THE SECURITY DIMENSIONS OF SPACE TRAFFIC MANAGEMENT

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Introduction[1]

Outer space is becoming a environment contested by many space-faring states as they pursue increasingly tactical military interests in this domain. In January of this year, China tested a direct-ascent hit-to-kill anti-satellite weapon system in low Earth orbit. The resulting collision of the land-based weapon with a weather satellite produced a 10% increase in trackable space debris. The estimated lifetime of much of this debris will be measured in tens, if not hundreds, of years. In the absence of a new international agreement for outer space dealing with the potential deployment of weapons into that domain, and the usage of yet other weapons based on the Earth that reach into outer space, armed conflict in this domain could seriously jeopardize humanity's sustainable use of outer space for the myriads of peaceful uses that benefit all of the inhabitants of the Earth.

Experience shows that negotiated arms control agreements have often been presaged by transparency, confidence- and security-building measures (TCSBMs) that have first built up the necessary critical will, often in times of crisis or increased tension, to address more permanently the national security interests of affected states. For example, it was the prelude of the failed Mutual and Balanced Force Reduction (MBFR) Treaty talks and the Conference on Confidence and Security Building Measures and Disarmament in Europe talks that ultimately resulted in the successful conclusion of the Treaty on Conventional Armed Forces in Europe (CFE). In this case the international community felt compelled to act and it did so very effectively. So in searching for TCSBMs that could possibly serve as a catalyst to address the Prevention of an Arms Race in Outer Space (PAROS) agenda item of the Conference on Disarmament, there is no better candidate than the rising international interest in the subject of space traffic management. In short, we should use the present challenges we all face as an opportunity to take much needed and overdue collective action.

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What is space traffic management?

Space traffic management is an operational idea for the safe exploitation of outer space as new space actors arise and as existing space-faring states increasingly make use of outer space for a variety of civil, military and commercial purposes. In accordance with the International Academy of Astronautics *Cosmic Study on Space Traffic Management* (2006), space traffic management means: the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference.

Space traffic management thus applies to three phases of spaceflight: launch, operations in-orbit and return to Earth. It envisages the use of technical and regulatory means to monitor space launches, the in-orbit manoeuvres of artificial satellites, as well as the planned and unplanned re-entry of vehicles and derelict spacecraft at the end of their useful lives. The concept deals primarily with freedom from both physical and radio-frequency interference to enhance the integrity of space operations. Not unlike the prior development of air traffic control for the safety of air travel, space traffic management will be needed to safely navigate artificial satellites through increasingly congested operations in outer space.

Recent space technology developments also call for the monitoring of space launch vehicles, artificial satellites and re-entry vehicles. The first of these developments is the continued production of space debris by the lack of sound de-orbit practices for the upper stages of space launch vehicles and for artificial satellites at the end of their useful lives. Resumed testing of anti-satellite weapon systems based on physical principles seeking to damage or destroy their targets, as opposed to electronic warfare principles tending to temporarily, locally and reversibly disrupt or deny communication signals, will exacerbate this critical environmental problem. The deliberate destruction of even a single large military satellite could nearly double the current space debris population around the Earth.[2] The world can ill afford numerous battles in outer space based on physical destruction methods as have been witnessed in the land, sea and air domains before it, because the space environment cannot quickly recover from such potentially catastrophic destruction, and there are no fast and ready remedies at this point to address the very serious problem of significantly increased space debris.

The recent development of artificial satellites capable of approaching, docking or manoeuvring close to another uncooperative artificial satellite will also raise the concerns of states whose satellites could be visited by such highly agile spacecraft. A satellite that is capable of an in-orbit repair mission for ordinary satellites could also be capable of inflicting damage or even destroying satellites during armed conflict. An analogy of an unannounced visit by one of these satellites will illustrate this newfound anxiety. Were a new passenger to sit down in the seat next to you out of all of the available empty seats late at night on a public bus, that act would likely elicit in you a primordial fight-or-flight response. The same dangers will arise in space operations as these new dual-use systems begin to gain wider use.

