Imperial College London – London Institute of Space Policy and law
UK Satellite Mega-Constellation Policy Project

ISPL Paper

Informing UK Space Policy

Satellite Mega-Constellation Safety and Security: Importance of Evidence-Based Information

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Abbreviations

AI	Artificial Intelligence
ASAT	Anti-satellite
BEIS	Department for Business, Energy and Industrial Strategy
CEP	Centre for Environmental Policy
EDTs	Emerging and Disruptive Technologies
ESA	European Space Agency
ICL	Imperial College London
ISPL	London Institute of Space Policy and Law
ISST	Institute for Security Science and Technology
LCA	Life Cycle Assessment
LEO	Low Earth Orbit
ML	Machine Learning
NATO	North Atlantic Treaty Organization
NEO	Near Earth Object
NSIP	National Space Innovation Programme
NSP	National Space Policy
NSSP	National Space Security Policy
STM	Space Traffic Management
TEISA	Terrestrial Environmental Impacts of Space Activities
UK	United Kingdom
UKSA	UK Space Agency
UNOOSA	United Nations Office for Outer Space Affairs
US	United States

Executive Summary

This Study, commissioned by Imperial College London (ICL) and conducted by the London Institute of Space Policy and Law (ISPL), illustrates that appropriate policies and strategies for space activities as in other policy areas must be based on sound evidence. It examines the Space Safety and Security aspects of satellite mega-constellations, identifying areas of concern that must be factored into the development of relevant policies and strategies. It enumerates the evidence-based information necessary to formulate policies in each area of concern and expertise to supply such information available in the United Kingdom (UK).

This tabulation below presents the specific sets of concerns identified, and is followed by a summary of each of them.

Mega-constellations: Space Safety and Space Security concerns	
A) Terrestrial Environmental Impacts of Space Activities (TEISA)	
1) Large scale satellite manufacturing	2) Numerous satellite launches
3) Constellation satellite brightness	4) Increased number of returning space debris
B) Space Debris (Creation and Impact)	
1) Business decision-associated risk	
2) Orbital congestion	3) Propulsion-associated collision and space debris risk
4) Software-associated risk	5) Lack of active debris removal and on-orbit repair service options, and of related incentives
C) Planetary Defence	
1) Interference with search for harmful asteroids and comets	2) Risk of satellite collision with asteroids, comets, meteoroids and cosmic dust
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1) Disturbance or loss of large numbers of constellation satellites due to space weather events	2) Premature constellation satellite de-orbiting caused by space weather events
E) Space Security	
1) Loss of access to national security services	
2) Cyber attack risk	3) Constellations performing as anti-satellite (ASAT) weapon systems
4) Risk to secure data transfer	5) Risk of direct attacks with ASAT weapons
F) Space Traffic Management (STM)	
1) General consideration	2) Co-existence of different systems and services
3) ‘Lame duck’ risk	4) Unauthorised sending of data into certain jurisdictions

A) Terrestrial Environmental Impacts of Space Activities

1 – Large scale satellite manufacturing

The manufacturing of large numbers of satellites and adequate launch vehicles per year to deploy and sustain mega-constellations can create and require the disposal of considerable amounts of (potentially toxic) waste material, involve significant consumption of (limited) natural resources, and leave a large carbon footprint.

2 – Numerous satellite launches

The tens to hundreds of satellite launches per year required to deploy and sustain mega-constellations can cause local noise pollution and involve the release of significant amounts of (potentially toxic) waste products, increasing global carbon emission and risk of local environmental damages. Frequent launches could also result in changes to atmospheric composition.

3 – Constellation satellite brightness

Constellation satellites situated in Low Earth Orbit (LEO) might be so bright that they are visible in the sky, potentially affecting terrestrial ecology as there are animals navigating by aspects of the sky such as star patterns. This can also affect observations by astronomers relying on terrestrial telescopes.

4 – Increased number of returning space debris

The deployment and maintenance of mega-constellations increase the amount of space debris falling back to Earth each year. Burned up debris could alter atmospheric composition. Space debris made of toxic material, storing toxic fuel or carrying toxic payloads surviving re-entry into Earth's atmosphere can lead to local terrestrial pollution and direct physical harm to flora and fauna, including humans.

Relevant evidence-based information

Environmental Impact Assessments, Life Cycle Assessments, other risk assessments, foresight activities, modelling of demisability of satellites and launchers, observation and modelling of orbiting space debris behaviour, investigation of eco-friendly satellite material and propulsion options, and the study of ways to darken satellite surfaces can provide critical evidence-based information.

B) Space Debris (Creation and Impact)

1 – Business decision-associated risk

Mega-constellation developers could take business decisions at the design and production phases that involve accepting certain failure rates of satellites in orbit due to the use of material of a lower than recommended standard for satellite manufacturing or less rigorous than recommended quality testing of satellite hard- and software if these measures enable low-cost satellite mass production. Consequent satellite failures can increase orbital collision and space debris creation.

2 – Orbital congestion

The more constellation satellites situated in similar orbits, the higher the chance for collision between such satellites, with existing space debris, and with other spacecraft within or crossing the same orbits, increasing the risk of orbital collision and space debris creation.

3 – Propulsion-associated collision and space debris risk

Electric propulsion is constellation satellites' most mass-effective propulsion method to manoeuvre to their predetermined orbits after release from the launchers and for de-orbiting manoeuvres. Such propulsion is slow and has many variables that can fail, increasing orbital collision and space debris risk. Chemical propulsion comes with a higher explosion risk.

4 – Software-associated risk

Software updates for constellation satellites or related ground control facilities can lead to unintended software problems interfering with the – (semi-)automated – processes for satellite flight operations, increasing the orbital collision and space debris creation risk.

5 – Lack of active debris removal and on-orbit repair service options, and of related incentives

The lack of well-established active debris removal and on-orbit repair services for defunct satellites, as well as of incentives for operators to pay for them, can increase the collision and space debris creation risk in the long run.

Relevant evidence-based information

Comprehensive risk assessments, the study of satellite material, satellite resilience, satellite manufacturing and quality testing procedures, satellite propulsion methods and natural and active debris removal options, as well as information gathered from automated and active space object tracking, the modelling of orbital dynamics, and uncertainty studies can provide useful evidence-based information.

C) Planetary Defence

1 – Interference with search for harmful asteroids and comets

Constellation satellites might be so plentiful and bright that they hamper the search for and timely preparation against asteroids or comets with the potential of striking Earth and causing significant harm.

2 – Risk of satellite collision with asteroids, comets, meteoroids and cosmic dust

The higher the number of constellation satellites, the higher the risk of asteroids, comets, meteoroids and cosmic dust hitting and rendering such satellites unmanoeuvrable or fragmenting them.

Relevant evidence-based information

Research in orbital mechanics, automated and active space object tracking, as well as the study of options to reduce satellite brightness and other observation impacts can provide critical evidence-based information.

D) Space Weather

1 – Disturbance or loss of large numbers of constellation satellites due to space weather events

Space weather events can disturb or lead to (temporary or permanent) partial or complete loss of constellation satellites, potentially rendering huge numbers of them unmanoeuvrable or transforming them into space debris at around the same time, suddenly making the use of the respective orbits unsustainable for everyone for a long time.

2 – Premature constellation satellite de-orbiting caused by space weather events

Space weather events can change the atmospheric draft on satellites in LEO, putting constellation satellites, mostly situated in LEO, at higher risk to de-orbit prematurely.

Relevant evidence-based information

Research aimed to better understand and predict space weather events, as well as to develop solutions to make satellites more resilient against such events, can provide critical evidence-based information.

E) Space Security

1 – Loss of access to national security services

Mega-constellation services might be employed to support national security. Loss of access to such services can impact a country's national security status, which makes addressing all the other issues that challenge the stable operation of mega-constellations presented here even more relevant.

2 – Cyber attack risk

Cyber attacks such as uploading malicious programmes or other malicious changes to software code against constellation satellites and relevant ground facilities can cause severe production delays and launch failures, or increase the collision and space debris creation risks in certain orbits considerably. Software plays a central role in each development phase, especially in the context of (semi-)automated processes.

