 km quickly. From there, it will begin changing the longitude of its ascending node to move its way through the cluster, approaching each object in turn. Since EDDE can change altitude relatively quickly, it can move vertically to approach each object closely as it moves in node.

EDDE rotates slowly end over end to provide stability and increased performance. Each end will be equipped with a camera to image each object, as shown in Figure 4. The EDDE orbit and orientation are controlled so that one of the ends can safely come within 500 m from each object. From this range, even nominal optics of about 5 cm diameter can provide resolution of about 5 mm on the targets. This resolution is 22 times that of the 3.67-m AMOS telescope on Maui.

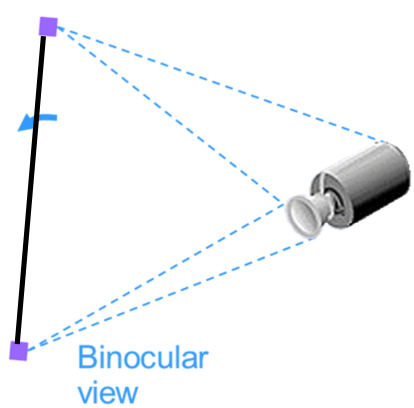


**Figure 4. EDDE Binocular Vision**

An example of this kind of debris survey results is shown in Figure 5. EDDE will be able to provide high-resolution photos even sharper than this image. Because of restrictions on imaging objects in orbit, we will obtain permission from each owner before acquiring images such as these.

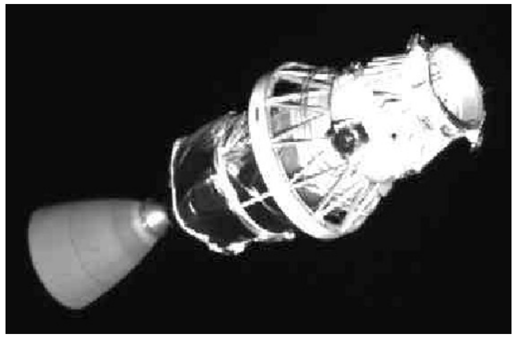

**Figure 5. Delta 2 Stage Imaged by the 28 kg XSS-10 in 2003. (USAF Photo)**

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

Our plan for dealing with these uncertainties is to propose several trajectory options to the JSpOC, select and publicly post an approved one, and have EDDE actively maneuver around other objects while staying within a defined maneuver volume centered on the posted trajectory[12]. 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 6 illustrates this with a reference trajectory and 2 keep-out zones. The zones are ellipsoids in a phase space of time, arc length along the reference trajectory, and altitude offset from the trajectory:

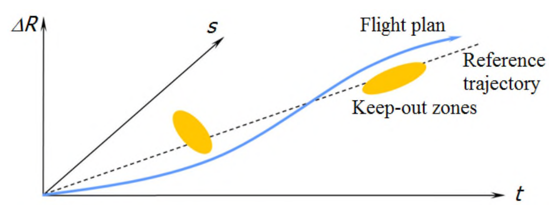


**Figure 6. EDDE Maneuvering Around Conjunctions**

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.

As noted earlier, a danger from <10 cm untracked debris does remain. This size threshold should soon decrease to 2-4 cm once the new S-band fence becomes operational. The threat from these objects 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.

The risk of a tether cut by small untracked shrapnel seems low enough for EDDE missions that distribute multiple small secondary payloads. They should take months, mostly near 500 km. Wholesale LEO debris removal will take years, mostly above 600 km, and a typical debris survey will take 2-3 years, but the tape survival rate will still be acceptable. The chance of EDDE tape cut is higher for those missions, due both to the longer duration and the larger populations of untracked debris above 600 km. We can afford to lose a few such EDDEs to cuts by small untracked shrapnel. Even if EDDE is severed, each half can maintain active avoidance of all operating satellites while it autonomously spirals down to a prompt re-entry.

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

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

We also studied data communication issues. It seems useful to get status data at least once/orbit, and we need low-latency video downlink plus low-rate uplink during rendezvous, inspection, and capture passes. Boeing suggested that we use existing commercial stations, mostly in the Arctic, for low-latency video. Globalstar may be more relevant for status downlinks.

