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Opportunities and Threats from Commercial Satellite Mega-constellations

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“Opportunities and Threats from Commercial Satellite Mega-constellations”
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CONTENTS

EXECUTIVE SUMMARY

This article examines the commercial mega-constellations which are being used to provide communications, imagery and early warning of missile launches. Mega-constellations are considered those constellations numbering in the hundreds of satellites, and mega-constellations in Low Earth Orbit (LEO) are hugely expensive to build and maintain. The US-owned Starlink constellation currently has 3,866 and is the largest mega-constellation providing communications/broadband services ahead of the UK OneWeb. The US Space Defence Agency, through its Transport Layer concept, has plans to launch up to 500 satellites providing military communications and early warning of missile launches.

For the war in Ukraine, the provision of Starlink has enabled Ukrainian forces to communicate on the battlefield and in some instances transmit to unmanned aerial vehicles (UAVs) to target Russian forces. Satellite imagery owned by private companies has contributed to the war, thus Russia has singled out commercial satellite operators and their association with Ukraine, leading a Russian foreign ministry official to label this support as "an extremely dangerous trend …quasi-civilian infrastructure may be a legitimate target for a retaliatory strike".

Although the US is ahead in mega-constellation implementation, China is planning to build the Guowang network in competition with Starlink, envisaging a mega-constellation of 12,992 satellites by 2034. Russia has similar plans with its Sfera concept of 640 small satellites. However, the war in Ukraine has raised significant doubt about whether this concept will progress. These mega-constellations are intended to provide communication, navigation and remote sensing. Commercial gains can be strategically implemented when the provision of communications helps to develop inter-state trade and the expansion of a nation's global influence.

NATO's evolving space strategy underscores the increasing significance of space in ensuring the Alliance's security and prosperity. While the accessibility and dual-use capabilities of space technology offer opportunities, the crowded and contested space domain also poses vulnerabilities. NATO's focus remains on enhancing existing space support rather than developing independent capabilities. Promoting the importance of international rules for space operations and the potential threats to space assets, NATO is committed to collective defence and cooperation while acknowledging the challenges of operating in this evolving domain.

1. INTRODUCTION

Mega-constellations in Low Earth Orbit (LEO) are hugely expensive to build and maintain. Given the nature of their operational orbit, these constellations need to be replaced much more frequently than, for example, satellites in Geostationary Orbit (GEO). While the US and EU may have the means to justify the expense of such sovereign constellations, most nations cannot afford this level of expense; thereby increasing the appeal of providers, such as OneWeb or Space-X. This circumstance places a reliance on critical mission support upon a commercial operator.

Large or mega-constellations of LEO satellites make it difficult for an adversary to deny access to satellite communications. As these constellations are not continually in the view of adversarial nations, they are especially well-suited to the deterrence of ground-based laser and kinetic effects. Additionally, by having a large number of LEO communications satellites, the sheer number of satellites passing over a particular region would make it extremely difficult for an adversarial nation to completely deny communications.

The US Department of Defence is working on a feasibility concept involving a proliferated constellation of satellites in LEO to enable space-based communications. The idea of building large constellations of small and lower cost satellites is to ensure a persistent service which is of interest to the commercial market. A satellite communication (SATCOM) service in GEO requires a relatively low number of satellites in the order of less than five for near-global coverage. Providing the same coverage at LEO requires several hundred satellites.

The war in Ukraine and the provision of Starlink to enable Ukraine to prosecute its defence has brought mega-constellations and its implications for national security to the fore. Consequently, this article examines the commercial mega-constellations which are being used to provide roles such as communications, imagery and early warning of missile launches. In particular, the development of the US-registered company Planet mega-constellation and China's ever-expanding quasi-commercial imagery satellites will be analysed.

It is important to note that China is also developing its own mega-constellation. This has passed through several iterations, and is now called Guowang. This concept will be outlined, with additional attention being given to some of the wider strategic implications for space security concerning potentially competing interests.

This paper commences with an overview of NATO's space strategy. This section delves into the overarching goals, objectives, and principles guiding NATO's approach and strategy to space operations. It highlights the importance of space as a domain for security and defence, emphasizing NATO's commitment to ensuring the resilience and effectiveness of space-based assets. Following the exploration of NATO's space strategy, the paper shifts its focus towards a detailed examination of specific commercial mega-constellations.

This paper also examines the emergence and significance of commercial mega-constellations across various domains, including communications, imagery, and early warning systems for missile launches. The analysis focuses on the development of the Planet mega-constellation. It also identifies China's expanding quasi-commercial imagery satellites, highlighting their implications for national security. The ongoing conflict in Ukraine further underscores the relevance of mega-constellations, with the provision of Starlink to support Ukraine's defence efforts. Furthermore, the paper outlines China's mega-constellation, known as Guowang, and explored its potential strategic implications for space security.

In summary, this paper sheds light upon the growing significance of mega-constellations, both in terms of national security and their impact on the international stage. The findings underscore the need for continued attention to the development and implications of these constellations to safeguard and enhance global security.

2. NATO'S EVOLVING SPACE STRATEGY

The importance of space for the security and prosperity of the Alliance and its Allies is growing.[1] It has greatly enhanced the capacity of NATO and its allies to proactively identify potential dangers and efficiently address crises. Nevertheless, the evolving utilization of space, and the rapid progress in space technology, has presented a spectrum of strategic possibilities as well as a series of geopolitical vulnerabilities. The accessibility, affordability, and capabilities of space technology and services have increased, and are no longer limited to a few technically capable nations. Most space capabilities are dual-use, serving civilian/commercial and military purposes. This streamlining of effort is advantageous to all parties but adds degrees of complexity to the space domain. As of May 2022, the number of active satellites in orbit exceeded 5,400, and private industry anticipates exponential growth in the forthcoming years.[2] From a security and defence perspective, space is becoming more contested, congested, and competitive. As NATO and its allies become ever more dependent upon space-based capability to ensure their strategic advantage, their vulnerability to hostile manipulation and/or direct attack will undoubtedly increase.

However, NATO's primary focus is not on developing its own independent space capabilities; rather, it aims to enhance its existing space support for operations and missions.[3] The recently released "overarching" space policy appears to build upon NATO's previous space policy from 2019. Crucially, however, the specifics of that policy have not been publicly disclosed. The current document asserts that NATO does not seek to become an independent actor in space. However, it acknowledges the increasingly crowded and contested nature of this domain and aims to complement the efforts of allied nations by engaging with relevant international organizations while avoiding unnecessary duplication of effort.

The policy outlines four key roles for NATO in the space domain:

1. Integrating space and related considerations into NATO's core tasks.

2. Serving as a forum for political-military consultations and information-sharing on relevant space developments related to deterrence and defence.

3. Ensuring effective provision of space support and understanding its impact on the Alliance's operations, missions, and activities.

4. Facilitating the development of compatibility and interoperability among Allies' space services, products, and capabilities.[4]

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[1] *See NATO Official Text, 'NATO's Overarching Space Policy', 17 January 2022, https://www.nato.int/cps/en/natohq/official_texts_190862.htm?utm_source=linkedin&utm_medium=nato&utm_campaign=20220117_space (accessed 31 May 2023).*

[2] *John Burton, Domenic Thompson, Alessandro Papa and Arthur Wong, 'International Space Collaboration and Security, A Journal of Strategic Airpower & Spacepower , Winter 2022, Vol. 1, No. 4, Special Issue: International Space Policy (Winter 2022), p.36.*

[3] *Greg Hadley, Air and Space Forces Magazine, 'NATO Publishes 'Overarching' Space Policy, Outlines 4 Roles It Could Play' , https://www.airandspaceforces.com/nato-publishes-overarching-space-policy-outlines-4-roles-it-could-play/ (accessed 31 May 2023).*

[4] *See NATO Official Text, 'NATO's Overarching Space Policy', 17 January 2022.*

In order to bolster these crucial roles, the policy establishes nine distinct “lines of effort,” encompassing myriad domains such as space support, space domain awareness, training and exercises. Given the evolving dynamics within the space domain, NATO acknowledges the urgent need to adjust to the resultant shift in the geopolitical landscape. This adaptation encompasses a recognition of the growing importance of mega-constellations in shaping the Alliance’s comprehensive space policy. The comprehension and effective management of the consequences associated with current mega-constellations represent pivotal components of NATO’s role in space. These efforts are crucial to ensure that space remains a critical asset in upholding the security and prosperity of both the Alliance and its member nations. The following sections of this paper will consider these issues in detail.

