Small Satellite Constellations: National Security Implications

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INTRODUCTION

"There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new."

Machiavelli

With the potentially exponential increase in small satellites, particularly those destined for mega-constellations, the world faces something of a dilemma – is this a good or bad development for national security? For the small satellite constellation advocates there is no doubt, they present an outstanding opportunity for the global community to access commercially competitive Space products and services at a fraction of the historic costs, with the potential to enhance national (and personal) security. However, for those troubled by national security threats and issues, the burgeoning capabilities, combined with the sheer numbers of miniaturised orbital assets, and the ever-reducing cost of entry into this developing marketplace, the emergence of small satellite constellations is probably mildly alarming. Which view is right? They both are!

Of course, this is not a simple debate (good vs bad), and the intellectual argument is somewhat skewed by the perspective one takes. Organisations committed to creating businesses associated with small satellite constellations will argue the very significant benefits to mankind of the low cost (or free) access to their services and products. For example, OneWeb's vision, "Internet access everywhere, for everyone" (OneWeb n.d.), is difficult to critique negatively, particularly as it resonates so eloquently with the values of freedom held dear by much of the global community. Depending on one's definition of national security, this type of capability could be seen as enhanced resilience and therefore beneficial to society and, therefore, national security. However, some states may view the vision with some concern, perhaps seeing it as a challenge to the systems that underpin the way their societies currently function. Similarly, nations that are the prime beneficiary of a constellation's products or services for national security purposes will doubtless argue for the benefits the capabilities offer and their right to exploit them; their adversaries might take a different view. Unsurprisingly for Space, the debate will most likely gravitate to one of responsible use, which again is skewed by perspective.

This article attempts to offer both views, for and against, with the aim of enabling the reader to decide whether they are optimistic or pessimistic, or indeed cautiously ambivalent about small satellite constellations. The article covers:

- Definitions. To create the context, the article begins by defining national security, small satellites and constellations. This section also provides a brief history of small satellites.

To consider whether and how a nation's security could be enhanced or degraded by small satellite constellations, the article turns to:

- National Security Enhancements. This section examines the potentially positive contribution of the emerging capabilities, examining *inter alia*: the capability enabling functions of small satellites; Anti-Satellite (ASAT) capability; and the ability to upgrade or enhance resilience of Space system functionality.
- National Security Risks. The next section covers the potential risks to national security: orbital congestion; frequency overcrowding; the danger to people, property and environments; the re-entry risk, the manoeuvre risk, the dangers of ride-sharing and piggyback launches; and, attacks by microsatellites.
- Managing the Risks. The penultimate section deals with the issue of managing the risks, covering observability; manoeuvrability; communication and controllability; the ability of small satellites to operate safely; regulation; liability; legality; and, ethical constraints.
- Conclusion. The article concludes with a brief summary and the authors' view on how we might progress in a way that embraces small satellite constellations responsibly, to optimise their benefits, while protecting global security concerns.

It is important to state that the legality of the activities small satellites may undertake is not considered in the positive and negative contribution sections.

DEFINITIONS

National Security

There are numerous definitions of national security and the concept has, over the last six decades, morphed from that of repelling unwanted influences (normally using the military), to maintaining freedoms, prosperity, self-determination and wellbeing (normally through use of all instruments of power).

Collins Dictionary defines national security as "A country's national security is its ability to protect itself from the threat of violence or attack" (Collins n.d.). The problem with this definition is that it does not address the subtlety of the threat of erosion of societal wellbeing due to the loss or erosion of services; this is important when we consider Space and satellite capabilities. As the 2015 UK National Security Strategy points out, "Economic security goes hand-in-hand with national security" (HM Government 2015), making the clear link between national security and society's ability to function. When considering the benefits and risks of small satellite constellations, while violence and attack are relevant, taking this view only would lead to a myopic perspective of the issues. Therefore, to situate the following analysis in a broader context, it is preferable to adopt Charles Maier's definition of national security (as presented in his unpublished paper for the MacArthur Fellowship Program, Social Science Research Council, 12 June 1990):

"A capacity to control those domestic and foreign conditions that the public opinion of a given community believes necessary to enjoy its own self-determination or autonomy, prosperity and wellbeing."

This definition encompasses the societal aspects of national security, and by implication issues such as security of a nation, individual and way of life, and the importance of assured (critical) services. For the purposes of this article those small satellite constellation capabilities that enable these elements are considered positive and those that degrade or deny the elements are negative.

