**Overcoming Orbital Debris Cleanup Challenges**

**The National Space Society (NSS) recommends that all spacefaring powers commit to limiting future orbital debris and to cleaning up existing orbital debris as soon as possible.**

**Specifically, NSS recommends that:**

* **there be greatly expanded public spending for public-private projects to develop cost-effective Space Situational Awareness (SSA) technology and systems.**
* **there be greatly expanded public spending for public-private projects to develop cost-effective deorbit and reuse technology.**
* **the Federal Aviation Administration (FAA) require (for the licensing of companies launching to LEO) clear demonstration that they will: A) use the shortest-life and least-crowded orbit compatible with the mission; B) include cost-effective spacecraft shielding against small impactors; C) safely deorbit or re-use dead spacecraft within two years post-mission; D) launch satellites with standard “handles” and modular, easily replaceable or accessible parts to facilitate remediation in case shielding or automated deorbiting fails; and E obtain insurance (as soon as it is available) to protect against liability claims and failure of spacecraft launch, de-orbit, or re-use.**
* **the international space community phase out 25-year post-mission free orbital parking by periodically shortening the allowed post-mission periods, while grandfathering in all spacecraft launched and operated in compliance with regulations then in force.**
* **insurance companies participate in any national or international agreements dealing with orbital debris mitigation or remediation.**
* **the United States openly and transparently begin removing, through COTS-type public-private space agreements, old US rocket bodies and dead satellites from LEO.**
* **the** **United States actively seek to include both Russia and China in its international, public-private efforts to clean up orbital debris.**
* **the White House create by executive order a new national entity called the Space Traffic Management Executive Committee (STM ExCom) to help carry out space debris cleanup in collaboration with analogous entities in spacefaring countries worldwide.**
* **the space entities responsible for any spacecraft already in orbit be grandfathered under the policies in existence at the time of their launch, so that they are not penalized by any new anti-debris policy or rule, which the STM ExCom develops in coordination with international entities.**
* **remediation funding come from the following three sources and systems: A) General *government* revenues for remediation of debris from past and future *government* satellite launches; B) A fee of perhaps 0.1% on the bills of all consumers of *commercial* satellite services worldwide for remediation of debris from future *commercial* satellite launches; C) Minimal, mission-duration “parking” fees, *on all companies* launching new spacecraft into any Earth orbit in order to fund debris remediation where debris Launching State and ownership *cannot be clearly ascertained*.**
* **the White House delegate contracting authority to the STM Coordination Office to fund commercial entities to carry out orbital debris cleanup through a monetary reward system using space agreements within a public-private COTS-type service-acquisition strategy.**
* **the federal government provide funds to the U.S. Naval Research Lab and other entities to *fully* develop technologies for tracking debris smaller than 10 cm in diameter and to facilitate commercial integration of these technologies into the eight emerging detection and tracking entities worldwide.**
* **international public-private consortiums study a wide range of debris management technologies and strategies, then developing the most promising ones.**
* **spacefaring countries utilize the International Space Station to spur international cooperation for testing and deploying orbital debris management technologies.**
* **spacefaring countries, along with public and private space-related entities within their borders, organize and participate cooperatively in an International Orbital Debris Convention, in compliance with OST Article IX, to clarify legal responsibilities and rights vis-à-vis orbital debris management.**

**INTRODUCING THE PROBLEM**

Orbital debris is any human-made and uncontrollable litter left in Earth orbit. It includes inactive satellites, rocket stages, and fragments created by collisions, explosions, and even normal operations. There are over 21,000 Earth-orbiting debris objects larger than a softball (10 cm) and over 500,000 shrapnel fragments between 1 and 10 cm. The number of shrapnel smaller than 1 cm exceeds 100 million (NASA 2013). With relative impact velocities sometimes higher than 26,000 mph (Marks 2009), even debris as small as 0.5 cm can take out spacecraft (Liou 2014). The number of debris objects *larger than* 1 cm will reach around 1 million in year 2020 (European Commission 2013).

The deliberate destruction in 2007 of the Chinese Fengyun satellite with an antisatellite weapon and the catastrophic 2009 collision between a defunct Russian Cosmos satellite and an operating Iridium satellite have together contributed to nearly as many currently tracked fragments as all previous fragmentation events together (NASA 2015). Largely because of the debris caused by these two events, NASA, analyzing data from six space agencies, estimates that if nothing is done there will be another catastrophic collision every five to nine years and the pace will accelerate (Liou 2014). At least some who have been studying orbital debris for many years believe that we may have already reached a “tipping point,” whereby orbital debris in congested Low Earth Orbit (LEO) altitude bands is colliding in a *runaway cascading debris-generation scenario*, often called the Kessler syndrome. Although this assertion is controversial and a debris cascade would take years to unfold, at some point a Kessler cascade would nevertheless make spacecraft viability in affected altitude bands virtually impossible (McKnight & Kessler 2012; Kessler & Cour-Palais 1978).

Orbital debris is an ever-growing hazard to the International Space Station (*NASA Orbital Debris Quarterly* News 2015) and the approximately 1,300 operating satellites, which represent only about 6 percent of the 21,000 tracked objects in orbit (Baiocchi & Welser 2015). Moreover, space companies are planning to launch thousands of new satellites in the near future (Davis 2015).

The threat to operating satellites that provide communications for television, radio, GPS, pagers, cell phone applications, navigation, search and rescue, weather and climate reporting, and national defense varies, depending generally on potential impact velocities and the mass of debris in the satellite’s orbital altitude and inclination.

Although it is difficult to determine what percentage of satellite failures are due to orbital debris strikes, as opposed to other causes such as meteoroid impacts, the increasing amount of orbital debris is undoubtedly a factor in annual economic losses in the satellite industry. In fact, claims paid out by insurance companies for on-orbit spacecraft failures just in 2013 reached $800 million (OECD Publishing 2014).

Future large structures in Earth orbit, such as commercial space stations, hotels, space solar power satellites, multi-satellite platforms, and settlements will also be vulnerable to orbital debris -- which will grow from future collisions, *even if we put no new spacecraft into Earth orbit* (Moskowitz 2011; Liou 2010 & 2014).

