Identifying Research Gaps in Key Environmental Indicators for Space

Project Report Commissioned by the UK Space Agency

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Summary and Recommendations

The UK Government's number one mission is to increase economic growth by building on the UK's well-established global reputation for research excellence and international partnership heritage. (Invest 2035: the UK's Modern Industrial Strategy)

The UK space sector is a key foundation for economic growth. The industry generates nearly £19bn in income, creates highly skilled, high productivity jobs and underpins almost 18% (£364bn) of UK GDP. (London Economics 2024) To meet the UK's growth ambitions and ensure the security and sustainability of the critical infrastructure on which the economy depends, the space environment must be managed in a sustainable way.

Well-established indices are used to monitor environmental conditions on Earth, for instance: greenhouse gas emissions; water consumption; energy efficiency; biodiversity; waste production; and so on. They provide a way to spot problems, set targets, track trends, understand outcomes and inform policies. They enable clearer understanding of costs, risks and trade-offs in the pursuit of economic growth.

By contrast, there are no globally agreed, consistently measured, indicators providing robust evidence of the environmental impacts in space and on Earth resulting from human activity in space. This means that space policy and strategy are developed with insufficient evidence of impacts and outcomes and efforts to reach international consensus are impeded.

The UK Space Agency commissioned this report from the Global Network on Sustainability in Space to explore research gaps relating to indicators of how human activity is impacting the space environment and Earth's atmosphere. It reflects views gathered through written contributions from 46 individuals representing research groups from 9 countries and verbal contributions from 38 speakers and 69 other participants over two online workshops held on 28 February and 10 March 2025.

The findings highlight that the rapid growth of human space activity has pushed past the boundaries of current understanding of the space environment, giving rise to new risks and hazards that are poorly understood and difficult to mitigate.

Participants agreed on some key knowledge gaps which must be filled for environmental impacts to be better understood and evidenced. These include:

- more accurate and timely measurement of the satellite and debris population, especially the small debris which can't currently be adequately measured nor monitored, but can cause mission failure;
- deeper understanding of how space weather events impact satellites and debris, including better feedback loops between space weather research and satellite operations;
- more systematic measurement of radio frequency spectrum interference and unintentional emissions of electromagnetic radiation from spacecraft; and
- better understanding of the impacts of the increasing volume of launch and re-entry on the Earth's atmosphere, given emerging evidence of the presence of particulate matter that doesn't occur naturally and which could have adverse effects for ozone depletion and climate change.

In addition to specific knowledge gaps, there was a shared view that more holistic measures of impacts, e.g.: ecological, economic, cultural, human health, etc. should be developed to ensure trade-offs are understood when operational and policy decisions are taken. It was also recognised that understanding the environmental impacts of human activity on and around the moon will require different approaches to those that are being developed for Earth's orbital environment.

During the workshops there were many calls for:

- An independent, international, civil reporting body to facilitate data sharing;
- An inclusive, democratic, international Space Traffic Management authority, akin to ICAO, to coordinate the safe use of space and monitor compliance with agreed rules and norms; and
- Embedding mandatory data sharing and environmental impact assessments in licencing processes.

This report outlines 10 recommendations for UK government actions to:

R1: Improve satellite and debris population measurement and monitoring.

R2: Gather more systematic evidence of radio frequency and optical impacts.

R3: Deepen understanding of space weather impacts.

R4: Join up across research disciplines and foster international collaboration to advance understanding of the atmospheric impacts of launch and re-entry.

R5: Seek to build consensus for developing a holistic indicator framework for the space environment.

R6: Encourage and facilitate better data sharing between the research community and satellite operators, including across international boundaries.

R7: Coordinate cross-disciplinary funding for space environmental impact research.

R8: Incentivise and facilitate cross-border research collaborations to address knowledge gaps.

R9: Support and facilitate knowledge sharing and awareness raising, to build understanding of the trade-offs between the benefits of human activity in space and the environmental impacts and seek to forge consensus for collective action on the part of international leaders.

R10: Work with stakeholders to develop a UK space traffic management policy and promote the development of global space traffic management solutions.

The UK Space Agency's remit doesn't extend to all the areas covered in this report. Nonetheless, it has a vital role to play. It's hoped that the findings and recommendations will be useful in informing the development of the UK's long-term space sustainability strategy and research roadmap.

Contents

1.0 Introduction

This Report documents the findings of a project delivered by GI3S Ltd., on behalf of the Global Network On Sustainability In Space (GNOSIS) for the UK Space Agency (UKSA) and makes recommendations for future research priorities.

The aim of the project was to explore the current gaps in research relating to indicators of the impacts of human activity on the space environment and on Earth's atmosphere.

The project was carried out between January and March 2025 and involved written contributions from 46 individuals representing research groups from 9 different countries and verbal contributions from 38 speakers over two half-day online workshops held on 28 February and 10 March 2025.

We are grateful to all the contributors who participated in this project for their views and insights. The names of all contributors are included in Appendix A.

1.1 Motivation

The UK Government's number one mission is to increase economic growth by building on the UK's well-established global reputation for research excellence and heritage of international partnership. (Invest 2035: the UK's Modern Industrial Strategy) The UK space sector is a key foundation for economic growth and exemplifies these strengths.

The latest Size and Health of the UK Space Industry report shows the industry generates nearly £19bn in income, creates highly skilled, high productivity jobs and underpins almost 18% (£364bn) of UK GDP. (London Economics 2024) To meet the UK's growth ambitions and ensure the security and sustainability of the critical infrastructure on which the economy depends, the space environment needs to be managed in a sustainable way.

The global space market is projected to grow to US$1.8tn by 2035 (World Economic Forum/McKinsey & Co. 2024). This assumes a safe, sustainable operational environment, yet there's a growing body of evidence that indicates that the space environment is being put at risk. For the UK, this creates vulnerabilities for a significant proportion of our national economy, while also undermining our growth ambitions by potentially limiting access to a high value global market.

Well-established indices are used to monitor environmental conditions on Earth, for instance: greenhouse gas emissions; water consumption; energy efficiency; biodiversity; waste production; and so on. They provide a way to spot problems, set targets, track trends, understand outcomes, and identify best policy practices. They enable clearer understanding of the costs, risks and trade-offs made in the pursuit of economic growth.

By contrast, there are no globally agreed, consistently measured, indicators providing robust evidence of the environmental impacts in space and on Earth resulting from the expansion of human activity in space.

This means that space policy and strategy are developed with insufficient evidence of impacts and outcomes and impedes efforts to reach international consensus.

There are published metrics relating to the space debris and satellite population. For instance, the European Space Agency's (ESA) annual Space Environment Report (ESA Space Debris Office 2025), US Space Command's Space-Track (Space-Track 2025) and NASA's Orbital Debris Quarterly News (NASA 2025). However, different reports draw from disparate and imperfect data sources and apply diverse modelling methodologies to derive estimates and forecasts. Without a consistent set of population metrics, it's impossible to say whether space has already become dangerously over-crowded or not.

