Space Debris and Nuclear Strategic Stability: Collision Risks and Attribution Potential in GEO

Roohi Dalal
Department of Physics and Astronomy, University of British Columbia
Department of Political Science, University of British Columbia
Aaron Boley
Department of Physics and Astronomy, University of British Columbia
Michael Byers
Department of Political Science, University of British Columbia

ABSTRACT

Space-based Nuclear Command, Control, and Communications (NC3) satellites face threats from both anti-satellite weapons and the space environment, including the growing amount of space debris. This raises the question of whether satellite failures due to debris or meteoroid impacts could be mistaken for intentional counterspace operations, a particularly worrisome possibility, as some nuclear states have maintained the option of a nuclear response to non-nuclear attacks on their NC3 architecture. We characterize the frequency and severity of debilitating debris and meteoroid collisions with NC3 satellites, and then assess existing technological capabilities to attribute satellite failures to either debris impacts or intentional interference. Noting that existing follow-up capabilities are likely insufficient for satellites in geosynchronous orbit, we recommend investment in attitude determination for observational follow-up after satellite failures.

1. INTRODUCTION

The United States National Nuclear Command, Control, and Communications (NC3) system plays an integral role in ensuring the security and strategic stability of the U.S. nuclear deterrent. The NC3 system is defined by the U.S. Air Force as the "means through which Presidential authority is exercised and operational command and control of nuclear operations is conducted" [1]. The 2022 Nuclear Posture Review (NPR) identifies five crucial functions of the NC3 system, namely "detection, warning, and attack characterization; adaptive nuclear planning; decision-making conferencing; receiving and executing Presidential orders; and enabling the management and direction of forces" [2]. Space-based assets are an important part of this system, in the form of early warning systems and communications satellites [3]. However, as noted by the 2018 NPR, states including Russia and China have been developing counterspace military capabilities to deny the United States the ability to conduct NC3 in addition to space-based intelligence, surveillance, and reconnaissance, as well as positioning, navigation, and timing [4]. The 2022 Missile Defense Review notes the need for investment in resilient NC3 to ensure the continued credibility of the nuclear deterrent "to keep pace with the evolving PRC and Russian threats, and avoid the possibility of evading U.S. sensor networks in a surprise attack" [5]. At the same time, space-based assets also face hazards from their orbital environment, including collisions with meteoroids and the growing amount of space debris. This novel web of threats raises several questions, including whether satellite failures due to debris impacts could be mistaken for intentional counter-space operations. Furthermore, considering the likelihood that the amount of debris will only increase in the coming years, one might ask whether debris could function as a deterrent against developing and employing counterspace capabilities, or be used to threaten national NC3 systems. We evaluate the potential risks and deterrence in regard to nuclear strategic stability arising from space debris as a threat to national NC3 systems.

The U.S. NC3 system currently relies on a number of satellites in a geostationary earth orbit (GEO), which is about 36,000 km in altitude above the Earth. These include the Defense Support Program (DSP) [6] early warning system and its follow-on capability, the Space Based Infrared System [7]. The U.S. Nuclear Detonation Detection System is hosted on a combination of global positioning system (GPS), DSP and other classified satellites [8]. GEO NC3 communications systems include the Military Strategic and Tactical Relay (MILSTAR) Satellite Communications System [9] and the follow-on Advanced Extremely High Frequency (AEHF) system [10]. The follow-on early warning capability, Next Gen Overhead Persistent Infrared (OPIR) [11], and communications system, the Evolved Strategic Satellite Communications program [3] are currently under development. These systems reportedly all rely on relatively small numbers of satellites (between 5 and 23 satellites each), which are large and expensive, and often carry multiple capabilities. Recognizing the vulnerability of these systems to attacks targeting individual satellites, the Department of Defense (DoD) has been expanding NC3 capabilities in low Earth orbit (LEO) [12]. For example, the Space Tracking and Surveillance System is a pair of satellites in LEO that form an experimental component of the U.S. Ballistic Missile Defense System [13]. The Space Force is in the process of deploying the Proliferated Warfighter Space Architecture, which is planned as a constellation of hundreds of LEO satellites used for both communications and missile defense and tracking [14]. This paper will focus primarily on threats to NC3 satellites in GEO, as these form the basis of the existing U.S. space-based NC3 architecture. We include a brief discussion of the LEO environment and threats in Section 4.