There are both non-technical and technical challenges to cleaning up orbital debris. Because the greatest debris threats lie in LEO (160 – 2000 km, particularly 750 – 1000 km) and GEO (35,786 km), this paper focuses mostly on those altitudes. *Non-technical* challenges consist of 1) adverse economic factors, *2)* policy and legal barriers, and 3) international/geopolitical sensitivities. *Technical* challenges include 1) inadequate Space Situational Awareness (SSA), which includes debris detection, tracking, and conjunction predictions and 2) lack of ready technology for removing or using orbital debris.

**MITIGATION (ALONE) WILL NOT STOP THE THREAT FROM GROWING**

In this paper, *mitigation* refers to any policy, activity, or technology that seeks to prevent orbital debris from coming into being or seeks to prevent debris from knocking a spacecraft out of service. Examples of debris mitigation include lowering a spacecraft at its end of life (EOL) to force the satellite to deorbit naturally within 25 years (“the 25-year guideline), or raising the orbit of a GEO spacecraft at its EOL to a graveyard orbit 300 km higher than GEO (Liou 2011), or shielding a spacecraft so that it will not be damaged by debris. In this paper, NSS gives recommendations for strengthening some of these mitigation policies and strategies.

Mitigation is important to help slow the growth of orbital debris. However, the space community is planning thousands of new launches within several years (Davis 2015), *and even without new launches* and with 90% compliance with the 25-year deorbiting-after-use guideline*,* orbitaldebris, because of future collisions, will *continue to grow in quantity and threat for at least the next 200 years* (Liou 2014; Liou 2011).

*Remediation* refers to *active* debris removal (ADR) or the active rehabilitation of defunct spacecraft (ASR) to produce operational ones. ADR means taking direct actions to remove debris objects from orbit (Liou 2015). ASR means taking direct actions to rehabilitate spacecraft by either refueling, repairing, or reusing of parts. Space entities could reuse defunct spacecraft or their parts by attaching functioning units to defunct spacecraft or their parts in a process called “cellularization” (Barnhart 2014).

Remediation also includes the eventual possibility of recycling a defunct spacecraft parts or metal for other types of on-orbit fabrication (Anzaldua 2014).

The altitudes with the largest number of objects pose the greatest *current* risk or threat to satellites. However, the altitudes with the highest *overall mass* represent the greatest *future* threat, because the more mass involved in collisions, the more destructive will be the debris (McKnight & Kessler 2012). Based on these criteria, and accounting only for *trackable* objects 10 cm or larger in LEO, orbits around 780 km are currently the most hazardous, and orbits around 780 km, 840 km, and 920 - 1000 km pose the greatest *future* threat or risk in LEO (McKnight & Kessler 2012). The good news is that NASA estimates that the LEO environment can be stabilized during the next 200 years with an ADR rate of five large objects per year carefully selected on the basis of mass and collision probability (Liou, “Controlling…” 2010).

Unfortunately, in terms of future debris creation, only around 40% of the about 6000 tons of material in Earth orbit is in LEO. The rest is in higher orbits (Liou, “A parametric…” 2010), half (c. 30%) in and near GEO, and most of the rest (< 30%) between LEO and GEO. Worse yet, the most dangerous debris, at least in LEO, consists of shrapnel currently too small to detect and track, i.e. objects smaller than 10 cm. Shrapnel between 1 – 10 cm number around 600,000 objects (European Commission 2013), and there are over a million objects as small as 0.5 cm that can take out a spacecraft (Liou 2014).

It therefore behooves the space community to quickly move beyond mere mitigation, and put increased effort into orbital debris *remediation* of debris objects 0.5 cm and over in size (Liou 2014). To carry out such remediation effectively, a great improvement in international Space Situational Awareness (SSA), which includes orbital debris detection, tracking, and conjunction reporting, will also be necessary.

***MITIGATION* OF SPACE DEBRIS IN THE FUTURE: FAA ROLE**

**The National Space Society recommends that the Federal Aviation Administration (FAA) require (for the licensing of companies launching to LEO) clear demonstration that they will:**

* **use the shortest-life and least-crowded orbit compatible with the mission;**
* **include cost-effective spacecraft shielding against small impactors;**
* **safely deorbit or re-use dead spacecraft within two years post-mission;**
* **launch satellites with standard “handles” and modular, easily replaceable or accessible parts to facilitate remediation in case shielding or automated deorbiting fails; and**
* **obtain insurance (as soon as it is available) against liability claims and failure of spacecraft launch, de-orbit or re-use.**

The Federal Aviation Administration (FAA), as the entity currently responsible for issuing launch permits based on its judgement of adequate liability insurance and safety characteristics, is the logical agency to judge the adequacy of deorbit-plans and insurance policies*.* The FAA would be able to coordinate internationally with analogous institutions in other countries through a national Space Traffic Management entity NSS proposes below under the title, “Remediation of Extant & Future Orbital Debris.”

At this time, deorbit services upon failure of automated deorbiting mechanisms are not commercially available, so pricing such insurance would currently be difficult. For this reason**, the NSS also recommends greatly increased public spending for public-private projects to develop cost-effective deorbit and reuse technology.** Deorbit-failure insurance would be fundamentally similar to purchasing insurance against launch vehicle failure. However, rather than simply paying out damages, the insurance companies would pay commercial contractors to dispose of, rehabilitate, or recycle the orbital debris through commercial contractors, along the lines described below. While the purchase of de-orbit insurance is in part a mitigation strategy, debris cleanup consequent to deorbit failure would be a remediation action.