Limited research has also been carried out to try to understand:

- the impacts of Space Weather on the growing debris and satellite population;
- the frequency and severity of radio frequency (RF) spectrum fragmentation/interference;
- the consequences of increased reflection of sunlight from satellites and debris; and
- the potential adverse effect of launch and re-entry on the Earth's atmosphere.

These are all areas where clear knowledge gaps remain. Consequently, policy and investment decisions are ill-informed and entail unknown levels of risk.

1.2 Methodology

In the first phase of this project, GNOSIS conducted a short online survey between 24-31 January. Members of GNOSIS and SPAN (the UK's Space Academic Network) were asked for their views on what should be included in a standard set of environmental indicators for space and the critical knowledge gaps where further research could add the most value. Email exchanges and interviews with the wider international space sustainability research community have also contributed to the content.

Responses were received from 41 survey participants and 5 additional direct contributions, bringing total respondents to 46. The organisations of contributors were based in 9 different countries, although a majority (70%) were from UK-based organisations. As a result, the views shared were skewed towards European and North American perspectives.

The survey responses were summarised, along with other relevant information drawn from a high-level review of publicly available information sources, in two Review Documents. These can be accessed here: https://gnosisnetwork.org/key-environmental-indicators-for-space/

In the second phase of the project, two half-day online workshops were held with international researchers and UK government attendees on 28 February and 10 March, 2025. The Workshop agendas can be found in Appendix B. The Review Documents were issued as background reading to Workshop attendees. In total, some 38 panellists and chairs and 69 other attendees participated in the workshops.

This report presents a summary of the key findings from the Workshops and proposes recommendations arising from the discussions.

1.3 Structure of Report

A number of knowledge gaps were explored during the workshops through panel members' introductory remarks and subsequent discussions - including exchanges posted by participants in the chat function. The workshops stimulated rich, wide-ranging explorations of the topics on the agenda. The recordings of the workshops can be viewed at https://www.youtube.com/@gnosis-space.

Where references were made in the workshops to information sources, or specific research papers or articles, these are cited in the text and/or listed in Appendix C.

The discussions could not comprehensively cover all knowledge gaps relating to environmental indicators for space in detail in the time available. However, they did highlight many key areas where future research could be prioritised. While care has been taken to validate workshop contributions, the views expressed throughout are those of the contributing attendees and this report represents a best-efforts attempt to summarise them.

Technical findings are summarised in Section 2 and policy findings in Section 3. Findings have been grouped thematically, rather than mirroring the workshop agendas.

Section 4 collates views from survey respondents and workshop attendees on key knowledge gaps and priority areas for future research.

Section 5 offers recommendations for UKSA consideration and Section 6 presents general conclusions.

2.0 Technical Findings

2.1 Monitoring and Measuring the Satellite Population

TF1 Effective Space Traffic Management (STM) relies on orbit propagation models, but small errors in initial conditions grow over time and uncertainty increases with factors like atmospheric drag, Space Weather, and frequent manoeuvring of satellites (e.g., Starlink's continuous orbit adjustments via electric propulsion). The high degree of uncertainty in current models associated with so many objects means that no accurate measure of the satellite population exists.

TF2 Many objects in the U.S. Space Surveillance Network (SSN) catalogue lack proper identification. This challenge is especially pronounced for small satellites deployed via rideshares, where tracking systems struggle to differentiate between multiple objects launched simultaneously. A significant fraction of the catalogued debris objects are currently “lost”. Of approximately 29,000 tracked objects in orbit, 1,016 have had no updated Two-Line Element sets (TLEs - the standardised format used by the SSN to identify objects; containing orbital parameters) for more than 2 years. As of February 2025, there were 432 payload objects in the catalogue that are not associated with particular satellites. In some cases, this is due to the fact that the objects are inoperable and it’s not possible to differentiate between them, however 251 of them (more than half the unidentified objects in the catalogue) were Chinese satellites. (McDowell J. n.d.)

TF3 More work is needed to establish a set of pristine initial population metrics that include all debris and relevant objects on which to base future projections. A more comprehensive data standard - providing more detail than TLEs - would be beneficial. There were suggestions that the US government has been looking at moving towards the orbit data message standard recommended by the Consultative Committee for Space Data Systems (Consultative Committee for Space Data Systems 2023) and that the latest US TraCSS data policy represents a significant shift in what is publicly available (Office for Space Commerce 2024).

TF4 Satellite operators use 2 or 3 different sources of Space Situational Awareness (SSA) data to track their own satellites and monitor the operating environment. There are inconsistencies across SSA data sources, so data validation and assurance are critical. Operators would welcome being able to assess the accuracy of SSA systems, particularly as they continue to develop automated collision avoidance systems. Without the ability to validate the consistency of SSA data across multiple sources, it is difficult to derive a single accurate population metric.

TF5 The precision of tracking data varies significantly across different tracking methods (e.g., radar, optical, and passive radio tracking). Some satellites are designed to be tracked with centimetre-level accuracy (e.g., the US Global Positioning System and European Galileo networks), sometimes via the inclusion of retro-reflectors to enable active laser ranging, but most objects have much larger uncertainties. Without more precise tracking, it's not possible to accurately assess maximum safe orbital capacity and operators are forced to make sub-optimal judgements about when to manoeuvre. The SSA community could potentially leverage the expertise of the community of precise orbit determination practitioners and exploit data associated with orbital assets that are already being tracked extremely precisely as a reference network. Looking at the discrepancies between various tracking systems and the reference data from precision tracking of specific objects could help with data validation.

TF6 The effects of climate change also have an impact on the accuracy of satellite and debris population modelling. Increasing CO_2 in the lower atmosphere results in cooling of the upper atmosphere, leading to a long-term decrease in thermospheric density. Models do not yet account for these long-term CO_2 cooling effects, leading to errors in assumptions about orbital decay. If satellites and debris stay in orbit longer than expected, this will increase collision risks.

TF7 Collision modelling incorporates three major risks: 1) risks of collision between active satellites; 2) risk of collision between active satellites and debris; and 3) between inactive debris objects. Currently, the rarest and mostly avoidable collisions are those in the first category, although the error ellipsoids of orbital propagation models today are such that the question of how close two objects are to colliding can often only be answered after they've passed each other. The second category are currently of most interest since, if the debris object's orbital path can be accurately assessed, and the other object is able to manoeuvre, potential collisions could be avoided. Limited understanding of the debris population makes this challenging – as will be explored in the next section of this report.