Small Satellites

There is no universally accepted definition of small satellites; accordingly, most commentators use their attributes to differentiate small satellites from large(r) satellites. Overall, small satellites, in comparison to large(r) satellites often have the following characteristics (Marshall 2008):

- Low cost ($50– $100 million)
- Fast turnaround (12–36 months from authority to proceed to launch).
- Use of latest technology.
- More than one satellite per launch or use of small affordable launch vehicles.
- Use of off-the-shelf technologies wherever possible (both commercial and other).
- Higher risk.
- Less complexity.
- Less durability.
- Less orbital time.
- Lower satellite and launch costs.
- Speedier deployment rates.

These attributes do not always stand up to scrutiny as differentiators, so the more common categorisation of small satellites is by mass or size. Elizabeth Mabrouk (2017) described the following classes of small satellite (Table 1):

Class	Mass (kg)
Mini-satellites	100-180
Micro-satellites	10-100
Nano-satellites	1-10
Pico-satellites	0.01-1
Femto-satellites	0.001-0.01

Table 1: Classification of small satellites

Sir Martin Sweeting, in his paper "*Modern Small Satellites–Changing the Economics of Space*", (Sweeting 2018, pp. 343-344) used similar but not exactly the same mass numbers for the different classes, and includes the specific class for 'small satellite' (Table 2):

Class	Mass (kg)
Small satellite	500-1000
Mini-satellites	100-500
Micro-satellites	10-100
Nano-satellites	1-10
Pico-satellites	0.1-1
Femto-satellites	<0.1

Table 2: Classification of small satellites

A 2017 International Institute of Astronautics (IAA) report (Cho and Graziani 2017) accords with Martin Sweeting's view, albeit combining the small and mini-satellite classes into one 100-1000 kg mini-satellite class. These differing views serve to highlight the lack of a common definition of small satellites, and as Finkleman (2013) highlights, the mass discriminant belies size, orientation, manoeuvrability and other discriminating attributes. The choice of orbital architectures for small satellites by any definition must consider these other characteristics. However, the *cursor* must be set somewhere, so for purposes of this article small satellites are those with a mass of <1000 kg.

CubeSats

It is worth a brief word on CubeSats, as many of the aspiring constellation providers are turning to this class of satellite. “CubeSats are a class of nano-satellites that use a standard size and form factor. The standard CubeSat size is "one unit" or "1U" measuring 10x10x10 cms. and is extendable to larger sizes; 1.5, 2, 3, 6, and even 12U. CubeSats now provide a cost effective platform for science investigations, new technology demonstrations and advanced mission concepts using constellations, swarms disaggregated systems (Mabrouk 2017). The image below (Fig. 1) shows how these “units” can be aggregated to provide different sized nano-satellites.

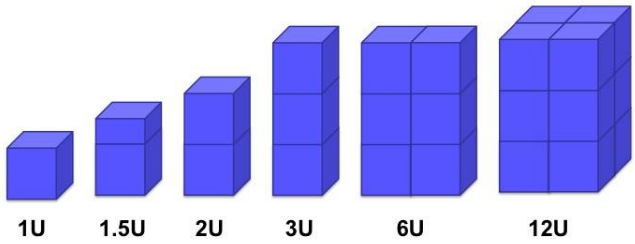

Figure 1: CubeSat units

Constellations

“A satellite constellation[...] is a system of satellites that work together to achieve a single purpose.” In line with this definition offered by Rouse and Haughn (2017), a constellation could be a relatively small number of satellites operating to provide a service (e.g the GPS constellation). However, this article will consider small satellites forming large-scale constellations (mega-constellations), which are primarily planned for Low Earth Orbit (LEO); these are generally perceived to offer the following capabilities:

- Continuous, multipoint data gathering.
- Fast download and upload speed.
- A global imaging capability and capacity.
- Modularity - the use of standardised units allowing flexibility such that satellites can cover the operations of other satellites.
- Networked - the use of satellites that work together in a network to disperse the system capabilities.
- Redundancy - the use of more satellites than are minimally required for the provision of the capability.

As such, these capabilities offer significant commercial opportunities for the constellation suppliers, specifically as the cost of (equivalent to traditional Space based) service provision promises to be materially reduced.

Making a constellation of satellites work has very specific challenges:

- Mission Design – constellations may have three forms of 'control' – controlled satellites where some degree of propulsion manoeuvre is possible; uncontrolled swarms of satellites with no form of propulsion, and something between the two utilising a slave/master approach. All of these approaches have weaknesses, covered in the vulnerabilities section below.

- Critical Mass – The mission architecture will define the coverage provided by the constellation, but whatever the architecture is, there will be a critical mass of satellites required to provide the coverage required.

- More Satellites, More Risk. If all the planned constellations are realised, the total number of operational satellites in orbit would quadruple, exacerbating the risk of catastrophic and cascading satellite collisions (Grush 2018). As constellations grow in size they can no longer be considered in isolation and potential coupling with the background satellite population will become an increasing issue.

