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The Space Infrastructure Vulnerability Cadastre: Orbital Debris Critical Loads

Adrian V. Gheorghie¹ · Daniel E. Yuchnovicz¹

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Abstract Orbital debris from over 50 years of human activity in space are threatening the operations of existing and future satellites and the sustainability of high-value satellite orbits. This technical memorandum calls for the development of a cadastre that depicts the vulnerability of critical satellite orbits to accumulating orbital debris. A space infrastructure vulnerability cadastre could serve as a governance tool for use by developers and operators of critical space infrastructures to better communicate the current and future vulnerability of high-value orbits to the accumulation of orbital debris. These high-value orbits are susceptible to “loss” for decades or centuries if generation of orbital debris continues unabated. The concept of environmental critical loads is applied to heavily used orbits as a way to indicate acceptable debris density for satellite operations, and when debris density / risk thresholds approach unacceptable levels that reduce the probability of sustaining spacecraft operations in those orbits.

Keywords Orbital debris · Satellite orbits · Space cadastre · Space infrastructure

1 The Orbital Debris Threat to Space Critical Infrastructure

Countries around the world are increasingly dependent on space assets to fulfill many civilian and military critical infrastructure functions such as communications, earth

imaging, navigation, and early warning systems. Sustainment of space assets is now paramount to the economies and security of spacefaring nations. In the United States, critical infrastructures are thought of as so important that their loss would have a debilitating effect on the security or economic welfare of the country (DHS 2013). Communications satellites and associated ground station assets are a part of the communications critical infrastructure in the United States (DHS 2010). Space is probably not recognized as a sector-specific critical infrastructure in the United States due to the crosscutting and global nature of its applications. Europe has already taken steps to classify space as a critical sector and actions are under way to classify certain space assets as critical infrastructures deserving of increased measures of protection (Schmierer 2015). The economic value of space assets cannot be overstated. According to the Satellite Industry Association, global industry revenues were USD 189.2 billion in 2013 (SIA 2014).

As we continue to place satellites into orbit these space assets are becoming increasingly vulnerable to loss due to the threat of anthropogenic and technogenic contaminants, collectively referred to as orbital debris. With orbital velocities and closing velocities exceeding 7 km/s, satellites are increasingly at risk of experiencing hypervelocity collisions with orbital debris (and other satellites). The consequence is loss of function or, more typically, complete destruction. As fragile, complex systems, spacecraft are vulnerable to debris impacts, especially debris of 1 cm and larger in diameter. The high cost of spacecraft also dictates few on-orbit spares and their complex nature means replacements take years to build and launch.

It is useful to think of the components of space critical infrastructure as comprising the physical asset (satellite) and the orbit in which the asset operates. As a first order

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approximation, orbits can be thought of as space highways whose locations are characterized primarily by their altitude above the Earth and the angle at which the orbit is inclined to the equator. We posit that satellite orbits are as important as the assets that occupy the orbits. While satellites are routinely replaced at the end of their operational life, orbits cannot be routinely replaced. While space is unfathomably vast, only a limited number of highly useful and sought-after orbits exist. Orbits are more susceptible to debris accumulation with increasing altitudes and/or with increasing inclinations. Accumulation of debris in high-value orbits increases collision risks to assets operating there and reduces the sustainability of this prized “real estate.” Therefore, the orbital environment should be maintained as a finite resource that must be protected and conserved accordingly. We submit that sustainability could be enhanced by more effective ways of characterizing the degree to which critical orbits are vulnerable to loss of usefulness due to the accumulation of space debris.

2 Valuable Satellite Orbits

Critical space assets occupy three broad orbital ranges. The low earth orbit (LEO) range includes an altitude band of 200–2000 km above the Earth, and has the advantage of close proximity to Earth and relative ease of access. Earth observation, surveillance, and human spaceflight occur in this orbital range. The medium earth orbit (MEO) range occupies altitudes from approximately 10,000–20,200 km. One of the more valuable orbits in MEO is at 20,200 km, called the semisynchronous orbit, where the satellite orbital period is exactly 12 h. This allows so-called “invisible utilities” like the signals from global positioning system (GPS) satellites to have lengthy transit times across the sky and remain in view of GPS receivers for extended periods. A geosynchronous orbit (GEO) altitude is approximately 35,786 km at a low or zero degree inclination and is prime real estate for the large communications satellites. Satellites in a “GEO” slot have an orbital period of exactly 24 h. The satellite appears to remain stationary in the sky, allowing Earth-based antennas to be permanently pointed at the satellite (Wertz 2011). Satellites in highly elliptical orbits (ELI) round out the remainder of the assets in valuable orbits. Of the total satellites operational in 2012, 419 were in GEO, 471 in LEO, 69 in MEO, and 35 in ELI orbits (SIA 2012). Of the 73 commercial satellite launches in 2014, 24 went to GEO, 10 to MEO, and 38 to LEO (SIA 2015). Figure 1 illustrates the approximate altitude ranges relative to the Earth along with the “graveyard” disposal altitudes for MEO and GEO orbits. Because satellites in MEO and GEO are not de-orbited at the end of their useful life, just enough fuel is saved to typically boost the satellite

into a higher orbit that will not interfere with operational satellites in MEO and GEO for decades to come. Figure 2 illustrates the basic orbital parameters. Other important parameters including the argument of perigee and true anomaly are not necessary for now to describe our concept of a vulnerability cadastre.

Satellites and their missions are optimized for a specific orbit. They typically remain in that orbit throughout their operational life, carrying just enough fuel to make orbit altitude corrections for collision avoidance maneuvers. Parameters such as mass, launch vehicle capability, cost, sensor field-of-view, antenna coverage or receiver gain / transmitter power are determined by the mission and orbit. Most LEO and MEO satellites are placed in circular or nearly circular orbits at inclinations specific to the mission. For example, surveillance satellites are placed in circular orbits with inclinations at or near 90 degrees to gain full coverage of the Earth’s surface, and are known as polar orbits. A satellite with a mission to observe mainly the equatorial region would be placed into a lower inclined orbit. GEO satellites are in circular orbits with an inclination of zero degrees, that is, directly above the equator to maintain a stationary position relative to a location on the Earth’s surface. Protection of LEO, MEO, and GEO orbits are important to sustaining space critical infrastructure.