Laser communication payloads are also a new technology to be introduced on artificial satellites that will raise the need for improved space situational awareness. Unlike radio communication technologies that exhibit large spill-over radiation patterns, these new capabilities will be far more secure against eavesdropping and interference methods due to their more tightly focused beams of light. As these on-board laser capabilities grow in number, new techniques, possibly based on close-proximity-operations-capable satellites, could be developed to meet national security requirements to exploit, disrupt or deny satellite laser communication signals in the service of national security interests on the Earth.

Satellites harming other satellites

Today, it is not unusual for space objects from different launching states to pass within 5km of one another for no other reason than certain orbits are preferable for certain missions. These events are called conjunctions. What is worrisome about such close approaches is that dedicated explosive warhead designs could be fashioned to damage or destroy space objects from about that range.[3] Thus satellites, specially designed or modified to inflict harm, could be introduced into outer space to harm other satellites after making an approach. Alternately, a specialized satellite may harm another satellite at range if it possesses large apertures to focus electromagnetic radiation tightly, or alternately, can generate a substantial amount of power to account for radiation intensity decreasing as the square of increasing range.

In the field of architecture there is a tenet that "form follows function" and this same tenet is observed in spacecraft design, because there are so many constraints acting on a satellite's design to meet the functional requirements of the mission. The cost of launching satellites into outer space also dictates that every single gram of a satellite's mass must make a contribution to an essential function. In the arms-control language of an earlier era, discernable features unique to an object's purpose were called "functionally-related observable differences" and this technique was primarily used to differentiate nuclear weapon from non-nuclear weapon delivery platforms under the Strategic Arms Reduction Talks (START) treaties.

For an example applicable to outer space, consider that an ordinary spacecraft will have one of several well-known configurations of rocket thrusters for the satellite to maintain its position and orientation. These rocket configurations are not well suited to turn ordinary satellites into "suicide" satellites to inflict damage on others through intentional collisions. Ordinary satellites will also not possess the dedicated sensors necessary to track targets for intentional collisions. Close-proximity-operations-capable satellites will, on the other hand, likely employ a different number and configuration of rocket thrusters to ensure that they do not collide by accident with satellites they are designed to approach safely. This specialized configuration of rocket thrusters can thus help discern low-threat satellites from other more dangerous dual-use satellites deployed in orbit. Such agile satellites will also employ dedicated radar, lidar and optical-tracking sensors to direct their precise rendezvous manoeuvres. Even greater specializations would be evident for dedicated space-based weapons, which, in addition to being agile, would also likely possess rocket thrusters of the size and orientation needed to move from one orbit to another quickly. Dedicated space-based weapons would also not likely use multiple redundant technologies to perform the end-game tracking function necessary to safely approach another satellite in order to keep the amount of fuel mass they must carry to an absolute minimum.

A harm index for satellites

Given that form follows function for artificial satellites, is it possible to assign a "harm index" to satellites based on a limited amount of information declared or collected by national technical means of observation? The answer to this question is yes. The answer must be affirmative, if for no other reason than a nation that is reliant on outer space for its national power base can never be caught unawares as to the emergence of new threats that would risk their assured use of artificial satellites upon which they depend for their military prowess on Earth. As outer space moves increasingly towards becoming a contested environment, space situational awareness will increasingly become a strategic tool to first ascertain, and then manage, the risk presented by the space activities of rival powers. Three questions consequently loom for every space object:

- Does the artificial satellite have the capability to harm another artificial satellite in close proximity or at range?
- Is the artificial satellite specialized enough to be classified as a space-based weapon, where “weapon” could mean “any device, specially designed or modified, to injure or kill a person or damage or destroy an object by the projection or the occlusion of mass or energy”?
- Does the owner or operator of the artificial satellite have the intent to harm another satellite?