Constellation Vulnerabilities

- Cyber – The need to communicate with the ground may create the ability for a third party to intervene in operations making the satellite and potentially the constellation vulnerable to cyber-attack.

- Vulnerability in design – Constellations made up of similar components have increased potential for systemic failure, due to common design elements.

- Jamming and spoofing – Jamming or spoofing a subset of constellation could impact the integrity of the system as a whole.

Small Satellites and NewSpace – The Rise and Rise of CubeSats

The phrase NewSpace is used to imply a different approach and ethos to more established methods and business models associated with new entrants to the Space sector, and characterised by agility, entrepreneurship, and exploitation of off-the-shelf technologies (Sweeting 2018).

CubeSats have contributed to the NewSpace dynamic and the progressive evolution of the small satellite market. Affordability of design, manufacture, launch and operation has dramatically increased the number of *Space fairing* nations (as shown in Fig. 2 below), mainly for education and technology demonstration purposes. Advances in related R&D (e.g. components and sub-systems miniaturisation) has also sparked a growing interest in civil, military and commercial applications for CubeSats (ESPI 2018).

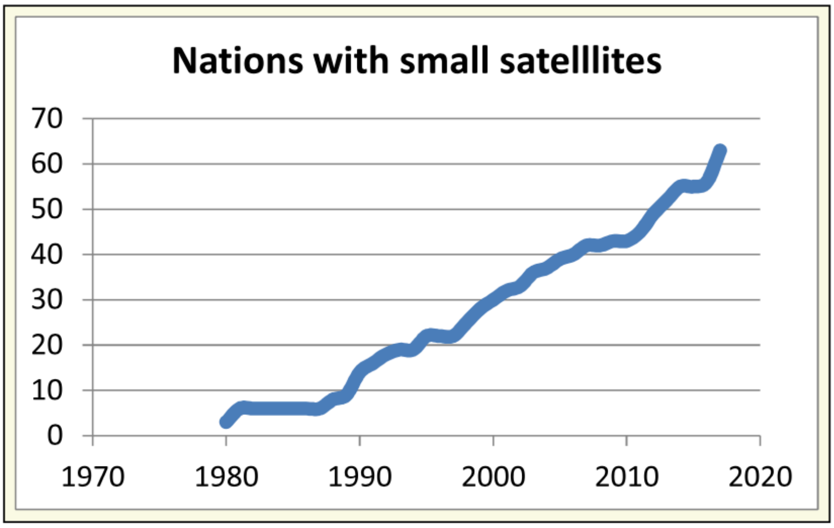

Figure 2: The rise of nations with small satellites (Sweeting 2018, p. 353)

The growth of use of CubeSats is set to increase significantly with the large number of proposed CubeSat constellations (Fig. 2). With limited size and weight, CubeSats cannot match the capabilities of larger traditional satellites. For example, large optics are not feasible, and uncertainty exists with the reliance on yet to be proven launch vehicles, which may limit military use. However, constellations offer applications and services that could challenge some traditional satellite capabilities (ESPI 2018).

National Security Implications

It is perhaps unsurprising that there are both positive and negative security implications associated with the deployment of small satellite constellations, particularly those destined to be mega-constellations. The next two sections cover the positive and negative influences on national security respectively. These will be examined through the lens of the potential capabilities the constellations might provide, and from the perspective of what constellations can do for a nation. This narrative does not comment on the potential *second order* impact on national security of a state resulting from an increased capability i.e. it could be argued that for some nation's, an increased military (particularly hostile) capability could serve to decrease a nation's security as it may be perceived to be more threatening.

THE POSITIVE NATIONAL SECURITY IMPLICATIONS

Enhancement of Security-Oriented Applications

The applications or services potentially provided by small satellite constellations may not be new or indeed novel, but their availability and cost could be transformational for national security, particularly for nations that have not previously had access to capabilities. Even those nations that have previously enjoyed access to capabilities provided by their own or allies' government-owned satellite assets may find the offering from the commercial sector cost-effective and compelling.

As suggested by Larsen (2017, pp. 302-303) and Marshall (2008, pp. 154-157, 166-178), small satellite mega-constellations with remote sensing, communications, broadcasting or navigation capabilities can offer functions that have potential to enhance a nation's security. Some notable functions are:

- Intelligence. A small remote sensing satellite mega-constellation positioned throughout LEO and the Medium Earth Orbit (MEO) has the potential to provide a global optical and radar reconnaissance capability, with continuous or near-continuous coverage. This offers a nation an intelligence gathering capability that can, in some cases, dramatically improve a state's ability to monitor an adversary's activities and to improve their early warning potential against military build-up, manoeuvres, activities and even long-range ballistic missile strikes. The latter becomes increasingly relevant as more and more actors engage in the development long-range ballistic missile capability.