Other countries, particularly Russia and China, also have space-based systems that form parts of their NC3 architecture. For example, Russia has recently deployed the Edinaya Kosmicheskaya Sistema (EKS) satellite system, a constellation of six GEO early warning satellites to replace the aging Oko program [15]. China has been developing satellite early warning systems over the past decade, particularly the Huoyan-1 class of Tongxin Jishu Shiyan satellites, a set of three satellites in GEO [16]. However, we note that the United States appears to be more reliant on satellites for NC3 than other countries [17, 18]. Moreover, the United States has explicitly stated that it would consider employing a nuclear response to attacks on its command and control infrastructure [4]. It is not clear whether other countries, such as Russia, have adopted a similar posture, although such a response would not be in line with China's "no first use" nuclear policy [19].

As countries continue to employ and grow space-based capabilities for national security, including NC3, a number of countries are also developing counterspace capabilities that would allow them to "deceive, disrupt, deny, degrade, or destroy space systems" [20]. Such capabilities include kinetic anti-satellite attacks, which use physical force to damage or destroy target satellites, and directed energy weapons, which use focused energy in the form of lasers, particles, or microwave beams to interfere with or destroy satellites. Counterspace attacks could also include electronic warfare, i.e. using radio-frequency energy to interfere with the communications between the satellites and ground systems through jamming or spoofing, and cyberattacks, which use software to control, interfere with, or destroy computer systems either on satellites or part of ground systems.

A number of countries are developing counterspace capabilities to target other states' space systems, potentially including NC3 architectures. China, the United States, Russia, and India have all conducted tests of destructive anti-satellite (ASAT) weapons [20]. Per the Secure World Foundation's 2024 Global Counterspace Capabilities report, the United States, China, and Russia all have some level of capability with directed energy weapons, and significant use of electronic warfare capabilities like jamming [20]. France also has some directed energy weapons capability, while Israel has extensively employed jamming capabilities [20]. Many other countries, including Iran, DPRK, Australia and Japan are in the process of developing (primarily non-destructive) counterspace capabilities [20].

Such offensive counterspace capabilities can be broadly viewed as destabilizing developments in terms of nuclear strategic stability. If used, they act to reduce situational awareness, which could make mistaken escalation to nuclear weapons use more likely [21]. For example, a strike against a country's early warning satellites during wartime could be misinterpreted as an attempt to blind that country to a strategic nuclear attack, even if it is just intended to allow conventional ballistic missiles to circumvent the country's defenses, as these satellites are used for both conventional and nuclear early warning [22]. The United States has also publicly maintained the option of a nuclear response to non-nuclear attacks on its NC3 architecture [23], and it is possible that other countries have privately adopted a similar posture. Thus, there is a clear risk of nuclear escalation arising from attacks on space-based NC3 systems.

2. CHARACTERIZING THE DEBRIS AND METEOROID THREAT

NC3 satellites also face threats in the form of collisions with space debris and meteoroids. The European Space Agency (ESA) defines space debris as all non-functional, artificial objects, including fragments and elements thereof, in Earth orbit or re-entering into Earth's atmosphere [24]. In GEO, identified sources of debris include "disintegration, erosion, collisions, detachment of coatings and paint flakes, accidental or intentional mission release, accidental fragmentation such as fuel tank explosions, intentional fragmentation from ASAT testing, particles released by solid rocket motors firing, and leaked coolant" [25]. The high altitude of GEO means that the negligible atmospheric drag does not contribute to orbital decay, causing most of these objects to remain in orbit indefinitely (although at certain sizes, radiative effects might become important). Debris can also include defunct or nonoperational satellites. The Inter-Agency Space Debris Coordination Committee (IADC) has, in their Space Debris Mitigation Guidelines, established a "protected region" to minimize debris in GEO [26]. Per these guidelines, operators should carry out an end-of-mission maneuver to move the satellite to a "graveyard" orbit outside the protected region. However, satellites in orbit prior to the issuing of these guidelines remain in drift orbits, which intersect the operational regions of GEO. Between 2019-2021, collisions with such objects have resulted in the production of over 1000 fragments, of which a few hundred are on orbits crossing through the protected region [27].