3 Sources of Orbital Debris and Susceptibility of Orbits to Debris Accumulation

All space activities are associated with debris-generating events. A brief list of the more common debris or debris sources include:

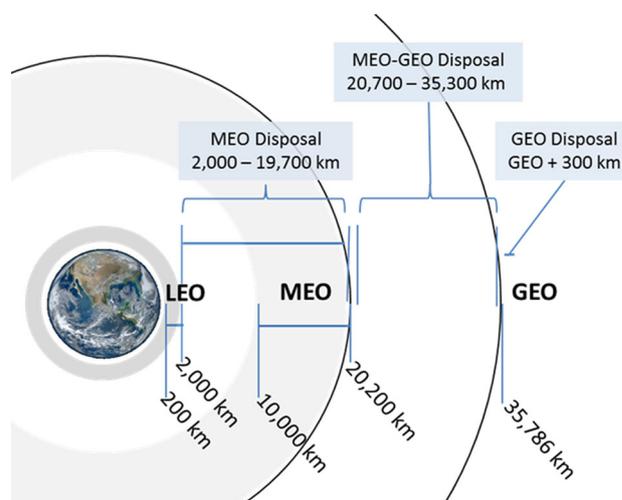


Fig. 1 Low earth orbit (LEO), medium earth orbit (MEO), and geosynchronous orbit (GEO) altitudes. *Source* The authors

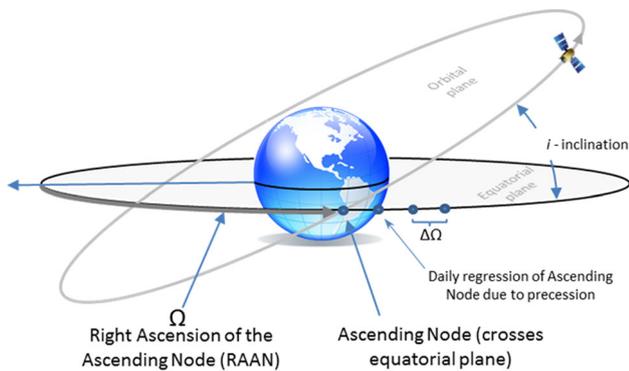


Fig. 2 Basic orbit parameters. *Source* The authors

- Spent launch vehicle stages / rocket bodies that are left in orbit;
- Launch vehicle stages that explode in orbit either before or after delivering their payloads;
- Satellite collisions with other satellites or with orbital debris;
- Nonoperational satellites (due to technical failure or end of mission life) that are not removed from orbit or placed in a graveyard orbit;
- Fragmentation of satellites due to technical failure (for example, propellant tank rupture, battery failure, or attack by a kinetic energy weapon);
- Spent solid rocket propellant particles;
- Paint particles.

An example of recent debris generation occurred in February 2015, when a debris field consisting of 43 trackable objects was observed near the US Air Force's DMSP-F13 weather satellite, leading some to conclude onboard batteries exploded (Berger 2015). Orbital debris accumulation by objects and mass is shown in Fig. 3.

However, the two most well-known recent debris generating events occurred in 2009 and 2007. In 2009, the operational US Iridium 33 satellite collided with the non-operational Russian Cosmos 2251 satellite at 790 km altitude and a closing velocity of greater than 11 km/sec, generating more than 2000 trackable debris objects. In 2007, the Chinese destroyed their nonoperational Fengyun-1C weather satellite during an antisatellite (ASAT) weapon test. While ASAT tests have been carried out by other nations as well, destruction of the Fengyun-1C propelled fragments from the nearly circular orbit of 845×865 km to orbits with a perigee and apogee range from 200 to 4000 km (NASA ODPO 2007). This event currently tops the list as the worst fragmentation event recorded as measured by the United States Space Surveillance Network

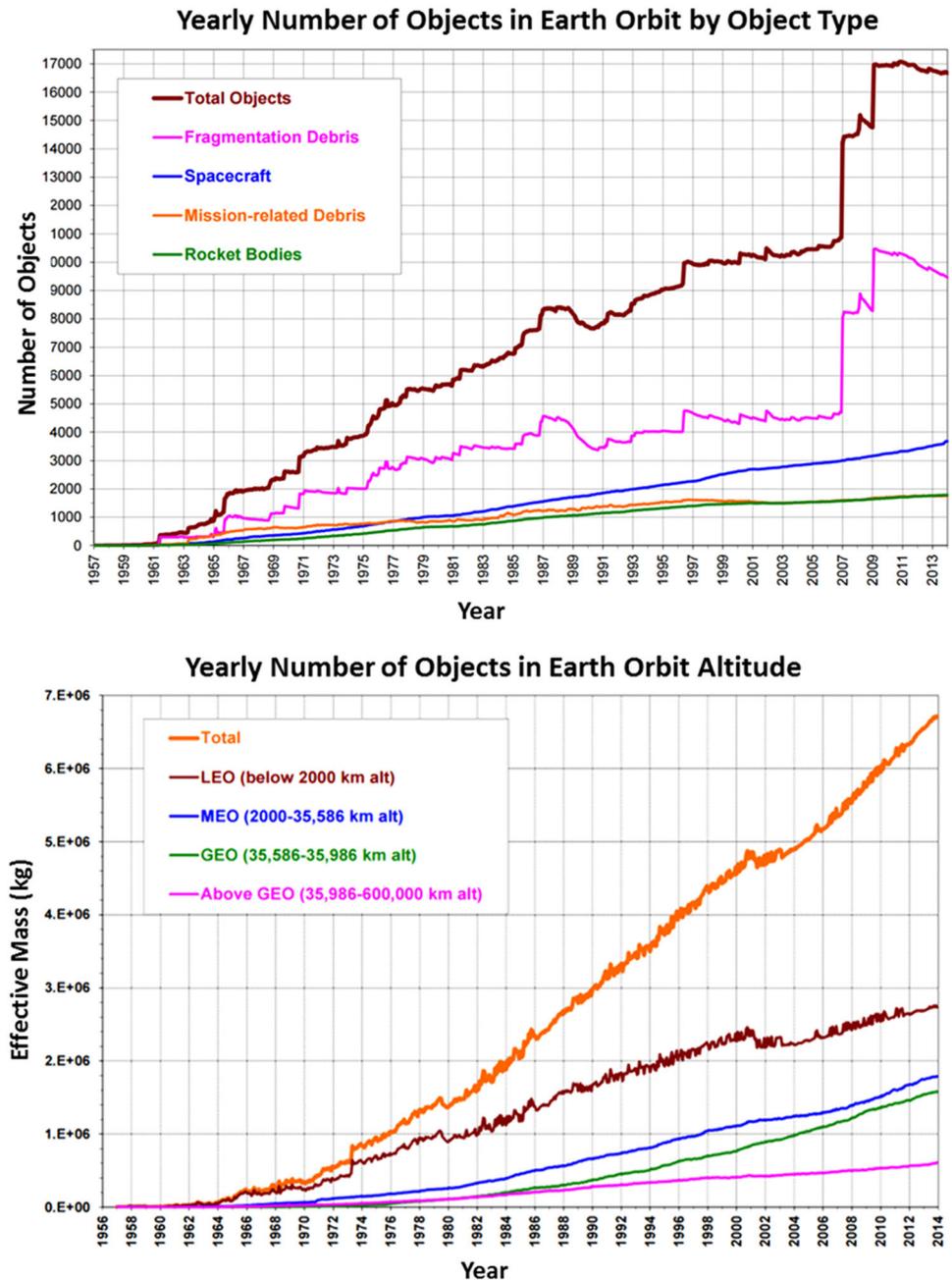
(NASA APPEL 2012). These 2007 and 2009 events are reflected in stepwise debris increases in Fig. 3.