A mitigation policy exists, which actually complicates implementating of better mitigation systems. Under USG Orbital Debris Mitigation Standard Practices (U. S. Government 2015), satellite companies are not required to deorbit or otherwise move their satellites to higher-altitude graveyard orbits until 25 years have passed after the end of the satellite’s mission. This policy, being adopted internationally, amounts to 25 years “free parking” post-mission. While an improvement over the previous no-limit-while-dead-on-orbit situation, free orbital parking post-mission for any object that cannot actively avoid all dangerous conjunctions still endangers operating satellites and other operating spacecraft. Therefore, **the NSS recommends that the international space community phase out 25-year post-mission free orbital parking by periodically shortening the allowed post-mission periods, while grandfathering in all spacecraft launched and operated in compliance with regulations then in force.**

Orbital debris cleanup would be facilitated if insurance companies offered lower premiums to companies utilizing reusable boosters, automatic deorbiting mechanisms, locator beacons, or other technologies facilitating either orbital debris mitigation or remediation. For these reasons, the **National Space Society recommends that insurance companies participate in any national or international agreements dealing with orbital debris mitigation or remediation.**

***REMEDIATION* OF EXISTING DEBRIS IN LEO**

Overview of Orbital Debris Objects in LEO

Tracked debris larger than 10 cm in diameter can range all the way up to 9-ton rocket bodies and 5-ton satellites. Most tracked LEO objects >1 kg are defunct, but intact, satellites or rocket stages. Three-quarters of the total mass of these objects consists of objects over a ton. Therefore, ton-class bodies (roughly half satellites and half rocket bodies) make up the most of the mass of approximately 2200 tons in LEO, leaving another 4100 tons of debris in higher orbits (Carroll….speaking 2014).

Ton-class Objects Make More Shrapnel in LEO

Removing orbital shrapnel in LEO without addressing their source, i.e. collisions between large orbiting objects, would be like bailing water out of a boat without repairing the hole in its hull. The greatest eventual danger will come from inevitable (without active intervention) catastrophic collisions between ton-class passive debris objects, producing both immediate and subsequently greater financial loss due to consequent shrapnel (Pearson 2012 & 2014). For this reason, **NSS recommends remediating large objects in LEO as soon as possible.**

Geopolitical Considerations

The International Space Station (ISS), while it serves as a testbed for emerging orbital debris cleanup technologies and techniques, offers us an ongoing way to engage the international community and overcome geopolitical rivalries. Russia, however, will no longer be participating in ISS activities after 2024. This future loss of cooperative engagement with Russia will be particularly unfortunate given that Russia and the United States were the major producers of debris composed of empty upper stages, the major source of future debris in LEO (Pearson 2012; Carroll…speaking 2014).

Launching governments, through their classification of technology “secrets” and their dual-use technology transfer rules, have shown themselves to be very sensitive about the attributes and capabilities of their satellites, especially military ones. Therefore, to induce international cooperation to remove, repurpose, recycle, or rehabilitate large debris objects, it is best to start with these much less sensitive, but still dangerous, upper stages (i.e. usually mostly aluminum-alloy tanks), which make up about half of the LEO debris mass. Although passivation, by expelling remaining fuel and discharging batteries, now keeps such stages from exploding, they remain dangerous in their uncontrolled state. Even so, capturing aluminum tanks would also be a lot less complicated than grabbing or manipulating satellites with solar arrays, antennas, and/or nuclear reactors.

About 693 tons of the spent stages in LEO, representing 41% of LEO-debris mass, consists of Russian rocket bodies (see below graphic). **Removing only Russian rocket bodies from LEO could reduce future shrapnel creation by nearly 62% (Pearson 2012).** This exceeds the 48% reduction that would occur if *all non-Russian* mass were removed from LEO.

**LEO Mass Ownership, Tons/Km Altitude (Carrol 2015)**

Nevertheless, \* NASA’s Commercial Orbital Transportation Services (COTS) program demonstrated a ***20 to 1 reduction*** *in development and acquisition* ***costs*** for its commercial cargo transportation services to the ISS (Zuniga 2015). This model used space agreements whereby NASA entered into partnerships with industry to jointly share cost, development, and operational risks to demonstrate new capabilities for mutual benefit. Recommendations for funding COTS-type programs are listed below.

As the US Government, in coordination with US companies, takes steps to clean up its own debris, the US should approach Russia for bilateral collaboration. A good start would be for talks between Russia and the US on the range of space operations and safety considerations, i.e., SSA, respective catalogs of space objects, national research and regulations for debris mitigation, conjunction analysis, etc. Ideally, these talks would lead to US/Russia bilateral orbital debris agreements, which would deal with about 86% of the mass in LEO.

Although United States – Russia relations have fallen to a low level since the cold war, there is a shared interest in and responsibility for ensuring that the space environment is safe and sustainable. Throughout such talks, the goal should be to demonstrate to Russia that it is in its own best interest to address the threat of orbital debris, regardless of what the US and other countries do. What can we therefore say to the Russians along these lines?

First, under the 1972 Space Object Liability Convention, all space objects, large and small, carry with them strict launching state(s) liability for reentry damage and (undefined!) “if at fault” on-orbit damage. Second, cleaning up the debris represents potential value in terms of already emplaced debris objects for repurposing. Third, if Russia collaborated with the US to remediate orbital debris, it would have a chance to advance its own space technology and industries, while keeping an eye on the advancement of space technology (including possibly laser technology) of other countries. Fourth, cooperation with the U.S. would offer a way to lower geopolitical tensions.

There is nothing for the U.S. and other countries to lose and much to gain by reaching out to Russia to clean up orbital debris. *The same goes for reaching out to China*, which has recently been signing agreements with Russia for cooperation in space, including in setting up a lunar station (Song 2015). Although the 2011 Wolf amendment effectively bars NASA from engaging in bilateral space agreements with China, there is growing debate over whether that legislation is counterproductive and should therefore be overturned (David 2015). For dealing with either country, provisions of the International Traffic in Arms Regulations (ITAR) would need also likely need to be amended.

Continuing to exclude China, the source of much orbital debris, from civil space cooperation will not prevent it from developing its own capabilities (Weeden 2015). Space weather, scientific research, exploration, disaster response, and global environmental monitoring are areas where the US and China could collaborate with each other and other interested countries in a way that would lower tensions while achieving positive gains (Weeden 2015).