## 4. Expected Survey Mission Results

EDDE has the ability to survey hundreds of objects in one mission. This debris survey mission will provide comprehensive information on a large number of debris objects all over LEO, including information on structural integrity and the surface condition of upper stages—information that cannot be obtained from the ground. EDDE can also fly by or rendezvous with any object at any inclination up to 2000 km altitude for high-resolution photos on this and other flights.

One of the payoffs of a survey may be getting close enough to get good images of "small but potentially lethal" fragments, according to J.-C. Liou[13]: "The well-shielded U.S. modules of the International Space Station (ISS) are protected against debris smaller than 1.4 cm. For a typical operational spacecraft, however, a hypervelocity impact by debris 5 mm and larger is likely to lead to mission-ending damage." Elsewhere Liou has said that most LEO satellite losses from impact will involve 5-10 mm debris. It would be very useful to image many lethal fragments in the centimeter range at popular altitudes (e.g., 700-860 km) well enough to resolve them clearly, because from the ground we can't estimate albedo or size, just brightness. In orbit we can get resolved images that tell us size, shape, tumble rate and axis, color, and possibly even hyperspectral imaging[14]. Centimeter-size objects are not now detected, but they can be optically detected and tracked and catalogued from the ground, and EDDE can be dispatched to image them. Knowing both actual size and area/mass (from orbit decay rate) lets us estimate the mass and hence lethality of cm-class debris.

Accurate data on actual configurations, including appendages and tumble axis and rate can be used to design various types of capture systems, including nets, harpoons, adhesive patches, and lassos. For example, the EDDE debris removal system discussed in the companion paper uses a large net on a long tether. Analysis shows that it can safely capture Zenit upper stages tumbling at up to 0.5 rpm, without the stage having enough tumble kinetic energy to climb out of the net. Smaller stages like Deltas can tumble up to several rpm without posing problems to EDDE's net capture system. There will be other limits on the tether lengths for harpoons, lassos, and adhesives, to keep the tumbling stages from wrapping up the tether and damaging the capture vehicle. Both the highest and average tumbling rates will be good capture design information.

The debris survey mission will also be able to record the number of micrometeoroid and debris impacts on objects at different altitudes, which will improve design information for safety of future satellites. Observing older debris objects will provide information on the density of micrometeoroids and small debris objects at nearly twice the altitudes measured by the NASA Long Duration Exposure Facility program[15] and its planned new facility on the ISS[16]. Observing active spacecraft could give the owners information on their conditions, and this might be possible by having EDDE maintain a much larger minimum separation during flybys, to preclude any chance of colliding with an operating satellite.

EDDE will also provide new information about the ionospheric density at different altitudes, latitudes and longitudes, because during its operation the total thrust reveals the local instantaneous electron density. This will give a continuous broad scale picture of electron densities both day and night during each EDDE mission. It will complement measurements from the Air Force DMSP satellites[17]. EDDE can also be equipped with additional instruments for other space weather measurements.

EDDE can also distribute multiple small metal spheres into different orbit planes over the ~600-1200 km altitude range, to allow better measurements of exosphere air density. Hollow polished aluminum balls about the size and mass of a ping-pong ball (4 cm and 3 grams) should be easily detectable by both the new S-band fence and modest ground-based telescopes. Low mass keeps the balls from contributing to the Kessler syndrome, and increases the observable response to small changes in exosphere density. Tracking the spheres should allow better atmospheric density estimation and modeling, and more accurate and actionable conjunction predictions. (To sense density at lower altitude, the ISS might periodically release similar balls. These balls might be somewhat heavier, depending on the desired balance between drag sensitivity and orbit lifetime.)

For EDDE itself, there is substantial value in gaining actual flight experience controlling EDDE during multiple close low-delta-V approaches of the EDDE end masses to many debris objects. The survey mission should aim to get closer and closer over time (both with the same object, on sequential orbits, and with different objects). The closer we get, the better the resolution can be. We really won't know how close we can reliably get without risking hitting objects until we try. We should aim to get EDDE close enough to allow capture by affordable-size nets, and also to allow affordable end-mass maneuvering for cooperative capture of future servicing vehicles.