Objects in GEO, due to their distance from Earth, have very low surface brightness and are therefore difficult to track. Currently, the DoD Space Surveillance Network (SSN) tracks discrete objects as small as 1 meter in diameter in GEO [28]. This tracking is done using the Ground-based Elecro-Optical Deep Space Surveillance (GEODSS) system of nine 1-meter class optical telescopes divided across three sites [29]. Objects smaller than the 1 meter limit are monitored sporadically due to the limited availability of sensors that would be sensitive enough to detect them [27]. There are about 1000 objects currently being tracked in GEO, but an estimated 33,000 objects crossing geosynchronous orbit larger than 1 cm (including objects on highly elliptical orbits that cross into GEO) [25]. At least a few hundred of these are on orbits that intersect the Protected Region, posing a threat to the satellites stationed there [30]. A 2018 study of collision frequencies in GEO estimated that a collision between a satellite and a debris object larger than 1 cm is likely to occur once every 4 years, while a collision between a satellite and a piece of debris larger than 20 cm is likely to take place once every 50 years [25]. The collision frequency is likely to be even higher today, given the amount of debris generation that has taken place [31] after the study was conducted in 2018.

Such collisions are not only expected to be frequent, but also likely to be disastrous, as the relative velocity of GEO collisions can be as high as 4 km/s, or nearly 9000 miles per hour [25]. Collisions between space objects are commonly modeled using the NASA Standard Breakup Model [32]. In this model, collisions can be either catastrophic, in which the entire masses of the two objects are fully fragmented, or non-catastrophic, which leads to fragmentation of the projectile and cratering of the target. The distinction between catastrophic and non-catastrophic events is based on the relative kinetic energy of the projectile divided by the mass of the target. If this ratio exceeds 40 J/g, the collision is deemed catastrophic. For a satellite with a mass of 1000 kg, which is typical of GEO systems, a collision with an aluminum particle smaller than 15 cm in diameter, with a relative velocity of 4 km/s will result in a non-catastrophic collision. For a relative velocity of 2 km/s, a non-catastrophic collision would occur with a piece of debris smaller than 24 cm. This means that the debris piece would crater into the satellite, likely affecting its functioning, but would not necessarily result in visible fragmentation. Thus, not only is debris of this size smaller than our tracking limits, making it unlikely that we would predict a collision taking place, but we also would not be able to easily observe the outcome of that collision, as the impacted satellite would not visibly break up and the small fragments of the colliding debris would themselves not be visible.

Debris collisions have also been modeled in laboratory experiments. For example, one set of experiments replicated satellite impacts in a lab, using target satellites that were approximately 20 cm×20 cm×20 cm in size and 1.5 kg in mass, struck by aluminum alloy solid spheres with a diameter of 3 cm and a mass of 40 grams [33]. The impact velocity of the projectiles was approximately 1.7 km/s, resulting in a kinetic energy to target mass ratio of ~40 J/g, placing it on the boundary of catastrophic and non-catastrophic events. This resulted in fragmentation of primarily the outer insulating layers and side panels of the satellite, with a total of ~1800 or ~1000 fragments, depending on whether the projectile struck the side of the satellite with a solar panel or not. The fragments that were produced were all smaller than about 0.2 m, i.e., smaller than our current tracking capabilities in GEO. Other tests conducted with similar sized satellites and projectiles but with a range of impact velocities show broadly similar results in terms of the size distribution of the resulting fragments [34]. These studies do not consider collisions with debris smaller than 1 cm, which is likely to be well under the catastrophic collision threshold. Despite the low impact energy to target mass ratio, such collisions could still result in irreparable damage to satellites. For example, such debris could create holes in radiators, and damage solar panels or sensors [35]. Cratering impacts are not as thoroughly studied and modeled in the literature as fragmentation events, leaving much uncertainty about their potential effects on spacecrafts [36].