3. MEGA-CONSTELLATIONS

Since the launch of the first manmade satellite in 1957, the space industry has developed its products by trying to trade-off between quality, time-to-build and cost. Mega-constellations have introduced a game-changing approach to satellite manufacturing and performance that allows us to improve all three, revolutionizing how we produce and operate space systems.

To date, there are two mega-constellations in orbit, the UK OneWeb and the US Starlink. These two constellations are outlined in further detail below. Both of these systems are utilizing hundreds to tens of thousands of satellites in LEO to deliver low latency broadband data services anywhere on the planet. Mega-constellation satellites occupy orbits between 400 and 1200km and, in order to be economically viable, are typically as small and low cost as they can be, whilst still able to deliver their services. Application areas range from low latency services for banking, to delivering internet access to remote areas, as well as services to aircraft, to ships and potentially to military users.

The need to build tens of thousands of satellites affordably has led to volume production. By bringing in robotics, automation and artificial intelligence (AI) to the manufacturing process and a statistical approach to quality control, OneWeb and Starlink have tried to establish processes similar to those of the civil aircraft industry or even the automotive industry.

Until today, most satellites were custom built with quality control maintained by strict protocols with humans in the loop. For mega-constellations, high volume procurements can amortise non-recurring expenditure. Modular design for low cost and ease of assembly allows human operators to work together with robots and automated systems to manufacture new satellites in a matter of hours. This new manufacturing process alongside the revolution in launcher technology (e.g. reusability, high cadence of launches, large number of satellites launched with a single launcher, etc) has revolutionized the ability to operate space systems and especially for military users.

Lt Gen Stephen N Whiting, Commander of the US Space Force's Space Operations Command, acknowledges the importance of connectivity amongst LEO communications constellations. He asserts that constellations be networked not only with the receivers on the ground but with each other. This connectivity may, however, lead to an increased cyber-attack surface. For each additional node added to a constellation, an equivalent vulnerability and associated risk is also introduced. It may be argued, therefore, that 'connectivity' represents the soft underbelly of integrated global networks.[5] In response, cyber security is an increasingly important part of any satellite constellation, as it ensures continued, secure support for combat missions.

New LEO constellations make cyber security more difficult because of the additional connectivity. Some GEO satellite communications operate on a simple bent pipe principle, in that a user terminal points to a single satellite, at a fixed position, and sends its signal back down to a ground station connected to a network. In a highly mobile multi-component LEO constellation, the entire constellation needs to orchestrate connectivity.

[5] *Shaun Waterman, LEO Constellations Connectivity Offers Risks, and Rewards, Air and Space Forces Magazine Execs Warn, 7 April 2022, accessed: https://www.airandspaceforces.com/leo-constellations-connectivity-offers-risks-and-rewards-execs-warn/*

Satellites, user terminals and ground control stations all need to be networked and controlled so that the satellites know where to send the data they receive.[6] Multiplex connectivity in new LEO constellations provides multiple advantages; however, the attack surface is broader as a result of an increased number of network entry points. This risk can be mitigated by encryption, although this would create a raft of additional costs that are likely to be transferred to the end consumer or service user. It follows that a delicate balance between cyber security and risk must be established.

To realize the potential for proliferated constellations in LEO for SATCOM, and especially for military users, some key technologies need to be addressed: on board processing, new antenna technologies and optical inter-satellite links. Optical communications, such as laser, are the key to forming the space mesh network.[7] This is critical to provide multiple, diversified connectivity paths to route information to and from space at the speed and scale to conduct multi-domain operations. Laser communications are important to negate the increasing ability of adversaries to threaten communications networks and to maintain connectivity between satellites. It is also vital that optical communications terminals are integrated into terrestrial and airborne systems to enable data to be sent and received in an operational setting. This infrastructure would require the wider adoption of phased array antennas capable of handling the rapid and continuous satellite beam handovers to the operation of the LEO and Medium Earth Orbit (MEO) constellations. Flexible terminals capable of seamlessly roaming across different governmental and commercial networks would be required to span the orbital regimes and operate over different frequency bands, waveforms and security levels.

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[6] *Shaun Waterman, LEO Constellations Connectivity Offers Risks and Rewards*

[7] *Gen Kevin P Chilton USAF ret. And Lukas Autenried, The Backbone of JADC2: Satellite Communications for the Information Age Warfare, Mitchell Institute, December 2021, accessed: https://mitchellaerospacepower.org/wp-content/uploads/2021/12/The_Backbone_of_JADC2_Policy_Paper_32-ver2.pdf*

3.1 OneWeb

OneWeb is a constellation of 648 small satellites built by Airbus, with a mass of around 150kg. It is deployed in LEO with an altitude of 1,200km. The first prototype satellites were launched in February 2019, and the deployment phase of the regular satellites commenced on the 6th of February 2020, deploying the first thirty-four satellite types. Initial Operating Capability (IOC) for the service was late 2021. As of March 2023, OneWeb had expanded its constellation in orbit to 618 satellites.[8] OneWeb requires 588 of its 648 constellation to be operational to provide a range of global services, with any additional satellites operating beyond that providing service resilience. OneWeb seeks to build a second-generation LEO constellation, estimated at $4bn, to be jointly developed with Eutelsat. The launches of this constellation are scheduled to commence in 2025.

Figure 1: One Web Constellation of LEO Communications Satellites[9]

[8] *Jason Rainbow, OneWeb Completes Constellation Deployment for Global Broadband, Space News, 28 March 2023, accessed https://spacenews.com/oneweb-completes-constellation-deployment-for-global-broadband/*

[9] *Image accessed https://www.airbus.com/en/products-services/space/telecom/constellations*

3.2 Starlink

Starlink is a subsidiary of the US spacecraft manufacturer, SpaceX. Starlink is developing a constellation of up to 12,000 small satellites, each with a mass of around 230kg. These will be deployed in three orbital regimes in LEO, with the first 1,500 satellites planned in an orbit of 550km. An initial prototype satellite was launched in May 2019. Thereafter, the deployment phase started in December 2019 with the launch of the first sixty satellites. As of April 2023, Starlink has 3,912 satellites in orbit with 3,866 operational.[10] Current analysis suggests that as Starlink's operating altitude is markedly lower than OneWeb, the Starlink system will require nearly two hundredfold the number of satellites than are planned for OneWeb.

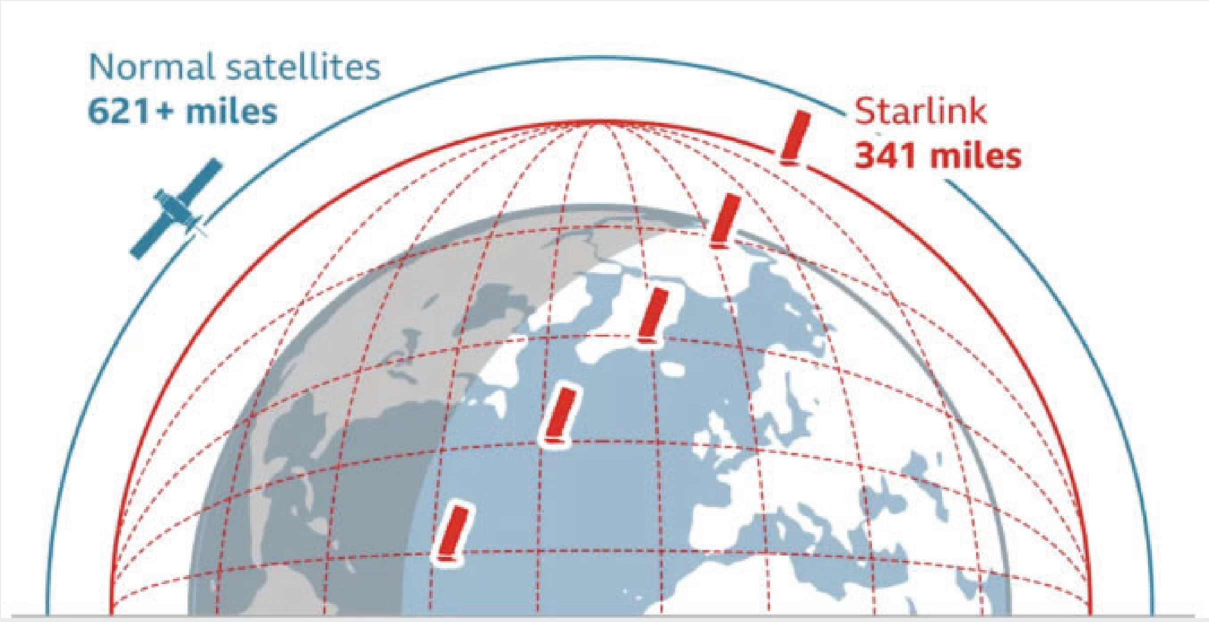

Figure 2: One Web Constellation of LEO Communications Satellites[11]