TF8 The development of large constellations like Starlink and OneWeb has led to increased risk of potential conjunctions in orbit. Starlink satellites' autonomous station-keeping - based on their own internal tracking data - was referenced as an example of how satellites in Low Earth Orbit (LEO) conduct frequent automated manoeuvres, yet external SSA providers don't always receive timely updates, so population and propagation metrics are inaccurate. AI-driven autonomous manoeuvring protocols will become even more necessary as the numbers of satellites grow. These *must* be designed with standardised decision criteria and fed with consistent data or different operators may respond unpredictably, increasing the risk of uncoordinated evasion manoeuvres leading to new conjunctions.

TF9 Operators have much more precise knowledge of their own satellites (e.g., attitude, drag profile, thrust capabilities), but many do not share this data with SSA networks, as it's viewed as proprietary. Incorporating these sorts of details into models could improve population metrics and propagation of future states. Current tracking data can be several hours old before it reaches decision makers, making rapid collision avoidance difficult. However, SpaceX has successfully shared GPS-based ephemeris data for its 7,000 satellites via Celestrak, showing that timely tracking at scale is possible.

TF10 With private and public sector investment going into ambitious plans to develop the cislunar economy, there is a need to begin now to develop cislunar environmental metrics, models and monitoring. Traffic management and debris mitigation approaches will not work the same way as they do in orbits more proximate to the Earth. Specifically, optical tracking from the Earth is unlikely to provide a useful contribution, due to the intrinsic brightness of the Moon itself.

2.2 Monitoring and Measuring the Debris Population

TF11 There are two primary space debris models; ESA's Meteoroid and Space Debris Terrestrial Environment Reference Model (MASTER); and NASA's Orbital Debris Engineering Model (ORDEM). These models estimate the number and distribution of debris, based on sometimes unknown fragmentation events and statistical extrapolations rather than direct observations. Tracking of large debris is done using ground-based radar stations bouncing signals off objects. Current radar sensitivity drops for objects smaller than 10 cm in Low Earth Orbit (LEO) and 30 cm in Geosynchronous Orbit (GEO), due to power and resolution constraints. Optical tracking - using telescopes to detect sunlight reflected off debris - is also used; however, debris objects aren't illuminated all the time, so optical tracking can't provide continuous monitoring. For debris smaller than 1cm, the MASTER and ORDEM models differ by a factor of 100 at some sizes. Debris between 100 microns and 1cm can't be accurately measured due to the lack of appropriate sensing techniques. The orbital lifetime of small debris is poorly understood, since atmospheric drag and solar radiation pressure affect small particles unpredictably.

TF12 Simulations carried out by University of Strathclyde suggest that some orbital regions may be approaching their "maximum carrying capacity." Once a region is too crowded, debris collisions are predicted to start a self-sustaining chain reaction (Kessler Syndrome theory). There is debate amongst the scientific community whether Kessler Syndrome is already taking place at some orbital altitudes. There is, however, no standard metric against which to evaluate this.

TF13 One impact of a small debris object can cause many small fragments to break off, some even larger than the original impactor, causing a debris multiplication factor. Alongside collisions, debris is also generated by the fragmentation of legacy objects left in orbit, as their materials degrade over time. More than 600 known fragmentation events have occurred, yet there are large uncertainties in how small the resulting fragments are and how many of those fragments remain in orbit vs.

those that have re-entered the Earth's atmosphere. The smaller an object is in LEO, the higher its area-to-mass ratio, and the faster it will de-orbit and burn-up in the Earth's atmosphere. It is assessed that the small debris population is being replenished - through collisions and other fragmentation events - at a faster rate than atmospheric drag can clear it. (ESA Space Debris Office 2025) However, the high degree of modelling uncertainties means there is no definitive baseline against which to evidence this.

TF14 Instruments have been used to examine the impacts of small debris in orbit, for instance, on the exterior surface of the International Space Station. De-orbited spacecraft have also been examined to attempt to measure the impact of small debris. Post-mission analysis of spacecraft solar panels and shields has revealed impact craters from even sub-millimetre debris. However, data is rare and only available for specific orbits and time periods. There is no method for tracking the wider distribution of small debris. A study carried out by the University of Kent assessed that mm to cm-sized debris poses the greatest threat to spacecraft in LEO, yet this segment of the debris population represents the most critical data gap. (Cornwell et al. 2025) It remains difficult, even with returned samples, to differentiate between impact features caused by human-made debris and the effects of natural micro-meteorites. The latter will remain a hazard even if human-induced effects on the environment are reduced. (See also TF17 below).

TF15 The impact energy of debris smaller than 1 cm in size can be too low to be reliably detected or characterised, and impact sensors themselves can be damaged or degraded by frequent impacts. This size is also too small for radar to detect. Nonetheless, objects in this range can penetrate spacecraft walls, damage sensors, and cause mission failures. Even 1 mm debris orbiting at 10 km/s can carry the kinetic energy of a bullet; a direct impact can disable a CubeSat or puncture a satellite fuel tank. Many satellite failures may be due to debris impacts, but it is almost impossible to prove. Forensic techniques to analyse impact damage are needed.

TF16 ESA has proposed two missions to try to gather more data on the small debris population: (i) a passive optical telescope placed in sun-synchronous orbit, pointing away from the sun to record the passage of small debris; and (ii) a deployable, thin-film sail placed in orbit with acoustic and optical sensors to detect micrometeoroid and debris strikes. The latter could provide direct statistical counts of debris in the 100 micron to 1 cm range, allowing scientists to estimate the actual debris flux in LEO for previously unmeasurable sizes. The latter mission is limited by the fact that it will make measurements at only one orbital altitude – comparable missions at multiple altitudes would provide a more comprehensive understanding of the problem.

TF17 It is very difficult to differentiate naturally occurring meteoroid particles from space debris caused by human activity (Azzi et al. 2024). Examination of parts of the Hubble Space Telescope after they were returned to Earth showed numerous hypervelocity impacts by micrometeoroids and human-made debris. Recent evaluation of the largest impact features indicated that the MASTER and ORDEM models may overestimate debris flux and underestimate micrometeoroid numbers (Kearsley et al. 2024), but the small debris environment is very dynamic, so models quickly become outdated. It should also be noted that meteoroid fluxes are time dependent; so-called “meteor storms” occur periodically that can result in marked changes in the observed rates.

TF18 It’s extremely challenging to model all the interactions that create debris. The materials being used in satellites and upper stages are rapidly evolving, so the way they generate debris is also evolving. Even if orbits can be ascertained for the smaller objects, there are large uncertainties in how many of these objects exist, and how long they remain in orbit, so propagating accurately for any length of time is very difficult. For instance, the materials and design used in the NASA DebriSat project - a hypervelocity-impact test carried out in 2014 to study fragmentation effects of a typical LEO satellite (Cowardin et al. 2023) - might be very different to the materials being used today. Changes to propulsion system technology will also have an effect.