No country alone can affordably clean up debris sufficiently to remove the threat of catastrophic collisions, and both Russia and China are key players in cleaning up orbital debris. **The National Space Society therefore recommends that the** **United States actively seek to include both countries in its international, public-private efforts to clean up orbital debris. To facilitate cooperation with China, the NSS also recommends that the US Congress repeal the 2011 Wolf amendment, which bars the use of Federal funds to conduct bilateral science exchanges with China.** Instead, Congress might consider limiting such exchanges to areas of overwhelming common interest such as space debris, planetary defense, and space weather.

**FACILITATING *REMEDIATION* OF EXTANT & FUTURE ORBITAL DEBRIS**

The worldwide space community and the public it serves needs national and international entities to cooperatively generate policies and guidelines for orbital debris cleanup. From the standpoint of international law, spacecraft and their debris are the responsibility of each space-faring government (*Treaty* 1967). Therefore, to honor this responsibility in matters of remediating existing or future debris, **NSS recommends that the White House create by executive order a new national entity called the Space Traffic Management Executive Committee (STM ExCom)** **to help direct space debris cleanup in collaboration with analogous entities in spacefaring countries worldwide**.

STM ExCom could be established *in full compliance with existing international treaties and law.* Under Article VI of the Outer Space Treaty (OST), the U.S. Government has agreed to authorize and continuously supervise the space activities of both its governmental agencies and its non-governmental entities (Treaty on Principles…, Art. VI 1967).Ideally, to be an effective actor in orbital debris related efforts, the STM ExCom and its connected offices would:

* be established quickly through Executive action;
* function within the Executive Branch of the U.S. Government (USG);
* have input from relevant USG agencies and private experts connected to Space;
* be flexible and nimble, i.e. able to react quickly to changing circumstances;
* have permanent staff provided by USG agencies, yet have the ability to form ad hoc committees, composed of USG employees and civilians, to plan and solve particular problems; and
* be able to interact cooperatively and transparently with national *and international* entities and persons, both public and private.

As it turns out, a national entity already exists that fulfills the above conditions and could *serve as a model* for a separate orbital debris management entity. The National Executive Committee for Space-Based Positioning, Navigation, and Timing (PNT ExCom), was created by Executive action in 2004, serves under the White House, and deals nationally *and internationally* with planning and problems arising from the GPS and Space-Based PNT. The STM ExCom would therefore be structured and staffed similarly, but with important variations, to the PNT ExCom. (See the notional organizational diagram for the STM entity below and Annex A for other details.)

The organizational chart above is only notional, and we expect it to be later refined. Although the STM ExCom would be the overall supervisory body, the **STM Coordination Office** would organize the actors, coordinate the action, carry out everyday work, and house permanent staff provided by the relevant Federal agencies.

Note that we are also proposing an **International Working Group** connected to the STM Coordination Office. The International Working Group, chaired by State, would be the body coordinating with the International Telecommunication Union (ITU), UN Office for Outer Space Affairs (UNOOSA), spacefaring countries, and international space entities, such as the Space Data Association.

**The NSS recommends that the space entities responsible for any spacecraft already in orbit be grandfathered under the policies in existence at the time of their launch, so that they are not penalized by any new anti-debris policy, which the STM ExCom develops in coordination with international entities.**

**ECONOMIC ASPECTS AFFECTING *REMEDIATION***

Adverse Economic Incentives in LEO

Almost all current users in LEO are public entities providing social benefits (Weeden 2013 & 2012). Publically provided societal benefits, such as national security, science, climate and weather monitoring, disaster response, natural resource management, and space exploration, are not particularly responsive to prices and markets. Although we are poised for massive growth in commercial LEO operations (Davis 2015), total private benefits currently from LEO only amount to $3 billion (Weeden 2013 & 2012). Complicating the picture, governments, especially their military agencies, are not yet open to mutually agreed-upon regulation of the LEO commons. The challenge therefore is to incentivize debris cleanup in LEO, even while the majority of currently operating satellites in that orbital band are government-owned and providing social benefits.

Consumers of Public & Private Satellite Services: Pay Now or Pay More Later

Commercial satellite companies providing communication services for television, telephone, radio, and Internet tend to operate in GEO. This will soon change, however, as commercial entities are making plans for services to be supplied from LEO as well (Davis 2015). Therefore, an economic incentive already exists to clean up debris in GEO, and there will soon be one in LEO. However, the technical challenges to carry out remediation at any altitude are daunting because of varying trajectories; tumbling debris; lack of adequate tracking of both small and large debris; and fueling systems and electronics emplaced without thought to later repair, replacement, or resupply.

Developing and utilizing technology and international systems for orbital debris cleanup is bound to be expensive. If the past is any indication, public and private space entities will eventually pass on these costs, through either through taxes or higher service fees, to the consumers of satellite services. However, the consumers of commercial and government-provided satellite services need to understand that *they are already in a “pay now or pay* ***more*** *later” situation*. If they wait until there are more catastrophic orbital collisions, these consumers will suffer disruption of satellite services, and their bills for cleanup will be much higher than if cleanup proceeds proactively (McKnight 2012). For this reason, our proposed funding mechanisms below entail proactively bringing in funds, either directly or indirectly, from end-consumers of satellite services before cleanup costs rise further.

**FUNDING & FUND USE FOR DEBRIS CLEANUP**

**To fund remediation in three separate debris target areas, the NSS recommends that funding come from the following three sources and systems:**

* **General *government* revenues for remediation of debris from past and future *government* satellite launches.**
* **A fee of perhaps 0.1% on the bills of all consumers of *commercial* satellite services worldwide for remediation of debris from future *commercial* satellite launches.\***
* \* Most tracked fragments change inclination by <1 degree from their source object, and most are traceable to not just a source owner, but a source object. However, sun-synch orbit (roughly 97-99 deg.) is the second most popular inclination (after 81-83 deg.), and *many countries use sun-synch*. Therefore, *if you do not detect and start tracking an object soon after it is launched, you may not be able to identify its owner or Launching State after you do find it* (Carroll 2014 NewSpace Conference).