  This *intelligence* has broader security applications too. The ability to access what is happening on the ground with near-continuous coverage offers real benefits for disaster monitoring, planning and relief, enhancing a nation's resilience, an important aspect of the wider national security.

- SIGINT. A small satellite mega-constellation in various orbits offer nations a signals intelligence (SIGINT) capability that for some could be a significant enhancement of their ability to gather intelligence. As above, SIGINT provides a state and its military the potential to monitor an adversary's command and control networks and gain an insight into military or government activities.

- Bandwidth. A military communications and broadcasting small satellite mega-constellation in LEO and GEO will increase demand for satellite communications bandwidth, with impact on spectrum availability for other uses.

- Navigation. Although this may be more in the realms of future capability, a small satellite mega-constellation may well provide navigation services, which complement those provided by large satellite Geostationary Orbital assets. This has the potential to enhance military navigation capability and provide a much-needed resilience to the loss of GNSS services. In addition to enhancing resilience and robustness of those capabilities that are reliant on Space-based navigation products, such services can support a nation's ability to effectively employ modern precision-guided munitions; for some nations this could be transformational.

- Timing. Again, more in the future than today, but a small satellite mega-constellation may have the ability to provide a timing signal of sufficient quality to enable time-reliant systems to operate. In addition to the resilience this may provide for military capability, it also offers to mitigate the loss of timing and therefore provide resilience to the critical national infrastructure sectors' that have a reliance on timing to function.

Provision of Anti-Satellite (ASAT) Capability

Notwithstanding the unacceptability or legality of such a capability, it is technically possible for an appropriately enabled small satellite mega-constellation to perform as an ASAT weapon system for the purpose of neutralising (perhaps temporarily) the functionality of an adversary's national security-oriented Space system in times of conflict. This is clearly contentious and there are risks associated with ASAT activities, not least the potential for a direct or indirect response that could be deleterious to the attacking nation's own national security. There is also the significant risk of debris of the ASAT action because of its kinetic nature, again raising the potential of an escalation of retaliatory action if other nations perceive a threat to their national security. Ultimately, this can jeopardise the stable use of outer Space or at least of certain orbits for any activity, including for the application of small satellite mega-constellations to advance states' national security, including personal security.

Drawing on the work of Baines (2004), Harrison et al. (2019, pp. 3-7) and Marshall (2008, pp. 160-162, 180-192), a small satellite mega-constellation can technically be configured as an ASAT weapon system, to employ a range of attack mechanisms.

- Kinetic – Direct Impact Attack. With an on-board propulsion system, a small satellite can be manoeuvred to a conjunction with an adversary's satellite, with the intention of neutralising or degrading a national security-oriented Space capability in times of conflict. This effect could also be achieved by 'nudging' another satellite to cause it to tumble. It is also possible for the attacking satellite to deploy pellets, specifically creating a targeted debris field with the intention of impacting and degrading an adversary's system.

- Kinetic – Proximity Attack – Explosion. A small satellite with on-board propulsion system combined with an explosive mechanism can be manoeuvred to close proximity of another satellite asset, and the charge initiated to damage the latter in times of conflict.

- Kinetic – Proximity Attack – Capture. A small satellite with on-board propulsion system combined with a method of capturing another orbital object, e.g. via a net or harpoon (University of Surrey 2018), and an explosive mechanism, can be manoeuvred to close proximity to another satellite asset, and the charge initiated to damage the latter in times of conflict.

- Data Disruption. An ability to move close to another satellite with on-board propulsion and a payload with a spoofing or jamming capability could render the target satellite unusable or deny its product to an adversary. Similarly, an electronic or cyber-attack system could corrupt data on the platform degrading its systems. Satellite based laser systems could also be employed to *dazzle* sensors, again eroding the data the sensors can both receive and manipulate.

As indicated above, it is reasonable to assume that a state's development and deployment of a small satellite mega-constellation aimed to advance its national security could be perceived by other states as a move that weakens their respective political and national security. This may lead to proliferation of these capabilities as states seek to develop and deploy better ASAT weapon systems capable of neutralising the functionality of adversary's small satellite mega-constellation. Naturally, the application of any kind of ASAT weapon system is likely to escalate tension and perhaps result in conflict where otherwise it would not have occurred. Debris resulting from ASAT operations will jeopardise the stable use of outer Space or some orbits.