## 5. Survey Mission Schedule and Cost

EDDE is a compact, 80-kg vehicle that can be flown as a secondary payload on scheduled launches of Atlas 5, Delta IV, Falcon 9 and other launch vehicles at low cost. This helps to reduce the cost of this and other EDDE missions. And as soon as it is launched, it will be able to generate revenue from sale of its pictures for SSA. These revenues can be used to develop and build nets for orbit clearing by dead satellite and debris removal from satellite constellation orbits for safety, such as OneWeb.

Ground development and construction of the first EDDE vehicle is expected to cost about $13M, and additional vehicles could cost as little as $4M each. The first EDDE vehicle could be ready for flight in 36 months. Component maturation and ground tests can be done in 12 months for $5M; building an 80-kg EDDE with power, sensors, control, and electronics, and procuring launch can be done in 18 months for $8M; integration, test, and launch will take 6 months and $3M; operating EDDE for one year for SSA and small payload deliveries will be another $2M. At the 36-month point, EDDE will receive immediate revenues from pictures of satellites and debris.

When EDDE is ready to fly in about 3 years, there should be adequate launch opportunities available. Two 80-kg EDDE vehicles can be packaged in one ESPA slot, or 1-2 EDDEs with nanosat payloads can use a new small launcher. EDDE could be launched as an ESPA-mounted secondary payload on any EELV mission to LEO (government or commercial), such as the Air Force Space Test Program, a DOD Atlas 5, Delta IV, or Falcon 9 or Heavy. Or if Launcher One, Electron, or any other small launch vehicle becomes both operational and comparably affordable to ESPA launch slots, we could launch on one of them.

Because EDDE is a low-cost secondary payload, and can change orbits from anywhere in LEO, the particular launch opportunity is not critical. That means that it can wait for the lowest-cost opportunity, no matter what orbit it results in. The lowest cost launch will probably be a secondary payload on an ESPA ring. CSA/Moog tells us that there will be ample ESPA flight opportunities in the next 3 years.

EDDE is ready for maturation and ground tests of its key components, and the Naval Research Lab's TEPCE[18] CubeSat is manifested on the second SpaceX Falcon Heavy. TEPCE is scheduled to test EDDE components in space in 2018. The 3U CubeSat is shown in Figure 7.

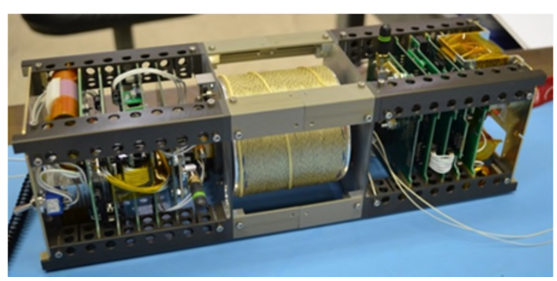

**Figure 7. NRL TEPCE CubeSat with EDDE Components**

## 6. Conclusions

This paper has described the development and status of EDDE, a revolutionary propellantless roving space vehicle for LEO. EDDE can provide improved space situational awareness for low Earth orbit for DOD and NASA far better than with ground-based telescopes.

Each EDDE can provide close-up surveys of objects of interest in LEO at the rate of up to 75 objects per year. These surveys can provide resolution of 5 mm with 2" optics from a distance of 500 m. We expect EDDE's cameras, located at the ends of EDDE, to be able to safely get within 500 m of any desired rendezvous or flyby target. Binocular vision with the cameras at the ends of EDDE will allow accurate ranging to the target during the approach, and the trajectory can be adjusted to give a safe minimum approach distance.

The EDDE debris survey mission will provide data on sizes, actual configurations, and tumbling axes and rates of large upper stages; it will also observe structural integrity and surface conditions of upper stages, which cannot be done from the ground. All this information can help design capture hardware and procedures for debris collection or removal.

This mission will also provide new information on current micrometeoroid density at different altitudes, and will provide continuous data on the electron density in the ionosphere versus altitude, latitude and longitude. EDDE could be ready to launch and perform this survey mission in 3 years.

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