The second question of this series is the most important question in need of an answer because a threat of such magnitude for one’s own satellites cannot ever go unmet by the lowest-risk combination of defensive and offensive means available in outer space or on Earth to avoid, accept, mitigate or transfer the risk of such observed deployments. Fortunately, the answer to the first two of these questions lies in just three engineering equations. These equations are:

- The Rocket Equation, which indicates the cost in terms of propellant mass for an artificial satellite to move from one orbit to another and thus how easy or difficult it is for a satellite to quickly approach another satellite in a different orbit.
- The Link Equation, which indicates whether an artificial satellite has an ability to irradiate another object with sufficient power for benign radio communication services or with sufficient power to damage or destroy the objects it could illuminate at range.
- The Energy Balance Equation, which indicates how much electrical power is generated, radiated for useful purpose and otherwise emitted as wasted heat from an artificial satellite as a function of time to ascertain whether it is saving enough electrical charge to rapidly discharge later.

When this information is combined with the orbital position and change in orbital position information made available by a space traffic management system, a "harm index", or a capability-based threat assessment, can be established for all space objects.

To answer the last question posited above, an estimate of a space actor's intentions can be made by contrasting their prior declarations with recorded observations, for example with prior notification of space launches; rendezvous, docking or close "fly-by" manoeuvres; and atmospheric re-entries. This contrast will result in a measure of a space actor's behaviour predilections over time. Commercial satellite operators are less likely to intentionally damage other objects than civil government operators who are even less likely than certain military operators. Thus both capabilities and intentions can be estimated to create a coherent threat assessment for all space objects operated by all space actors.

Space traffic management plus additional information improves space security

A space traffic management system can provide the position, geometry and motion data for states to calculate harm indices in order to allay fears of intentional damage or destruction from dual-use satellites, such as close-proximity-operations-capable satellites. Additional information is required, however, to perform these analyses with any confidence. This information can come from additional state declarations, open source information collection and other national technical means of observation.

Consider for example the specific case of the Rocket Equation:

$m_f = m_i \cdot e^{-(\Delta v / Isp \cdot g_0)}$

where,

m_f is the final mass of the rocket,

m_i is the initial mass of the rocket,

e is the natural logarithm,

Δv is the change in velocity of the rocket,

g_0 is the acceleration due to gravity at mean sea level, and

I_{sp} is the specific impulse of the rocket fuel at mean sea level defined as the rocket thrust divided by the mass flow rate for the propellant type.

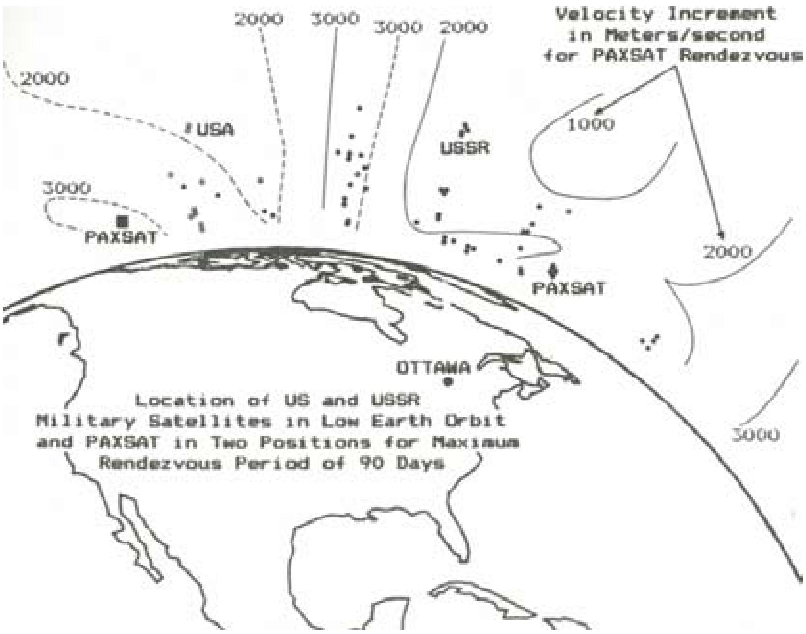
It is noted that the difference in the initial mass and the final mass of the rocket is the amount of rocket propellant used to perform an orbital manoeuvre. Thus, additional state declarations of an artificial satellite's total dry mass (here m_f), total wet mass (here m_i), and the specific impulse of its rocket thrusters (I_{sp}), is sufficient to calculate the change in velocity (Δv) available to a satellite to perform orbital manoeuvres. When this information is contrasted with the cost of orbital manoeuvres calculated from its orbital elements and those of another satellite, one can quickly determine whether a satellite is capable of a rendezvous or an intercept attempt. In other words, one can determine whether a satellite can reach another satellite using the position information collected by a space traffic management system and just three declared, estimated or measured properties of the satellite under consideration.