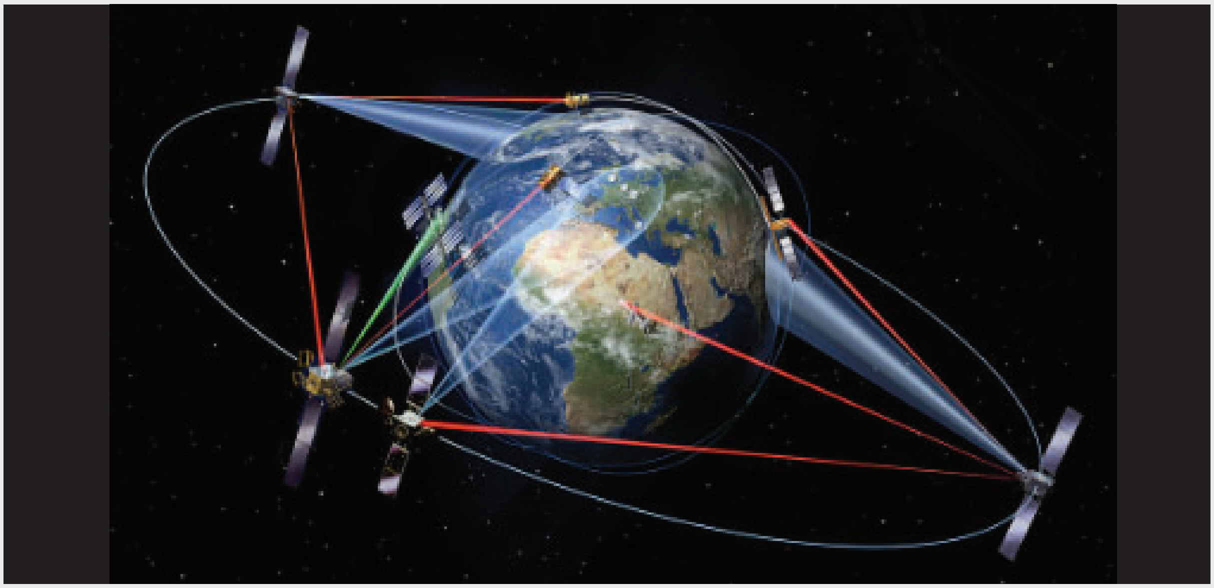

Figure 3: Optical Inter-Satellite Links and satellite-to-ground communications[12]

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[10] *Jonathan McDowell's estimate in Starlink Satellite Train How to see and track in the night sky, 21 April 2023 accessed: https://www.space.com/starlink-satellite-train-how-to-see-and-track-it*
[11] *Image accessed https://www.bbc.co.uk/news/technology-62339835*
[12] *Image accessed https://airbusus.com/laser-communication/*

3.3 Proliferated LEO (pLEO) Tracking Layer Concept

The US Space Development Agency (SDA) was founded in 2019 with the task of rapidly launching hundreds of satellites for the National Defence Space Architecture. The first launch of Tranche 0 took place in April 2023 and put a batch of 10 communication and missile tracking satellites into orbit. The second launch of Tranche 0 launched in September 2023 and consists of ten Transport Layer and six Tracking Layer satellites. Tranche 1 consists of 126 satellites which are to be launched in 2024, with a further 18 experimental satellites to follow.[13] Tranche 1 is a network of small satellites in LEO that is designed to expand the ability to detect and track missiles, using low latency data connectivity. The SDA is planning to place constellations within 1,000-1,200km orbit because satellites in orbits below 600km are becoming increasingly congested and at risk to the increasing amount of space debris at that altitude. Final modelling for the constellation varies, with as few as three hundred to more than five hundred satellites potentially envisaged.

Tranche 2 Transport Layer (T2TL) has three parts. The SDA anticipates a total of seventy-two satellites called the Beta phase. The primary mission for the Beta satellites is UHF and S-band tactical coverage. Beta is also to provide an in-orbit mesh network involving laser communications, as well as laser and Ka-band communication to the ground. The next phase is for 100 Link 16-enabled T2TL Alpha satellites. The final aspect is the T2TL Gamma in 2024, to include UHF and S-band satellites with enhanced, anti-jam waveforms.

A fully operational constellation would be capable of providing ninety-five percent of the Earth's network coverage with at least two satellites in view, and ninety-nine percent of this coverage with only one. This would provide virtually universal connectivity at any time of the day. Synchronized communication between satellites fitted with Inter-satellite Links (ISLs) in LEO will reduce path loss and latency and will ensure time-sensitive targeting.[14]

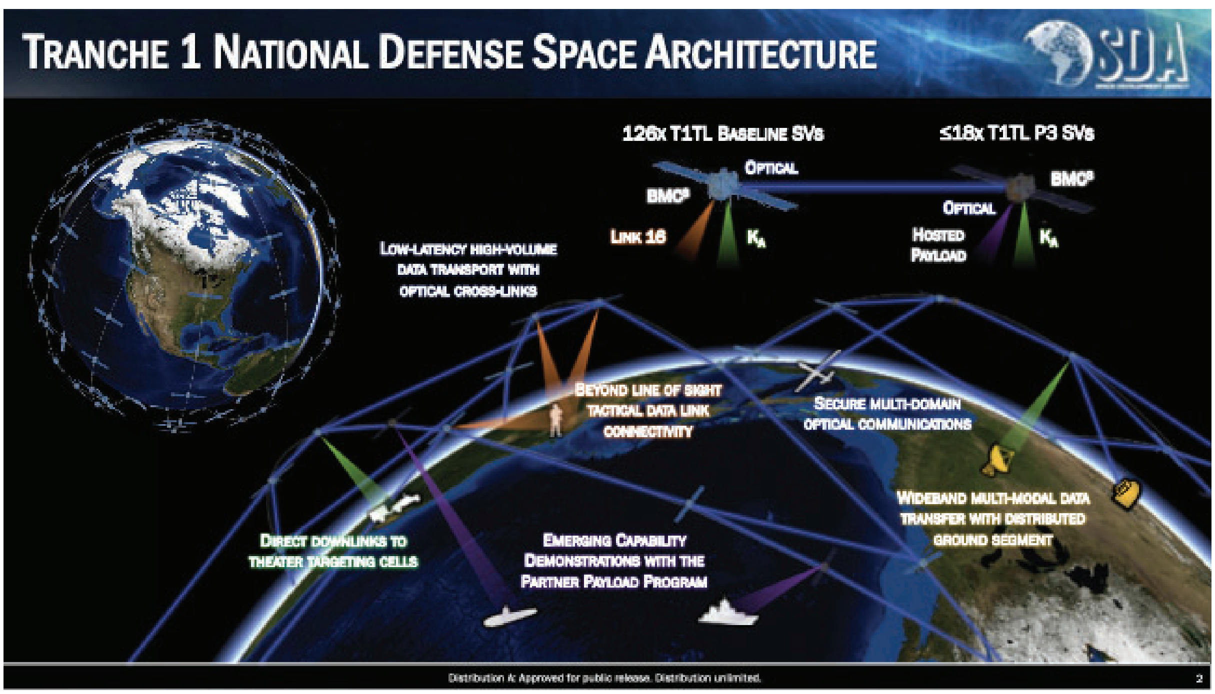

Figure 4: The Space Development Agency plan to establish Tranche 1 Transport Layer, a mesh of 126 optical interconnected space vehicles to be launched in 2024[15]

