AMORE: Applied Momentum for Orbital Refuse Elimination

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1. ABSTRACT

The need for active orbital debris remediation has increasingly gained acceptance throughout the space community throughout the last decade as the threat to our assets has also increased. While there have been a wide variety of conceptual solutions proposed, a debris removal system has yet to be put in place. The challenges that stand in the way of action are formidable and range from technical to political to economic.

The AMORE concept is a nascent technique that has the potential to address these challenges and bring active debris remediation into reality. It uses an on-orbit low energy neutral particle beam (~10 keV, TBD) to impart momentum onto medium (5 mm – 10 cm) debris objects in Low Earth Orbit (LEO), thereby reducing their kinetic energy and expediting their reentry. The advantage of this technique over other proposed concepts is that it does not require delta-V intensive rendezvous, has an effective range that allows daily access to hundreds of debris objects, and does not create policy concerns over violation of international treaties.

In essence, AMORE would be a medium-sized high power satellite with one or more particle beams fed by a large propellant tank, and an on-board tracking sensor that provides beam control. The particle beam would be similar to existing Xenon Hall Current Thrusters being used today, with the addition of a beam lens that would collimate and aim the beam. The primary technical challenge of this concept is the focusing, pointing, and closed loop control of the beam that is necessary to maintain effective momentum transfer at ranges up to 150 km. This effective range is critical in order to maximize daily access to debris objects. Even in the densely populated 800 km debris band, it can be expected that a single AMORE system would be within 150 km of any debris object about 10% of an orbit. Space is big, and range is critical for timely, cost effective debris removal.

Initial analysis indicates that a single AMORE vehicle operating in the 800 km regime could lower the perigee of >180 kg debris to a 25 year reentry orbit annually. The actual performance of a system would be highly dependent on the debris regime. An operational AMORE system would likely involve several vehicles operating autonomously for continuous remediation of existing and future debris.

2. INTRODUCTION

At this point in time, the issue of orbital debris needs little introduction. Agencies from NASA to the United Nations have groups dedicated to studying the problem, generating advocacy, and developing and implementing solutions. Well publicized events such as the 2007 Chinese ASAT test and the 2009 Iridium / Kosmos have thrust the potential detrimental effects of orbital debris into the public's awareness, even before Hollywood dramatized debris collisions in 2013's *Gravity*.

The topic of orbital debris can be divided into subtopics of: tracking and characterization, protection, mitigation, and remediation. To date, the space industry has focused on the first three subtopics. Surveillance networks find and track debris, critical areas on spacecraft are hardened against impact (and vehicles are maneuvered to avoid larger debris objects), and various practices have been instituted in order to mitigate the creation of debris from new launches. The fourth subtopic, active remediation, has been studied extensively and programs have been proposed, but no active remediation systems have been flown to date.

DARPA's Catcher's Mitt Study took a comprehensive look at active debris remediation [1]. It found that the class of orbital debris size that poses the greatest threat is medium, which is roughly 5 mm – 10 cm. Spacecraft can typically be shielded against debris smaller than 5 mm, and objects larger than 10 cm can be effectively tracked and avoided through maneuvers. The study further concluded, however, that removal of large debris makes the most sense in the short term because no effective solutions have been developed to address medium debris. By removing large debris with high risk of collision, we can at least reduce the amount of new medium debris that is generated.

The manner in which large debris is removed from orbit is distinct from that of medium debris. Removal of large debris objects would focus on intact vehicles in a one-on-one rendezvous scenario where a remediation satellite physically interacts with a debris object at a very low relative velocity. This scenario requires a substantial amount of system delta-velocity (ΔV) to rendezvous with individual debris objects, but is efficient in that each debris object represents significant mass. In contrast, remediation techniques that require rendezvous with individual medium size debris objects would require a prohibitive amount of ΔV. This drives the need for a method which does not require rendezvous and can be performed at range and with high relative velocities.

One technique that has shown promise in several studies is the use of lasers to apply energy opposite a debris object's velocity vector. Laser Orbital Debris Removal (LODR or LDR) has been proposed at least as far back as the 1980's Strategic Defense Initiative days [2] and likely received the most support during the mid-1990's with NASA's Project ORION [3]. The prevailing thought (though far from consensus) regarding LDR seems to be that it is fundamentally sound, but has some challenges. In addition to the technical challenges discussed in the ORION and Catcher's Mitt final reports, some of the challenges of LDR involve the policy and safety aspects of high power lasers being fired in or into space.