Orbital mechanics severely constrain an artificial satellite's ability to move to another orbit without substantial effort. It is as if each satellite is dropped into the bottom of a gravity well by its placement in one particular orbit and a great deal of effort (Δv) must be spent to climb out of that well to manoeuvre into a different orbit. Once the satellite locates itself in that new orbit, however, it will again find itself at the bottom of another gravity well. Thus any anti-satellite weapons stationed in outer space would likely be found in the same general volume of space as their potential targets. Similarly, orbital bombardment systems and orbital ballistic missile defence systems would likely be deployed into low Earth orbits that would provide regular coverage of regions of the Earth likely to be targeted.

Figure 1 illustrates the Δv cost functions for two of these gravity wells in low Earth orbit based on two initial orbital positions for the PAXSAT A spacecraft. This spacecraft was a concept for a close-proximity-operations-capable satellite to determine whether a space-based weapon ban could be verified by in-orbit remote sensing techniques. Also depicted in the figure are the locations of superpower military satellite deployments characteristic of the era, based on open source data collected during the study. The lines denoting the Δv costs of manoeuvring the satellite from its initial orbit to another location is also depicted.

The Δv cost functions displayed in Figure 1 are minimum-cost rendezvous manoeuvres because they make use of an assist from the Earth's non-spherical shape in order to precess the PAXSAT A orbit to match its target satellite's orbital plane in the right ascension direction within a period of 90 days. This is a strategy that trades time-of-flight for significant fuel savings. A more rapid rendezvous interval would require much more energy expenditure than that depicted here, since plane-change manoeuvres are the most expensive types of orbital manoeuvres to perform. The consequence of the Δ*v* cost functions depicted in Figure 1 is that once a close-proximity-operations-capable satellite is placed into any given orbit, it is not necessarily going to be able to visit another satellite quickly enough to pose an immediate military threat, and it is not necessarily going to make multiple visits to numerous other satellites without first refuelling. Dedicated space-based weapons would look and act differently from such satellites, and such satellites would likewise look and act much differently from ordinary, more benign types of artificial satellites.

Figure 1. Cost of proximity operations in low Earth orbit



Source: Spar Aerospace Limited, *PAXSAT A Study of the Feasibility of a Space-Based System to Determine the Presence of Weapons in Space*, 1984.

Continuing with the harm index, the dimensions of radio-frequency apertures or electro-optical apertures on an artificial satellite, taken together with either measurements or declarations of a satellite's maximum radiated power and its frequencies of operation, can be used to assess the potential risk that such a satellite may disrupt or deny the radio frequency signals of another space object, or further damage or destroy another space object at range. The equation used in these assessments is the Link Equation typically employed by national radio frequency licensing bodies and by the International Telecommunication Union for satellites in the geostationary orbit. The relative position and motion data needed to calculate range between satellites could come from the information collected by a space traffic management system. Any space-based object that is specially designed or modified to damage or destroy another object at a significant range will possess specialized features for that intended mission. Recall, for example, some of the conceptual designs that had emerged from the Strategic Defense Initiative programme of the United States and its counterpart in the Soviet Union during the mid to late 1980s.

Finally, certain declarations associated with maximum power generation, heat rejection rates and maximum energy storage capabilities could help bound the extent of possible harm indices for satellites through the use of an Energy Balance Equation. In the absence of state declarations, open source information and national technical means of observation could be used to collect data to estimate such capabilities. For example, the measurement of the dimensions of a satellite's solar panels will enable an estimate of the power a space object would have available to project at another object in space or on Earth.