In addition to debris, GEO satellites also face a collision risk from the meteoroid population. Meteoroids are defined by the International Astronomical Union to be particles between about 30 microns and 1 meter in diameter [37]. These small, solid particles are produced by the decay of comets and collisions between asteroids. While space debris dominates collision risks in LEO, the meteoroid flux is larger than that of debris at higher altitudes such as

GEO [38]. Studies of the meteoroid flux using the Meteoroid Engineering Model (MEM 3) [39, 40] and the modified Cour-Palais damage equation [41, 42] have shown that meteoroids will penetrate millimeter-thick aluminum at GEO altitudes at a rate of approximately 1.5 m^{-2} yr^{-1} (with the area element referring to a single side of an idealized cubic satellite) [38]. As the meteoroid distribution [43] is dominated by small particles, less than ~1 g in mass (a size of approximately 0.6 cm based on the Cour-Palais mass-density model [44]), we can expect that these collisions and penetrations will be non-catastrophic, resulting in potential debris damage in the interior of a satellite, but no visible fragmentation.

It is possible that we have observed the failure of GEO satellites due to meteoroid or small debris impacts in the past. For example, the European Space Agency's GEO communications satellite, Olympus, failed due to multiple anomalies during the peak of the Perseid meteor shower on August 11, 1993 [45]. The satellite lost its attitude control and began spinning out of control [46]. While there is no conclusive cause for the failure, it is very possible that it was caused by damage from a meteoroid impact from the increased meteoroid flux during the Perseid shower, and subsequent investigations have noted that this a "probable" cause [47]. There have also been unexplained recent failures of GEO satellites, such as the failure of Indonesia's Telkom-1 satellite in 2017, which was considered an "antenna anomaly" [48]. While there was no evidence that Telkom-1 collided with another object, telescope observations from ExoAnalytic Solutions showed that the satellite started tumbling quickly after the incident, accompanied by a cloud of debris [49]. Three other GEO satellites unexpectedly failed in summer 2017, including the SES AMC-9 and NSS-806 satellites, which each lost a significant number of transponders, and the EchoStar-3 satellite, which stopped communicating and started tumbling [49]. Given the rates of non-catastrophic meteoroid and debris collisions discussed above, it is quite possible that these failures were caused by debris and/or meteoroid collisions that did not lead to complete fragmentation of the satellite.

3. ASSESSING CAPABILITIES FOR SATELLITE FAILURE ATTRIBUTION

Collisions with debris and meteoroids clearly have the potential to be disastrous for satellites, leading either to their breakup or to an inability to execute certain functions. Moreover, we have seen that the limits on our tracking capabilities in GEO are such that we would not be able to track the projectile debris if it is smaller than ~1 meter, nor would we be able to see fragments in the aftermath of the collision if they are similarly small. If the piece of debris is small enough to cause cratering rather than fragmentation, then there would no unusual remnants for us to see. As a result of these limitations, it has been suggested by many that a debris impact could be mistaken for intentional counterspace operations by an adversary, particularly in times of crisis, leading to accidental escalation [35, 50-52]. For example, if a nation loses its ability to communicate with one or more of its NC3 satellites in GEO, it could be interpreted as an attempt to blind the nation's defenses to an incoming nuclear strategic attack, even if it were actually a piece of debris or a meteoroid impacting the antenna or transponder. It might be possible that this could lead the nation to make a decision to preempt the supposed attack with a nuclear attack of its own. We will now evaluate whether this is a realistic scenario, in terms of whether we would actually be unable to differentiate between a debris or meteoroid collision and some form of intentional counterspace attack.

Not every form of a counterspace attack could be confused with an undetected debris or meteoroid collision, as many attacks would have detectable signatures. The launch of kinetic direct ascent ASAT tests would be easily detected by early warning satellites. Co-orbital ASAT weapons which have been developed in the past, including Russia's Istrebitel Sputnikov [53] and Luch (which does not have a confirmed mission, but is suspected to be a co-orbital ASAT weapon due to its odd maneuvers) [54] satellites, have been large enough to track with current capabilities, so we would be able to detect any maneuvers that approach NC3 satellites. Directed energy attacks and electronic warfare against space systems would also be preceded by close approaches to target satellites. However, cyberattacks would be more difficult to detect and attribute; we therefore focus on our ability to distinguish between such attacks and accidental debris/meteoroid collisions.