Dispersion of the debris is illustrated in Fig. 4. A satellite in an orbital plane possesses angular momentum, like a gyroscope, with the orbital plane's momentum vector coincident with the gyro axis. Like a gyroscope, the orbital plane is subject to precession, in this case, due to gravitational torques from nonuniform mass distributions within the Earth. The amount of precession per day, $\Delta\Omega$, is the angular change in the right ascension of the ascending node (RAAN), and is proportional to the cosine of the inclination angle and altitude of the orbit (Wertz 2011). Thus, between the precession and additional energy imparted to the particles due to explosion or collision, orbital debris can disperse widely throughout an orbit at lower inclinations, but will disperse less in polar orbits (inclination near 90°), contributing to debris density in polar orbits.

One quantification of orbital debris is the measure of debris spatial density (number of particles in a unit volume), and another is debris flux, a measure of particles per unit area over some period of time, for example, a year. The spatial density of debris across the three orbital regimes is plotted in Fig. 5, indicating where the most used and therefore susceptible orbits lie. Clear peaks in debris density are seen in LEO, MEO, and GEO. The lower plot in Fig. 5 illustrates the increase of debris in LEO, growing by over 100 % below 1,000 km in just seven years. The Iridium/Cosmos collision and Fengyun-1C destruction accounts for most of the increase (NASA ODPO 2014b). The operational community is debating the new concept of small satellites, in particular, "cubesats." These low-cost, small satellites are generally launched as secondary payloads and jettisoned into orbits that can enable them to remain aloft for many years, well beyond the internationally recognized period of deorbiting the satellite within 25 years of retirement. In one recent case, a cubesat was placed in an 800 km orbit, potentially orbiting for 700 years due to lack of deorbit propulsion or deployable drag devices (de Selding 2015). Orbits are susceptible to debris for two primary reasons: they are highly utilized and crowded; and the atmospheric/aerodynamic drag forces that cause debris to eventually fall out of orbit in a fiery return to Earth are vanishingly small above LEO.

While the debris generation sources described are sufficient to degrade valuable orbits, there is also a growing threat of intentional debris generation by enemy combatants or rogue nations whose intention would be to deny their enemies critical space infrastructure. Even rogue nations with rudimentary ASAT capabilities are a threat. This was explored in a gaming exercise by Gheorghe and Vamanu (2007), who showed that publically available

Fig. 3 Accumulation of orbital debris, 1956–2014. *Source* NASA ODPO (2014a, p. 10), *Top* reprinted with permission; NASA ODPO (2015a, p. 9), *bottom* reprinted with permission



software and satellite orbital information could be used to calculate the proper intercept course to result in an ASAT-based satellite kill. They concluded that space should be viewed as a readily-vulnerable critical infrastructure.

Debris or derelict satellites can occupy valuable orbits for a few months in the case of lower LEO debris, to thousands if not millions of years for objects in GEO. Debris lifetimes increase dramatically in the upper LEO regime of approximately 600–1000 km, and lifetimes of debris in orbit above 2000 km can for practical purposes be considered indefinite (GlobalSecurity 2011).

Debris in higher LEO orbits can decay through, and interfere with, spacecraft operating in lower orbits. Atmospheric drag is the only significant contribution to the removal of energy of orbiting objects below 600 km. The amount of drag experienced by an object is related to the object's area to mass ratio (ballistic coefficient) and the effects of solar cycle heating on the Earth's thermosphere. Any object above 1000 km will be essentially free of any atmospheric drag and in orbit indefinitely. Satellites in GEO, for example, could be regarded as new and permanent astronomical bodies, orbiting for thousands of future