[13] *US Space Development Agency Prepares for Launch, Aviation Week & Space Technology, 13 December 2021*
[14] *Nicholas Eftimiades, Small Satellites: The Implications for National Security, Atlantic Council, May 2022, 16*
[15] *Image accessed https://news.satnews.com/2022/03/16/terran-orbital-to-support-the-space-development-agencys-tranche-1-transport-layer/*

An advantage of a pLEO constellation is the added resilience that tens, potentially hundreds, of satellites provides. Constellations of this scale present a prominent target for a range of adversarial actors. Conversely, the sheer number of potential targets may increase resiliency from kinetic threats, such as the Russian NUDOL (see figure below), the Nivelir, and China's DN-1 direct ascent systems. Crucially, however, non-kinetic counterspace threats, such as radio frequency jamming and high-power microwave weapons, could affect multiple satellites in LEO, albeit for a limited amount of time.[16]

3.4 Guo Wang

China has demonstrated an active interest in satellite mega-constellations. The state-owned China Aerospace Science and Technology Corporation (CASC) plans to have a 300 satellite Hongyan LEO communications constellation. Comparably, the state-owned China Aerospace Science and Industry Corporation (CASIC) is developing its own 156 satellite Xingyun communications constellation.[18] In 2020 China made an application for 12,992 LEO broadband satellites. This constellation is called GuoWang.[19,20]

In April 2021, China's state-owned Assets Supervision and Administration Commission created a new state-owned enterprise called China SatNet. Its headquarters will be in a new industrial zone in Hebei province, 100km south of Beijing, and its mission is to build China's mega-constellation programme for LEO internet satellites known as GuoWang (national network). Whilst China has developed several programmes with

Figure 5: Russian Anti-Satellite (ASAT) test, 15 Nov 2021. NUDOL successfully intercepted Russian Cosmos 1408 orbit (in blue) using a direct-ascent NUDOL kinetic weapon. The red field is the debris field depicted by AGI.[17]

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[16] *Christopher Stone, Orbital Vigilance: The Need for Enhanced Space-Based Missile Warning and Tracking, Mitchell Institute Policy Paper, June 2022, accessed https://mitchellaerospacepower.org/wp-content/uploads/2022/06/Space_Based_Early_Warning_Policy_Paper_36-FINAL.pdf, 17.*
[17] *Image accessed https://www.youtube.com/watch?v=b52F9R9ByOY*
[18] *Matthew A Hallex and Travis S Cottom, Proliferated Commercial Satellite Constellations, JFQ 97, 2020 accessed: https://ndupress.ndu.edu/Portals/68/Documents/jfq/jfq-97/jfq-97_20-29_Hallex-Cottom.pdf?ver=2020-03-31-130614-940*
[19] *There are three accepted variations of this name: Guo Wang, GuoWang and Guowang.*
[20] *Larry Press, Update on China SatNet's GuoWang Broadband Constellation – Can They Do It? 3 February 2022, accessed https://circleid.com/posts/20220203-update-on-china-satnets-guowang-broadband-constellation-can-they-do-it.*

this aim since 2018, the establishment of SatNet is likely an effort to streamline and quickly develop the constellation. The creation of SatNet put it at the same level as CASIC and CASC and provided it with significant autonomy and increased state support.[21]

CASC and CASIC lead China's internet constellation projects. CASC worked on the Hongyan constellation which aimed to have 320 satellites in LEO by 2020, though this programme has seemingly stagnated. In 2019 a new company, the East is Red Satellite Mobile Communication Company, was created by CASC to oversee the Hongyan project, with sixty satellites planned for delivery by 2022, and a second phase complete with several hundred satellites in orbit by 2025. However, since the launch of Hongyan-1 in 2018 no further satellites in the series have been launched.

CASIC created a parallel project called Hongyun, which was to have a total of 156 satellites by 2022. Paralleling the outcomes of the Honyan project, it appears that after the initial launch, no further satellites were ever launched in the series. CASIC finalised a second constellation, called Xingyun, with two satellites launched in May 2022. Despite a launch schedule of eighty satellites by 2023, the failures of the Kuaizhou-11 launch vehicle has meant that no further satellites in the series have materialized.

In 2021 the Hongyan and Hongyun projects underwent major changes under the direction of the Central Government. China clearly stated its ambition to build an "integrated space-land information system" aimed at providing space-based communications networks that are interoperable.[22] In September 2020, China applied to the International Telecommunications Union (ITU) for frequency registration for two broadband constellations totalling 12,992 satellites for the Guowang 1 and 2 constellations. Under ITU regulations, a state has seven years to place at least one satellite in orbit. Following this initial launch, it has two years to place ten percent of the constellation, and five years to complete fifty percent. Thus, China has until 2027 to place at least one satellite in the Guowang constellation, 1,299 satellites by 2029, 6,496 satellites by 2032, and all 12,992 by 2034. This would require that China launch 200 satellites per year starting in 2023.

China is significantly behind both Starlink and OneWeb; however, it has the capacity to become a significant strategic competitor through the provision of a low-cost user terminal. China could achieve this through a range of public subsidies, with established technology companies, such as Huawei, ZTE and CETC, becoming plausible candidates for service delivery.[23]

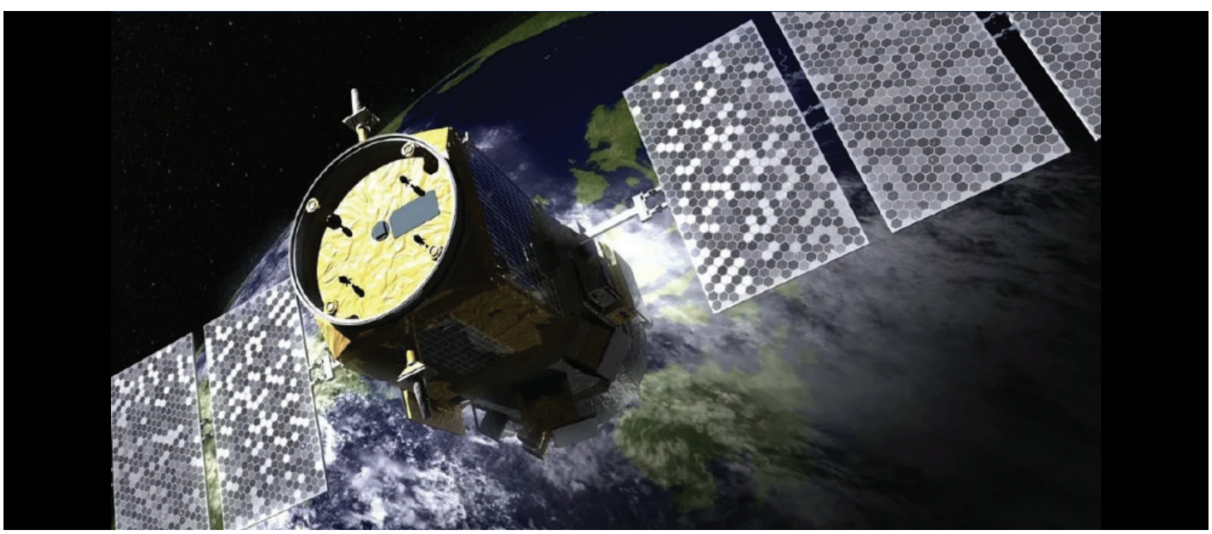

Figure 6: Illustration of Guowang LEO communications satellite[24]