3 – Constellations performing as anti-satellite (ASAT) weapon systems

A mega-constellation could perform as an ASAT weapon system in times of conflict, e.g. by constellation satellites being put at a conjunction course with an adversary's satellite to destroy the latter.

4 – Risk to secure data transfer

Secure data transfer among a large number of satellites and an extensive ground infrastructure needs to be guaranteed, taking into account data exposures, as well as jamming, uploading of malicious programmes or other malicious changes to software code, and spoofing by adversaries.

5 – Risk of direct attacks with ASAT weapons

There is the risk of direct attacks with kinetic ASAT weapons against individual or clusters of constellation satellites, or other kinetic weapon system against ground infrastructure.

Relevant evidence-based information

Information gathering on space weaponisation, assessment of cybersecurity risks and solutions, and the study of redundancy measures can provide useful evidence-based information.

F) Space Traffic Management (STM)

1 – General consideration

All the aforementioned concerns need to be considered in the development of a mature international STM system.

2 – Co-existence of different systems and services

Mega-constellations and their services will have to co-exist with other current and future space-based, ground and aerial systems and their services. It requires an international STM system that ensures that the deployment and use of mega-constellations causes no significant interference, including frequency interference, with other space activities and vice versa, and that there is access to and exchange of relevant data among all involved actors.

3 – 'Lame duck' risk

A constellation could become a 'lame duck' project, e.g. due to operator bankruptcy. The collision and debris creation risk increases without fail safes in place to ensure the continued safe operation of the constellation.

4 – Unauthorised sending of data into certain jurisdictions

The rise of communications satellite mega-constellations aiming to provide global coverage requires an STM system offering a reasonable procedure to peacefully resolve the issue of unauthorised sending of data into certain jurisdictions at the domestic and international level.

Relevant evidence-based information

The study of international approaches, standards and interoperability, taking account of civil and military actor involvement, can provide useful evidence-based information. Research to improve understanding of export control regulations, Space Situational Awareness, data-sharing agreements, space debris mitigation guidelines, industry standards and best practices, space object registration, licensing requirements and radio-frequency regulations are integral in this regard.

Capabilities and expertise of Imperial College London to provide evidence-based information

This Study concludes that ICL has capabilities and expertise to produce relevant evidence-based information, including through its Space Lab, an ICL network of excellence, and the Institute for Security Science and Technology.

1 Background

With the United Kingdom (UK)'s growing involvement in and reliance on space as well as increasing international focus on space activities it is especially timely to examine the necessary and best available tools to the UK Government in developing its Space Policies and Strategies. The international nature of space makes it necessary for the Government to be well-informed in policy, strategy, legal and technology developments internationally to both regulate UK activities and negotiate internationally.

Space systems and services such as telecommunications, Earth observation and navigation, with the underlying science and technology continuously advancing, are central and become evermore critical to many aspects of life on Earth. In particular, they have relevance for national security and socio-economic development and welfare in developed states such as the UK. Naturally, increasing reliance on space creates vulnerabilities that need to be met and diminished. To achieve resilience in space services and systems requires appropriate policies based on sound evidence. Changing space capabilities as technology advances spawn policy challenges not only in space but also other areas of activity.

The UK Government interest in a satellite mega-constellation, namely OneWeb, intention to promote domestic launch services for small satellites, the UK's lead in the technology and production of small satellites and its promotion of space research and development evidence the UK's full engagement in every aspect of space activity. As this engagement grows the dependence on space will increase making the formulation of Space Policy in general and Space Safety and Security Policy in particular of significant importance.

This Study, commissioned by Imperial College London (ICL) and conducted by the London Institute of Space Policy and Law (ISPL), argues especially that mega-constellations such as OneWeb, situated in the crowded Low Earth Orbit (LEO), come with a series of potential Space Safety and Security concerns that the Government needs to address within its Space Policy. Otherwise, it will become a serious challenge to ensure responsible behaviour in space and to maintain the constellation's long-term safety and security in the wake of several satellite constellation of hundreds or thousands satellites aimed to provide certain service under development or at least proposed globally.

In addressing safety and security of LEO two factors are crucial for the UK to keep in mind:

a) UK at present is the only European country with a strong stake in mega-constellations; and
b) the latter will radically change the space environment with possible unforeseen impact on its use.

2 Satellite mega-constellation definition

The space community has not yet settled on a definition for the term 'satellite mega-constellation'. This Study considers a satellite mega-constellation to constitute a constellation of at least one hundred satellites that provide certain services such as global broadband. This aligns with many mega-constellation references within the community.[1] If required, researchers and others interested may further categorise mega-constellations along factors such as satellite types, service functions, user base, orbits and swarm behaviour.[2] Naturally, discussions of mega-constellation deployment and operation also need to take into account relevant terrestrial infrastructure, including on the operator and user side.[3]

3 UK interest in satellite mega-constellations

The UK Government's current major Space Policy and Strategy documents, namely the National Space Policy[4] (NSP) of 2015 and the National Space Security Policy[5] (NSSP) of 2014 do not directly address mega-constellations.[6] Nonetheless, the UK Government acquired part ownership in OneWeb in 2020. It also provides funds via the UK Space Agency (UKSA) for some mega-constellation-related research activities. The available information allows concluding that the Government engages in OneWeb and aforementioned research activities in the pursuit of the policy objectives of

a) advancing the UK's socio-economic development and welfare, and
b) enhancing the domestic space-related scientific and technological capability.

Additionally, there are indications that the Government considers the potential to employ OneWeb in the pursuit of the policy objectives of

c) safeguarding the UK's national security, and
d) increasing the UK's international prestige and influence.[7]

1 See the references in, e.g.: 'A satellite mega-constellation' (18 July 2018) <https://www.esa.int/ESA_Multimedia/Images/2018/07/A_satellite_mega-constellation> accessed 26 March 2021; Jeff Foust, 'Mega-constellations and mega-debris' (*The Space Review*, 10 October 2016) <https://www.thespacereview.com/article/3078/1> accessed 26 March 2021; 'What is Mega-Constellation' (*IGI Global*) <https://www.igi-global.com/dictionary/mega-constellations/71927> accessed 26 March 2021; however, there are others, e.g. an ICL academic staff member interviewed for this Study, who consider constellations with satellites numbering in the higher double digits, e.g. the Iridium constellation, to be a mega-constellation. For more information on Iridium, see: 'Iridium® Satellite Communications' (Fact Sheet, Iridium Satellite LLC 2020) <https://www.iridium.com/download/?dlm-dp-dl=256574> accessed 12 March 2021.

2 Based on ISPL expertise and interviews with selected ICL academic staff in February and March 2021.

3 For example, OneWeb stated in its FCC Form 321 application in 2016 that the space segment 'will be supported by a network of multiple Ka-band gateway antennas. The gateway antennas will be 2.4m in size, have connectivity with major peering points around the world, and be placed at locations that provide the required connectivity to the satellite constellation. In addition, the OneWeb System will have low-cost, easy-to-install Ku-band user terminals that will communicate using parabolic, phased array, and other antenna technologies. The user terminals will be handed over from one OneWeb satellite to another both seamlessly and frequently.' As cited in: Ward A Hanson, 'In Their Own Words: OneWeb's Internet Constellation as Described in Their FCC Form 312 Application' (2016) 4(3) New Space 153, 157.

4 HM Government, 'National Space Policy' (HM Government, December 2015) <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/484865/NSP_-_Final.pdf> accessed 31 March 2021.

5 HM Government, 'National Space Security Policy' (UKSA/13/1292, HM Government, April 2014) <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/307648/National_Space_Security_Policy.pdf> accessed 31 March 2021.