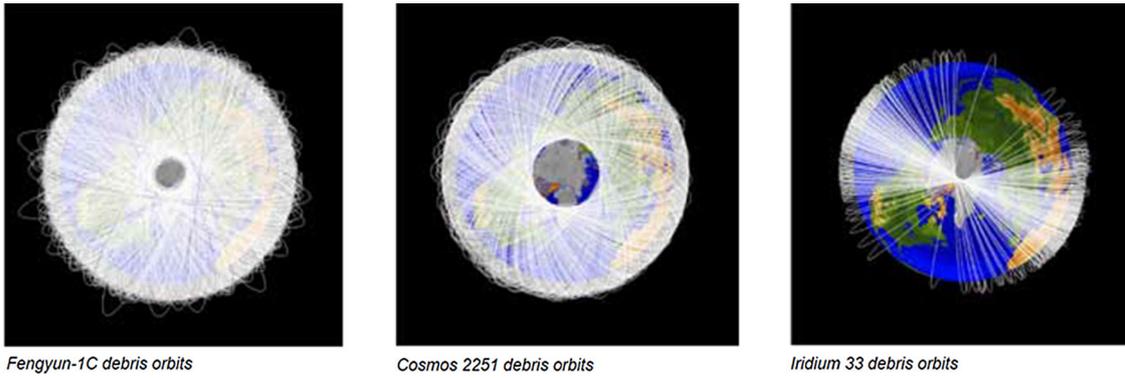
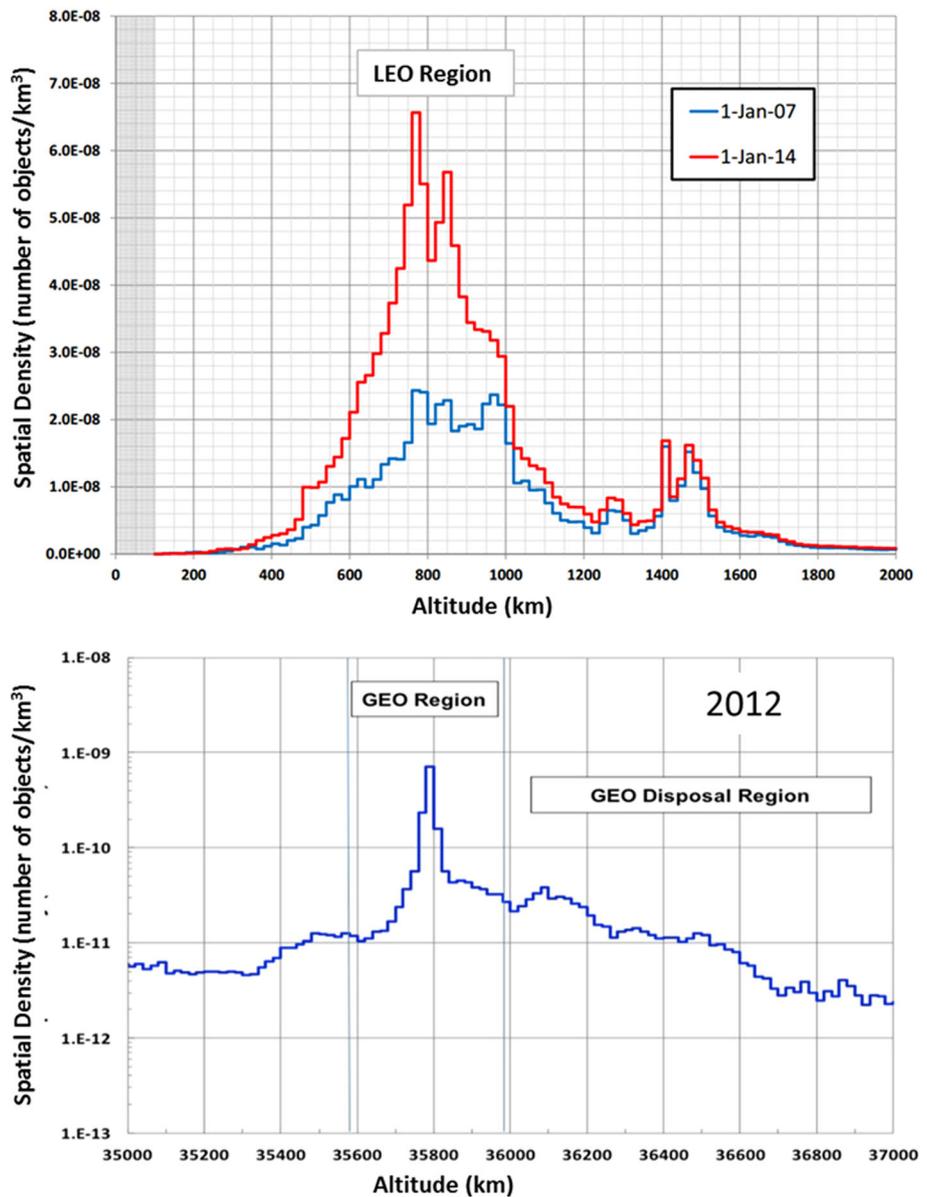


Fig. 4 Debris dispersion as of July 2012 of the 2007 Fengyun-1C destruction and the 2009 Cosmos 2251 and Iridium 33 collision. *Source* NASA ODPO (2012, p. 2). Reprinted with permission

Fig. 5 *Top* debris spatial density increase in low earth orbit (LEO) from 2007 through 2014. *Bottom* orbital debris in geosynchronous orbit (GEO) in 2012. *Source* NASA ODPO (2014b, p. 10). *Top* Reprinted with permission; NASA APPEL (2012, p. 14), *bottom* Reprinted with permission



generations. It is interesting to consider that scientists 100 generations from now could still be tracking orbital debris and spacecraft from our first 50 years of spaceflight. Most events that generate orbital debris are unintentional and can be limited with sufficient effort like end-of-life passivation, boosting to disposal orbits, or deorbiting. However, debris cleanup is at best difficult, and at worst impossible.

4 Consequences of Orbital Debris

Spacecraft are vulnerable systems with an inherently high degree of susceptibility to hypervelocity debris impact. Both elaborate modeling of the debris environment or direct optical and radar observation are used to quantify the collision risk to spacecraft. A hypervelocity collision with debris much larger than about 1 cm in diameter essentially ends the mission with the potential to generate a new debris cloud that could persist for decades or longer. While spacecraft carry protective shielding against micrometeoroids and particles smaller than 1 cm in diameter, impacts from paint flecks caused craters in the windows of the Space Shuttle orbiter (NASA APPEL 2012). Onboard redundancy provides a small degree of resiliency, and can reduce susceptibility to single point failures such as loss of a transmitter or receiver due to a small orbital debris impact.

Operators of many high-value satellites and crewed vehicles choose to perform conjunction analyses (collision assessments) between their spacecraft and trackable debris, and if necessary, execute collision avoidance maneuvers. In the United States, National Aeronautics and Space Administration (NASA) policy requires routine conjunction analyses for all NASA assets with the capability to maneuver (NASA OSMA 2009; NASA ODPO 2009). Collision avoidance maneuvers performed by the International Space Station (ISS) are summarized in Fig. 6. With no inherent propulsion, the ISS must rely on visiting Russian or European vehicles to boost its altitude to avoid debris. Given the debris density in Fig. 5, the probability of a collision between orbital debris and a 10 m² object indicate the risk increases from 1 in a million at 200 km altitude to a peak probability of greater than 1 in 10,000 at altitudes just below 800 km. The probability decreases slightly to 1 in 100,000 at approximately 1300 km and jumps again to about 1 in 50,000 in the 1400–1500 km range before slowly decreasing with altitude. As an example, the probability of collision with the 10 m² object at 400 km (ISS altitudes) is roughly 1 in 100,000. This probability increases for the ISS due to its larger area (Ailor et al. 2010).