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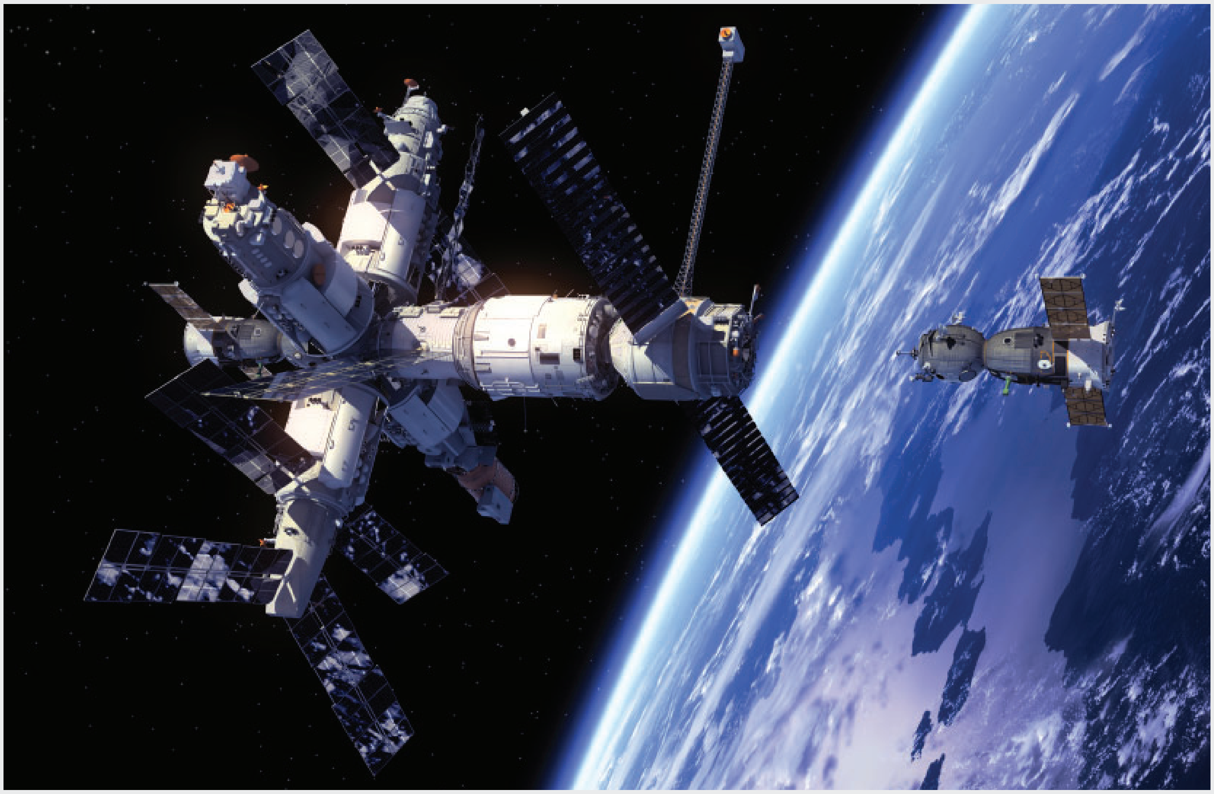
[21]MakenaYoung&AkhilThadani,LowOrbit,HighStakes:AllinontheLEOBroadbandCompetition,CSIS,December22,https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/221214_Young_LowOrbit_HighStakes.pdf?VersionId=vH1lp3dD7VcHGRcvuF9OdzV2WJc_KG42, 11
[22]Marc Julienne, "China in the Race to Low Earth Orbit: Perspectives on the future internet constellation Guowang", Asie.Visions, No. 136, Ifri, April 2023, https://www.ifri.org/en/publications/notes-de-lifri/asie-visions/china-race-low-earth-orbit-perspectives-future-internet, 11
[23]Marc Julienne, "China in the Race to Low Earth Orbit: Perspectives on the future internet constellation Guowang", 19.
[24]Image accessed https://www.spacevoyaging.com/guowang-the-chinas-massive-satellite-constellation-is-launching-soon/

3.5 Jilin-1

The Jilin-1 constellation is China's remote sensing constellation. It is marketed as having been developed solely for commercial use; however, it is under a degree of influence from the Chinese Government. The first Jilin-1 satellite was launched in 2015 and is operated by Chang Guang Satellite Technology Corporation, a subsidiary of the Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP). CIOMP is a state-owned company and, as such, raises doubts over the proposition that Jilin is a wholly commercial endeavour. The 2030 objective of the Jilin constellation is to image the entirety of the Earth's surface every ten minutes. Once complete, the constellation will comprise 138 satellites, with over sixty of these satellites having been launched to date.[25] The Jilin series of satellites have a sub-metre resolution electro-optical, multi-spectral, hyperspectral, infra-red, and video capability. The highest resolution offered in the series of 0.5 metres is the Jilin-1 Kuanfu-01C[26] launched in May 2022.

3.6 Russia's Plans

Russia is also considering the advantages of mega-constellations. Roscosmos, Russia's space corporation, announced plans to build the 288 satellite Efir Constellation to provide global broadband by 2025. This is part of a larger project to build 600 communications and optical imagery satellites to provide global coverage in LEO.[27] In July 2022, Dmitry Rogozin, the General Director of the Roscosmos State Corporation, announced the deployment of the Sfera satellite system which comprises 640 small satellites to provide communication, navigation and remote sensing.[28] The Efir Constellation is a component of the Sfera project, as Roscosmos has merged several projects into the Sfera project. A consortium is developing the project with the participation of Roscosmos and the State Corporation Bank for Development. Additionally, the Foreign Economic Affairs is understood to be partly financing the project, estimated at 300 billion rubles. It is likely, however, that Russia's costly invasion of Ukraine will have a significant impact upon the development of this programme.



[25] *Adrian Bell, China Launches 16 more Jilin-1 satellites atop Chang Zheng 6, NASA Spaceflight, 10 August 2022, accessed https://www.nasaspaceflight.com/2022/08/cz6-launches-16-jilin-1/*

[26] *Andrew Jones, China launches new batches of Jilin-1 commercial remote sensing satellites, Space News, 5 May 2022 accessed: https://spacenews.com/china-launches-new-batches-of-jilin-1-commercial-remote-sensing-satellites/*

[27] *"Russia to Create Orbital Internet Satellite Cluster by 2025," TASS, May 22, 2018, available at <http://tass.com/science/1005554*

[28] *Sfera Satellite System Gets Green Light, Space Watch, July 2022, accessed: https://spacewatch.global/2018/07/sfera-satellite-system-gets-green-light/*

3.7 Proliferation of LEO Satellites for Intelligence Surveillance and Reconnaissance (ISR)

Large constellations of ISR satellites deliver a high temporal rate, offering advantages such as increased temporal resolution or higher revisit rates. However, large constellations of small satellites are currently limited in ground resolution due to the compact size of the satellites, thus restricting the optics or the SAR sensors either in size or in transmission power.[29] A large number of space-based ISR satellites are harder to counter, whether in terms of laser dazzling or jamming, in comparison to a lower number of larger and more capable systems.

The Earth Observation (EO) market has moved towards commercial constellations of large numbers of small satellites, albeit fewer than the communications mega-constellations. The EO constellations range from dozens to hundreds of satellites. This commercial space capability has increased access to EO capabilities for national security applications.[30] The US company Planet already operates a constellation of over 200 small satellites, which offers medium resolution at 3-5m. Planet also has thirteen SkySats which are 100kg satellites of sub-metre resolution. Planet's constellation orbits are sun-synchronous or polar orbits. In November 2017, it achieved a major technological milestone in capturing the Earth's landmass once per day.[31] The imagery from Flocks and SkySats, both cubesats, can be fused to sharpen the medium resolution Flock imagery.