The proposed STM Coordination Office described above, working closely with the FAA and Department of Commerce, and in consultation with international entities such as the Satellite Industry Association (SIA) and Space Data Association, would ideally assess parking fees based on a calculation of the increased relative debris-creation threat that each new launch represents, and scaled to modestly underestimate the resulting costs. That calculation in turn would be based on an estimate of the mass density of the orbit into which the new spacecraft is being launched, with higher fees being assessed on companies launching large, long-duration spacecraft to the most densely crowded LEO orbits. (See Annex B for notionally suggested rates, which show that small startup companies launching to low orbits would be paying minimal fees.) Space companies will therefore likely try to avoid launching into the most crowded orbits, and this will help to hold down the threat.

Concerning funds gathered from end-consumers of commercial satellite services, we suggest that the charge appearing on the end-consumer’s bill be specifically identified as an “Orbital Debris Mitigation and Remediation Fee.”A fee, so imposed, will have two very beneficial effects: 1) it would raise over $80 million/year (The Tauri Group….” 2015) and 2) it will instantly make consumers aware that there is a need for orbital debris remediation in the orbital band from which they are receiving satellite service. Consumers will also realize that they are playing an important part in maintaining satellite services to them.

* The Executive Branch has contracting authority as implied from the theory that the U.S. Government is charged with performing public duties, and to fulfill these obligations, contract formation is not only proper, but necessary (CON 210: Government Contract Law). As a practical matter the U.S. Congress often limits or adjusts Executive contracting authority through legislation (ex: NASA Authorization Act of 2010).

To explain further a key point, under this monetary reward system, funds would be gathered into three different funding pots for debris remediation in three different situations: 1) government-caused debris, 2) commercially caused debris, and 3) debris where the Launching State and ownership is unclear. The **STM Coordination Office**, working closely with the FAA, would award the reward money under COTS-type agreements to private companies only upon a company achieving pre-negotiated pay-on-performance milestones, the last milestone being successful debris remediation. Insurance companies, paying for deorbiting in lieu of satellite company action, would also pay for remediation through a similar acquisition strategy. In this way, no entity need pay for expensive development projects, or for failures, but *only for results*.

Sufficiently high monetary rewards would entice private entities to compete for space agreements by creatively using various technologies to remediate both large and small debris. Moreover, private companies attempting such remediation would necessarily have to collaborate, perhaps via sub-contracts, with Space Situational Awareness (SSA) entities in order to carry out successful remediation. Thus, SSA entities would be able to evolve their technologies based on involvement in actual remediation efforts instead of theoretical ones.

**OVERCOMING THE LACK OF ADEQUATE SPACE SITUATIONAL AWARENESS (SSA)**

Before orbital debris can be removed, stored safely, or rehabilitated through refueling or repair, it must be tracked in real time and down to a size that is still dangerous yet cannot be practically shielded against, i.e. 0.5 cm (Liou 2014). The USAF Joint Space Operations Center (JSpOC), through its Space Surveillance Network (29 telescopes & radars), tracks > 20,000 debris objects roughly the size of a softball (10 cm) or larger. Using several sightings for each object being tracked, JSpOC, only determines the object’s position every 90 minutes and gives conjunction predictions seven days in advance and with error-bars of 1.5 – 10 km (Beason 2014). Satellite owners know that 9,999 out of 10,000 warnings will likely be false alarms. Therefore, they ignore most warnings. Better tracking of objects, including those < 10 cm, could lead to much fewer false alarms and better satellite owner compliance (Riot 2012).

Fortunately, The U.S. Naval Research Laboratory (NRL), Geospace Science and Technology Branch, has recently patented its Optical Orbital Debris Spotter (OODS), a compact, low cost, low power space debris concept that can be integrated into larger satellite designs of flown independently on board nano-satellite platforms (Parry 2015). The OODS throws up a laser light sheet capable of detecting debris as small as 0.01 cm near the host spacecraft for near real-time characterization of debris fields. Because this technology is just now emerging, however, it will have to go through a period of testing and development before deployment.

Hand-in-hand with emerging small debris detection technology, eight new detection and tracking systems are also emerging, and three are commercial. (See Annex C.) On the potential buyer side of the market are large commercial operators such as Intelsat, Iridium, GlobalStar, Orbcomm, Eutelsat, and others. They may buy directly or become indirect buyers through organizations like Space Data Association (SDA) or ComSpOC using SSA data to provide analysis for them. Small and single-satellite operators may just buy data piecemeal for their satellites. Universities may buy data for research purposes (Levin 2014 & Ferster 2015).

Therefore, potentially interested buyers and potentially capable sellers exist. What appears to be missing is a debris data-trading floor to facilitate buying and selling. A civilian-run and regulated Debris Data Exchange, operating like a stock exchange (Levin 2014). Although the aforementioned SDA is an non-profit, international data cooperative with more than 25 dues-paying companies and government agencies voluntarily sharing data (Ferster 2015), the potential exists with this or a similar organization to develop and spin off a trading entity for buying and selling high-value SSA data.

In sum, **NSS recommends that the USG provide funds to NRL and other entities to *fully* develop technologies for tracking debris smaller than 10 cm in diameter and also to facilitate commercial integration of these technologies into the eight emerging SSA entities.**

**OVERCOMING THE LACK OF READY TECHNOLOGY FOR ORBITAL DEBRIS *REMEDIATION***

Because of the attenuation of the atmosphere increases as distance from the Earth’s surface increases, the length of time that orbital debris persists depends on its altitude. Debris persists few days if under 200 km (125 mi); a few years if between 200 km and 600 km (370 mi); decades if the debris is between 600 km and 800 km (500 mi); and centuries if over 800 km. The difficulty of detection and tracking with Earth-based sensors also increases with increasing altitude, as does the difficulty faced by Earth-launched remediating spacecraft, especially those using chemical propulsion. This situation, therefore, favors space-based sensors and remediating spacecraft using non-propellant propulsion, or at least less-expensive non-chemical propellant propulsion.

Although most of the *tracked*debris is in LEO, with the greatest concentration found between 750 – 1100 km altitude, total debris numbers and total mass peak at different altitudes (see graph below). This means that the greatest current threat is around 780 km altitude, the greatest future threat will be around 840 km, as the rocket bodies that compose most of the debris mass at that altitude will inevitably begin colliding with one another (McKnight & Kessler 2012).