3. AMORE CONCEPT

The AMORE concept described here employs a low energy Neutral Particle Beam (NPB) to impart small amounts of kinetic energy to debris objects. The ORION study considered laser power densities on the order of 250 MW/cm^2 in order to achieve ablation of various surface types [3]. This large amount of directed energy presents a political challenge for those that must explain how such a system is not a weapon that violates treaties. In contrast, the AMORE NPB would exceed expected performance if it managed a flux of 5 W/cm^2.

The AMORE concept is an on-orbit debris mitigation satellite in Low Earth Orbit (LEO) that targets debris within a range of roughly 100 km, and imparts momentum opposite the debris object's velocity. Targeting is performed by an on-board sensor and the system would operate continuously and autonomously, gradually decreasing the perigee of debris objects that come within range. AMORE is not intended to be an immediate solution to the orbital debris problem, but would rather be an ongoing effort to help stabilize the LEO debris environment. It could also be deployed in a more tactical manner, such as immediately after a debris generation event. As AMORE's primary target would be medium sized debris, a future architecture would also include other assets to remove large intact vehicles and stages.

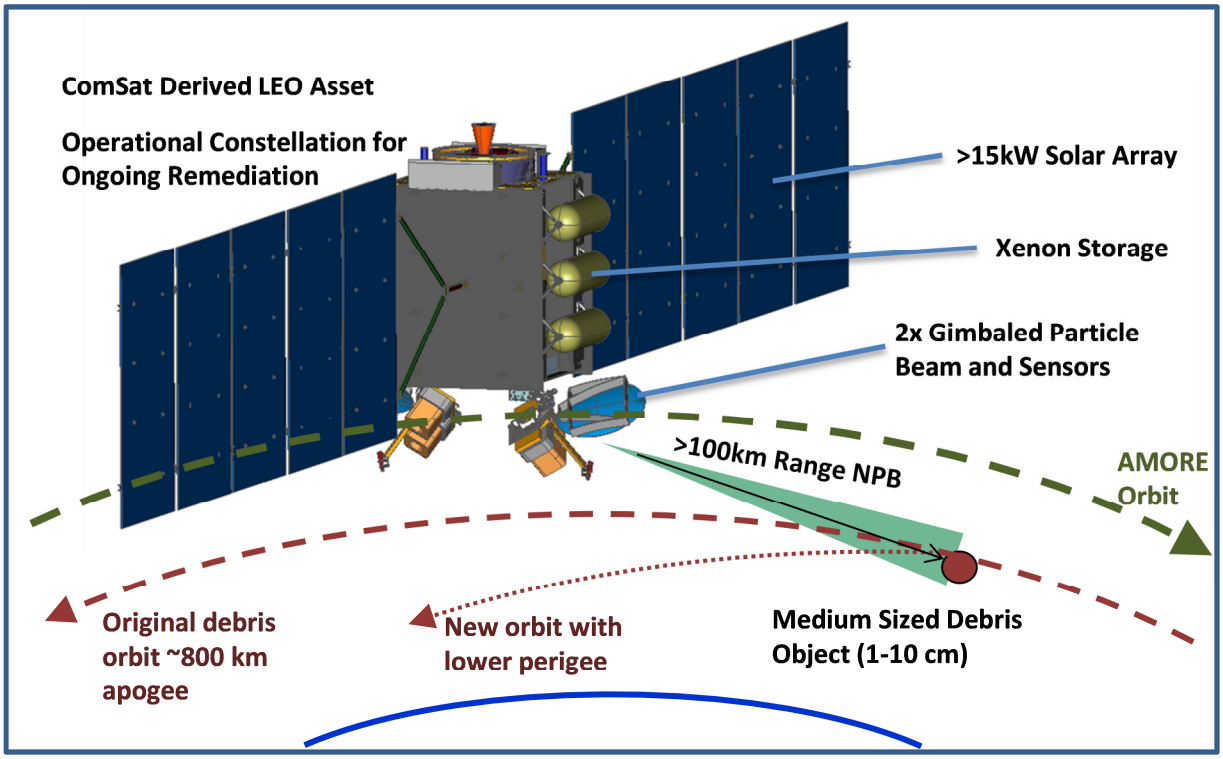

Fig. 1: AMORE Concept

AMORE is envisioned to be a medium-sized satellite, roughly the size of a typical commercial geostationary communications satellite (ComSat). Indeed, a ComSat bus is well suited to host AMORE as it inherently has high ΔV and power capability. The NPB would likely be similar to the Xenon-fed Hall Current Thrusters (HCT) that are used on the latest generation ComSats and would use the same propellant management system and tanks. Current ComSats can provide upwards of 15 kW of continuous power, including through a 72 minute eclipse at GEO; this provides the basic power system capability required to support a LEO mission with a >10 kW NPB. The concept shown in Fig. 1 shows an AMORE vehicle with two gimbaled NPB's fed by 3000 kg of Xenon. Co-boresighted with each NPB is a sensor suite that would provide debris tracking and targeting.