Not all operational spacecraft have the ability to maneuver away from orbital debris and are thus at greater

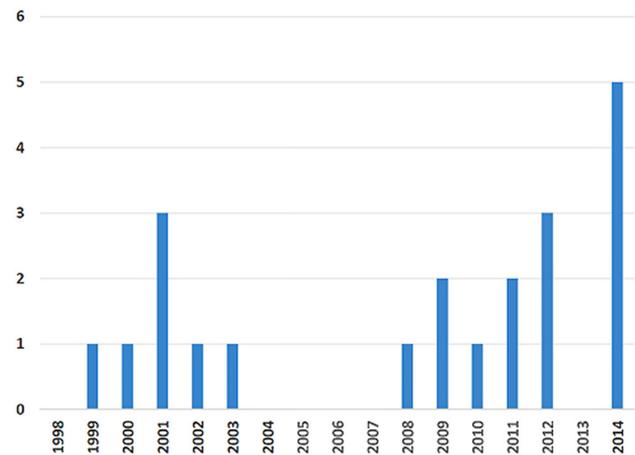


Fig. 6 Number of collision avoidance maneuvers performed by the International Space Station, 1998–2014. *Source* NASA ODPO (2015b, p. 1). Reprinted with permission

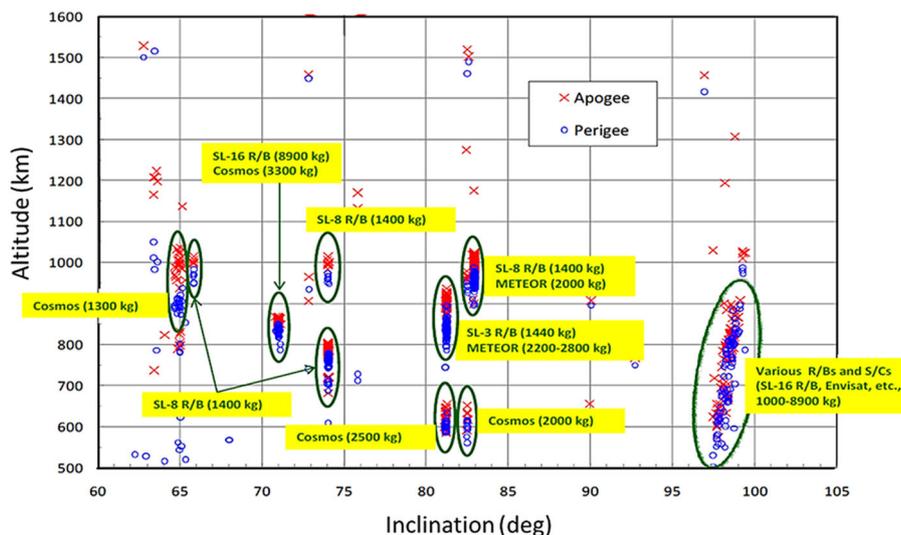
risk. Moreover, maneuvering fuel is precious and operators cannot afford to maneuver satellites unnecessarily or for low-probability, high-consequence conjunctions.

By mission rules, the ISS would execute a collision avoidance maneuver if the probability of debris penetrating a $\pm 0.75 \text{ km} \times \pm 25 \text{ km} \times \pm 25 \text{ km}$ box centered on the spacecraft was greater than 10^{-4} .

Heavily used orbits, defined by altitude and inclination, are becoming congested with both spent launch vehicle stages, that is rocket bodies (R/B), and operational and nonoperational spacecraft (S/C) (Fig. 7). A concept called the Kessler Syndrome was introduced in the 1970 s to describe the situation in an orbit, where random collisions between debris would eventually produce a spatial debris density greater than the natural meteoroid environment. This “cascading collisions” concept was borrowed from the theory of planetary ring formation, and suggests debris collisions could increase spatial debris density to a point that would prevent satellite operations in those orbits (Kessler and Cour-Palais 1978; Kessler 1991). Evidence suggests this may be occurring in heavily used orbits. Continuing to add spacecraft and upper stages to these orbits, especially at altitudes above 600 km and high inclinations will worsen the problem, eventually making the risk of operating in these orbits intolerably high by shortening spacecraft lifetimes (Kessler et al. 2010).

International governance policies exist to reduce debris generation through multiple technical and operational means (IADC 2007). Incomplete compliance with the measures are increasing the chances that orbits become more “polluted” with debris, and increase the probability of destructive hypervelocity impacts. A spacecraft operator’s action to not maintain the fuel reserve needed to boost a satellite to a disposal orbit or deorbit, either through

Fig. 7 Large mass objects in high inclination orbits. Note: R/B denotes rocket bodies, S/C denotes spacecraft. Source NASA ODPO (2011, p. 6). Reprinted with permission



neglect or profit motives, or to not reenter a spent upper stage rocket in order to devote that fuel to lofting heavier payloads, could ultimately end in a consequential explosion or collision that generates harmful debris with detrimental effects on all nation’s assets and the shared orbits. The more spacefaring nations become dependent on space critical infrastructures, the more interested they should become in the conservation of “orbital infrastructure.” Orbital debris has no national boundaries.

5 Communicating the Vulnerability of Space Critical Infrastructure

A new approach is presented as a way to increase the awareness that accumulating orbital debris can infringe on the sustainment of current and future space critical infrastructure. The concepts of a space critical infrastructure vulnerability index and cadastre is introduced and conceptually developed to provide a vulnerability and consequence-based visualization of the orbital debris threat. This representation could serve as a compelling communications tool in debris mitigation and reduction governance efforts.

5.1 The Concept of a Vulnerability Index Map and Risk Cadastre

A cadastre is traditionally a record, survey, or map of the value, extent, and ownership of land. Detailed boundaries and property lines can be shown along with topographical information. Thanks to Geographic Information Systems (GIS), cadastral maps are commonplace. When overlaid with data that represent various forms of environmental

risk and vulnerability from nuclear, chemical, or biological accidents, these maps acquire a prominent added value. Our approach is best understood by analogy. A vulnerability cadastre geographically indicates areas that have some probability of experiencing harm with high-expected consequences for either the occupying population (satellites in this case) or the environment (high-value orbits). The simplest form of a risk and vulnerability cadastre is of an expected casualty or fatality effect area due to an accidental release of toxic liquids, gases, or explosions, overlaid on a map. Density levels of the toxic substance in the unique environment are developed from models (both simple and sophisticated) in order to derive the risk contours. This type of cadastre is featured in the rapid risk assessment methodology recommended by the International Atomic Energy Agency (IAEA 1996). More complex cadasters include buildings and terrain features to develop more accurate dispersion maps of airborne toxins and biological agents. Concentrations of an environmental contaminate can be indicated with limits that range from tolerable to intolerable, leading to increased morbidity or death. We next introduce a method of quantifying the vulnerability of an orbit to debris accumulation.