Image: ESA. From Darren McKnight, Donald Kessler, “We’ve Already Passed the Tipping Point for Orbital Debris.” 26 September 2012.

Many technologies have been proposed for orbital debris *remediation*. The idea behind these proposed technologies is either to remove debris, repurpose defunct satellite parts, or rehabilitate defunct satellites by refueling or repairing them. We describe several of the more promising debris remediation technologies and practices below. Unfortunately, few of the emerging debris cleanup technologies described below have been developed beyond Technology Readiness Level (TRL) 4. We therefore cannot predict which technological approaches will become cost-effective ways to remediate the variety of orbital debris at various altitudes. Moreover, the best remedies will differ depending on a debris object’s altitude, size, shape, type, ownership, and launching state(s). For all these reasons, **NSS recommends that international public-private consortiums study and test a wide range of debris management technologies and strategies, then develop the most promising ones.**

Ground-Based Lasers to Deflect or Remove Debris

One proposed way to deal with large debris objects is simply to nudge them with ground-based pulsed-lasers to prevent collisions.Because only 6% of future shrapnel in LEO is likely to come from multi-ton collisions over 1000 km in altitude, nudging debris below 1000 km could suffice for the immediate future (Carroll, “Can….” 2014). Nudging large objects to avoid collisions would leave the objects mostly intact, however, and possibly dangerous on other occasions.

Ground-based pulse lasers could theoretically deorbit small objects in LEO by nudging them to slow their velocity. In this concept, a powerful ground-based laser would ablate the front surface off a debris target to slow and thereby deorbit it (Carroll, “Can….” 2014). Although the exact lowest to highest debris size-range susceptible to ground laser deorbiting is currently unknown, the above optically equipped and powered laser should be able to deorbit small kg objects in the 10 cm – 1 meter size range.

Larger objects, because of their lower surface area to mass ratios, would take longer and longer as mass increases, until deorbiting by laser becomes impractical due to cost and extended time needed for the deorbiting.For this reason, deorbiting multi-ton debris objects with ground-based lasers is not practical (Carrol, “Can….” 2014).

 Phipps et al. 2011 LODR Concept.

Space-Based Lasers to Remove Debris

The issue of space-based high-power lasers for large debris removal is geopolitically contentious, and such systems are very costly. However, low power space-based lasers to remove small debris objects might be affordable(Carroll, “Can….” 2014) and more geopolitically palatable if transparently operated, civilian-based, and international in scope.

Because of their enormous number and diminutive nature, and even with the emerging OODS technology described above, debris as small as 0.5 cm will remain difficult to track, much less remove. If small object tracking dramatically improves, however, a pulsed-ultraviolet-laser technology that Claude Phipps is developing may provide an affordable way to remove it (Phipps 2014).

This technology would consist of active small debris removal using laser ablation directed from a spacecraft such as the ISS. This new system would use head-on, interaction on debris objects with 20 – 40 kw bursts of UV pulses from a 1.5 meter diameter aperture to clear out small debris in a 400-km thick LEO band. Cost analysis by Phipps estimates a cost of less than $1000 to deorbit each small object within a few months - not exactly cheap, but likely to be much less expensive than other technologies for removing this dangerous threat.

Any space-based laser system is bound to raise contentious geopolitical issues. Such issues could be ameliorated, however, by keeping such systems transparent, civilian-based in the consensus-selection of targets and timing, but with military veto power.

Propellantless Remediation Vehicles in *LEO*

NASA JSC has proposed minimizing the LEO debris count of objects larger than 10 cm by removing 5 – 10 of the most threatening multi-ton objects per year (Pearson 2014). Doing this with rockets lifting single-use grasp-and-deorbit or grasp-and-rehabilitate vehicles could cost $1billion per year and would need to be continued indefinitely.NASA’s only debris removal program thus far has been an ElectroDynamic Debris Eliminator (EDDE) vehicle development program, a phase III Small Business Innovation Research (SBIR) project that ended in May 2014 (Pearson 2014).

Even considering learning curves, ion rockets will likely be around 6 times as costly as propellantless vehicles and chemical rockets about 20 times as costly.A project using ten EDDE vehicles over seven years could theoretically remove 1000 tons of upper stages, reducing future collisional shrapnel by 79% at a projected average cost of less than $500 per kg and an average annual cost of about $70 million. Part of the cost savings comes from the fact that non-propellant vehicles could be launched as secondary payloads (Pearson 2012; Carrol, “Delivery….” 2014; Pearson 2014).

Ton-Class Objects in *GEO*: Slower, But Still Dangerous

The space community does not currently know much about the debris situation in GEO, largely because it is too distant (35,786 km) to measure debris objects smaller than about 60 cm across (Anikumar 2004). We do know, however, that there are more than 1300 multi-ton objects in GEO, and about 70% are not operating and are currently uncontrollable (de Selding 2013).

Even though the collisional velocity of such objects would be much lower than in LEO (impact velocity peaks at about 1.5 km/sec or 3,350 mph), they remain dangerous to working satellites and to potential remediating spacecraft because of their high mass. Moreover, uncontrollable objects are subject to gravitational perturbations than increase orbital eccentricity and relative inclination leading to dangerously high velocities crossing the operational torus within which controlled satellites operate (Rossi 2011).

In reaction to these dangers, the International Telecommunication Union (ITU) has placed increasingly strict requirements on the station-keeping ability of new satellites and demands that satellite owners guarantee their ability to safely move the satellites out of their orbital slots and into “graveyard” orbits, 300 above GEO, at the end of their lifetime (“U.S. Government…” 2015). Unfortunately, evidence is mounting that these *new ITU requirements are insufficient to have a major effect on collisional frequency*. In fact, an altitude increase of at least 2000 km would have to be used to reduce by one order of magnitude the long-term collisional risk among geostationary satellites and explosion fragments (Anselmo 2000).