6 This will likely change with the next UK Space Policy document, expected to be published later in 2021.

7 See Attachment to this document for more information.

Table 1 shows the presently most prominent mega-constellation projects under development:

Constellation project name	Principal company	Application field	Considered total number of operational satellites	Expected orbital altitudes
OneWeb	Network Access Associates Limited	Communications (broadband)	6372	~1200 km[8]
Project Kuiper	Amazon.com Services LLC (Amazon)	Communications (broadband)	3236	~590-630 km[9]
Starlink	Space Exploration Technologies Corp. (SpaceX)	Communications (broadband)	42000	~328-580 km[10] (initial plan: ~1125 km)
Telesat Lightspeed	Telesat Corp.	Communications (broadband)	298	~1015-1325 km[11]

(Table 1: Most prominent mega-constellation projects under development as of March 2021); (Notably, numbers might differ slightly among sources)

However, many more mega-constellation projects are under development or have at least been under consideration, as presented by NewSpace Index[12] and in Table 2:

Constellation		Alt.	$a_\odot$ for zenith	Satellites above horizon			Satellites above $z_{\max} = 60°$			Orbital period	Magnitude at zenith	$z = 60°$
	N	h [km]	γ_o [deg]	$a_\odot$ [deg]	%	N	$a_\odot$ [deg]	%	N	P [h]	[mag]	[mag]
	1	2	3	4	5	6	7	8	9	10	11	12
SpaceX Starlink												
340	7518	340	−18.3	−36.6	2.5%	190.3	−23.0	0.2%	12.6	1.51	3.2	4.8
550	1600	550	−23.0	−46.0	4.0%	63.5	−30.1	0.4%	6.2	1.58	4.2	5.9
1150	2800	1150	−32.1	−64.2	7.6%	214.0	−44.9	1.2%	34.8	1.79	5.8	7.5
OneWeb	648	1200	−32.7	−65.4	7.9%	51.3	−45.9	1.3%	8.6	1.81	5.9	7.5
Amazon Kuiper												
590	784	590	−23.8	−47.5	4.2%	33.2	−31.3	0.4%	3.4	1.60	4.4	6.0
610	1296	610	−24.1	−48.2	4.4%	56.6	−31.9	0.5%	6.0	1.60	4.5	6.1
630	1156	630	−24.5	−49.0	4.5%	52.0	−32.5	0.5%	5.6	1.61	4.5	6.1
Sat Revolution	1024	350	−18.6	−37.1	2.6%	26.6	−23.4	0.2%	1.8	1.52	3.2	4.9
China CASC	320	1100	−31.5	−63.0	7.4%	23.5	−43.9	1.2%	3.7	1.78	5.7	7.4
China LuckyStar	156	1000	−30.2	−60.4	6.8%	10.6	−41.7	1.0%	1.6	1.74	5.5	7.2
China Commsat	800	600	−23.9	−47.9	4.3%	34.4	−31.6	0.4%	3.6	1.60	4.4	6.0
China Xinwei	32	600	−23.9	−47.9	4.3%	1.4	−31.6	0.4%	0.1	1.60	4.4	6.0
India AstroTech	600	1400	−34.9	−69.8	9.0%	54.0	−49.7	1.6%	9.9	1.88	6.3	7.9
Boing	2956	1030	−30.6	−61.2	7.0%	205.6	−42.4	1.1%	31.2	1.75	5.6	7.2
LeoSat	108	1423	−35.2	−70.3	9.1%	9.9	−50.1	1.7%	1.8	1.89	6.3	7.9
Samsung	4700	2000	−40.4	−80.9	11.9%	561.2	−59.2	2.7%	124.8	2.11	7.0	8.7
Yaliny	135	600	−23.9	−47.9	4.3%	5.8	−31.6	0.4%	0.6	1.60	4.4	6.0
Telesat LEO	117	1000	−30.2	−60.4	6.8%	7.9	−41.7	1.0%	1.2	1.74	5.5	7.2
(Iridium)	66	780	−27.0	−54.0	5.5%	3.6	−36.5	0.7%	0.5	1.66	5.0	6.6
Total	26 750					1605			258			

Notes. The list includes the number of satellites (Col. 1) and their altitude in km (Col. 2). Column 3 is the elevation of the Sun for which a satellite at Zenith is just illuminated, also for which half the satellites in range are illuminated; by construction, it is also the angle Zenith-Centre of Earth-Satellite at which the satellite is on the horizon. Considering the cases of satellites above the horizon and above a zenithal distance of 60°, the table also lists the minimum solar elevation required to illuminate all these satellites (Cols. 4 and 7); the fraction of the constellation that is in range (Cols. 5 and 8) and the corresponding number of satellites in range (Cols. 6 and 9). For reference, the orbital period is listed (Col. 10), as well as the magnitude of a satellite at zenith (Col. 11) and at $z = 60°$ (Col. 12), for an intermediate solar phase angle of 90°, considering our simple photometric model.

Table 2: Overview of selected satellite constellations by Hainaut and Williams[13]

8 Based on information in: Jeff Foust, 'OneWeb slashes size of future satellite constellation' (*SpaceNews*, 14 January 2021) <https://spacenews.com/oneweb-slashes-size-of-future-satellite-constellation/> accessed 9 March 2021; 'Privacy Notice' (*OneWeb*, 11 February 2019) <https://www.oneweb.world/privacy-policy> accessed 27 January 2021.

9 Based on information in: Jeff Foust, 'Amazon unveils flat-panel customer terminal for Kuiper constellation' (*SpaceNews*, 16 December 2020) <https://spacenews.com/amazon-unveils-flat-panel-customer-terminal-for-kuiper-constellation/> accessed 29 March 2021; Caleb Henry, 'Amazon's Kuiper constellation gets FCC approval' (*SpaceNews*, 30 July 2020) <https://spacenews.com/amazons-kuiper-constellation-gets-fcc-approval/> accessed 29 March 2021; 'Project Kuiper' (*Amazon*) <https://www.aboutamazon.com/news/tag/project-kuiper> accessed 30 March 2021.

10 Based on information in: 'Petition Of Starlink Services, LLC For Designation As An Eligible Telecommunications Carrier' (FCC Petition, Starlink Services, LLC, 3 February 2021) <https://ecfsapi.fcc.gov/file/1020316268311/Starlink%20Services%20LLC%20Application%20for%20ETC%20Designation.pdf> accessed 15 March 2021; Caleb Henry, 'SpaceX submits paperwork for 30,000 more Starlink satellites' (*SpaceNews*, 15 October 2019) <https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/> accessed 17 March 2021; Matt Williams, 'Starlink's satellites will be orbiting at a much lower altitude, reducing the risks of space junk' (*Phys.org*, 6 May 2019) <https://phys.org/news/2019-05-starlink-satellites-orbiting-altitude-space.html> accessed 31 March 2021.

11 Based on information in: Sandra Erwin, 'Thales Alenia selected to build Telesat's broadband constellation' (*SpaceNews*, 9 February 2021) <https://spacenews.com/thales-alenia-selected-to-build-telesats-broadband-constellation/> accessed 8 March 2021; 'Telesat Lightspeed™' (*Telesat*) <https://www.telesat.com/leo-satellites/> accessed 29 March 2021.

12 'NewSpace Index' (*NewSpace Index*, 1 January 2021) <https://www.newspace.im/index.html> accessed 30 March 2021.

13 Oliver R Hainaut and Andrew P Williams, 'Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains' (2020) 636 Astronomy & Astrophysics 1, 2. Hainaut and Williams add in their paper that this table 'lists publicly known future mega-constellations that are in development, the number of satellites that are planned for launch, and the orbital altitude *h* of the satellites. The

4 Space Safety and Security concerns

As in the case of the term 'satellite mega-constellation', there is no authoritative definition of 'Space Security' and 'Space Safety' within the space community. The UK Government's current main Space Policy documents NSP[14] and NSSP[15] do also not provide clear definitions. Building on previous ISPL research, this Study considers Space Security to concentrate on intentional human-caused space-related threats, e.g. anti-satellite (ASAT) weapons and cyber attacks, as well as the use of space for terrestrial security purposes. Similarly, this Study considers Space Safety to focus particularly on natural and unintentional human space-related hazards, e.g. space debris, space weather and spacecraft design errors, and discusses them along the following five subject areas:

- ❖ Terrestrial Environmental Impacts of Space Activities (TEISA);
- ❖ Space Debris;
- ❖ Planetary Defence;
- ❖ Space Weather; and
- ❖ Space Traffic Management (STM).[16]

This Study has identified various Space Security field and Space Safety field concerns associated with the deployment and use of mega-constellations. They emerge from interviews with selected ICL academic staff, ISPL expertise and information provided in government material, news articles and secondary literature.