As part of an ongoing remediation program, AMORE should be highly autonomous with a minimal ground support requirement. The sensors on-board will acquire, track, and target debris objects, but there will also need to be an active interface with the ground based surveillance networks. Because the NPB is low energy and poses minimal risk of collateral damage to other assets, the particle beam can be automatically discharged when the on-board computer determines that a debris object can be engaged. The major cost of fielding an AMORE system is in the vehicle cost and launch cost, not in the operations cost. Therefore, it is most cost efficient to maximize the on-orbit lifetime of the vehicle. Current ComSat hardware is typically designed for 15 years or greater, so it is reasonable that the AMORE system should meet a similar requirement. The primary drivers on AMORE life will be the consumable Xenon as well as wear items in the particle beam source, such as the cathodes in an HCT. There is typically a tradeoff between thruster life and performance that will be a challenge as AMORE seeks to push performance higher than current state of the art [4].

4. AMORE PERFORMANCE ANALYSIS

The key to tactical efficiency for AMORE is simple: impinge as much particle mass onto a piece of debris at as high a relative velocity as possible. More strategically, AMORE needs to engage debris as often as it can and impart as much anti-velocity delta-V as it can over a vehicle's lifetime, within the constraints of current satellite

technology. The analyses below assume that AMORE operates around 800 km, where the current cataloged debris population is 5E-08 objects per km³ [5].

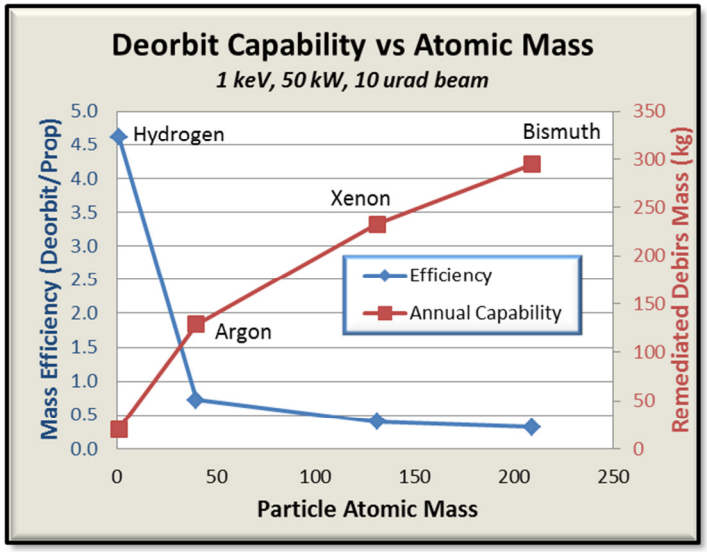

Fig. 2: Particle Mass

Unlike LDR, AMORE does not have a minimum intensity requirement to achieve effects. This enables the use of a wide range of particle beam types from high velocity and low mass rate to low velocity and high mass rate. The particle type trade here is very similar to the ion thruster propellant trade. For a given power, higher atomic mass propellants yield larger thrust at lower efficiency. Fig. 2 shows a comparison of deorbit capability for various particle types for a notional 50 kW beam. The lighter particles attain a higher speed that increases the specific momentum transfer efficiency, but the lower mass flow rate results in a slower rate of momentum transfer. The heavier particles yield a higher annual deorbit capability. Xenon is the current propellant of choice for ion thrusters. In addition to its high mass, it has a relatively low ionization energy and stores efficiently as a liquid with a specific gravity of 2.9, though it does require a pressure vessel. Bismuth Hall Thrusters are an emerging technology that may improve the deorbit capability of AMORE [6]. For the purposes of the proof-of-concept analyses here, Xenon is the assumed particle.

Continuing the ion thruster analogy, the next NPB parameter to consider is particle energy. Again holding available power as a constant, the thruster trade is specific impulse versus thrust. This corresponds to specific momentum transfer efficiency versus rate of momentum transfer. Higher particle energies (velocities) yield higher momentum transfer per unit mass, but also result in lower beam current within a power constraint. As shown in Fig. 3, lower beam energies result in less deorbit capability for a given mass on target, but allow for faster deorbit times due to a higher mass flow rate.