5.2 Coupling Critical Loads with a Cadastre

The concept of critical loads is employed in pollution studies to convey the vulnerability of geographical areas to environmental contamination that exceeds a certain threshold. That threshold is referred to as the “critical load.” According to the US National Atmospheric Deposition Program—NADP (2013, p. 2), a critical load is defined as “...the quantitative estimate of an exposure to one or more pollutants below which significant harmful

effects on specified sensitive elements of the environment are not expected to occur according to present knowledge.” Based on these definitions, a notional graph of the relationship between cumulative contaminate load and resultant effect is illustrated in Fig. 8. Critical loads are based on a dose–response relationship, where the accumulation or deposition of contaminant doses eventually exceed the harmful threshold, which is the critical load of contaminants in the ecosystem is exceeded and damage occurs (Enviropedia 2013). Atmospheric transport is the primary dose deposition mechanism. The concept of critical loads was introduced in 1988 by the United Nations Economic Commission for Europe (UNECE) on Long Range Transboundary Air Pollution as a tool for the development of abatement strategies and agreements on reduction of regional air pollutants (Hultberg et al. 1994). If a contaminant remains under the critical load value, the effect on the sensitive ecosystem receptor or target is minimal, and the ecosystem is not degraded further. However, environmental effects become noticeable once the critical load is reached as shown in Fig. 8. In Fig. 9, the critical load concept has been combined with a terrain cadastre, resulting in a sophisticated risk and vulnerability cadastre. Knowing the present, target, and critical loads, the cadastre can be calibrated to visually convey the risk or vulnerability of geographical areas to an environmental contaminant. We suggest a compelling visual risk and vulnerability cadastre could be developed for orbital debris (WHO 2000).

5.3 Development of a Space Critical Infrastructure Vulnerability Cadastre

The concept of critical loads may have a natural extension to the effect of orbital debris on space critical infrastructure. As the debris spatial density in an orbit increases, the target load with safety factor threshold would eventually be exceeded (Fig. 8). Satellite operators may begin to notice

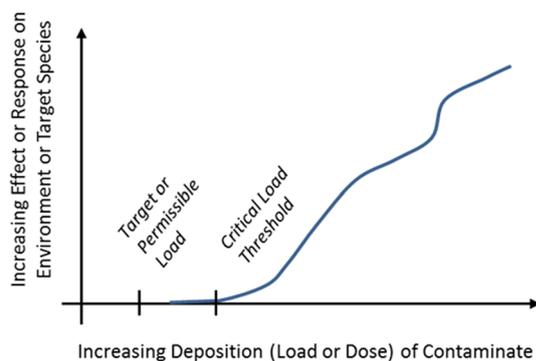


Fig. 8 The concept of target, critical, and present environmental loads. *Source* The authors

effects beyond this threshold with the risk of operational problems increasing. Beyond the critical load threshold in that orbit, the debilitating effects on space assets would become more pronounced. Increasingly frequent debris impacts would degrade operations or shorten mission life, catastrophic collisions could end missions, and an increased number of expensive collision avoidance maneuvers would need to be executed by operational spacecraft. Such maneuvers shorten mission life by depleting fuel reserves. Only the lowest orbits in LEO, below approximately 600 km, have a degree of resiliency and sustainability due to the cleansing effect of atmospheric drag and solar cycles. Resiliency of an orbit could potentially be defined as the availability of atmospheric and gravitational forces to cause debris to reenter the atmosphere in a reasonable amount of time (a few days to a few years). Unfortunately, the concept of resiliency is essentially nonexistent in higher orbits, making the accumulation of debris in these orbits problematic and reducing their sustainability.

A developmental approach is proposed in Fig. 10. The general concept used in environmental science is to establish target and critical levels of contaminants, that is sources that could be tolerated at target receptors or locations before the pollution or operational risk becomes unacceptable. On the “Pollutant” side of Fig. 10 we seek to measure and develop representations of the present orbital debris environment; and on the “Receptor at Risk” side we seek to establish the target load and critical load values (for example, debris spatial density for the high-value orbits). The concept for target and critical loads would be established by an international body such as the Inter-Agency Space Debris Coordination Committee (IADC), using the risk governance concept of As Low as Reasonably Acceptable (ALARA). Requirements development would be a trade between the needed spatial/temporal resolution in an orbit and existing measurement capabilities.

Establishing target and critical loads would be a challenge, but there are approaches to set the minimum (target load) and maximum (critical load). For example, in each high-value orbit, the target debris load would indicate the maximum amount of debris acceptable to spacecraft operators and insurers based on shielding, impact risk, numbers of collision avoidance maneuvers likely for an average size satellite operating in that orbit, and longevity of the debris. As an intermediate step to the realization of a vulnerability cadastre, the vulnerability of a single orbit to loss or reduced utilization could be represented by a vulnerability index map in order to work through the details of this concept.

A theoretical orbit vulnerability index is presented in Fig. 11. A modified Torino color-coded scale for near-

Fig. 9 Example of a risk cadastre of contaminate dispersion in complex terrain driven by atmospheric dispersion forces. *Source* Gheorghe and Vamanu (Gheorghe 2005). Reprinted with permission