As demonstrated by this Study, ICL has capabilities and expertise to produce relevant evidence-based information, including through its Space Lab, an ICL network of excellence, and the Institute for Security Science and Technology (ISST).

list is neither complete nor accurate, as it is based on generic web searches, operator websites, and on official documents submitted to the Federal Communications Commission (FCC). Some of the constellations have already been cancelled. Other, non-telecommunication constellations have filed documentation with the FCC. Overall, this list should therefore be considered only as a representative list of a variety of constellations and a large number of satellites, rather than an exact representation of what will be launched in the coming years, [...]. The original Iridium constellation is also included, although its size and effects are negligible compared to the others.'

14 HM Government (n 4).

15 HM Government (n 5).

16 For the previous ISPL research, see: Christoph Beischl, 'Contribution of Evidence Based Information by Imperial College London. Informing UK Space Safety Policy' (Report, ISPL and ICL Space Lab, 31 March 2020) 5–6 <https://www.space-institute.org/app/uploads/1603297587_Informing_UK_Space_Safety_Policy_ICL-ISPL_Final_Report_20201007.pdf> accessed 12 March 2021; a copy of it is also available here: Christoph Beischl, 'Contribution of Evidence Based Information by Imperial College London. Informing UK Space Safety Policy' (Report, ISPL and ICL Space Lab, 31 March 2020) <https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/space-lab/public/Informing-UK-Space-Safety-Policy_ICL-ISPL-Final-Report_20200910.pdf> accessed 12 March 2021.

4.1 Terrestrial Environmental Impacts of Space Activities (TEISA)

Viikari rightly observed that "[s]pace exploration is a polluting industry in various ways and in all its phases."[17] Mega-constellations are no exception. In particular, this Study has identified the following mega-constellation-specific Space Safety concerns relevant to TEISA.

4.1.1 Concerns

Design and Production phases:

The deployment and replenishment of mega-constellations consisting of hundreds or thousands of satellites necessitates the continuous manufacturing of large numbers of satellites and adequate launch vehicles per year. The terrestrial extraction and transport of relevant natural resources, the satellite and launcher production process and the transport of satellites and launchers or parts thereof between production, test and launch facilities can create and require the disposal of considerable amounts of (potentially toxic) waste material, involve significant consumption of (limited) natural resources, and leave a large carbon footprint.[18]

Launch phase:

Launching hundreds and thousands of satellites for the deployment and replenishment of mega-constellations requires tens to hundreds of launches per year. These launches involve storage and consumption of large amounts of fuel and the release of significant amounts of (potentially toxic) waste products, increasing the global carbon footprint and risk of local environmental damages. Launch failures can have especially strong localised repercussions. Moreover, frequent launches impact the local environment in the form of noise pollution. Also, frequent exposure to and disturbance by launcher exhaust could result in changes to atmospheric composition with unknown consequences.[19]

Use phase:

Satellites forming mega-constellations, which are mostly situated in LEO, might be so bright due to sunlight reflected by them that they are visible in the sky. This could not only negatively affect astronomy but also terrestrial ecology as there are animals navigating by aspects of the sky such as star patterns.[20]

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17 Lotta Viikari, *The Environmental Element in Space Law. Assessing the Present and Charting the Future* (Martinus Nijhoff Publishers 2008) 29.

18 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021. For some indication of the high satellite and launcher production cycles behind the deployment of mega-constellations, see, e.g.: Cat Hofacker, 'How to make a megaconstellation' (*Aerospace America*, March 2020) <https://aerospaceamerica.aiaa.org/features/how-to-make-a-megaconstellation/> accessed 30 March 2021; Caleb Henry, 'Three rules for building a megaconstellation' (*SpaceNews*, 8 July 2019) <https://spacenews.com/three-rules-for-building-a-megaconstellation/> accessed 30 March 2021.

19 Based on ISPL expertise, as well as information provided during interviews with selected ICL academic staff in February and March 2021 and in: Brian Sheen, 'Mega constellations and their impact on astronomy' (*ROOM*, 4 June 2020) <https://room.eu.com/community/mega-constellations-and-their-impact-on-astronomy> accessed 24 March 2021.

20 Based on information provided during interviews with selected ICL academic staff in February and March 2021 and in: ibid; for some more information on animals using aspects of the sky to navigate, see, e.g.: Fiona McMillan, 'From dung beetles to seals, these animals navigate by the stars' (*National Geographic*, 4 November 2019) <https://www.nationalgeographic.com/animals/article/stars-milky-way-navigation-dung-beetles> accessed 24 March 2021.

Disposal phase:

The combination of numerous satellites making up constellations, the planned limited satellite life time and the frequent launches to deploy and replenish constellations leads to large amounts of space debris, including intentionally de-orbited defunct satellites and launcher stages, falling back to Earth each year. This debris will either burn up in the atmosphere or survive reentry. Over a long enough period this burning-up could alter the atmospheric composition with unknown consequences, similar to the Launch phase mentioned above. Space debris made of toxic material, storing toxic fuel or carrying toxic payloads that reach the Earth's surface can lead to local terrestrial pollution. Also, items that survive reentry into Earth's atmosphere can physically harm the flora and fauna, including humans, through direct hits. In particular, propulsion tanks have considerable potential to survive re-entry into Earth's atmosphere since they are often built to withstand strong forces and shaped in a way that makes them act like ballistic objects. These challenges are especially problematic in the case of uncontrolled or unscheduled de-orbiting of satellites and launchers or parts thereof, or where operators are not willing or required by domestic regulations to share relevant information.[21]

4.1.2 Relevant evidence-based information

Findings of Environmental Impact Assessments, Life Cycle Assessments (LCAs) and other risk assessments, as well as foresight activities involving expert workshops with participants from various fields, can provide critical evidence-based information. Additionally, modelling of re-entry and demisability of satellites and launchers, observation and modelling of orbiting space debris behaviour, investigation of eco-friendly satellite material and propulsion options, and the study of ways to darken satellite surfaces can produce valuable information.

ICL has capabilities and expertise to conduct research producing relevant evidence-based information. For example, its Centre for Environmental Policy (CEP) has experience in LCAs and other risk assessments. There is the opportunity to involve CEP students in related research as part of their academic engagements. ICL researchers have studied combined chemical-electric propulsion systems, which enable satellites to conduct controlled re-entry manoeuvres when they reach their end-of-life. Furthermore, ICL currently engages with a private actor in creating launcher propulsion fuel from methane released by agriculture and livestock that, combined with oxygen, has the potential to lead to a 'better than zero' launch phase carbon footprint scenario. An interviewed ICL academic staff member highlighted that the UK, including through ICL, could become the leader in developing carbon neutral

21 Based on ISPL expertise, as well as information presented during interviews with selected ICL academic staff in February and March 2020 and in: Debra Werner, 'Aerospace Corp. raises questions about pollutants produced during satellite and rocket reentry' (*SpaceNews*, 14 December 2020) <https://spacenews.com/aerospace-agu-reentry-pollution/> accessed 9 March 2021; Staff Writers, 'Escalating Satellite Reentry Risk of Internet Mega Constellations' (*Space Safety Magazine*, 15 August 2015) <https://www.spacesafetymagazine.com/space-debris/falling-satellite/escalating-satellite-reentry-risk-of-internet-mega-constellations/> accessed 12 February 2021.

propulsion systems.[22] Adding to that, the ICL-ISPL UK Space Safety Policy Project of 2020 found that various ICL departments have technical capabilities and expertise that could help address TEISA concerns.[23]

4.2 Space Debris

It is broadly accepted within the space community that "[t]he most prominent environmental problem connected with space activities is space debris. 'Space debris' is a general term referring to all tangible [hu]man-made materials in space other than functional space objects."[24] The European Space Agency (ESA) estimated that in January 2021 there were around 34,000 debris objects greater than 10 cm, around 900,000 debris objects greater than 1 cm to 10 cm, and around 128 million debris objects greater than 1 mm to 1 cm in Earth orbit.[25] Mega-constellation deployment could have a negative impact on the space debris population. Moreover, the deployment and use of mega-constellations could be impacted by space debris. In particular, this Study has determined the following set of mega-constellation-related concerns relating to Space Debris.