Obstacles and opportunities

Many of the necessary technologies needed to implement a space traffic management system are available to a diverse set of states. There is increasing evidence that the necessary technologies are not all that demanding. Infrasound detectors used to monitor nuclear weapon test explosions on the Earth appear also to be able to detect space launch events.[5] In parallel to the use of such arrays for detecting meteorite events, infrasound detectors should also be able to detect artificial re-entry vehicles and re-entering satellites. Space object tracking devices can be a simple as a set of stopwatches, binoculars and star charts. Several one-metre-diameter earth-based telescopes, when combined with a simple radio frequency fence,

ought to be sufficient to establish an initial space traffic management system. More developed states may wish to launch modest space-based telescopes to track space objects, as Canada plans to do with its Project Sapphire mission being developed by the Department of National Defence.
Some governments could oppose the formation of a space traffic management system on national security grounds, in order to maintain a veil of secrecy for their operations in a domain in which it is extremely difficult to hide space objects from persistent observation by a collection of dedicated ground-based and space-based observatories. Nevertheless, the challenges posed by these arguments can be addressed by managed-access architectures for the space traffic management system and through the natural proliferation of space situational awareness systems underway in China, India, Russia, the United States and European Union among others. Finally, the use of constellations of remote-sensing satellites to collect information will diminish the need to protect the orbital elements of a few reconnaissance satellites because the constellations will provide continuous surveillance of any desired region of the Earth.

Much infrastructure and many institutions and operational practices also already exist for the development of a space traffic management system. In terms of institutions, the International Civil Aviation Organization (ICAO) has several decades' worth of experience in handling more complicated national systems of systems for air traffic control. The International Telecommunication Union (ITU) also has a long service record of coordinating radio frequency signals for artificial satellites in geostationary orbit. Finally, the UN Office of Outer Space Affairs (UNOOSA) maintains the space object registry on behalf of the United Nations. In terms of new potential forums, the Committee on the Peaceful Use of Outer Space or the Conference on Disarmament could take up as part of their work programmes the safety and security dimensions of space traffic management simultaneously or even jointly.

Conclusion

The continued assured access to outer space by all nations must preclude violence or accidents that would result in long-lived space debris. Newly introduced "dual-use" satellites capable of close-proximity operations with other satellites, while not dedicated weapons in themselves, could perform a limited but still dangerous role during armed conflict. Were outer space to become a hotly contested environment in the future, dedicated space-based weapon placement might also then be witnessed. For these reasons, all nations that derive benefit from the use of outer space should support the development of a space traffic management system for its promised safety gains and thus enormous commercial benefits. Consideration of state declarations concerning the objects they launch into outer space could also result in additional security gains to help prevent armed conflict in outer space. Recognition that artificial satellites can be assessed for their potential harm, and aided by a simple definition of a weapon (as presented here), might also lead to international consideration of codes of conduct for outer space wherein nations would first pledge to prohibit the placement of weapons in outer space, prohibit the testing or use of weapons against artificial satellites, and prohibit the testing or use of any artificial satellite itself as a weapon. With that critical will first established, formal agreements might then become more feasible.

Notes

1 The views expressed in this paper are those of the author and do not necessarily represent the views of the Department of Foreign affairs and International Trade or the Government of Canada.

2 David Wright, "Orbital Debris Creation by Kinetic-Energy Anti-Satellite Weapons", draft paper for *Celebrating the Space Age: 50 Years of Space Technology, 40 Years of the Outer Space Treaty*, 2–3 April 2007, Palais des Nations, Geneva.

3 "The maximum weapon effects would extend to a few miles for pellets and to tens of miles for nuclear weapons", in Richard Fitts (ed.), *The Strategy of Electromagnetic Conflict*, Peninsula Publishing, 1980, p. 175.

5 Dr. Peter Brown, "The Potential of the International Monitoring System Infrasound Network for the Detection of Rocket Launches", Final Report, 5 September 2006, Department of Foreign Affairs and International Trade Canada, ISROP Study Contract Number IDC 0061.