As discussed above, AMORE does not rely on a certain beam intensity to achieve transfer of momentum. At 100 km range, a 10 cm object subtends 1 micro radians (urad). In order for a beam to achieve 100% mass on target, it would need a divergence of 1 urad, coarsely assuming a uniform distribution and perfect aimpoint control. Beam divergence will affect the efficiency of AMORE as less mass is on target. Assuming a uniform distribution in the defined beamwidth, the effect of increasing divergence on deorbit mass capability is shown in Fig. 4. If the goal for an effective system were 100 kg per year, then 10 urad divergence needs to be achieved. Divergence of a collimated particle beam will be dominated by diffusion in the LEO plasma environment. Near term work will analyze what level of divergence can be expected, as well as

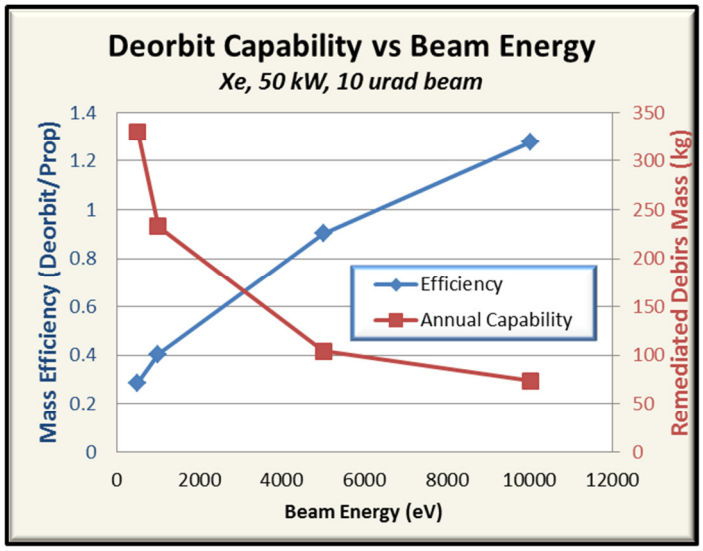

Fig. 3: Beam Energy

what level of pointing control can be achieved. These two factors are key to the performance of AMORE and its viability as an economically sustainable debris remediation method.

The divergence performance target also sets the bounds for the sensor performance required for on-board targeting. The notional concept is for the NPB aperture to be co-boresighted with the targeting sensors. Both would be mounted on a precision gimbal. Both the gimbal and the sensor should have a resolution and accuracy on the order of 1 urad in order to minimize pointing errors and maximize beam on target. The concept for the sensor would be to use a small visible telescope for bearing. Initial radiometry analysis indicates that a 5 cm aperture would be sufficient to reliably track 1 cm objects from 100 km. A 0.2 degree field of view (FOV) with a 2k focal plane yields 1.6 urad pixels, and minimal centroid processing would be required to achieve sub urad accuracy. The simplest implementation would be to receive ground surveillance tracking to cue the on-board sensor; a 0.2° FOV would require a 340 m position accuracy for handoff

The need for on-board range estimation has not yet been evaluated, but may be required to support predictive aimpoint control. A 1 keV Xenon beam has a 1.65 second time of flight at 100 km, which results in an 18 km relative translation at an average 11 km/s relative rate [1]. To maximize beam on target duration, sensor range can be extended reasonably to 200 km or greater. The tradeoff for greater operating range is higher average power. As shown in Fig. 5, increasing the operating range linearly increases the amount of debris deorbited. Quantity of debris accessed increases with the square of range, but this gain is offset by the fact that efficiency drops off with the square of range as the beam divergence results in less mass on target, as shown in Fig. 6. Assuming the NPB operates half the time a debris object is in range, then the beam duty cycle increases with the square of the range, resulting in quadratically increasing average power consumption for