4.2.1 Concerns

Design and Production phases:

Business decisions at the Design and Production phases could increase the collision and space debris creation risk. Those developing mega-constellations could be tempted to accept certain failure rates of satellites in orbit due to the use of material of a lower than recommended standard for satellite manufacturing or less rigorous than recommended quality testing[26] of satellite hard- and software if these measures enable low-cost satellite mass production. Satellites failing to be manoeuvrable or moving in unpredictable patterns due to hard- or software failures have increased potential to collide with other spacecraft or existing space debris. Each collision can result in the fragmentation of the involved spacecraft into piles of space debris and further fragmentation of involved existing space debris, increasing the total number of space debris in the respective orbits.

Launch and Use phases:

There is a risk that the deployment of mega-constellations per se could increase the collision and space debris creation risk, especially in LEO where most constellation satellites are likely to be situated. The more satellites

22 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.
23 See the findings presented in the ICL-ISPL UK Space Safety Policy Project's internal Report on Imperial College London Space Safety Capabilities and Expertise.
24 "Debris thus includes spent satellites themselves, ejected instrument covers, upper stages [...], fragments thereof, etc., that is objects which originate from what were functional space objects but which no longer serve a useful purpose. The definition also encompasses leaking fuel and coolant droplets, paint flakes and micro[-]particulate matter, as well as tools dropped during space walks and garbage dumped in outer space by [… crewed] space missions, for instance. Hence everything launched into outer space has the potential to become space debris." Viikari (n 17) 31–32.
25 'Space debris by the numbers' (8 January 2021) <https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers> accessed 10 March 2021.
26 For example, limited pre-flight testing, limited testing of end-of-life operations, and batch testing instead of testing of individual satellites or parts thereof.

situated in similar orbits, the higher the chance for collisions between such satellites, with existing space debris, and with other spacecraft within or crossing the same orbits. Again, each collision can result in the fragmentation of the involved spacecraft into piles of space debris and further fragmentation of existing space debris, increasing the total number of space debris in the respective orbits.

Constellation satellites are usually launched in clusters and electric propulsion is the satellites' most mass-effective propulsion method to manoeuvre to their predetermined orbits after release from the launchers. Electric propulsion acceleration, however, is comparably slow, making collision avoidance manoeuvres, especially when travelling through already crowded orbits, harder to accomplish. Adding to that, electric propulsion systems have many variables that can fail and render a satellite unmanoeuvrable and ultimately stranded in an undesirable orbit, increasing the local collision risk. Notably, chemical propulsion as an alternative comes with a higher explosion risk. Any satellite explosion would, of course, increase the space debris population.

Further, software updates for constellation satellites or related ground control facilities aimed to fix bugs or improve operations can lead to unintended software problems interfering with the – (semi-)automated – processes for satellite flight operations, including automated avoidance manoeuvre mechanisms. This can increase the involved constellation satellites' collision and space debris creation risks, with all the negative impacts outlined before.

Disposal phase:

Failures in a satellite's propulsion system could render any intended de-orbiting plan void or put the satellite in question on an unintended course, increasing the collision and space debris creation risk of these satellites. Linked to that, the use of electric propulsion systems, which are slow, could make any unplanned collision avoidance manoeuvre during a satellite's Disposal phase, especially when travelling through already crowded orbits, hard to accomplish. Also, the eventual life-time of satellites might be longer than initially intended, requiring satellite propulsion systems for de-orbiting manoeuvres to work beyond the expected end-of-life.

A related yet separate concern is that there are currently no well-established active debris removal or on-orbit repair services for defunct satellites available. Even if they are, mega-constellation operators have presently little incentive to pay for any of them without strict regulations in place. In the long run, this could increase the overall collision and space debris creation risk in mega-constellation orbits.

Overall, the worst case space debris scenario is the so-called Kessler Syndrome,[27] making orbits unusable for a long time. Moreover, it should not be forgotten that orbital collisions involving constellation satellites might lead to the loss of critical functions provided by such constellation, with significant impacts for life on Earth. As a general

27 Jakub Drmola and Tomas Hubik, 'Kessler Syndrome: System Dynamics Model' (2018) 44–45 Space Policy 29; 'FAQ: Frequently asked questions' (*ESA*) <https://www.esa.int/Safety_Security/Space_Debris/FAQ_Frequently_asked_questions> accessed 31 March 2021.

comment, it shall be further added here that the orbital collision risk is elevated by the lack of binding international space debris mitigation strategies, mandatory international coordination among spacecraft operators, and obligatory international interoperability standards among satellite systems.[28]

4.2.2 Relevant evidence-based information

This Study holds that comprehensive risk assessments, the study of satellite material, satellite resilience, satellite manufacturing and quality testing procedures, satellite propulsion methods and natural and active debris removal options can provide useful evidence-based information. Moreover, information gathered from automated and active space object tracking, the modelling of orbital dynamics, and uncertainty studies is important in this regard.

ICL has capabilities and expertise to engage in research producing relevant evidence-based information. For example, ICL has expertise in risk assessments and statistical analysis. It has capabilities to model orbital collisions and satellite re-entry on a large scale. It has a high level of experience in space-specific and transferable technology testing, failure and worst case scenario analysis, as well as addressing uncertainty issues and studying ways to achieve optimisation. ICL also works on combined chemical-electric propulsion systems, enabling controlled re-entry manoeuvres when satellites reach their end-of-life.[29] Furthermore, the ICL-ISPL UK Space Safety Policy Project of 2020 found that various ICL departments have technical capabilities and expertise that could help address Space Debris concerns.[30]

4.3 Planetary Defence

This Study has identified the following mega-constellation-specific concerns falling under the Space Safety subject area of Planetary Defence.

4.3.1 Concerns

Use phase:

First, satellites forming mega-constellations, mostly situated in LEO, might be so plentiful and bright due to sunlight reflecting on them that they hamper the search for and timely preparation against Near Earth Objects

28 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.
29 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.
30 See the findings presented in the ICL-ISPL UK Space Safety Policy Project's internal Report on Imperial College London Space Safety Capabilities and Expertise.

(NEOs), generally constituting "asteroids or comets that pass close to the Earth,"[31] with the potential of striking Earth and causing significant local, regional or global harm.[32]

Second, the higher the number of constellation satellites, the higher the risk of NEOs, meteoroids and cosmic dust hitting such satellites, potentially rendering them unmanoeuvrable or fragmenting them, ultimately increasing the orbital collision and space debris creation risk.[33]

4.3.2 Relevant evidence-based information

Research in orbital mechanics, NEOs, meteoroids and space dust, automated and active space object tracking, as well as the study of options to reduce satellite brightness and other observation impacts can provide critical evidence-based information.

ICL has capabilities and expertise to produce relevant evidence-based information. It has at least one academic staff member raising awareness of the problems for astronomy presented by mega-constellations with operators, as well as the public in general.[34] Moreover, the ICL-ISPL UK Space Safety Policy Project of 2020 determined that various ICL departments have technical capabilities and expertise that could serve addressing Planetary Defence concerns.[35]

4.4 Space Weather

Space weather, a consequence of solar activity, including components such as coronal mass ejections, solar flares and solar energetic particles, affects mega-constellations. In particular, this Study has determined the following mega-constellation-related concerns falling under the Space Safety subject area of Space Weather.

31 'Hazard Overview. Near Earth Objects' (Natural Hazards Partnership, April 2016) <http://www.naturalhazardspartnership.org.uk/wp-content/uploads/NEO_Hazard_Overview.pdf> accessed 31 March 2021.

32 Based on information provided in interviews with selected ICL academic staff in February and March 2021 and in: Hainaut and Williams (n 13) 11.

33 Based on information provided during interviews with selected ICL academic staff in February and March 2021. Some potential space dust hazard is also indicated in: 'Space dust kills satellites like tiny atom bombs' (*The Economist*, 17 August 2017) <https://www.economist.com/science-and-technology/2017/08/17/space-dust-kills-satellites-like-tiny-atom-bombs> accessed 16 March 2020.