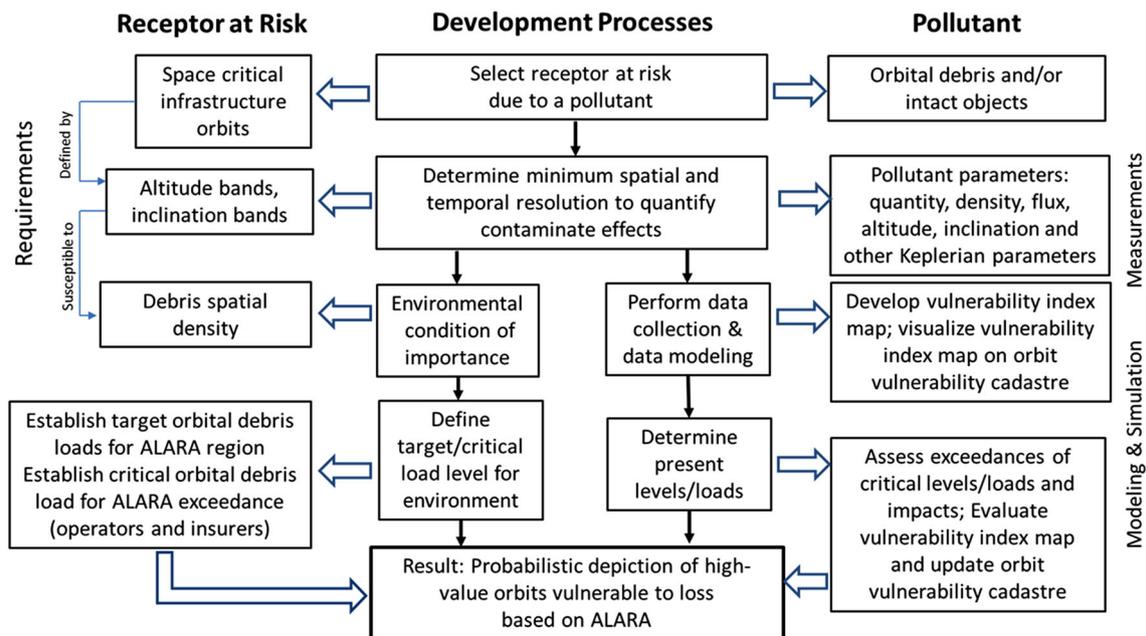
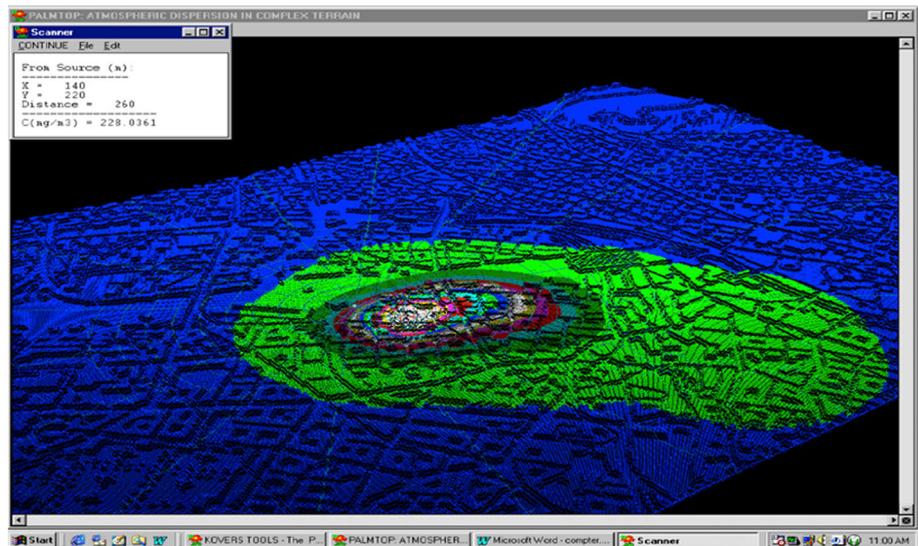


Fig. 10 Approach to developing a high-value orbit vulnerability index map and risk cadastre. *Source* The authors

Earth objects could be used, for example, to convey the consequence of increasing levels of debris density in each orbital vulnerability index map. Target loads are also useful in that they can provide a measure of how much carrying capacity in total debris the orbit can hold before reaching the next highest threshold. The left side of the vulnerability index map in Fig. 11 shows three thresholds of debris loads that the orbit could “carry.” Target loads would probably need to be set increasingly lower above 600 km due to the increasing lifetime of debris at higher altitudes. Target loads would need to be even lower for

MEO and GEO due to the multicentury or multimillennia lifetimes of debris in those orbits. One benefit of being in the geostationary arc is that the relative velocity between spacecraft is very low compared to the hypervelocity rates in LEO. Thus, chances of hypervelocity collisions in GEO are much lower when compared to LEO. Establishing target and critical loads would also be useful in determining the types and degrees of mitigation and remediation necessary to sustain high-value orbits. International policy and guidelines could be updated to support maintaining orbits below target or critical load thresholds.

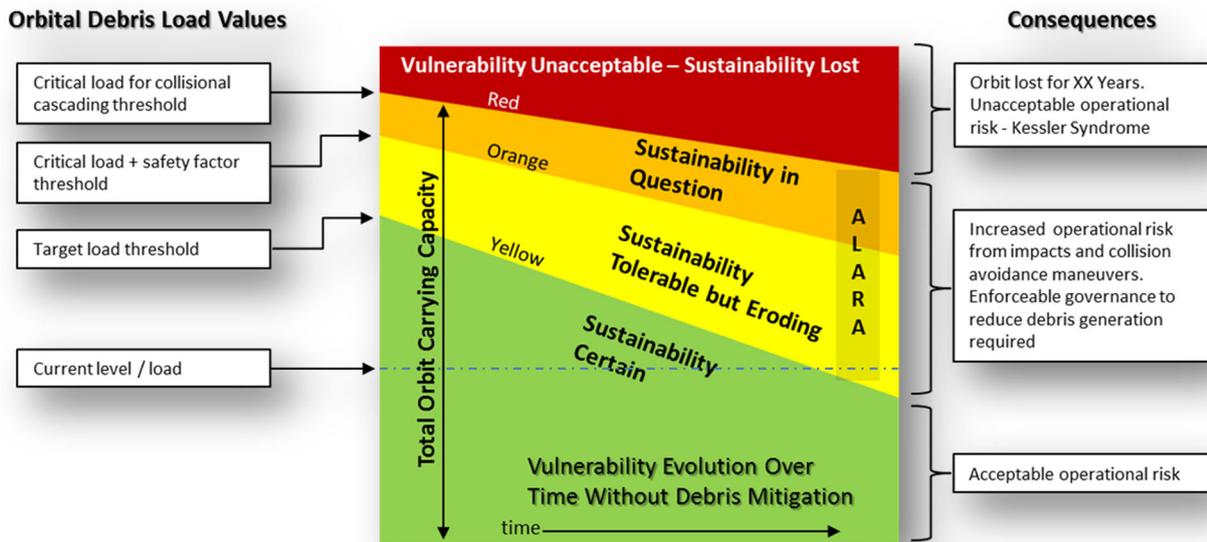


Fig. 11 Theoretical vulnerability index map with thresholds for a specific orbit (altitude and inclination). *Source* The authors

The values of target and critical loads for a specific ecosystem are based on careful study and analysis. For critical orbits, defining target and critical loads will be influenced by factors specific to the space domain. While critical loads may be set by the capabilities of current orbital debris shielding technologies (for example, Whipple Shields) or by the satellite operators' and insurance companies' risk tolerance, target loads may be more challenging to define. Once the target load threshold has been reached for a critical orbit, policy may dictate no new operations unless debris remediation measures are included in the launch vehicle and satellite to minimize the probability of generating additional debris and exceeding the critical load threshold. Debris remediation measures drive up system costs through increased design complexity and mission complexity, and may be a cost burden for emerging spacefaring nations. But it is a small price to pay to maintain the sustainability of critical orbits. An agreed-upon strategy or policy is necessary to set target loads and how the orbit is used after the target load is exceeded.