TF19 The European Research Council has funded research by Warwick University into the use of large arrays of optical telescopes paired with complementary metal-oxide semiconductor (CMOS) devices to detect and characterise space objects (both debris and satellites). While the large data volumes generated create a challenge, this technology could enable timely monitoring for both astronomy and SSA purposes – improving the accuracy of population metrics. The Science and Technology Facilities Council has funded Warwick University research looking at the feasibility of using event-based sensing as an alternative to frame-based techniques involving, e.g., CMOS images, to significantly reduce data rates.

2.3 Monitoring and Measuring Optical and RF Impacts

TF20 The International Telecommunications Union (ITU) manages the allocation of RF spectrum globally. ITU's Radio Regulations, which have treaty status, specify that certain frequency bands are allocated for radio astronomy - requiring that these bands be protected from interference from other services. Wideband observatories such as the Square Kilometre Array (SKAO) – which is led out of the UK’s Jodrell Bank - and the Netherlands Institute for Radio Astronomy’s Low Frequency Array (LOFAR) are also protected as designated “radio quiet zones”, where the use of ground-based radio spectrum is tightly controlled from about 50/100 Megahertz up to 25 Gigahertz. However, the increase in LEO satellites - which are in motion relative to the Earth and so cover much more of the sky each time they orbit - is starting to increase the likelihood of beam-to-beam interaction with radio telescopes, creating nonlinearities where the entire observation is lost for a period of time. These are caused, in the main, by the very strong downlinks satellites use to connect to ground stations, and the “out of band” harmonics that these can generate. (See also TF22 below.) Active services like communication satellites have been coordinated to share spectrum for years, but passive services like radio astronomy can’t currently share with active services. Boresight avoidance techniques (aligning satellite beams away from radio telescopes) have shown some success with Starlink but are not enforced across all operators.

TF21 There is emerging evidence that radio frequency spectrum interference (RFI) from multiple constellation networks is also beginning to impact satellite operators. Satellite operators have always had to deal with the potential for RFI. Technical solutions were found to deal with sources of interference when multiple satellite networks were developed over time in GEO, and later for satellites operating in Medium Earth Orbit (MEO). But the rapid increase in satellite numbers in LEO has presented new challenges for spectrum sustainability. ESA has funded a study (https://connectivity.esa.int/projects/thrimos) to look at better ways of monitoring and cataloguing the RF emissions properties of space objects. The concept of Space Situational and Spectrum Awareness (SSSA) was introduced during the workshop, i.e., incorporating spectrum conjunction analysis into SSA systems. This would require more systematic measurement of spectrum usage than is done today.

TF22 Astronomers at SKAO have recorded evidence of Unintentional Electromagnetic Radiation (UEMR) emissions associated with the normal functioning of the electronic systems on board satellites. The example was given of OneWeb and Starlink satellites in LEO - which operate using Ku bank in 11 Gigahertz - emitting in very low frequencies around 100 Megahertz. LOFAR has detected emissions indicating that Starlink Gen2 satellites generate stronger “leakage” than earlier models. Multiple satellites can create a "continuous noise floor," making it impossible for radio telescopes to detect faint cosmic signals.

TF23 Astronomers lack precise data on satellite emissions to properly predict and avoid interference. Observations from radio astronomers could potentially help in identifying which part of the electronics is responsible for the worst UEMR, while better collaboration with satellite manufacturers and operators could lead to improved technical designs to mitigate the issue. Stronger shielding and emissions filters could potentially form part of mitigation solutions, but without more systematic measurement of emissions, it is difficult to assess the costs versus benefits of mitigation efforts.

TF24 Satellites are also increasingly causing interference for optical astronomy. The National Optical-Infrared Astronomy Research Laboratory (NOIRLab) has demonstrated that large telescopes, such as the Blanco Telescope in Chile, are particularly vulnerable due to their high exposures and wide fields of view. Image processing software is used to remove streaks in optical observations, but that causes loss of data and reduced sensitivity for faint objects, making it harder to detect transient events like asteroids, exoplanet transits or supernovae. To accurately remove the effects of satellites in observation data sets, astronomers require consistent magnitude measurements for satellites at different altitudes, angles, and illumination conditions, but current brightness estimates from satellite operators are often inaccurate or inconsistent. Knowledge of their Bidirectional Reflectance Distribution Function (BRDF) is necessary for precise brightness modelling, but this information is not always shared by operators. Astronomers are therefore calling for transparent sharing of accurate satellite tracking, ephemeris and brightness data. Standardised magnitude measurements would be helpful. There are concerns that survey telescopes like the Vera Rubin Observatory will be impacted the most, since they repeatedly observe the same area of the sky over long periods of time. Satellite streak contamination can potentially diminish the scientific value of expensive assets that have taken decades to build (and thus have not been designed to deal with so many satellites passing through their fields of view).

TF25 There are some indications that increased night sky brightness is being caused by sunlight reflected and scattered by the satellite and debris population, whose direct radiance is a diffuse component when observed with the naked eye or with low angular resolution photometric instruments. According to preliminary estimates, this may already have reached an approximate 10 percent increase over the brightness of the night sky determined by natural sources of light. This is the critical limit adopted in 1979 by the International Astronomical Union for the light pollution level not to be exceeded at the sites of observatories (Kocifaj et al. 2021 and Barantine et al. 2023). An observation was made that the majority of life on Earth is nocturnal and the ecological impact of increasing the night sky brightness could be quite profound and lead to cascading effects that are currently poorly understood. There are also potential cultural and human health impacts from increasing night sky brightness that are yet to be investigated. More consistent measurement of the brightness and reflectivity of satellites and debris is needed if impacts are to be assessed.

TF26 Some satellite operators are experimenting with darker materials and anti-reflective coatings, but their effectiveness depends on: how long they’re in orbit and their level of resistance to degradation from exposure to Ultra Violet light and Space Weather. Some are also experimenting with satellite orientation adjustments to minimize reflection angles. There is a challenge in balancing the requests from astronomers for “darker” satellites whilst maintaining sufficient reflectivity to enable SSA systems to track objects. If objects are unobserved for large periods of time, it can be difficult to re-establish their identities and orbits and population metrics are degraded. There was a suggestion that it would be helpful to optical astronomers if satellites could be kept below 600 km, as they would spend less time reflecting sunlight at night.

2.4 Monitoring and Measuring Space Weather Impacts

TF27 Space Weather is a major factor in space sustainability. The thermosphere (100–500 km altitude) expands and contracts in response to solar activity, altering atmospheric density and, consequently, dispersal of debris and creating unpredictable changes in satellite drag. If a satellite's drag coefficient is miscalculated, re-entry predictions can be in error by days-to-weeks. Solar activity is highly volatile, making accurate measurement of thermospheric conditions extremely challenging.