Rocket-Propelled “Catcher” or Service-Tender Spacecraft in LEO & GEO

Concerned aerospace engineers have proposed various grasping or manipulating spacecraft as catchers or service-tenders, including those utilizing balloons, nets, harpoons, and robotic grapplers (Nock 2013; Quigley 2014; Rutkin 2014; Spark 2012; Foust 2012; Clean Space ESA 2015). In some concepts, the spacecraft would simply grab and plunge to deorbit. In other concepts, the spacecraft would refuel or otherwise rehabilitate a defunct satellite. To be useful in LEO, however, rocket-propelled spacecraft would have to be carry enough fuel to match repeatedly and precisely the speed and direction of target debris moving at different speeds, orbits, and altitudes. The cost of designing, developing, testing, and launching such rocket-propelled spacecraft does not appear to be economically feasible (Bonard 2014). This situation again militates for utilizing propellantless or solar electric propulsion as much as possible for these spacecraft.

On the other hand, because relatively fewer satellites operate in GEO and because of their high commercial or military value, even rocket-propelled service-tender spacecraft at that altitude might turn out to be economically feasible (Foust 2012). It is perhaps for this reason, that the DoD’s DARPA, under a demonstration project called Phoenix, is teaming up with the private sector to harvest and “repurpose” still functional components of nonworking satellites in GEO to create new space systems at hoped-for greatly reduced cost (Dykewicz 2013 & Barnhart 2014).

Beginning in 2016, the Phoenix Project proposes to attach nano-satellites to parts of retired U.S. government and commercial satellites, making the debris a resource. In a process called, “cellularization,” nanospacecraft separately carrying out functions such as power, communications, and attitude control would be launched into orbit as secondary payloads. A service-tender spacecraft would then be telerobotically directed to attach such miniature devices to large antennas or other large parts of dead satellites to produce working satellites at a fraction of the cost of new ones launched from Earth.

DARPA’s cellularization approach is not the only game in town for rehabilitating spacecraft in GEO. Vivisat, a joint venture of ATK and US Space LLC, is proposing a Mission Extension Vehicle (MEV), which would attach to a satellite and take over the satellite’s stationkeeping activity, thus extending its useful life. Canadian aerospace company, MacDonald, Dettweiler and Associates (MDA) Space Infrastructure Servicing (SIS) vehicles, which would use its manipulators to refuel or repair a spacecraft (Foust 2012).

 “Touchless” Electrostatic & Electrostatic-Electromagnetic Disposal of Debris

Another potentially affordable way to clean up LEO and GEO, and perhaps other orbits also, is by using a space-based electron gun or beam emitter to either deflect debris, or tug debris objects to deorbit or reorbit (Bonard 2014; Inamdar 2013; Hans 2014). Electron beam technology is very mature, and the energy needed to generate the electron beam is orders-of-magnitude lower than what is needed for high power lasers. For these reasons, this technology offers a low-cost path for debris removal. The exact size range of debris amenable to this treatment is unknowable at this time, but will likely include kg-class to ton-class objects, at least for towing with electrostatic tethers (described below).

To deorbit a small to medium-sized debris object in LEO or low-MEO by electromagnetic deflection, a spacecraft would direct a beam of electrons to a debris object. The beam would remotely impart an electrostatic charge to the object. Earth’s magnetic field would thereupon exert a force on the electric charge of the debris crossing its field lines at high speed. Over time, the orbit would become highly elliptical and would intersect the Earth’s atmosphere more and more deeply until the increasing friction brings it down.

To collect (by electrostatic tether) an object for deorbit from LEO or for reorbit into a GEO “graveyard” orbit, a beam-emitter spacecraft would generate an electron beam at a debris object, thus remotely imparting an electrically negative potential on the object while the emitting spacecraft or spacecraft part remains relatively positive. The spacecraft could then remotely collect small or large debris, whether metal or non-metal. The same technique could be used in GEO to tug defunct satellites to a disposal orbit.

The big advantage of electrostatic “touchless” technology is that the deflector or tug spacecraft can operate with a separation distance of multiple craft radii, thus greatly reducing the risk of collision, even if the target object is tumbling. In addition, the cost is likely to be much lower than the cost of using propellant-using catcher spacecraft. The disadvantage in GEO, however, is that the higher “graveyard” or “disposal” orbits envisioned would not in fact remove the debris from the cislunar econosphere, and such tumbling debris could therefore create a danger to future highly eccentric/elliptical Earth orbiting spacecraft.

The International Space Station (ISS) has a large power-generation capacity and is already in LEO. An electron beam device could therefore be integrated thereon for testing and deployment as add-on module, avoiding the need to develop and launch a new spacecraft.A transparent, international program, involving space agencies of several countries, could implement projects using touchless or other debris-remediation technologies. Here again, testing and deployment on the ISS would facilitate international cooperation. For all these reasons, **NSS recommends utilizing the ISS to spur international cooperation for testing and deploying orbital debris management technologies.**

**TOWARD THE FUTURE: ESTABLISHING RESPONSIBILITIES & RIGHTS IN SPACE**

Besides the Article VI requirement for “continuing supervision,” Article VIll of the Outer Space Treaty (OST), calls on the Launching State to retain “jurisdiction and control” over any object it launches, whether that object, or even pieces of that object, cease to function or not*.* Removing a debris object *or even its fragments* therefore requires the consent of the State Party on whose registry it was launched (Listner 2012). However, as mentioned above, determining the State Party can be a daunting task for small fragments in popular orbits.

Complicating this picture is the fact that Article VI and VIII of the OST pertain to “Launching States,” who are *not necessarily the owners* of launched spacecraft. After all, the “Launching State(s)” for a rocket and its payload include the country owning the satellite at the time of launch, the country owning the rocket at that time, and the country from which the rocket was launched. Moreover, selling and re-registering an object does not transfer Launching State liabilities to the new owner or registrant. Yet, no matter the owner, Articles VI and VIII, place full responsibility for supervision, jurisdiction, and control of space objects (apparently including fragments) on the Launching State(s). How, then, can this responsibility and its concurrent liability be transferred to a company attempting to remove or otherwise remediate orbital debris?