Rapid Upgrade Potential

Given the anticipated life cycle of constellation based small satellites – according to Larsen (2017, p. 279), as little as 9-18 months – there is significant potential to upgrade the security related capabilities in response to a changing threat, thus creating a form of small satellite capability *race*. With Marshall's deliberations in mind (Marshall 2008, p. 166), this is likely to be significantly more cost-effective than reliance on larger satellites remaining at the *cutting edge* (although advances in configurable software and on orbit manufacturing could challenge this hypothesis). It is the nature of small satellite constellations that there is a continuous replenishment requirement as satellites reach the end of their mission and deorbit. It is advantageous that these new small satellites can be built with a more recent generation of technology, thus upgrading the technological standard of their respective Space system. Related to this is the fact that the necessary frequent replenishment missions permit operators to accept more risk in testing technology with a potentially lower readiness level, as well as to enjoy faster learning cycles in technological development.

Enhanced Resilience of Space Systems

As distinct from larger satellites, security-oriented small satellites have some features that make them innately resilient to certain types of ASAT attack. As societies (and military) reliance on many Space based products increases, the prospect of assured capability is extremely important to national security.

Leaning on related previous discussions (Baines 2004, pp. 150-152, 167-170; Larsen 2017, p. 303; Marshall 2008, pp. 166-182; Querejazu and Randazzese 2017, pp. 5-6), some of these features arguably are:

- <u>Small Size</u>. The smaller the satellites, the harder they become for an adversary to target them individually with physical ASAT weapons. Size also contributes to their individual resilience to Space debris, as they are less likely to be impacted in random collisions. However, by contrast, for constellations, the large number of small satellites also makes it <u>more</u> probable that Space debris hits one of them at some point – that said, the innate resilience of sheers numbers in mega-constellations is likely serve to mitigate this threat.

- <u>Number and Orbital Dispersion</u>. A constellation can comprise tens, hundreds or even thousands of satellites situated in one or more orbits. As such, achieving a successful attack against a variety of small satellites will be extremely challenging for an adversary. Similarly, a large number of satellites, potentially throughout different orbital locations make environmental events in Space such as solar flares less of a threat to their collective capability. A few specific attributes can influence the difficulty an adversary would have to target and degrade a mega-constellation, and the innate resilience the system has to environmental threats:
  - The large number of satellites in the constellation, and potentially small number in particular orbital planes.
  - The distribution of different payloads amongst the satellites and orbits, providing a degree of system modularity. This presents the adversary with a challenge – which small satellites in the constellation do they target.
  - The satellites' potential to perform their tasks collectively and individually, presenting an adversary with a similar challenge to above - how to target effectively.
  - Satellite-to-satellite link or networking capability and multiple Space-ground links or hops, which deliver innate resilience and redundancy.

- <u>Potential to Deploy Decoys</u>. Hiding decoy satellites in the constellation to increase the overall Space system resilience against ASAT weapon attacks is a viable option, again challenging adversaries to determine which satellites to target.

Reconstitution of Space System Functionality

Assuming the worst where an adversary has successfully degraded a mega-constellation or its capability, the ability to cost-effectively reconstitute the system will significantly enhance a state's national security, especially when compared with the challenge associated with reconstituting larger satellite capabilities. As, mentioned in previous writings related to this topic (Baines 2004, pp. 150-152, 167-170; Larsen 2017, p. 303; Marshall 2008, pp. 179-182; Querejazu and Randazzese 2017, pp. 5-6), the attributes and characteristics of mega-constellations provide opportunity to reconstitute the system and capability comparatively rapidly. In particular:

- Launch. Their small size and weight means that multiple small satellites can be launched together and with a relatively low price tag. Many commercial and state launch services for small satellites are under development, offering a state more options to launch them rapidly and responsively. This also enables a state to build on-demand infrastructure, and to store large quantities of spare satellites at relatively low cost. Small satellites might be launched as secondary payloads to large(r) satellites.

- Speed of Development and COTS. Small satellites are associated with fast, low-cost development and production cycles, due to the use of modular design and commercial off-the-shelf (COTS) products.

Notably, a potential beneficial secondary effect of a high Space system resilience and reconstitution ability against ASAT weapon attacks is that it can dissuade or deter an adversary from carrying out such an attack in the first place.

THE NEGATIVE NATIONAL SECURITY IMPLICATIONS

Increased Orbital Congestion

The deployment of mega-constellations in one or more similar orbits can lead to orbital congestion, potentially impairing or preventing the safe operation of security-oriented Space objects in the orbits. There is also potential that congested orbits become progressively difficult to cross. Drawing on some related deliberations by ESPI (2018), Finkleman (2013), Greco (2019, pp. 105-106), Larsen (2017, pp. 277, 279-280, 289-290, 296-302), Marshall (2008, p. 178) and Shaw and Rocher (2016, pp. 319-321, 325-327), several notable attributes of small satellite mega-constellations, including with regard to operators, that affect this are:

- Number of Small Satellites. The deployment of small satellite mega-constellations comprising tens, hundreds or even thousands of satellites positioned in one or more orbits can overcrowd the orbits and increase the risk of collision. Reportedly (Sweeting 2018, p. 356), the proposed small satellite mega-constellations (as of around early 2018) shall encompass nearly 25,000 small satellites, with ca. 23,000 for communications, 1500 for EO, and 800 for various services. Any such collision will lead to an increase in Space debris, exacerbating the core problem. Although statistically unlikely, even with mega-constellations on orbit, an exponential increase in Space debris could catalyse the so-called Kessler syndrome, where a chain reaction of conjunctions could render some orbits unusable.