TF28 Space Weather can damage satellite materials and systems, and major solar storm events can render satellites inoperable. The surface layer of the reflecting parts of a satellite is affected by continuous exposure to high energy electrons, protons and photons from the sun. Spacecraft surface charging from plasma interactions can lead to electrostatic discharge, potentially damaging electronics. Deep dielectric charging (penetration of high energy electrons into satellite insulation) can cause delayed failures. High energy particles from solar storms can flip memory bits in onboard processing systems, causing unexpected behaviour. Radiation can degrade solar panels over time, reducing power generation. Improving the ability to evaluate the severity of solar storm events earlier would help to build resilience against some of these adverse impacts.

TF29 ESA has been investigating the effects of the strong solar storm that took place in May 2023. After that event, satellites lost altitude faster than expected and some anomalies occurred, though it is unclear whether those were caused by the storm or other factors. ESA's satellite anomaly database collects data on malfunctions, but most entries are anonymized due to security concerns, and satellite operators rarely disclose full details of anomalies, making it difficult to assess how often Space Weather is responsible.

TF30 There are challenges in integrating Space Weather into STM systems. Improved forecasting is needed to prevent unexpected orbital shifts that increase the risk of satellite collisions. The Met Office Space Weather Operations Centre (MOSWOC) is responsible for issuing operational Space Weather forecasts in the UK. It is one of only a handful of 24/7 Space Weather prediction centres around the globe. They use a model called the Advanced Ensemble electron density Assimilation System (AENeAS), a physics-based, 4D data assimilation model of the coupled ionosphere-thermosphere system developed by the University of Birmingham. AENeAS applies a background model and assimilates data from various sources to improve the accuracy of ionospheric and thermospheric density forecasts and is updated every 15 minutes.

TF31 MOSWOC are working to integrate Space Weather forecasting into the UK National Space Operations Centre (NSpOC). Short-term forecasting over 24-48 hour periods is relatively well-developed, but longer-term forecasting is much harder due to uncertainty in solar cycles, which fluctuate unpredictably. The lack of standardised Application Programming Interfaces (APIs) for Space Weather data makes it hard for researchers to analyse large datasets. However, there are initiatives trying to tackle that challenge, for example: the Heliophysics Data Application Programmer's Interface (HAPI) (https://hapi-server.org), which is a standard specification that simplifies data access for Heliophysics time series data; and the VirES interface (https://vires.services) for accessing data from ESA's Swarm mission, which is carrying out a highly detailed survey of the Earth's geomagnetic field.

TF32 One of the biggest challenges in Space Weather forecasting is a lack of timely density data. During geomagnetic storms, energy is deposited at high latitudes, leading to localized density enhancements, but predicting where and how this occurs is difficult. Current models (e.g., the Jacchia-Bowman 2008 Empirical Thermospheric Density Model, Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere model, Thermosphere-Ionosphere-Electrodynamics General Circulation Model) struggle with storm-time density variations. Density changes can vary by a factor of 10 during major storms, but models often underestimate or overestimate the magnitude. Space Weather-driven density variations can alter satellite orbits unpredictably, leading to incorrect conjunction predictions, which force operators to undertake unnecessary collision avoidance manoeuvres.

TF33 Terrestrial weather models use thousands of sensors, but Space Weather models rely on only a few satellites at Lagrange Point 1. With insufficient density data, drag forecasts remain highly uncertain. An ESA mission consortium led by the University of Warwick has proposed a constellation of eight satellites to measure neutral density, plasma properties and magnetic fields in LEO: the Revealing Orbital and Atmospheric Responses to Solar Activity (ROARS) mission. The aim of the mission would be to provide high-resolution, timely density data to help refine orbital lifetime predictions and support better-informed collision avoidance decisions through reducing errors in orbit propagation.

TF34 Researchers at Northumbria University are using magnetometer readings from satellites to work out what magnetic currents are flowing in and out of the earth. The Superconducting Magnetic Field Network (SuperMAG) is a worldwide collaboration of organisations and national agencies that currently operate more than 300 ground-based magnetometers, measuring magnetic perturbations from the ground. The Super Dual Auroral Radar Network (SuperDARN) has been operating as an international co-operative organisation for over 25 years, measuring plasma flows directly, allowing researchers to monitor Space Weather conditions in the Earth's magnetosphere. There is work beginning in collaboration with some of the large constellation networks like OneWeb to see what data can be gathered from their assets to better understand magnetic currents in near-Earth space.

TF35 There is currently a data gap in auroral imaging data. It has been two decades since there have been global auroral imaging capabilities. ESA is developing a mission for a constellation of satellites that would provide continuous visibility of the aurora in both hemispheres at all times.

TF36 Solar radiation continuously alters satellite rotation. Sunlight absorbed by a satellite is re-radiated isotropically, as thermal emission, which creates a small torque called the Yorp Effect (Yarkovsky-O'Keefe-Radzievskii-Paddack Effect). That effect makes an object, if it's no longer actively controlled, spin up or spin down, not just around its principal axis, but also in a tumbling around more than one axis. Tumbling debris is harder to track - uncertainty in rotation affects both optical signatures and radar cross-section measurements - and would be harder to remove from orbit via a debris removal service. Spinning objects may also fragment due to centrifugal stress, generating secondary debris. Studying polarisation signatures that reveal surface reflectivity changes allows researchers to measure spin rate changes over time. Recent findings by the University of Hertfordshire show that defunct satellites in GEO exhibit long-term spin changes, and some debris fragments exhibit chaotic tumbling, likely due to Space Weather effects.

2.5 Monitoring and Measuring Atmospheric Impacts from Launch and Re-entry

TF37 The volume of satellites re-entering the Earth's atmosphere is (understandably) growing in line with the rapid growth in the satellite population. UKSA funded work led by University of Southampton that found that an estimated 76 tonnes of material burned up in the atmosphere in 2022. That figure is projected to increase to 3,500 tonnes per year by 2033 due to the de-orbit of planned mega-constellations. (Kim & Williams 2025)

TF38 A project conducted in 2023 by the US National Oceanic and Atmospheric Administration (NOAA) used NASA high-altitude aircraft to take measurements and found evidence that metals from re-entry are accumulating in the stratosphere. Measurements showed that 10–20% of stratospheric aerosols contain metals from spacecraft. Over 20 metals were measured. In addition to aluminium, exotic elements were detected such as niobium and hafnium, which are used in the exhaust cones of second stage SpaceX rockets. It is notable that the study found measurable quantities of non-naturally occurring elements in the stratosphere that can be linked with a specific part of a specific launch vehicle.

TF39 There are rising concerns that materials being deposited in the mesosphere and stratosphere will accelerate global warming. Most satellites are made of high percentages of aluminium, which turns into aluminium oxide (alumina) when burned at high temperatures such as experienced during re-entry. University of

Southampton research has shown that small changes in re-entry conditions, for example in velocity or pressure, affect how materials vaporise and re-form into particles. Alumina is a highly reflective compound, meaning it could influence Earth's radiation balance. However, its exact optical properties at different particle sizes are poorly understood.