34 Based on information provided during interviews with selected ICL academic staff in February and March 2021.

35 See the findings presented in the ICL-ISPL UK Space Safety Policy Project's internal Report on Imperial College London Space Safety Capabilities and Expertise.

4.4.1 Concerns

Use phase:

First, space weather events can disturb or lead to (temporary or permanent) partial or complete loss of satellites making up mega-constellations, potentially rendering them unmanoeuvrable or transforming them into space debris, ultimately increasing the orbital collision and space debris creation risk. In this regard, it needs to be especially understood that, while all satellites are vulnerable to space weather events, in the case of mega-constellations such events could cause the disturbance or loss of not just a few but large numbers of satellites at around the same time, suddenly making the use of the respective orbits unsustainable for everyone for a long time. Second, space weather events can change the atmospheric draft on satellites in LEO, putting constellation satellites, mostly situated in LEO, at higher risk to de-orbit prematurely, potentially expediting the consequences discussed under the TEISA subject area above.[36]

4.4.2 Relevant evidence-based information

This Study holds that research aimed to better understand and predict space weather events, as well as to develop solutions to make satellites more resilient against such events, can provide critical evidence-based information.

ICL has capabilities and expertise to conduct such research, including through its Space Lab, an ICL network of excellence.[37] This is also highlighted in the ICL-ISPL UK Space Safety Policy Project of 2020.[38]

4.5 Space Security

This Study understands Space Security as to concentrate on intentional human-caused space-related threats, e.g. ASAT weapon and cyber attacks, as well as the use of space for terrestrial security purposes. It has determined the following set of mega-constellation-associated concerns in the Space Security field.

4.5.1 Concerns

Design, Production, Launch and Disposal phases:

Cyber attacks against constellation satellites and relevant ground facilities are of particular concern to constellation developers. Software plays a central role in each phase of mega-constellation development, especially in (semi-)automated processes, potentially including in the form of Machine Learning (ML) and Artificial Intelligence

36 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.
37 Based on information provided during interviews with selected ICL academic staff in February and March 2021.
38 See the findings presented in the ICL-ISPL UK Space Safety Policy Project's internal Report on Imperial College London Space Safety Capabilities and Expertise.

(AI), for, e.g., large scale satellite manufacturing and satellite flight operations, including collision avoidance. Cyber attacks such as uploading malicious programmes or other malicious changes to software code against satellites and ground facilities can cause severe production delays and launch failures, or increase the collision and space debris creation risk in certain orbits considerably. The problem is exacerbated by the fact that different parties might be involved in the overall constellation development and there is a strong and continued connectivity of many different parts on the ground and in space, increasing the number of potential points of attack. While the option to reconfigure satellite units in relation to their neighbouring satellite units and not to the whole system can increase resilience to attacks directed against parts of the constellation, this has the inherent danger that an adverse actor could employ malicious software to lure the whole constellation into a different state by getting access to only one or a few satellite units.[39]

Use phase:

Mega-constellation services might be employed to support national security.[40] Loss of access to such services can impact a country's national security status, which makes addressing all the other issues that challenge the stable operation of mega-constellations presented in this and the other sections even more relevant for governments.

Mega-constellation operators have to make sure that they guarantee secure data transfer among a large number of satellites and an extensive ground infrastructure, each of which is a potential entry point for an adversary. This includes measures against data exposures, jamming, uploading of malicious programmes or other malicious changes to software code, and spoofing.[41]

There is the risk of direct attacks with kinetic ASAT weapons against individual or clusters of constellation satellites, or other kinetic weapon system against ground infrastructure.[42] While any satellite operator has to deal with this concern, successful ASAT attacks against mega-constellations could increase the collision and space debris creation risk in certain orbits significantly, with the further consequences discussed in the Space Debris section above.

39 Based on information provided during interviews with selected ICL academic staff in February and March 2021 and in: Mohamed Khalil Ben-Larbi and others, 'Towards the Automated Operations of Large Distributed Satellite Systems. Part 1: Review and Paradigm Shifts' Advances in Space Research <https://doi.org/10.1016/j.asr.2020.08.009> accessed 31 March 2021; 'Automating collision avoidance' (*ESA*, 22 October 2019) <https://www.esa.int/Safety_Security/Space_Debris/Automating_collision_avoidance> accessed 31 March 2021; Henry, 'Three rules for building a megaconstellation' (n 18).

40 Based on information presented in, e.g.: 'UK government secures satellite network OneWeb' (*GOV.UK*, 20 November 2020) <https://www.gov.uk/government/news/uk-government-secures-satellite-network-oneweb> accessed 1 February 2021; Sandra Erwin, 'U.S. Army signs deal with SpaceX to assess Starlink broadband' (*SpaceNews*, 26 May 2020) <https://spacenews.com/u-s-army-signs-deal-with-spacex-to-assess-starlink-broadband/> accessed 9 March 2021; Mark Roberts, Christoph Beischl and Sa'id Mosteshar, 'Small Satellite Constellations: National Security Implications', *Handbook of Small Satellites* (Springer Link 2019).

41 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.

42 Based on information provided during interviews with selected ICL academic staff in February and March 2021 and in: Roberts, Beischl and Mosteshar (n 40).

Linked to that, a mega-constellation could perform as an ASAT weapon system in times of conflict. For example, constellation satellites with an on-board propulsion system could be put at a conjunction course with an adversary's satellite to destroy the latter. A mega-constellation could be used for hundreds of such attacks.[43]

4.5.2 Relevant evidence-based information

Information gathering on space weaponisation, assessment of cybersecurity risks and solutions, and the study of redundancy measures can provide useful evidence-based information.

ICL has capabilities and expertise to provide such information. For example, ICL academic staff members conduct research in cybersecurity, AI and ML, as well as Internet of Things technology and techniques,[44] the findings of which are likely transferable into mega-constellation research. ICL has ISST, engaging in, among others, the theme of Space and Transport.[45] Notably, ISST Co-Director Deeph Chana chairs the NATO (North Atlantic Treaty Organization) Advisory Group on Emerging and Disruptive Technologies (EDTs)[46] that, in a recent report, determined Space as "the key theatre of the future within which NATO must lead in the development of a technologically proliferated environment that is demonstrably driven by values and ideals. Primarily, the domain of Space should be viewed as an opportunity to deliver on its global good objectives [...] rather than a platform for perpetuating archaic conflict narratives. The opportunity for global thought leadership in EDTs presents itself and should be taken."[47] Additionally, ICL has expertise in 3D printing if in-situ satellite manufacturing needs to be addressed.[48]

4.6 Space Traffic Management (STM)

According to the often cited definition by the International Academy of Astronautics, STM "means the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference."[49] This Study calls special attention to the following set of mega-constellation-associated concerns that affect the development

43 As discussed in, e.g.: ibid.
44 See also the involvement of ICL in the PETRAS National Centre of Excellence: 'PETRAS' (*PETRAS*) <https://petras-iot.org/> accessed 12 March 2021.
45 Based on ISPL expertise and information provided during selected interviews with ICL academic staff in February and March 2021.
46 Max Swinscow-Hall, 'NATO should be a global driver of a values-based innovation agenda' (*ICL*, 4 March 2021) <https://www.imperial.ac.uk/news/216413/nato-should-global-driver-values-based-innovation/> accessed 31 March 2021.
47 NATO Advisory Group on Emerging and Disruptive Technologies, 'Annual Report 2020' (Report, NATO 2020) 11 <https://www.nato.int/nato_static_fl2014/assets/pdf/2021/3/pdf/210303-EDT-adv-grp-annual-report-2020.pdf> accessed 31 March 2021.
48 Based on ISPL expertise and information provided during selected interviews with ICL academic staff in February and March 2021.
49 As cited in: Sebastien Moranta, Tomas Hrozensky and Marek Dvoracek, 'Towards a European Approach to Space Traffic Management' (ESPI Report 71, ESPI, January 2020) 3 <https://espi.or.at/publications/espi-public-reports/send/2-public-espi-reports/494-espi-report-71-stm> accessed 17 March 2020.

of a mature international STM system, currently considered by many in the space community a requirement to ensure responsible behaviour in space long-term.