Under the long tradition of Maritime Salvage Law dating back to the time of the ancient Greeks and Romans,a person who voluntarily preserves at sea any vessel, cargo, freight, or other recognized salvage from danger has traditionally been able to collect a reward (i.e. reward) proportionate to the value of the object salvaged. Maritime nations have most recently codified such custom and law in the International Convention on Salvage 1989. The Convention even considers protection of the environment as part of salvage, awarding a salvor who prevents oil pollution, for example, special compensation termed *liability salvage* instead of *property salvage* (“Law of Salvage” 2015).

Unfortunately, there is no space equivalent to the ancient maritime Law of Salvage, which gives a private party the right to salvage an abandoned vessel after peril or loss at sea, *no matter the owner or country of vessel registration*. Nor is there a space equivalent of the 1972 London Dumping Convention, which prohibits the disposal at sea of vessels, aircraft, platforms, and other debris. An International Orbital Debris Convention, however, could promulgate rules analogous to some in maritime law for the removal, reuse, recycling, or rehabilitation of orbiting objects by salvors, who would collect rewards through the reward system described above.

Such salvage rules could even address removing orbiting shrapnel clusters from the Earth-orbit environment by compensating salvors with *liability* salvage. Key to making such rules work, however, would be the formulation of legal mechanisms for *voluntary and involuntary loss of ownership of and responsibility for the objects to be salvaged*. There would also have to be special salvage exemptions or other provisions for sensitive military satellites. Yet a motivated space community, by means of an International Orbital Debris Convention, could *enlist space-appropriate provisions from these maritime legal systems into an international legal codification to deal with orbital debris*, while resolving the legal uncertainties surrounding Articles VI and VIII of the OST. Is there justification for another international convention in the OST?

**\*** Such a Convention, while international, need not be under the auspices of the United Nations (UN). Indeed, the International Code of Conduct, which was intended to be under the UN (that status recently challenged) and which only dealt with orbital debris mitigation, has languished (Listner 2015).

**Annex A**

As can be seen from the schematic just below, the PNT ExCom, the model for our proposed ODM ExCom, has input from relevant USG agencies and international entities, plus from private persons through an Advisory Board, sponsored by NASA (GPS.gov).

Source: GPS.gov; <http://www.gps.gov/governance/excom/>

The permanent staff for the PNT ExCom are in the GPS-PNT National Coordination Office. Connected to the GPS-PNT National Coordination Office is a GPS International Working Group and Ad Hoc Working Groups needed to do planning and solve problems nationally and internationally. Through the GPS International Working Group, the whole structure feeds into the International Committee on Global Navigation Satellite Systems (ICGNSS) from the U.S., Russia, China, Europe, India, and Japan. ICGNSS operates under the auspicious of the UN Office for Outer Space Affairs (UNOOSA).

Because the permanent staff of the GPS-PNT National Coordination Office plans and quickly solves GPS-PNT issues through national and international coordination and consensus, it has considerable flexibility, nimbleness, capacity, and reach.

The White House by executive action through the U.S. Space-Based Positioning, Navigation, and Timing Policy of December 15, 2004 established the above-described executive offices (U.S. Space-Based 2004). Funding and staffing for the entity largely comes from the U.S. agencies involved.

Although the purview of the (Space-Based**)** PNT ExCom and its offices could theoretically be expanded to include orbital debris, an analogous entity, focused specifically on orbital debris cleanup and coordinating with PNT ExCom, would likely do a much better job coordinating a national and international effort to clean up Earth’s orbits.

**ANNEX B**

 Alt(km)    5 kg     200 kg    1000 kg   Typ. Orb. life
  400       $20       $70         $200         3 months     (eg, deploy from ISS)
  450     $240      $800       $2.4K        8 months
  500       $2K      $7K        $20K        2 years
  550      $15K     $50K    $150K        5 years
  600    $100K   $330K     $1M       12 years
  650    $400K   $1.3M      $4M        25 years
  700      $1M     $3.3M     $10M       50 years

Credit: Joe Carroll, October, 2015

**ANNEX C**

Examples of emerging SSA sellers include the Commercial Space Operations Center (ComSpOC) run by Defense contractor Analytical Graphics, Inc.(AGI), currently using more than 28 optical sensors within eight optical sites, three radio frequency interferometry sites, and two radar instillations to track 6000 to 7000 space objects so far (Loomis 2015 and Commercial 2015).Defense contractor Lockheed Martin has also recently announced that its own effort to develop an orbital debris tracking site in Western Australia (Loomis 2015).

Another emerging SSA seller ExoAnalytic Solutions, is offering a software suite called ExoAnalytice Space Operations Center (ESpOCTM) that can process and interpret optical data from small telescopes in real-time. ExoAnalytic also has a web-based application called SpaceFront™ that enables rapid analysis of astrometric and radiometric data for resident space objects (RSOs) observed by the ExoAnalytic global sensor network. Using such data, SpaceFront™ provides orbital debris conjunction alerts, expected minimum miss distance, and expected time of closest approach. (ExoAnalytic 2015).

Some emerging free or minimal-fee providers of orbital debris data include:

1) the USAF Academy Center for Space Situational Awareness, deploying its Falcon Telescope Network involving twelve universities around the world(USAF 2013);

1. the International Scientific Optical Network (ISON) started by Russian astronomers in 2005, which joins 35 observation facilities with 80 telescopes in 15 countries(Molotov 2014);

3) a consortium of Lawrence Livermore National Laboratory, Naval Postgraduate School, and Texas A&M University deploying its Space-based Telescopes for the Actionable Refinement of Ephemeris (STARE), with a goal to have 18 3U Cubesats in LEO, each with a small telescope to observe objects predicted to have close conjunctions with valuable assets(Riot 2012);

4) the Canadian Space Agency’s Near Earth Object Surveillance Satellite (NEOSSat) launched last year and carrying a 6 inch telescope in a sun-sync orbit to find and track debris in high Earth orbits as one of its missions (NEOSSat 2015); and

5) the Space Surveillance and Tracking (SST) Consortium Agreement signed by representatives of France, Germany, Italy, Spain and the United Kingdom in June 2015 will see its members cooperating to provide an EU-wide Space Surveillance and Tracking Framework to help protect European space infrastructure, facilities and services.

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