TF40 In UKSA-funded research led by University of Leeds, atmospheric chemistry models predict that aluminium will react with ozone and water vapour during re-entry to produce aluminium hydroxide, not alumina. Laboratory experiments show that heterogeneous chemistry on aluminium hydroxide surfaces may activate chlorine species, leading to ozone depletion. There is an absence of physical chemical parameters needed to conduct a definitive study, but a current sensitivity study looking at worst case scenarios is indicating a ratio of aluminium to currently naturally occurring iron in the atmosphere a factor of two above cosmic inputs. This is predicted to increase substantially due to the rising volume of re-entering objects.

TF41 There are no laboratory facilities capable of replicating stratospheric conditions, but laboratory measurements have been done at room temperature looking at the levels of concentrations of copper required to start changing reaction rates with the sulfuric acid that is a key component of stratospheric aerosols. There are already relevant concentrations of copper in the stratosphere from the ablation of spacecraft, which contain significant amounts of copper, both in the wiring and the aluminium alloys.

TF42 Polar stratospheric clouds are ice or nitric acid clouds that form on fewer than 1:1,000 pre-existing particles in the stratosphere. If even a tiny fraction of particles changes composition, the way these clouds form could change, leading to increased ozone depletion. Establishing a baseline measure of naturally occurring particles and determining an affordable methodology for monitoring changes could be a valuable indicator of environmental impacts of human-led space activity.

TF43 Some of the challenges relating to understanding the atmospheric impacts of re-entry include a lack of data about spacecraft materials and reliance on meteorite-based atmospheric models. However, meteoric dust is dominated by iron, magnesium, and silicon, while satellite re-entry produces aluminium, titanium, and niobium oxide, all with very different chemical properties. Satellite manufacturers are reluctant to share detailed data on material composition, so re-entry models currently assume simplified material properties, but spacecraft actually contain composite materials with complex thermal behaviours.

TF44 There's a lack of relevant testing facilities and few direct observations of re-entry processes and material dispersal. Researchers are using plasma wind tunnels to study how ablation happens, but speeds are much too low, so the physical parameters are not truly representative of the atmosphere. There's a need for in situ observations. A suggestion was made to mount balloon campaigns above 30 kilometres, to capture particles and return them for detailed analysis. In-flight measurements of the process of ablation is extremely technically challenging because the high plasma density surrounding a re-entering object makes data collection and transmission impossible. Temperatures during re-entry can exceed 1,600°C.

TF45 Current test facilities are designed to test whether objects survive ablation; they're not designed to conduct tests of the generation of chemical by-products, so a completely different concept for testing is required. UKSA has commissioned a study through Belstead Research to design a test campaign for what could potentially be tested in existing facilities.

TF46 Each re-entering object may be very different. To model atmospheric impacts, researchers would want to know an object's: shape; thermal dispersal properties; re-entry profile; tumbling action; material composition and the proportion likely to vaporise vs. survive; etc. This is a nascent research area with a lack of peer-reviewed studies to inform research efforts. UKSA have commissioned a literature review by researchers at Durham University, Purdue University and Warwick University to help inform future research priorities. ESA is planning a mission to attempt to gather data during re-entry of an "average LEO spacecraft": the Destructive Re-entry Assessment Container Object (DRACO) mission. If successful, it could provide new data about how materials behave when re-entering, but it will not be able to provide data about how particles are formed, nor dispersed.

TF47 The effects from atmospheric ablation today may still be small compared to Chlorofluorocarbon-related ozone depletion. However, with growing re-entry rates, we may reach a critical threshold where the majority of particles in the stratosphere may contain metals from spacecraft which historically weren't there before, and which significantly impact ozone chemistry. More observational data is needed to detect potential regional ozone depletion over areas with frequent re-entries (e.g. the South Pacific, where many controlled re-entries occur).

TF48 While it is known that small injections of metallic particles can change conductivity significantly, it is not known how the particles from atmospheric ablation upon re-entry disperse globally. It is difficult to predict whether there might be electromagnetic impacts from metal particles that might accumulate over decades.

TF49 A study led by the Technical University of Braunschweig compared the amount of matter entering the upper atmosphere from natural sources (meteoroids) and human sources (rocket bodies, satellites, other debris). This estimated that the mass injected into the atmosphere from human sources had increased from 0.4 kilotons in 2019 to 0.75 kilotons in 2023. Future scenarios based on announced satellite constellation growth plans predict that the mass injected into the atmosphere from

20,000 satellites would be on the order of 1.7 kilotons, rising to 5.3 kilotons for a population of 75,000 satellites. This would be significant in comparison to the naturally occurring mass - which is around 12 kilotons/year. (Schulz et al. 2024)

TF50 A significant proportion of the mass launched into space survives re-entry. Ground survival rates are estimated as: rocket core stages 70%; rocket upper stages 35%; satellites and debris 20% (Schulz et al. 2024). This is becoming an increasing source of concern for environmental and safety impacts on the ground. Risks to aviation in flight from re-entering rocket bodies and parts of satellites represent a very low probability event with very high consequences, but the probability is increasing with the rising volume of launch. Airspace is more frequently being closed or restricted due to risks from re-entering space debris. In effect, this is exporting risk from the space sector directly onto the aviation sector. With the projected numbers of satellites indicated in licence application filings, there will be no place on Earth that won't have satellites re-entering overhead, but there will be some areas that have much higher densities of re-entering objects than others. The impacts will be global, but unevenly distributed. (Wright et al. 2025) As an example, the orbital inclination of the Starlink constellation is 53 degrees, leading to an expected peak in re-entries at around 53 N and 53 S. The former has the clear potential to affect the UK. Compiling global data on the number and duration of incidents when airspace is affected by re-entering objects could form a useful part of a framework of environmental impact indicators.

TF51 Recent modelling studies by the University of Colorado and NOAA investigating atmospheric impacts of rocket emissions have shown that kerosene-fuelled rockets produce large amounts of black carbon (soot), which can heat the stratosphere, generating up to 2 kelvin warming effect in the hemisphere where the emissions occur, leading to year-round ozone loss. (Maloney et al. 2022) Earlier researchers have studied how solid rocket motors emit alumina directly into the stratosphere. (Dallas et al. 2020) Studies into methane and hydrogen rocket fuels are ongoing.

TF52 While some natural phenomena inject particles into the atmosphere, the effects are different. Volcanic eruptions release orders of magnitude more particles than rockets, however, volcanic sulphate aerosols fall out of the atmosphere faster than metallic particles from rocket exhaust, meaning their long-term impact is different. The ability to distinguish between naturally occurring particles and those from human sources is an important aspect of measuring atmospheric impacts relating to launch and re-entry.