4.6.1 Concerns

First of all, it is fair to state here that all the issues identified in the sections above need to be considered in the development of a mature international STM system. In particular, all issues increasing the collision and space debris creation risk need to be taken into account.

Use and Disposal phases:

At a more specific level, this Study points out that mega-constellations and their services will have to co-exist with other current and future space-based, ground and aerial systems and their services. As such, a mature international STM system needs to be crafted in a way that ensures that the deployment and use of mega-constellations causes no significant interference with other space activities and vice versa, including in terms of signal interference due to serious frequency overlaps among system operators enabling similar services. Notably, maintaining safe spacecraft operations in and across the various (crowded) orbits requires access to and exchange of data among all involved actors, especially since mega-constellations are expected to rely on (semi-)automated operation processes in orbit.

Related to that, there is the issue that a constellation with hundreds or thousands of satellites in orbit could become a 'lame duck' project, e.g. due to bankruptcy of the operator. The collision and debris creation risk increases without fail safes in place to ensure the continued safe operation of such a constellation.

Lastly, with the rise of communications satellite mega-constellations aiming to provide global coverage, there is a need for an STM system offering a reasonable procedure to peacefully resolve the issue of unauthorised sending of data into certain jurisdictions, e.g. breaching China's Great Firewall, at the domestic and international level. Such breaches can create diplomatic incidents or lead to retaliatory actions among affected states.[50]

4.6.2 Relevant evidence-based information

This Study argues that the study of international approaches, standards and interoperability, taking account of civil and military actor involvement, can provide useful evidence-based information. Research to improve understanding of export control regulations, Space Situational Awareness, data-sharing agreements, space debris mitigation

50 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.

guidelines, industry standards and best practices, space object registration, licensing requirements and radio-frequency regulations are integral in this regard.

ICL can provide technical input, including through its Space Lab, an ICL network of excellence, and ISST, which addresses, among others, the theme of Space and Transport.[51] Moreover, the ICL-ISPL UK Space Safety Policy Project of 2020 determined that various ICL departments have technical capabilities and expertise that could serve addressing STM concerns.[52]

51 Based on ISPL expertise and information provided during interviews with selected ICL academic staff in February and March 2021.
52 See the findings presented in the ICL-ISPL UK Space Safety Policy Project's internal Report on Imperial College London Space Safety Capabilities and Expertise.

Attachment: OneWeb; UK mega-constellation research; UK-UNOOSA collaboration

OneWeb:

OneWeb, legally trading in the UK and the EU as Network Access Associates Limited,[53] is a private company registered in England and Wales and headquartered in London attempting to establish a LEO satellite mega-constellation, including relevant terrestrial infrastructure such as associated ground control facilities, gateway earth stations, and user terminals, providing commercial but affordable high-speed, low-latency broadband connectivity worldwide. OneWeb aims to serve Alaska, the Artic Seas, Canada, Greenland, Iceland, Northern Europe and the UK in 2021 and to offer global service the following year.

After "the Company and certain of its controlled affiliates [...] voluntarily filed for relief under Chapter 11 of the Bankruptcy Code in the U.S. Bankruptcy Court for the Southern District of New York" in March 2020, the UK Government, through the Secretary of State for Business, Energy and Industrial Strategy, and India-based Bharti Global Ltd decided to invest $500 million each, becoming the primary shareholders in November 2020 and lifting OneWeb out of the Chapter 11 proceedings. In January 2021, OneWeb further announced that it secured additional funding of $350 million from Japan-based SoftBank Group Corp., gaining a seat on the Board of Directors and becoming OneWeb's third primary shareholder, and $50 million of United States (US)-based Hughes Network Systems, LLC, investing through its parent company EchoStar. Prior to that, OneWeb received, among others, £18 million from UKSA through ESA in 2019 in support of OneWeb's Sunrise Programme to "develop cutting-edge technologies needed to enable future ambitions, whether it be in satellite hardware, ground infrastructure or the responsible use of space (end of life de[-]orbiting)."

Initially working towards a constellation of 47,844 satellites in orbits of around 1,200 km,[54] OneWeb now plans with a reduced number of 6,372 satellites,[55] with the first-generation system consisting of 648 satellites. 110 satellites were launched by mid-January 2021. Ofcom authorises the system's spectrum use and has made International Telecommunication Union spectrum filings for the company's use.[56]

53 Originally, it traded as WorldVu Satellites Limited.

54 "32 planes of 720 satellites each at an inclination of 40 degrees, 32 planes with 720 satellites each at an inclination of 55 degrees, and 36 planes with 49 satellites each at an inclination of 87.9 degrees": Foust, 'OneWeb slashes size of future satellite constellation' (n 8).

55 32 planes of 72 satellites each at an inclination of 40 degrees, 32 planes with 72 satellites each at an inclination of 55 degrees, and 36 planes with 49 satellites each at an inclination of 87.9 degrees: ibid.

56 Based on information in: Thomas Seal, 'SoftBank Returns to Invest in Musk Satellite Rival OneWeb' (*Bloomberg*, 15 January 2021) <https://www.bloomberg.com/news/articles/2021-01-15/softbank-returns-to-invest-in-musk-satellite-rival-oneweb> accessed 8 February 2021; 'Oneweb Secures Investment from Softbank and Hughes Network Systems' (*OneWeb*, 15 January 2021) <https://www.oneweb.world/media-center/oneweb-secures-investment-from-softbank-and-hughes-network-systems> accessed 5 February 2021; Foust, 'OneWeb slashes size of future satellite constellation' (n 8); 'OneWeb Streamlines Constellation' (*OneWeb*, 13 January 2021) <https://www.oneweb.world/media-center/oneweb-streamlines-constellation> accessed 5 February 2021; 'OneWeb's Successful Launch, Paves the Way for Commercial Services' (*OneWeb*, 18 December 2020) <https://www.oneweb.world/media-center/onewebs-successful-launch-paves-the-way-for-commercial-services> accessed 5 February 2021; 'OneWeb Successfully Emerges From Chapter 11, Announces New CEO and Recommences Satellite Launches' (*OneWeb*, 20 November 2020) <https://www.oneweb.world/media-center/oneweb-successfully-emerges-from-

Lastly, OneWeb is a consortium partner of the Satellite Applications Catapult-led Backhaul Radio Access with Integrated LEO (BRAIL) project. The other partners are LiveWire Digital Ltd and the University of Strathclyde. In short, BRAIL shall demonstrate high speed data transfer through space using OneWeb satellites to SA Catapult's 5G network at the latter's connectivity research and innovation centre in Westcott, Buckinghamshire. This shall support the development of connectivity solutions for poorly served areas. The project received at least funding of £510,757 via UKSA's National Space Innovation Programme (NSIP).[57]

Regarding Section 3, the OneWeb-associated Government policy objectives of advancing UK's socio-economic development and welfare, as well as of enhancing its space-related scientific and technological expertise, emerge from the Government declaration that becoming a shareholder of OneWeb demonstrates its "ambition to put Britain at the forefront of a new commercial space-age." The Government further stated it wants "to use this investment as a platform to promote UK jobs and supply chains and protect UK critical assets and intellectual property." Moreover, then-Secretary of State for Business, Energy and Industrial Strategy Alok Sharma asserted at that time that "[t]his deal gives us the chance to build on our strong advanced manufacturing and services base in the UK, creating jobs and technical expertise." Then-Chief Executive of UKSA Graham Turnock also suggested that the Government's OneWeb investment "can play a vital role in our economic recovery[from the Covid-19 impact]." He added that "[g]lobal connectivity has never been more important and there is a significant opportunity for satellite constellations to deliver a range of valuable services to consumers, businesses and government."[58]

An indication of the Government's potential pursuit of the policy objective of safeguarding the UK's national security is its press release concerning its OneWeb investment reading that "[t]he UK government

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chapter-11-announces-new-ceo-and-recommences-satellite-launches> accessed 5 February 2021; 'OneWeb Files for Chapter 11 Restructuring to Execute Sale Process' (*OneWeb*, 27 March 2020) <https://www.oneweb.world/media-center/oneweb-files-for-chapter-11-restructuring-to-execute-sale-process> accessed 4 February 2021; 'OneWeb deepens its commitment to the UK which will create more than 150 new jobs in its London Headquarters' (*OneWeb*, 13 June 2019) <https://www.oneweb.world/media-center/oneweb-deepens-its-commitment-to-the-uk-which-will-create-more-than-150-new-jobs-in-its-london-headquarters> accessed 8 February 2021; '£18m for OneWeb satellite constellation to deliver global communications' (*GOV.UK*, 18 February 2019) <https://www.gov.uk/government/news/18m-for-oneweb-satellite-constellation-to-deliver-global-communications> accessed 8 February 2021; 'Privacy Notice' (n 8); Hanson (n 3). First citation in seventh link. Second citation in eight link.