- Default Rate and Mission Life of Small Satellites. Small satellites linked to mega-constellations still seem to have a rather problematic default rate, suggesting reliability may be an issue. For example (O'Callaghan 2019), SpaceX's first 60 small satellites launched as part of its 'Starlink' small satellite mega-constellation project suffered a 5% failure rate (3 out of the 60 satellites did not work). Considering that Starlink shall consist of around 12,000 satellites at altitudes from 550-1100 km by the early 2020s, such a failure rate would result in around 600 inoperable satellites in these orbits just from this project. Furthermore, the mission life of small satellites can be short in some cases – according to Larsen (2017, p. 279), as little as 9-18 months, and not all of them might be successfully deorbited. Each of these factors can increase the amount of Space debris in certain orbits, with the related consequences outlined under the previous point. This problem is compounded by the potential frequency of replenishment launches, necessary to maintain the constellation, that may also leave further Space debris in the form of launcher components.

- Lack of public registration of small satellites. In the past, states have sometimes failed to register and to update the registration information of Space objects for which they bear responsibility under international law, in the dedicated and publicly accessible United Nations Register of Objects Launched into Outer Space (UNOOSA n.d.), and their respective national registers. In the case of the UN registry, the information would include (Convention on Registration of Objects Launched into Outer Space, art. IV):

  (a) Name of launching State or States;
  (b) An appropriate designator of the space object or its registration number;
  (c) Date and territory or location of launch;
  (d) Basic orbital parameters, including:
      (i) Nodal period,
      (ii) Inclination,
      (iii) Apogee,
      (iv) Perigee;
  (e) General function of the Space object.

  Arguably, states' negligence to publicly register and frequently update the registration information of (mega-)constellation forming small satellites for which they are internationally responsible can increase the collision risk in the constellation's orbit(s). Operators with Space objects in the constellation's orbit(s) may lack important official information to properly predict, prepare for and respond to potential conjunctions. Even the identification of the (mega-)constellation forming small satellites' actual operators might prove challenging.

- Insufficient Tracking Capabilities and 'Stealth' Satellites. There is no guarantee that an operator of space objects outside of mega-constellations has access to Space Situational Awareness capabilities that allow sufficient tracking of small satellite mega-constellations. Similarly, there is no guarantee that an operator of a mega-constellation has access to Space Situational Awareness capabilities that allow for tracking others' space objects, especially small satellites in other mega-constellations. Additionally, some satellites might be designed to have a minimal radar cross section and reduced emissions signature, specifically to better protect them from an adversary's ASAT capabilities. Thus, the deployment of one or more small satellite mega constellations can create a situation in which some operators of Space objects are unable to ensure safe navigation in the constellations' orbit(s), increasing the respective collision risk.

- Manoeuvrability. Small satellites often have no or only a limited onboard propulsion system. In the case of mega-constellations such a technical restriction can increase the collision risk as the satellites are unable to manoeuvre away from a conjunction. Furthermore, constellation operators will have difficulty actively de-orbiting satellites at the end of their mission to avoid having them become Space debris. A rule of thumb is that the higher the orbit of a satellite, the longer it will take to de-orbit without intervention.

Overcrowded Radio Frequencies

Building on discussions by Larsen (2017, pp. 283-287) and Shaw and Rosher (2016, pp. 313-314, 317, 321-324), operators are likely to want to use similar radio frequencies to communicate with their constellations, which over time will become a limited resource, and are subject to heavy international (mainly through the International Telecommunication Union) and national level regulation. As such, the deployment of various small satellite constellations in one or more similar orbits can lead to (localised) overcrowding of such radio frequencies. This overcrowding may lead to the degradation or denial of security-oriented capabilities. Moreover, it can make operators' interference-free communication with and thus safe control of their Space objects difficult, with a consequential increase in the collision risk.

Adherence to the international spectrum regime of the ITU has a further security implication. Use of radio frequencies outside the agreed international regulatory regime can create intergovernmental discord that can grow into an intergovernmental conflict, possibly diminishing states' national security.

Danger to People, Property and the Environment

Somewhat drawing on thoughts provided in Shaw and Rosher (2016, pp. 320, 326-327) and Staff Writers (2015), the deployment of mega-constellations has the potential to marginally increase the danger to people on Earth (injury), people's property (damage) and the environment (pollution).