3.0 Policy Findings

3.1 Governance

PF1 Multiple entities - US Federal Communications Commission (FCC), International Telecommunications Union (ITU), Interagency Debris Committee (IADC), United Nations Committee on Peaceful Uses of Outer Space (UNCOPUOS), etc. - deal with satellite regulations, but there is no single governing body to enforce global standards. There was common agreement amongst workshop attendees that this is impeding progress towards more sustainable management of the space environment.

PF2 The need for global cooperation on SSA and satellite tracking was a recurring theme. Workshop attendees expressed the view that there is a need for a single standardised global space object registry, and that operators should be required to report essential data (e.g. position, velocity, status, manoeuvre plans) to an independent, non-military body that ensures data neutrality, and reassures operators that their proprietary information would not be disclosed.

PF3 There was a discussion about the need for an international STM organisation, something like the International Civil Aviation Organization (ICAO) and the way it works with the aviation sector. It was posited that what makes ICAO successful is that it is inclusive and democratic. 193 countries are members, all of which are signatory states to the Convention on International Civil Aviation. The view was expressed that a democratic structure like ICAO can only be created for STM if more countries are involved in, and benefit from, space. It follows that it's in the interest of established space nations to support capacity building for emerging space nations.

PF4 Current satellite licensing frameworks do not require satellite operators to minimize optical nor RF interference. University of Edinburgh is leading work to produce a report for UKSA on the prospects for a standards-based approach to optical brightness of satellites (e.g., ISO certification for satellite brightness) and whether that could help mitigate impacts. It was demonstrated that the introduction of debris mitigation guidelines by NASA in 1995 led to a measurable reduction in the amount of debris produced by satellite operators. Some space agencies (e.g., CNES, the French Space Agency) assess mission compliance with best practice guidelines before licensing. This could be expanded globally.

PF5 The ITU spectrum allocation process is too slow (8-year cycles) to keep up with rapid technological advances. Satellite operators are assigned specific frequency bands, but many don't use their full allocations and are reluctant to share information about spectrum usage due to competition concerns. Without proper monitoring, valuable spectrum could be wasted or inefficiently allocated.

PF6 Current ITU rules only regulate intentional RF transmissions; there are no limits on UEMR from satellite electronics. However, if the unintentional emissions from satellites were intentional - i.e., emitting from antennae rather than electronics - they would exceed allowed interference levels in protected radio bands by a large margin. Stronger policy frameworks and international standards are needed to address UEMR. The point was made that responsible licenced operators do comply with existing RF regulations and changing those would have consequences for their businesses. It was generally agreed that there is a need for: awareness to be raised outside the astronomy community; greater collaboration between satellite operators and the astronomy community; new or updated guidelines to reflect the new realities of the increased satellite population in LEO; and, in due course, regulatory reform.

PF7 UNCOPUOS is the key multilateral forum for seeking agreement on guidelines, standards and rules for sustainable use of space. The UNCOPUOS Guidelines for the Long-term Sustainability of Outer Space Activities, adopted in 2019, were the first set of global guidelines agreed by UN member states to encourage greater focus on long-term sustainability in space policy decisions (United Nations Committee on Peaceful Uses of Outer Space 2021). Having taken eight years to develop and adopt, plus a further two before publication, they don't address all aspects of managing the environmental impacts of human space activities. Between 2019 and the first quarter of 2025, the number of satellites in orbit grew from approximately 2,500 to 12,000 (data source: https://orbit.ing-now.com). It was generally agreed that the pace of UN mechanisms for building policy consensus have been outstripped by the pace of the expansion of the space economy.

PF8 Nonetheless, many workshop participants expressed the view that the UN remains the most effective forum for agreeing global frameworks for measuring and managing the environmental impacts of human activity in space. In 2023, the ITU adopted an agenda item to consider the protection of radio quiet zones and radio telescopes from interference from large satellite constellations when the international treaty governing use of RF spectrum is next reviewed (due to take place in 2027). In 2024, the UNCOPUOS Science and Technology Sub-Committee agreed to add the issue of optical and RF impacts on astronomy to its agenda. The issue of UEMR should be included in those agenda items.

PF9 There is no formal agenda item in any UN committee relating to the issue of atmospheric impacts of launch and re-entry. This remit may fall between UNCOPUOS and the UN Environment Assembly (UNEA). As one of the top ten funders of the UN Environment Programme (UN Environment Programme 2025), the UK is in a strong position to encourage UN engagement with this issue. However, within the UK, this policy remit straddles more than one government department. UKSA could seek to raise awareness with relevant environmental policy leads.

PF10 There was a suggestion that satellite operators should be required to conduct environmental impact assessments for re-entries. Some national agencies already require assessments of uncontrolled re-entries, but this is not yet an international standard. It was suggested that UNCOPUOS should expand its space sustainability guidelines to cover atmospheric impacts.

PF11 Many sustainability models focus on a single aspect of space sustainability but fail to integrate broader impacts. UKSA-funded research at the University of Southampton is looking at how systems dynamics modelling techniques can be used to map feedback loops between different sustainability factors, examining the interconnections between, for example: economic/political factors and satellite/debris population increases; population drivers and conjunction rates/collision risks; debris mitigation and atmospheric pollution from re-entry; spectrum management and radio astronomy; etc. This approach tries to understand trade-offs between multiple factors and how that impacts decision making.

PF12 There have been a number of recent initiatives aimed at developing more holistic methods of assessing the environmental impacts of space missions and strengthening best practice guidelines and standards. Speakers referenced several of these, including: ESA's Zero Debris Charter (European Space Agency 2023) and LCA handbook (European Space Agency 2021); the Space Sustainability Rating (https://spacesustainabilityrating.org); and Earth and Space Sustainability Initiative (https://www.essi.org/).

PF13 Several speakers advocated for a lifecycle approach, assessing the full environmental cost of satellites, from construction to decommissioning. A team of environmental scientists at the University of Exeter have been researching the broader environmental costs of the acceleration of space activity, including evaluating the comparative risks and benefits of services provided through space infrastructure versus those provided through terrestrial infrastructure. For example, they've evaluated the environmental impact of the resources consumed in processing and storing hundreds of petabytes of Earth Observation data. (Wilkinson et al. 2024)

PF14 ESA's LCA handbook (European Space Agency 2021) - based on the International Standards Organisation's methodology for Life Cycle Assessment - outlines a number of indicators for measuring the impact of space missions on human health, natural environment, and natural resources; as well as the flows of resources throughout the life of a mission.

PF15 The Space Sustainability Rating (https://spacesustainabilityrating.org) was developed through work led by the École Polytechnique Fédérale de Lausanne as a voluntary system assessing the sustainability of space missions. The assessment process implemented in 2021 involves operators submitting technical evidence which is input into formulae to calculate values against six factors:

1. Mission index - a quantifiable metric of the consumption of the space environment based on well-known mission parameters computed by the ESA Space Debris Office.
2. Detectability, identification and tracking.
3. Collision avoidance capabilities.
4. Compliance with best practice design standards.
5. Data transparency and sharing.
6. Compatibility with external services, such as STM systems and future debris removal services.