57 'Government funds UK companies at the forefront of space innovation' (*GOV.UK*, 7 December 2020) <https://www.gov.uk/government/news/government-funds-uk-companies-at-the-forefront-of-space-innovation> accessed 1 February 2021; for more information on space-related facilities around Westcott, see: 'Westcott Space Cluster' (*Westcott Space Cluster*) <https://westcottspacecluster.org.uk/> accessed 2 February 2021.

58 'UK government secures satellite network OneWeb' (n 40); this conclusion is also supported by statements in: 'UK government to acquire cutting-edge satellite network' (*GOV.UK*, 3 July 2020) <https://www.gov.uk/government/news/uk-government-to-acquire-cutting-edge-satellite-network> accessed 5 February 2021; and: Ministerial Direction from Alok Sharma, 'OneWeb' (26 June 2020) <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/902925/OneWeb_-_ministerial_direction.pdf> accessed 5 February 2021; it shall be added here that, despite the Government's public highlighting of the economic potential of its OneWeb investment, the Accounting Officer for BEIS Sam Beckett wrote in a letter to then-Secretary of State for Business, Energy and Industrial Strategy Alok Sharma "that whilst there may be a commercial case for investing alongside other commercial investors if you accept advisors' assessment of One Web's business plan projections, as a standalone high-risk investment with a possibility that the entirety of the investment is lost and no wider benefits accrued, I cannot satisfy myself that this investment meets the requirements of Value for Money as set out in Managing Public Money. Therefore, whilst I believe the risks around the other Accounting Officer standards of regularity, propriety and feasibility are manageable, Managing Public Money requires me to seek a direction from you." See: Request for Ministerial Direction from Sam Beckett, 'OneWeb' (26 June 2020) <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/902931/OneWeb_-_request_for_ministerial_direction.pdf> accessed 5 February 2021. Citations in first link.

will have a final say over any future sale of the company, and over future access to OneWeb technology by other countries on national security grounds."[59] Additionally, there seems to be some consideration to employ "OneWeb's first generation system [...] to develop an innovative and accurate timing capability in a project with the UK-based space hub Satellite Applications Catapult that requires no satellite changes and minimal ground network modification. OneWeb intends to introduce PNT capabilities on subsequent generations of satellites, to complement existing services, and to provide additional global resilience for this critical infrastructure."[60]

An indication of the Government's potential pursuit of the policy objective of increasing the UK's international prestige and influence is then-Secretary of State for Business, Energy and Industrial Strategy Alok Sharma writing in his Ministerial Direction to the Accounting Officer for the Department for Business, Energy and Industrial Strategy (BEIS) Sam Beckett "that OneWeb, a UK-based company, represents an opportunity for UK interests globally. [...] There could be wider, less quantifiable benefits of signalling UK ambition and influence on the global stage."[61]

UK-supported mega-constellation research:

Besides its OneWeb involvement, the Government through UKSA's NSIP has contributed funds of at least £348,061 to Lynk Global UK Limited, a subsidiary of the US-based company Lynk Global,[62] and consortium partners With Reason Ltd and Farm.ink to facilitate the development of LynkCast, in particular to "bring the critical information services such as weather forecasts and alerts to users direct from the satellites to the mobile phones in their pockets." LynkCast will use Lynk Global's planned – several thousand LEO satellite strong – mega-constellation to offer global mobile phone connectivity with unmodified mobile phones.[63]

UKSA has further provided funding to the following notable projects that consider employing nano-satellite constellations – without much information whether these would amount to mega-constellations in the future – or advancing CubeSat capabilities, potentially fostering mega-constellation development:

First, there is the "High resolution thermal infrared space telescopes for globally monitoring the energy efficiency of buildings" project led by the University of Cambridge, also involving Super-Sharp Space

59 'UK government secures satellite network OneWeb' (n 40).
60 'Network' (*OneWeb*) <https://www.oneweb.world/network> accessed 31 March 2021.
61 Ministerial Direction from Sharma (n 58).
62 For Lynk Global's official website, see: 'Lynk' (*Lynk Global*) <https://lynk.world> accessed 2 February 2021.
63 Based on information in: 'Government funds UK companies at the forefront of space innovation' (n 57); Rachel Jewett, 'Lynk Co-Founder Says Satellite-to-Cell Tech Will Be "Bigger than 5G"' (*Via Satellite*, 30 March 2020) <https://www.satellitetoday.com/innovation/2020/03/30/lynk-co-founder-says-satellite-to-cell-tech-will-be-bigger-than-5g/> accessed 2 February 2021; Elizabeth Howell, 'SpaceX Competitor Creating "Cell Tower" In Space' (*Forbes*, 10 October 2019) <https://www.forbes.com/sites/elizabethhowell1/2019/10/10/spacex-competitor-creating-cell-tower-in-space/> accessed 2 February 2021. Citation in first link.

Systems Ltd and Open Cosmos Ltd as consortium partners. The project aiming to advance monitoring of buildings' energy output has received at least £294,041.26 via UKSA's NSIP to "study how the data can be used and develop prototypes for an innovative unfolding telescope for a nanosat constellation giving the required ground resolution (7 metres) with frequent revisit rates."

Second, there is the "Hyperspectral Microwave Sounder Constellation of Nanosatellites for Climate change And Mitigation" (HYMS CONCAM) project headed by RAL Space. The project covers "rigorous analysis" and the development of "the Hyperspectral Microwave Sounder, a first of its kind, designed to provide unprecedented resolution of global moisture and temperature profiles in a highly compact form factor, allowing for a constellation deployment that will dramatically enhance global weather forecasting and climate monitoring." NSIP-based funding has amounted to at least £494,022.

Third, there is the "Laser Optical Communications for CubeSats" project led by Northumbria University and involving ISOCOM Limited as consortium partner. The project wants "to replace the existing low-speed radio frequency transceiver used in CubeSats with the high-speed, light weight and lower power free-space optical transceivers, enabling a step-change in our approach to communications constellations and space science missions. By the end of this project, a test-bed design will have been developed together with a mission design study for future testing of the system in space." UKSA through NSIP has provided at least funding of £367,659.82.[64]

UK-UNOOSA collaboration:

In January 2021 the UK and the United Nations Office for Outer Space Affairs (UNOOSA) signed an agreement aimed to "help nations ensure that outer space remains safe and sustainable for future generations", pointing out that, among others, "the emergence of large constellations of satellites and the increased risks of collision all affect the long-term sustainability of space activities." Being considered in line with the Guidelines for the Long-Term Sustainability of Outer Space Activities, adopted by the United Nations Committee on the Peaceful Uses of Outer Space in 2019, this UK-UNOOSA agreement involves UKSA funding of £85,000 for events and outreach activities identifying examples of sustainable use of space. Notably, "[t]his partnership [...] is the first time the UK has funded a project with UNOOSA." Moreover, "[i]t is [...] the first project to be funded from the international element of [UKSA's NSIP], launched in October 2020 to support collaborative projects between UK organisations and international partners."[65]

64 'Government funds UK companies at the forefront of space innovation' (n 57).
65 'UN and UK sign agreement to promote space sustainability' (*GOV.UK*, 26 January 2021) <https://www.gov.uk/government/news/un-and-uk-sign-agreement-to-promote-space-sustainability> accessed 1 February 2021; 'UN Office for Outer Space Affairs and United Kingdom sign agreement to promote space sustainability' (*UNOOSA*, 26 January 2021) <https://unoosa.org/oosa/en/informationfor/media/press-release_-un-

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