Each of the many launches has the potential to fail and to distribute hazardous material, which could result in injury, property damage or environmental pollution. Additionally, every launch emits potentially harmful and CO_2 increasing pollutants into the atmosphere.

De-orbiting and burning up of the many launcher parts and short-lived small satellites in the atmosphere can be considered a form of pollution. Parts that do not burn up have potential to injure people, cause property damage and pollute the environment otherwise. Naturally, the higher the number of launches and small satellites per constellation, the higher the risk to people, property and the environment.

MANAGING THE ISSUES

As stated previously, in many respects what is a positive for the national security of one nation is very likely to be negative for another. Therefore, in terms of managing the issues around mega-constellations, the approaches taken are less focused on enhancing the positives or minimising the negatives; they are centred on the concept of the *responsible use of Space* i.e. promoting what would generally be perceived as reasonable behaviour.

There are potentially significant strategic, legal or standards-based approaches (e.g. no-go zones, or driving behaviour through an internationally agreed view of the asset and liability obligations) that may have a role in the future. Indeed, there is some guidance already in place, which is pertinent to small satellite mega-constellations; the text below comes from ISO/CDC/20991 (as cited in: Cho and Graziani 2017, p. 31):

> *"This standard describes minimum requirements for small spacecraft.*
> *Small spacecraft may employ untraditional spacecraft development and management philosophy. These spacecraft projects are usually budget-limited or mass-limited, which makes a single (exclusive) launch unaffordable.*
> *The scope of this standard encompasses different categories of small spacecraft, so-called mini-, micro-, nano-, pico- and femto-, as well as CubeSat spacecraft. Therefore, for the sake of convenience, the term "small spacecraft" is used throughout this document as a generic term.*
> *Regardless of the development philosophy, there are minimum requirements every spacecraft shall comply with. This standard explicitly states those requirements and also refers to existing applicable standards. In that sense, this standard serves as the top standard to cover the minimum requirements for various stages of small spacecraft system life-cycle with emphasis on design, launch, deployment, operation, and disposal phases. In this way, (1) safety, (2) harmlessness to co-passengers and launcher, and (3) debris mitigation, are all assured.*
> *This standard is addressed to small spacecraft developers, as well as dispenser providers and the launch operators."*

Verification was added to address the issue on how the requirements described above should be verified. ISO/CDC/20991, provides (as cited in: Cho and Graziani 2017, p. 33):

> *"6 Verification*
> *Verification of compliance with requirements listed below shall be documented with sufficient precision and quality to allow review and approval by the appropriate authority.*
>
> - *Safety (5.2)*
> - *Main payload, adjacent payload(s), and launcher harmlessness (5.3)*
> - *Debris mitigation (5.4)*
> - *Use of radio frequencies (5.5)*
> - *Testing related to safety, debris mitigation, and harmlessness to co-passengers and launcher (5.7)*
> - *CubeSat (5.8)*
>
> *The documentation regarding these verifications may be required by the launch operator to guarantee harmlessness to the main passenger or the co-passengers of the flight."*

However, international Space law and protocols are notoriously slow to implement, and the *problem* is here now. Therefore a more tactical approach to mitigating the risks associated with mega-constellations is needed.

There are a number of technical solutions that can be implemented as characteristic of responsible use:

Situational Awareness

The ability to determine the location of a satellite at any time is critical to the safe operation of small satellite constellations, as with any space object. In the case of small satellite constellations that have limited or no manoeuvrability, the choice of orbit architecture has to balance the cumulative time a satellite can be observed by limited ground-based sensors and the area of the Earth it can sense over time. This balance will determine the optimal inclination and apogee of the orbit chosen.

Observation of the satellites by radio telescopes could be more ubiquitous as they will inevitably have radio frequency signatures from both electronic devices on-board and communication transmissions. These can provide highly accurate orbit observations. (Finkleman, 2013)

Collision Risk - Manoeuvrability

The ability to manoeuvre a satellite, combined with accurate situational awareness, will obviously reduce the risk of conjunctions. Such capability would require either propulsion or the use of aerodynamic characteristics. The mass limitations of many small satellites, such as small CubeSats, will not allow storage of chemical propellant on-board. A better alternative is electronic propulsion, but its use is limited by the lengthy period of continuous thrust that may be required. Such thrust is necessitated by the few hours within which satellite trajectories can be estimated.

There are other possible alternatives, such as catalysis of gas or fluid into high-pressured gaseous propellant, but these also add mass to the satellite. All these possibilities for manoeuvre are only really effective for small orbital or attitude corrections and not for conjunction avoidance. (Finkleman 2013, p. 2)

Re-entry Risk

Spacecraft and launcher upper stages in LEO will deorbit naturally by orbital decay by the operation of drag and gravity at random and by uncontrolled re-entry. They can also be deorbited in a controlled re-entry to a known location, using on-board propellant. A controlled re-entry would also require reliable on-board computer, attitude control and other sub-systems, that add to the cost of the space object.