We can now ask whether a debilitating debris or meteoroid impact would leave any observational signatures that would allow us to conclude that the satellite was not the target of a cyberattack. That is, we examine whether debris collisions can be ruled out as a cause of satellite failure. In doing so, we assume that all communication with the satellite is lost, i.e. we do not receive any information directly from the satellite about its failure, such as abnormal acceleration, a change in the satellite attitude, or any other signatures of potential failure causes. Any information regarding these changes would have to be inferred from follow-up observations rather than relying on satellite communications. For example, one could use observational methods to determine whether an uncommanded change of satellite attitude has occurred [55]. This assumes that a cyberattack would leave the attitude control system of a satellite unaffected, but the satellite would lose attitude control capabilities from a debris or meteoroid impact. This is plausible, as a cyberattack on an NC3 satellite might be designed to only interfere with the satellite's mission, rather than affecting other aspects of its functioning, like attitude control. As described above, we have observed satellites like Olympus begin to tumble when possibly hit by small debris or a meteoroid. One could detect a tumbling satellite by variations in its brightness, however this data would take time to collect and process, especially as it would need to be collected at night. Other methods to determine the satellite attitude include Satellite Laser Ranging (SLR) and Inverse Synthetic Aperture Radar (ISAR) images. SLR is commonly used to measure distances to Earth-orbiting satellites using laser pulses that are reflected by cubed corner retroreflectors (CCRs) on the satellites. Any satellite attitude change would be noticed in the form of a reduction in the returned photon counts, as the CCR is tilted away from the ground-based SLR station [56]. Although this would be a quick way to detect a change in satellite attitude, the use of SLR requires satellites to be already equipped with retroreflectors. On the other hand, ISAR uses radar imaging to generate a high-resolution two-dimensional image of a satellite, and does not require special equipment to be pre-installed on the satellite. The quadratic and higher order phase terms of ISAR images, which cause defocusing of the image, can be leveraged to measure the satellite attitude [57]. As this process uses radar, it can be carried out at any time of day. It is not clear whether these are methods currently employed by the United States and other countries to follow-up on satellite failures.

A collision with a debris particle could also result in changes to the orbital velocity of a satellite. An inelastic collision between a satellite of mass 1000 kg and a 3 g particle, with a relative velocity of 0.5 km/s [45] would result in an impulse velocity of about 0.15 cm/s. The largest velocity change and subsequent displacement of the satellite from its orbit would happen if the debris impact were along the track of the satellite, or anti-track (the smallest velocity change would be if the impact were normal or cross-track). For an along-the-track/anti-track impact with an impulse velocity of 0.15 cm/s, the displacement of a GEO satellite from its orbit would be ~0.08 arcsec, or 16 meters over the course of an hour, or 1.9 arcsec (385 meters) over the course of one day. However, the uncertainties associated with DoD SSN orbit predictions for objects in GEO are on the order of a kilometer, due to the long time delay (up to 1 week) for the SSN to update orbital two-line elements to include recent maneuvers [45]. Thus, it is unlikely that one would be able to conclusively detect such displacements and attribute them to debris collisions over the timescale of a day.

One other possibility could make use of the Geosynchronous Space Situational Awareness Program (GSSAP), a system of U.S. satellites in GEO that collect data for space situational awareness. These satellites have the ability to perform Rendezvous and Proximity Operations (RPO), which allows the satellite to maneuver near an object of interest for characterization and surveillance [58]. With limited publicly available information about the capabilities of the GSSAP satellites, it is not clear whether their imaging capabilities would be able to detect debris craters in a satellite and differentiate them from shadows, paint chips and other expected deformities. Additionally, the act of maneuvering one of the GSSAP satellites to approach the failed satellites would take significant time and fuel, further limiting their utility. However, they could be employed in collaboration with other observational methods described above to attribute the causes of a satellite failure.