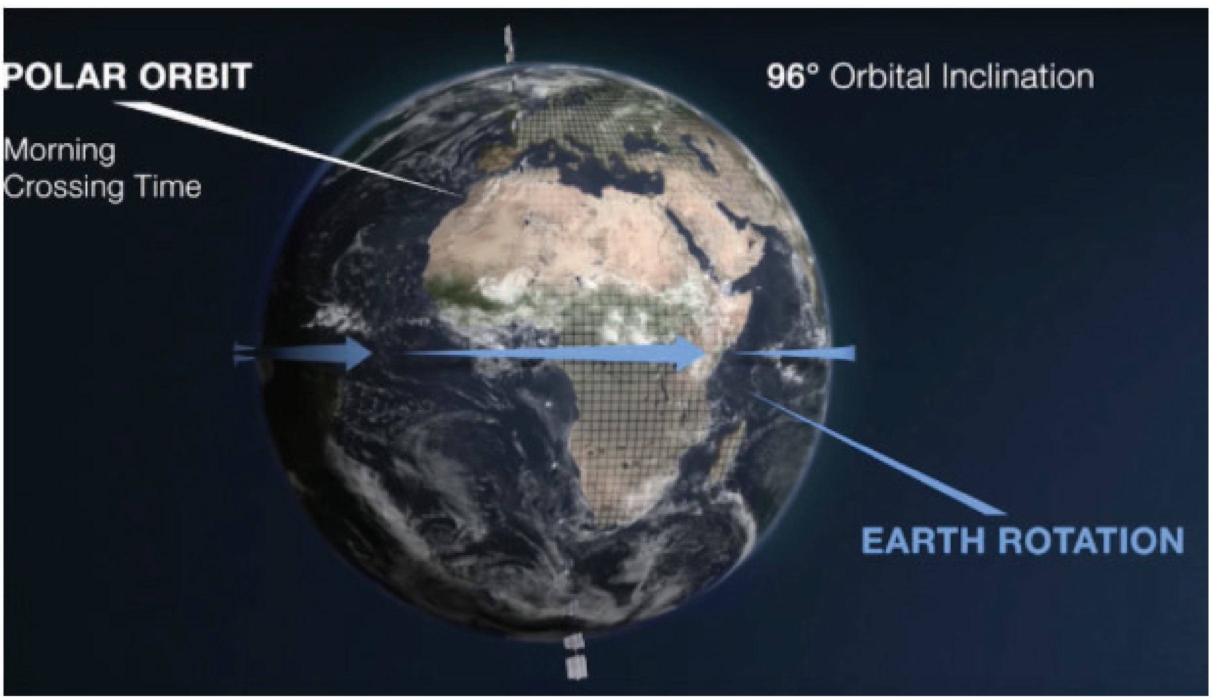


Figure 7: Planet constellation scanning the Earth[32]

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[29]Lt. Col. Tim Vasen, Commercial Small Satellites in Low Earth Orbit, Joint Air and Space Power Conference, June 2020, accessed: https://www.japcc.org/essays/mega-constellations/

[30]Matthew A. Hallex and Travis S Cottom, Proliferated Commercial Satellites Constellations: Implications for National Security, JFQ 97, 2020 accessed https://ndupress.ndu.edu/Portals/68/Documents/jfq/jfq-97/jfq-97_20-29_Hallex-Cottom.pdf%3Fver%3D2020-03-31-130614-940, 22.

[31]Michael Baylor, Planet Labs targets a search engine of the world, Jan 2018, NASA Space Flight, accessed: https://www.nasaspaceflight.com/2018/01/planet-labs-targets-search-engine-world/

[32]Image accessed https://www.nasaspaceflight.com/2018/01/planet-labs-targets-search-engine-world/

4. STRATEGIC IMPORTANCE OF MEGA-CONSTELLATIONS IN LEO

The strategic importance of mega-constellations is found not only in their vast economic benefits, but also in their critical value to a country's strategic infrastructure. Reliable access to advanced space-based architecture enables a country to shape the strategic environment and structure the governance in which it operates. Denying an adversary or competitor access and freedom to exploit their space-based critical national infrastructure (CNI) dependencies will precipitate strategic, military, and economic advantage.[33] Nevertheless, mega-constellations require the authorization for thousands of orbital frequencies from the ITU. Frequencies tend to be reserved on a first come, first served basis. It follows that China and Russia must act quickly to mitigate the potential US monopoly on LEO communications mega-constellations.

These constellations offer military applications, as evidenced by the war in Ukraine. The Ukrainian Armed Forces have benefitted from a resilient telecommunications system thanks to Starlink. These dual-use systems are highly resilient and are difficult to damage through kinetic means, thus providing a decisive advantage over other systems.[34] The ability of Starlink to provide both tactical and strategic communications has been fundamental to the operation of Ukraine's territorial defence. This has afforded Ukraine the ability to provide valuable command and control over its forces and prosecute its military campaign. In the absence of the Starlink system, the Ukrainian Government and its armed forces would, almost certainly, have encountered myriad obstacles to their command, control and communications networks.

The primary aim of internet constellations is to provide a commercial service and the associated economic benefits. Although the definitive business model is still to be demonstrated, the first entrant is likely to capture the lion's share of the market. Commercial gains can become a strategic advantage when the provision of communications helps develop inter-state trade and expands a nation's global influence. China's technological ambitions are laid bare with the Digital Silk Road Initiative, which is seeking to develop a digital infrastructure alongside the Belt Road Initiative. China sees the development of a LEO internet constellation as a factor of power and influence in its strategic competition with the United States. This is in line with China's broadening definition of 'warfare' and its whole-force approach.

In the US, SpaceX's Starlink, Amazon's Project Kuiper and Boeing are expected to be the major competitors in the market. As of November 2022, Starlink has launched over 3,500 satellites offering coverage in more than fifty markets.[35] Amazon's Project Kuiper constellation is expected to launch its first satellite in 2023, with half of its constellation operational by 2026, and full implementation by 2029. Amazon will use Arianespace, Blue Origin and United Launch Alliance to undertake eighty-three launches over a period of five years.

[33]Sharpe, J., Moustakis, F.,Trichas, M., Terrill, D. (2023). What Does the PRC's Space Program Mean for Great Britain and the West? Available at: https://www.thespacereview.com/article/4612/1.
[34]Marc Julienne, "China in the Race to Low Earth Orbit: Perspectives on the future internet constellation Guowang", Asie.Visions, No. 136, Ifri, April 2023, https://www.ifri.org/en/publications/notes-de-lifri/asie-visions/china-race-low-earth-orbit-perspectives-future-internet, 8.
[35]Makena Young & Akhil Thadani, Low Orbit, High Stakes: All in on the LEO Broadband Competition, CSIS, December 22, https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/221214_Young_LowOrbit_HighStakes.pdf?VersionId=vH1lp3dD7VcHGRcvuF9OdzV2WJc_KG42, 10.

The increasing number of satellite mega-constellations under development in the next time frame is likely to compound the problem of crowding in LEO and contribute to signal interference. The significant benefit of mega-constellations is, primarily, the ability to provide improved and rapid communications across shorter distances. This provides higher data transmission or low latency, thereby making LEO constellations more attractive for a range of commercial and military activities.One key challenge is that of adjacent satellite interference (ASI), which generates signal interference from spacecraft and other orbital constellations.[36] Satellite operators are well-aware of operational constraints owing to close satellite spacing. In response, they typically develop coordinated uplink and downlink power density limits along with expected ASI levels for each satellite. However, with the development of the Chinese GuoWang mega-constellation, and associated geopolitical tensions, it is unlikely that this level of satellite operator cooperation will occur. This could result in an increasing amount of ASI occurring between operators.

China's motivation to develop the GuoWang mega-constellation is to compete with Starlink and other companies. This would enable China to beam internet services that could directly influence China's population, thereby aiding the Chinese Communist Party (CCP) to maintain its grip on power. The proliferation of internal CCP propaganda is highly likely to be a significant motivating factor in controlling information accessible from LEO mega-constellations, whilst simultaneously contributing to China's push to develop its sovereign satellite network.

[36]Kartik Bommakanti, The Race for Mega Satellite Constellations: Crowding and Control in Low Earth Orbit, Observer Research Foundation, 1 May 2021, https://www.orfonline.org/expert-speak/the-race-for-mega-satellite-constellations-crowding-and-control-in-low-earth-orbit/

5. CASE STUDY: UKRAINE WAR

Commercial communication satellites are enabling Ukrainian command and control systems. In the hours before its invasion of Ukraine, Russia undertook a cyber attack to deny connectivity between the US-run commercial satellite network, Viasat, and its thousands of ground terminals. The Russian cyber attack not only had an impact on the Ukrainian government and military actors but simultaneously damaged the terminals of civilian customers across Europe and affected thousands of wind turbines in Germany.[37] Tens of thousands of satellite modems had their internet service interrupted after a Denial of Service (DoS) attack with destructive commands to overwrite key data. This highlights the wider impact that cyber attacks can have on critical national and international infrastructure.

During this same time period, the Organisation for Security and Cooperation in Europe (OSCE) was monitoring the Ukrainian border using UAVs, and became subject to GPS signal interference. The day prior to the Russian invasion of Ukraine, a Ukrainian long-range UAV temporarily lost control due to a Russian Krasukha-4 EW system. Russia continues to employ GPS jamming throughout the conflict (see figure below). During March and April 2021, over sixty percent of the OCSE's UAV flights encountered GPS interference.[38] This jamming was corroborated by HawkEye360 in February 2022, which similarly detected GPS interference between Ukraine and Belarus, as well as that encountered by the OSCE UAVs in the southeast of Ukraine.