To achieve the less costly uncontrolled re-entry within twenty-five years, as stipulated in current debris mitigation guidelines, the orbital perigee is lowered to an altitude that increases atmospheric drag. The re-entry location of an uncontrolled space object, necessarily at a shallow angle, can at best be predicted within a margin of ±2,740 km, due in part to uncertainty of atmospheric density at the time of re-entry.

In the absence of agreed international norms on risks posed by re-entry of space debris, there are varying national thresholds stipulated by some countries, but by no means all space active countries. For example, French law prohibits uncontrolled re-entries from January 2020. The US has no proposal to change its existing acceptable risk threshold defined by NASA in 1997 of 1 in 10,000 per re-entry.

Although the re-entry risk associated with the light satellites in mega-constellation is small and would meet the US threshold. However, the increasing number of launches for the predicted mega-satellite constellations will result in a growing population of dead satellites and launch upper stages that would lead to many daily re-entries. These would escalate the risk of damage and injury on the ground, at sea and to flying aircraft, unless uncontrolled re-entry is banned or acceptable risk thresholds are internationally agreed and enforced. (Staff Writers, Escalating Satellite Reentry Risk of Internet Mega Constellations)

Regulatory, Legal, And Ethical Constraints

The growing capability and manoeuvrability of CubeSats in particular pose security, policy and regulatory challenges for governments responsible for their authorisation and supervision. The balance has to be struck between ensuring and managing security associated with the current and foreseen growth of the CubeSat market and meg-constellations while not unduly hampering the NewSpace market dynamic. The approaches, regulations, standards and guidelines will inevitably be at the national level, although they need to be internationally harmonised to develop a shared framework; (ESPI 2018, p. 2).

It has been argued that small satellite constellations do not and cannot meet current regulatory requirements, let alone as they might evolve and regulations develop. In addition there are a number of ethical and technical guidelines relating to satellites, without differentiating between small and large satellites. Clearly these will have to be refined and developed to be effective; (Finkleman 2013, p. 5).

There can be little doubt, that some international solution is needed to regulatory, legal and ethical issues surrounding small satellites and mega-constellations. As mentioned previously, there is a critical balance to be struck, between making the activities safe for all and promoting the markets that will inevitably grow with the capabilities.

Liability Considerations

An indirect threat to a state's national security is its international liability (e.g. fault liability in orbit, and absolute liability on Earth) to damage caused by small satellite mega-constellations for which it bears liability under international law. Importantly, even if the constellation is operated by a private entity, the state bears the liability. Once again, the need for an understanding of the responsible use of these capabilities is paramount and could be exercised through a robust regulatory and licensing regime. However, what is acceptable *responsible* behaviour for one nation may not be the same for another, so once again there is need for international norms.

An operator's mishandling of a mega-constellation can potentially wreak havoc to foreign operators' Space objects in the same orbit(s). This can expose the state liable for the constellation to catastrophic losses and thus strain its financial stability, which in turn can affect its national security. Also, if the liable state is unwilling to pay up for any of the above, there is the potential for an international conflict.

CONCLUSION

The world does indeed face a dilemma with the emergence and proliferation of small satellite mega-constellations. The potential benefits to national security are very significant, particularly for those nations for whom the access to cost-effective Space capability is new. But even for the traditional Space-faring nations, there are very considerable national security advantages associated with the exploitation of small satellite mega constellations: intelligence, SIGINT, bandwidth, navigation, timing, ASAT, the ability to rapidly upgrade and reconstitute Space capabilities or enhance the resilience of Space systems. These are all potentially significant national security positives, for some nations, transformational.

But all these potential benefits come with some risks to national security: potentially increased orbital congestion, overcrowded radio frequencies and the danger to people, property and the environment.

It is fair to say that one nation's benefit could well be another nation's threat or risk, so the dynamic of the impact of small satellite mega-constellations on national security is not straight forward. It is clear that to optimise the benefits and mitigate the risks, both must be managed, ideally internationally. It is likely that any legal or regulatory approach at the international level could well take considerable time to agree and implement, which points to national solutions in the short-term, perhaps based on the concept of *responsible use of Space*.

While this article is intended to provide some food for thought, it would be odd not to offer some concluding remark. Small satellite mega-constellations are here now, and the sub-sector is only destined to grow. Are they a good thing? They do offer much, particularly in the realms of national security in its widest sense. However, it is necessary to exercise caution, if only to ensure that the commercial opportunities can be realised, and the potential benefits to national security are delivered.

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