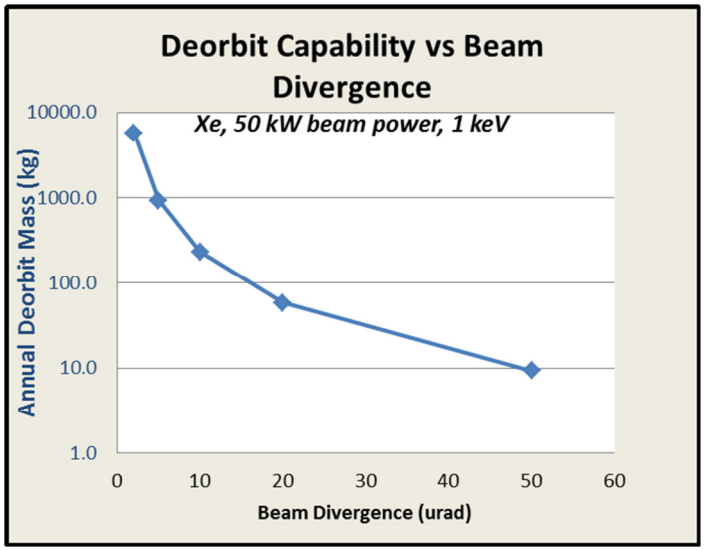

Fig. 4: Beam Divergence

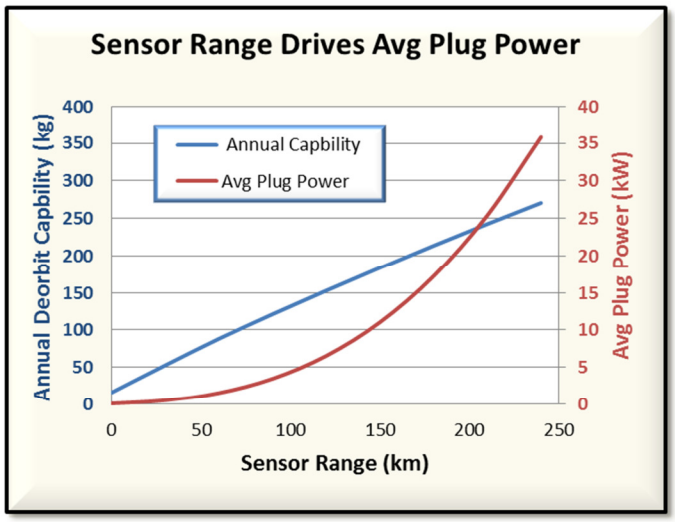

Fig. 5: Sensor Range

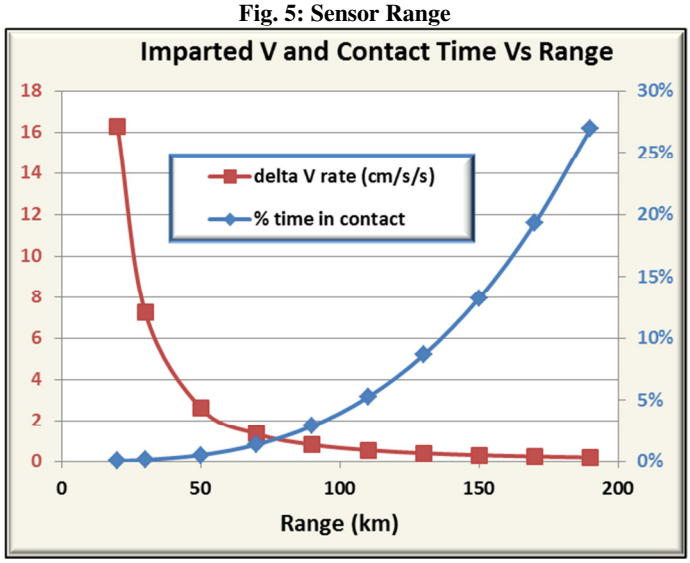

Fig. 6: Delta-V Rate

increasing range.

Momentum must be imparted onto debris objects in the anti-velocity direction in order to reduce orbital energy. Geometrically, this means that AMORE will primarily discharge its NPB at objects coming toward it, with the exception of objects that are close to co-orbital but that are at lower orbital velocities and therefore are moving away. An operational AMORE concept would have to rely on an automated mission planning tool that optimizes total debris remediation within constraints such as power, debris approach, debris size, geometry, range, and lighting.

5. CONCLUSION

The AMORE concept is a fundamentally sound orbital debris remediation technique. Its directed NPB is essentially a focused Hall Current Thruster that can apply momentum to medium sized debris objects without rendezvous. The key to success for AMORE is developing the ability to achieve particle beam divergence less than ~10 urad on a 10 keV class beam. Analysis indicates that within the electrical power limits of an on-orbit asset, heavy and slow particles are more effective at transferring momentum than faster lighter ones, assuming a constant beam divergence. If a 10 urad beam divergence could be maintained, then a 1 keV Xenon beam with a current of 50A would be capable of remediating 184 kg of debris annually. Such a system would use 284 kg of Xenon a year at an orbital average power of 11 kW, meaning it could be accommodated by medium sized modern ComSat and operate for 15 years. Near term future work should focus on evaluating beam control techniques to determine what level of divergence is within reach. This will establish whether or not AMORE is economically feasible.

6. REFERENCES

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