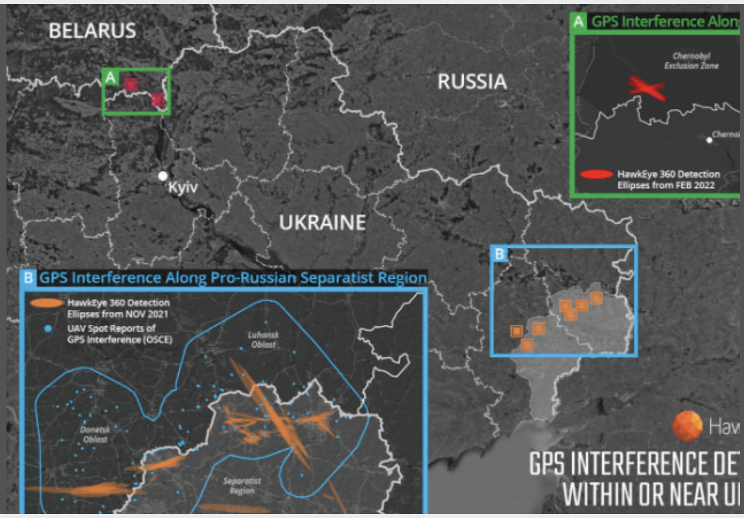

Figure 8: HawkEye360 detects GPS interference along the border between Russian and Ukraine, and Belarus and Ukraine in Feb 2022.[39]

[37] *The War in Ukraine and the European Space Sector, ESPI Briefs, May 2022, https://espi.or.at/publications/espi-executive-briefs/send/5-espi-executive-briefs/612-the-war-in-ukraine-and-the-european-space-sector*

[38] *"OSCE SMM Spot Report 16/2021: SMM Long-Range Unmanned Aerial Vehicle Lost Due to Dual GPS Signal Interference Assessed as Jamming near Government-Controlled Stepanivka," Organization for Security and Co-operation in Europe, June 30, 2021, https://www.osce.org/special-monitoring-mission-to-ukraine/491383.*

[39] *Image accessed https://www.he360.com/hawkeye-360-signal-detection-reveals-gps-interference-in-ukraine/*

After the attack on ViaSat, the Ukrainian government sought assistance from SpaceX to bolster its connectivity through commercial LEO broadband. Thousands of Starlink terminals were delivered to Ukraine, which reconnected the Ukrainian government to the internet.[40] Although Russia has attempted to jam SpaceX's Starlink ground terminals, SpaceX was able to counter the attack by fixing lines of code ensuring the Russian attack was ineffective.[41] Russia continues to attempt to jam Starlink but has had limited success. Ukrainian forces have praised Starlink for allowing them to maintain communications and target Russian forces more effectively with artillery and drones. However, Starlink has reportedly taken active steps to prevent Ukrainian forces from using Starlink to provide data to assist their UAVs and send video to correct artillery fire.

Figure 9: Starlink antenna of the satellite-based broadband system[42]

5.1 The Use of Mega-constellation Satellite Imagery during the War in Ukraine

Satellite imagery owned by private companies has contributed to the war in Ukraine. In August 2022 imagery from Planet showed that an attack on a Russian base in Crimea by Ukrainian forces had caused more damage than Russia had suggested in public reporting.[43] This imagery was singled out by Ukraine's President Zelenskyy as evidence of his country's progress in the war. The use of commercial satellite imagery during the war has served as a means of independently verifying strategic claims made by both sides. Media companies have seized upon satellite imagery provided by mega-satellite companies, such as Planet Labs, to enable them to inform the state of the battlefield to the wider public. The Ukrainian Government has routinely requested data from international private satellite companies. It is reported that US companies were providing imagery to Ukraine minutes after the data was collected as of April 2022.[44] It is noted that Russia has recognized the strategic value of commercial satellite imagery to the Ukrainian government.

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[40] *Kari A. Bingen, Kaitlyn Johnson, Makena Young and John Raymond, CSIS Space Threat Assessment 2023, 14 April 2023, https://www.csis.org/analysis/space-threat-assessment-2023, 18.*

[41] *Kari A. Bingen, Kaitlyn Johnson, Makena Young and John Raymond, CSIS Space Threat Assessment 2023, 18*

[42] *Image accessed https://www.scmp.com/news/world/article/3194039/heres-what-know-about-elon-musks-1-million-starlink-terminals*

[43] *Mark Borowitz, The War in Ukraine Shows How Important Private Satellite Companies Have Become – Especially in Times of Conflict, 16 August 2022, accessed https://news.satnews.com/2022/08/16/the-war-in-ukraine-shows-how-important-private-satellite-companies-have-become-especially-in-times-of-conflict/*

[44] *Mark Borowitz, The War in Ukraine Shows How Important Private Satellite Companies Have Become – Especially in Times of Conflict, 16 August 2022, accessed https://news.satnews.com/2022/08/16/the-war-in-ukraine-shows-how-important-private-satellite-companies-have-become-especially-in-times-of-conflict/*

On the 27th of October 2022, a senior Russian foreign ministry official warned that commercial satellites from the United States and its allies could become legitimate targets for Russia, if they were involved in the war in Ukraine. Konstantin Vorontsov, Deputy Director of the Russian Foreign Ministry's Department for Non-Proliferation and Arms Control, stated at the United Nations that the United States and its allies were trying to use space to enforce Western dominance. Vorontsov specifically highlighted the use of Western Satellites to aid the Ukrainian war effort as being "an extremely dangerous trend" and that "Quasi-civilian infrastructure may be a legitimate target for a retaliatory strike."[45]

Russia did not mention any specific companies, nor did they confirm whether they consider imagery from mega-constellations provided to Ukraine, or the specific use of Starlink, as the main provocation by Ukrainian forces. The ambiguity of this statement was probably intended to serve as a threat to all commercial satellite operators that are providing a service to Ukraine.

The public statement raises an extremely important national security consideration for commercial mega-constellation operators and raises the proposition that they are seen by Russia in this instance as a target for its counterspace capabilities. A consideration for satellite operators is that commercial satellite systems are increasingly being seen as targets by hostile nations. The number of counterspace systems, such as the Russian capabilities previously discussed continues to increase.[46] Likewise, China is actively pursuing Laser Directed Energy Weapons (LDEW) for counterspace use and is likely to have an operational capability within the next five years. This could conceivably be used to dazzle and potentially damage a satellite's imaging sensors in LEO. Comparably, Russia has been working on LDEW programmes for dazzling and damage to imaging satellites in LEO. The GEO belt in the next five to ten years is likely to be outside of the technical capabilities of adversarial nation's capabilities to interfere using LDEW against GEO ISR satellites.

Figure 10: China's ground-based laser ASAT at Xinjiang Province[47]

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[45] *Konstantin Vorontsov, Deputy Director of the Russian foreign ministry's department for non-proliferation and arms control, quoted at the United Nations First Committee, Reuters 27 October 2022, accessed https://www.reuters.com/world/russia-says-wests-commercial-satellites-could-be-targets-2022-10-27/*

[46] *See further elaboration of the threat from Russian and China's Counterspace see articles Matthew Mowthorpe, The Russian Space Threat and A Defence Against it with Guardian Satellites 13 June 22, The Space Review and Matthew Mowthorpe and Markos Trichas, A Review of Chinese Counterspace Activities, The Space Review, 1 August 2022,*

[47] *Image accessed https://freebeacon.com/national-security/satellite-photos-show-chinese-anti-satellite-laser-base/*

6. SECURITY IMPLICATIONS OF MEGA-CONSTELLATIONS

LEO mega-constellations are networked not only with the receivers on the ground but with each other. This connectivity may lead to an increased cyber attack surface and additional vulnerabilities.[48] For each additional node added to a constellation, the risk is increased. The additional connectivity of new LEO constellations makes cyber security more difficult. The large, fast-moving constellation needs to orchestrate connectivity. Consequently, satellites, user terminals and ground control stations all need to be networked and controlled so that the satellites know where to send the data they receive. Multiplex connectivity in new LEO constellations provides multiple advantages; however, the large number of network entry points broadens the attack surface.

The increasing number of mega-constellations providing imagery could prevent military operations from being undertaken without the element of surprise being achieved. Moreover, the availability of military-quality imagery to media outlets could evidence military build-up or any aircraft being prepared for operations. This same imagery could be seen by a potential adversary and could alert them of an impending military action. Whilst this is not an entirely new concept , mega-constellations have ensured that the market has increased exponentially, and that the entire globe is covered more comprehensively.