5.4 Potential Usage

Operators would want the high-value orbits maintained in the green vulnerability areas in Fig. 11, where sustainability is certain and risk to their assets are low. In the yellow ALARA region, operational risk increases. Any operator wishing to place satellites into an orbit measured as having a "yellow" vulnerability index could be required

to guarantee that they would execute debris mitigation procedures. This could mean 100 % compliance with postmission disposal recommendations for both their satellite and upper stage launch vehicle per IADC (2007), or pay a fine. The money could be used as a "toxic waste site superfund" to support implementation of active debris removal concepts. Perhaps even more compelling than fines would be to deny licensing of the frequency spectrum to repeat offenders. The satellite is useless if not allowed to transmit.

The yellow ALARA region is where the spacecraft insurers could take an active role, ensuring that reliable, 100 % postmission disposal systems are designed into the spacecraft they insure. Getting the insurers involved is perhaps the greatest lever in the commercial sector. The orange portion of the ALARA region is where the debris environment is eroding the safety margin built into this band, signaling the orbit is well on its way to becoming unusable for some duration into the future and that sustainability will be lost. Once in the red zone, launches to that orbit would need to stop until the environment was remediated by either drag effects in LEO or by active debris removal. The LEO region below 600 km is vulnerable to large amounts of debris due to its usage, but is the most resilient region due to the cleansing effect of atmospheric drag. Vulnerability index maps for LEO would have to be updated frequently, especially since debris from higher LEO orbits pass through lower orbits on their way to eventual reentry into the atmosphere.

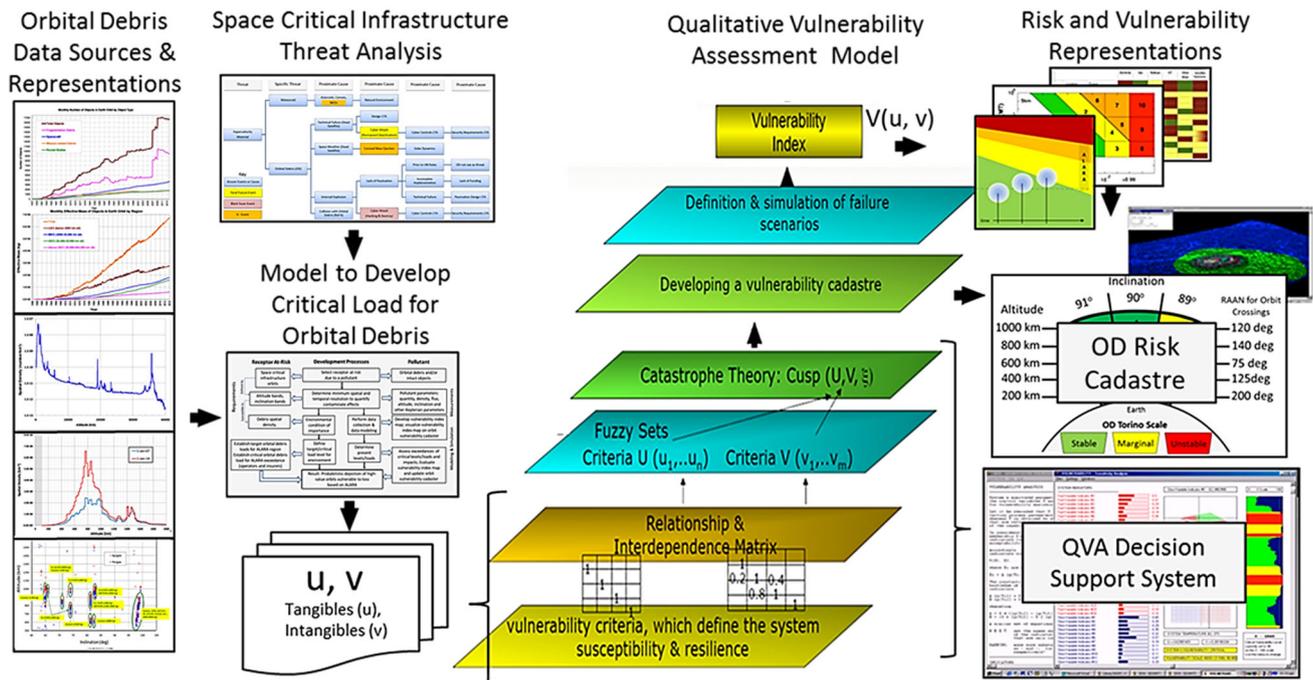


Fig. 12 Proposed development architecture of a space critical infrastructure risk cadastre using new and existing tools and approaches. *Source* The authors

5.5 Conclusion and the Path Ahead

An integrated approach to developing cadastral representations of orbital debris risks is needed. One such concept is illustrated in Fig. 12, which leverages qualitative vulnerability assessment (QVA) tools and decision support systems (DSS) (Gheorghie and Vamanu 2004). Numerous tangible and intangible variables would be used to determine target and critical loads and ultimately the vulnerability of orbits and their visual representations. While no one representation may meet the requirement of conveying the level of operational risk inherent in an orbit, such tools would help rapidly explore the vulnerability index map and cadastre representations.

Ultimately, the goal is to develop a clear and compelling method of communicating operational risks to the current and future users of critical orbits as well as the insurers. Useful visualization of orbit vulnerability cadasters will be difficult due to the fact that debris can disperse from an initial altitude/inclination, for example, due to a continuous change in RAAN (see Fig. 2) in nonpolar orbits. Both the vulnerability index map and visualization of a risk cadastre would need to be calculated frequently for each specific orbit of interest. For debris measurement, existing modeling approaches would be of great use. For example, orbital debris models like ORDEM 3.0 could be used to propagate “witness plates” in specific, high-value orbits that are standard sizes or represent specific spacecraft to determine the spatial density or flux of debris (Stansbery and Matney

2014). But setting target and critical loads, enforcement of mitigation, and navigating the politics may be more difficult than engineering a cadastral representation.

An ideal “home” for the proposed vulnerability index map and cadastre would be either the satellite insurers, IADC, or in the Space Security Index “Theme 1: Condition and knowledge of the space environment” and “Theme 4: Outer space governance” (SSI 2014). United Nations outer space organizations could benefit as well. The US Department of Homeland Security could also adopt such a communications tool for use in governance of the Communications Critical Infrastructure. The bottom line is to persuade space policy makers to enforce orbital debris mitigation policies and develop monetary or sanction-like policies for noncompliance to finally “bend the space debris curve” back in the direction needed to sustain our critical space infrastructure.

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