While ESA has, in the past, been able to characterize fragmentation events as collision-induced without explicit evidence for an impactor [59], this is done over longer timescales that one likely would not have access to when making decisions in times of crisis. We thus suggest that the primary concern with attribution of satellite failures is not an inability to do so, but rather the time and resources needed. It is not clear, based on the capabilities currently employed by the U.S. military, whether small but debilitating debris or meteoroid impacts could be quickly identified via attitude changes, orbital displacement, or follow-up via GSSAP. As a result, crisis stability might be severely undermined by the development of non-destructive ASAT capabilities (such as cyberwarfare), in tandem with a growing population of space debris in GEO. The failure of an early warning satellite could be a precursor to an imminent nuclear attack, and in times of heightened tensions or warfare, one might be inclined to respond, either symmetrically or asymmetrically, instead of waiting hours or days for follow-up to determine the cause of the failure.

4. THE SITUATION IN LOW EARTH ORBIT

While the discussion above has focused on GEO as the primary location for U.S. NC3 satellites, the situation in LEO is considerably different. Satellites in LEO are more vulnerable to counterspace attacks carried out from the ground, particularly directed energy weapons and electronic warfare, whose intensity follows an inverse square law in distance. The debris population in LEO is also much higher, with an estimated 40,500 objects larger than 10 cm and an additional 1.1 million objects between 1 and 10 cm [60]. These objects have a higher orbital velocity than those in GEO, about 8 km/s, and are not limited to a narrow band as they would be in GEO, increasing the potential for collisions. However, debris tracking capabilities in LEO are also significantly better than in GEO, due to the proximity to Earth. The SSN tracks discrete objects as small as 5 cm in LEO and provides collision alerts to satellite operators [28]. Moreover, follow-up after satellite failures would also be much quicker and easier for satellites in LEO. The average relative velocity for collisions in LEO is 10 km/s, much larger than that in GEO [45]. This means that collisions are much more likely to be catastrophic, leading to complete fragmentation of the satellite, which would be easily detectable by the absence of the complete satellite body and the presence of large debris pieces. If the collision is not catastrophic, the change in the semi-major axis of the satellite from such a collision would be about 50 m, for an along-track or cross-track collision between a 1000 kg satellite and a 3 g particle, which might be detectable, especially relative to other satellites in a constellation. However, orbital propagation in LEO is very sensitive to uncertainties in the modeling of non-gravitational forces, particularly atmospheric drag, as the dependence of the atmospheric density on perturbing forces from solar activity is very difficult to predict. For example, it has been shown that missing a prediction of a geomagnetic solar storm can lead to an incorrect estimation of the collision probability between two satellites by a few orders of magnitude [61]. Due to the uncertainties in atmospheric density, we likely cannot rely on comparing orbital displacement to orbital predictions in order to attribute satellite failure to a debris collision. However, methods to determine satellite attitude like Satellite Laser Ranging and Inverse Synthetic Aperture Radar imaging are much more powerful in LEO than GEO, as the strength of electromagnetic signals after propagation and return scales as inverse to the fourth power. Thus, although NC3 satellites in LEO are more vulnerable than those in GEO to both counterspace attacks and collisions with debris, it would be easier and quicker to determine the cause of satellite failure. For this reason, we suggest that it is unlikely that a debris impact could be mistaken for a counterspace attack against a satellite in LEO, i.e. LEO debris is not destabilizing.