China, through its Jilin constellation of military-quality imagery satellites, could ensure that any future adversaries would have a ready supply of imagery. This could not only alert potential NATO adversaries of an impending attack, but also provide invaluable imagery to enable hostile actors to conduct their military operations. Similarly, if Russia is able to field its intended mega-constellation, it could provide imagery to its client states.

An advantage of the US pLEO constellation is the added resilience that large numbers of satellites provide. The pLEO constellation would be capable of providing ninety-five percent of the Earth with at least two satellites in view, and ninety-nine percent of the Earth with at least one satellite in view. This would provide connectivity almost anywhere and at virtually anytime. Synchronized communication between satellites fitted with ISLs in LEO will ensure time-sensitive targeting. This will enable the US and the wider NATO Alliance the ability to deliver operational effects anywhere on the Earth and take advantage of the force multiplier that space provides.

[48] *Sharpe, J., Trichas, M., Terrill, D. (2023). Is the CIA Security Triad Still Relevant for the Military?. Unpublished manuscript.*

7. CONCLUSIONS AND RECOMMENDATIONS

Given NATO's growing dependency on space-based capabilities, it is important for the Alliance to fully appreciate and explore the implications and opportunities mega-constellations pose. NATO needs to actively engage with the rapid technological advances being made in the commercial space sector through mega-constellations and fully exploit these capabilities. One potential opportunity is to develop a mega satellite constellation for the detection of passive radio frequency signals. This could provide an invaluable operational capability to identify, characterise and geolocate opposing forces.[49] A key advantage of RF detectors in LEO is their capacity to enable audible detection of other high frequency emitters. Using sensors such as a passive RF allows signals to be gathered and their intent estimated. By hosting these sensors on multiple external platforms, the sensors can triangulate the signal and determine its origin. This is useful for wideband systems as it removes the need for multiple antennas on a single satellite. Multiple platforms also provide disaggregated resilience to jamming by incorporating a large baseline area of detection. The Alliance needs to fully appreciate the range of space-based assets available and how to capitalize on them.[50]

NATO policies need to be developed to obtain the Alliance-wide operational advantage from a commercial entity's output. Moreover, member states must use their influence to support and/or enhance a commercial entity's space and ground segment resilience. It is recommended that NATO advances doctrine, tactics and techniques to maintain its operational advantage gleaned from commercial space, thus ensuring that opposing forces are not able to deny and interfere with these critical systems.

A challenge for NATO using commercial mega satellite constellations would be that of data security. Keeping military data separate from that available in the public domain would be critical; and, although it is possible to have military enclaves within commercial organizations, the question of whether this a viable option in times of conflict must be raised. When working with a commercial service provider, the scale of the datasets required also needs to be determined. For example, would NATO be purchasing the entire repository or would it capitalize upon specific subsets of the data? These initial questions have significant implications in terms of the security of the data.

A key challenge for NATO concerning SATCOM and a mega-constellation is that of adopting policy, doctrine and regulations. The constellation requires regulatory frameworks, licensing and approvals to prevent potential blue-on-blue actions. NATO should baseline system requirements, with National Caveats as required to move voice and data efficiently. As a starting point, it is necessary to ask whether technological developments will be a commonly funded initiative, or where the Alliance will demand individual nations to contribute funds directly.

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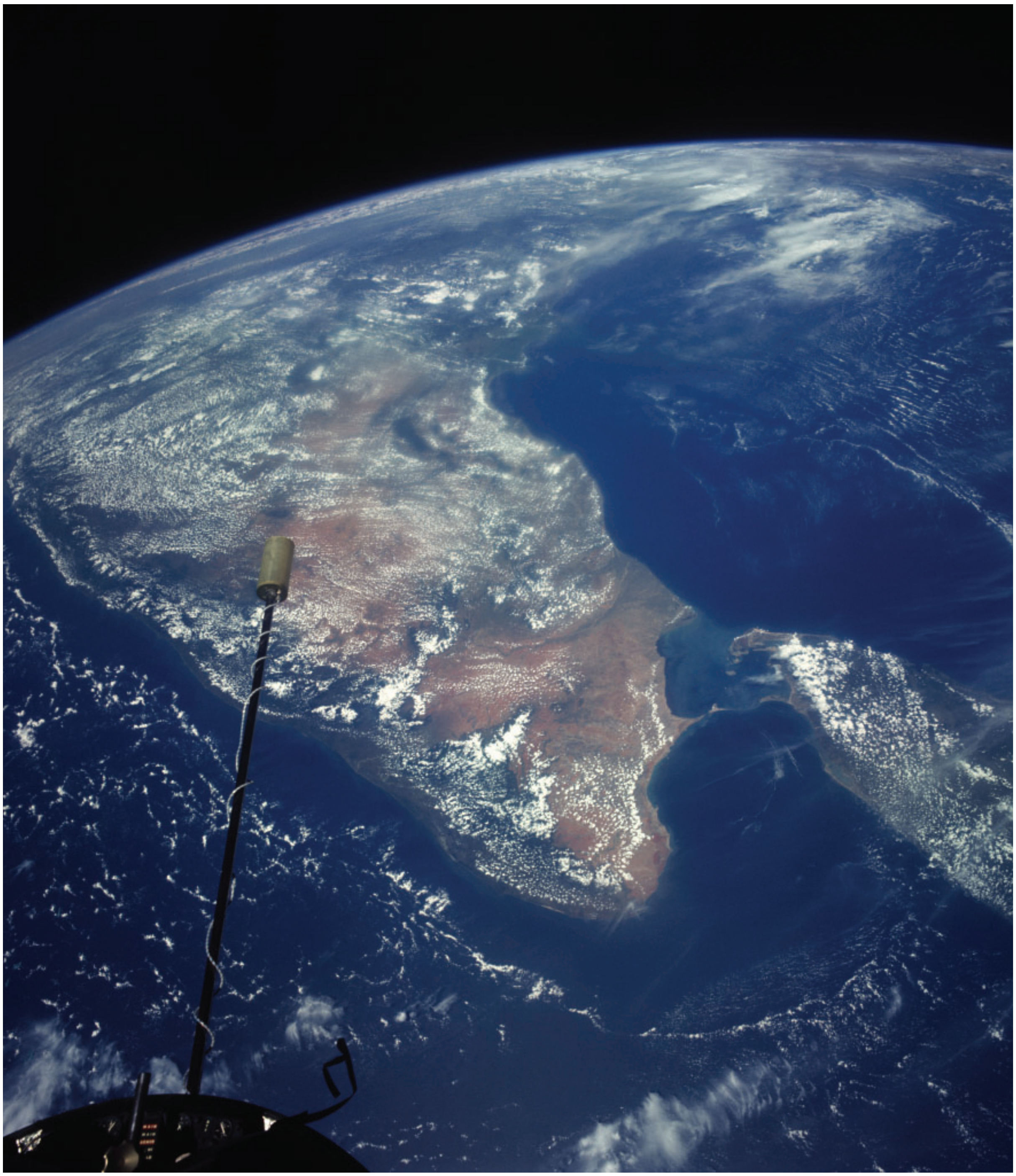
[49] *Sharpe, J., Trichas, M., Terrill, D., Moustakis, F. (2023). The Interplay of Domains: Space, Cyber, and Special Operations on the Global Stage. Unpublished Manuscript.*

[50] *Sharpe, J., Moustakis, F.,Trichas, M., Terrill, D. (2023). The Implications of the UK's National Space Strategy on Special Operations. Available at: https://www.thespacereview.com/article/4604/1.*

It is recommended that NATO and its member states move towards a "policy today for tomorrow" approach. This would allow key issues to be identified and the necessary policies and procedures developed in anticipation of implementation at a later date. This would enable the Alliance to keep abreast of the rapid developments in space and enable a timely and informed response to the ever-changing factors of modern warfare. In this manner, the need for dialogue with service providers to establish the parameters for working with commercial entities and to determine whether this is a truly viable option requires dedicated attention. Starting this dialogue early will also enable NATO to have a greater level of control and use, as the implications to NATO operations of buying a service which is already launched is vastly different from NATO joining at the commencement of production or design.



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