5. BROADER STRATEGIC IMPLICATIONS OF THE GROWING DEBRIS POPULATION

In addition to the possibility of mistaking debris impacts for counterspace attacks against NC3 satellites, there are other ways in which debris could be either stabilizing or destabilizing, which we will now briefly explore. One suggestion in the literature is that space debris acts as a deterrent, preventing states from conducting more frequent kinetic ASAT tests or engaging in counterspace attacks [62, 63]. In part due to several kinetic ASAT tests in the past few years, including the March 2019 Indian test [64], and the November 2021 Russian test [65], satellites in LEO face greater collision risks, requiring more frequent collision avoidance maneuvers and greatly complicating operations. It has been suggested that debris generated by aggressive actions in space can increase future costs to the aggressor, in the form of potential destruction of their own satellites by debris, disincentivizing them from engaging in such attacks [62, 63]. In this sense, debris can be seen as enhancing arms race stability, as it can make states reluctant to test ASAT weapons, particularly kinetic ones, and therefore limit the ability of states to develop such capabilities. It is true that only a handful of states with launch capabilities have tested kinetic ASATs (the U.S., Russia, China, and India) [20], suggesting that there might be some deterrent effect already in play [63]. While these four states have engaged in ASAT tests in the recent past, each additional test will increase the potential cost to these actors, suggesting that these states could be deterred from additional testing in the near future. This notion is supported by the recent U.S. announcement of a commitment to not conduct destructive, direct ascent ASAT testing [66], followed by similar unilateral declarations from over 30 other countries [67] and a UN General Assembly resolution upholding this commitment [68]., The potential for space debris impacts to be misinterpreted as counterspace attacks might also limit debris-generating activities, such as kinetic ASATs. For these reasons, debris can be viewed as stabilizing with respect to arms race stability, particularly for countries that would require further testing to build a robust destructive ASAT capability. However, while it might limit the development of destructive ASAT weapons, it would not prevent states from pursuing other counterspace capabilities, including directed energy weapons, electronic and cyber warfare.

The argument above assumes that all nations and actors have a vested interest in minimizing the amount of debris and keeping LEO usable. It might be possible that states or non-state actors with very little reliance on space-based assets (e.g. for communications or navigation), could choose to intentionally pursue debris creating capabilities in order to weaken states that rely heavily on space-based assets [63]. Although it is unlikely that a non-state actor would develop launch capabilities, another nation could, for example, intentionally conduct a number of kinetic ASAT tests to increase the amount of debris [69], possibly posing a fatal threat to the U.S. NC3 architecture and other essential satellite systems.

6. CONCLUSIONS

Overall, space debris has a number of implications for nuclear strategic stability which should be further studied and addressed. Perhaps the most concerning is the impact on crisis stability. Particularly in GEO, where NC3 satellites are vulnerable to both collisions with debris/meteoroids and counterspace attacks in the form of cyberwarfare, follow-up to ascertain the cause of satellite failure might be particularly difficult due to the large distances we must contend with. This is concerning when, in times of crisis, one might misinterpret a debris or meteoroid impact to be a counterspace attack intended to blind one to an incoming nuclear attack. In such a situation, one might not have sufficient time to follow-up to determine to cause of the satellite failure before deciding on how to respond. This situation might be assessed in a similar vein to questions of entanglement (via dual-capable weapons) and strategic stability, where the intentions of an adversary are unclear during the available response window. If we believe that dual-capable weapons are destabilizing and could lead to inadvertent escalation [70], then we should be equally concerned about the effects of debris. At the same time, debris might actually bolster arms race stability, by imposing significant costs on countries that test kinetic ASAT weapons.

To mitigate the risks associated with debris collisions, nations should focus on developing their ability to track debris. The smaller the limits of our tracking systems, the more likely it is that we will be able to prevent collisions or at least know that a satellite was hit by a piece of small debris. Nations should also improve upon their ability to follow-up satellite failures and ascertain the causes, which is particularly important for investigating possible meteoroid strikes. This could include technology development in the form of Satellite Laser Ranging and Inverse Synthetic Aperture Radar imaging for satellite attitude determination, as well as improvement of the modeling of satellite orbits to reduce uncertainties associated with non-gravitational forces. Additionally, nuclear weapons states need to factor the risk of false alarms, such as those that could be caused by debris or meteoroids, into their nuclear response policies and protocols. Maintaining a nuclear posture that allows for a nuclear response to non-nuclear attacks on NC3 infrastructure is dangerous and destabilizing without a presumption in place that loss of an NC3 satellite is due to a non-hostile factor unless proven otherwise. By taking these measures, the international community would move closer to eliminating the destabilizing aspects of space debris, an increasingly important effort as the amount of debris continues to grow rapidly.

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