PF16 There have also been calls for adding an 18th UN Sustainable Development Goal (SDG) for space sustainability. The presentation of a project led by University College London for the Organisation for Economic Development highlighted that SDGs can provide clear, measurable targets and indicators that are widely recognised and can be used to engage the public and policymakers and ensure accountability via annual progress reports. However, the workshop discussion recognised that there are challenges to designing space sustainability-related SDG targets. There is a need to balance economic interests and the benefits of space activities (e.g. digital inclusion, climate monitoring, etc.) against their environmental costs. It is difficult to find metrics that are meaningful, measurable, and can be tracked in a way that incentivises compliance.

PF17 There was a general agreement that to be effective any environmental indicator framework needs to be integrated with regulatory requirements and financial incentives (e.g. through lower insurance costs or the ability to attract investment). It should be noted that few LEO satellites are currently insured, so making insurance mandatory might also have a positive impact. However, governments are understandably cautious about the impact on businesses and their customers of costs associated with regulatory requirements.

PF18 Space agencies and commercial companies have announced ambitious plans to develop the cislunar economy. There is a concern that policy solutions for managing the cislunar environment are lagging far behind the pace of technological activity. The advent of commercial operators establishing their presence on the Moon is highlighting the need for more attention to be paid to this policy area.

3.2 Operational Policy Considerations

PF19 The adoption of autonomous manoeuvring systems by constellation network operators makes it imperative for there to be a policy solution for coordination across autonomous systems, or they will amplify inter-constellation collision risks. Tools such as Georgia Institute of Technology's Virtual Environment for Space Traffic Analysis (VESTA) could be used to develop and test manoeuvring guidelines.

PF20 It is difficult to attribute an anomaly on orbit to a specific cause, whether system failure or impact damage, and whether impacts result from natural materials or human-made debris. This makes regulation and attribution of liability extremely challenging.

PF21 It was recognised that spectrum is a scarce resource. Technical and policy solutions need to be found to allow spectrum sharing, which would be a significant departure from the way in which spectrum has been managed historically. There was a suggestion that if an operator does not fully use its assigned spectrum, it should be reallocated to others; and general agreement that any future STM system would need to include a means for operators to coordinate frequencies to reduce RFI. Timely global spectrum monitoring could help detect RFI earlier and collaboration with operators is needed to identify and mitigate sources of RFI.

PF22 The UK Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) programme - jointly funded between the UK Science and Technology Facilities Council and Natural Environment Research Council has fed research outputs into the Met Office to improve Space Weather forecasting. The programme was highlighted as a successful model for bridging gaps between funding bodies and for realising benefits from research through operational application. The hope was expressed that proposals for a follow-on programme for SWIMMR would include processes to facilitate knowledge gained from operations flowing back into the research community.

PF23 The Coordination Group for Meteorological Satellites (CGMS) has recently taken Space Weather onto its agenda and set up a space sustainability focused group on Space Weather Coordination (https://cgms-info.org/about-cgms/space-weather-coordination-group). The group is currently looking at best practices for satellite collision avoidance. It plans on examining the current Space Weather services used by satellite operators to avoid collisions, monitor space debris, re-entries, etc., and identify ways to improve those services. It will report its findings to UNCOPUOS, the World Meteorological Organization (WMO) and other international bodies.

3.3 Data Sharing

PF24 A number of voluntary data-sharing initiatives were highlighted in the workshops, including: the Global Satellite Operators Association (https://gsoasatellite.com); Space Data Association (https://www.space-data.org); and the Swiss start-up Spacetalk (https://www.spacetalk.ch). The panel members discussed the potential for mandatory automated data sharing requirements - similar to AIS (Automatic Identification System) in maritime tracking or ADS-B (Automatic Dependent Surveillance-Broadcast) for aircraft. They also agreed on the need for something like an Activity Status flag in the catalogue, to improve the accuracy of satellite population metrics and SSA services.

PF25 It was suggested that there needs to be a forum in which China feels they have an equal role in determining how SSA data is shared. This will become even more critical as large Chinese constellations are deployed. The International GNSS Service brings together analysis centres from across the world, including China, to compare different approaches to orbital analysis for GNSS satellites and learn how they could improve and may serve as an example of how this has been achieved in the past.

PF26 The UK Met Office is working on integrating Space Weather forecasts into space traffic monitoring, but more collaboration is required with satellite operators. Space Weather has been on the UK's National Risk Register since 2012, but policymakers need more regularly updated risk assessments and that would require more data sharing between operators and the research community. Many satellite operators do not publicly share anomaly data, making it difficult to study Space Weather impacts. Operators fear reputational damage if failures are linked to their spacecraft. Insurance companies hold detailed failure records, but these are confidential. There was a suggestion that historical anonymized data could be released for scientific study and that the government should seek to create a trusted data-sharing framework that anonymises sensitive operator data but allows researchers access.

PF27 There is a lack of detailed data on satellite composition, so modelling is based on assumptions about the materials used. If actual material compositions were shared by manufacturers and operators, potential environmental impacts could be more effectively analysed. Most operators treat that information as core intellectual property and thus highly commercially sensitive, so they're reluctant to share it with researchers. It was observed that academics are incentivised to publish their research, while industrial researchers simply may not see the point of investing time and resources into sharing their in-house research findings. Operators might also fear additional regulatory burdens will be placed upon them - with cost implications.

PF28 Data sharing practices and standards are key for supporting both research and effective STM. The UK's Turing Institute has deep expertise in defining data standards, data sharing practices, ethics, etc. The space community could learn from their work.

3.4 Fostering Collaboration

PF29 Making observations of debris reflectivity and tumble rates requires the use of large telescopes. However, it is not straightforward to access those telescopes for non-astronomy purposes. Often, supporting research into non-astronomical topics is not explicitly included in the remit of the funding bodies and telescope operators. It was observed that funding for something like understanding Space Weather impacts for SSA purposes currently cuts across the funding remits of UKSA and two UK Research Councils. That makes securing long-term funding for cross-cutting inter-disciplinary research quite challenging.

PF30 There was a discussion about how UK funding streams for exploratory space science and applied operational research are often treated as the same and drawn from the same budgets, when the target research outcomes are very different. There is little research funding available for data and knowledge flowing back from operations into science. This means opportunities are lost for two-way flows of knowledge and data between satellite operators and researchers working on space environmental sustainability topics.

PF31 Sometimes it's difficult for individuals working in research institutions to really understand the full impact of their work. UKSA could help ensure that the socio-economic impact of space research is realised. There was a suggestion that UKSA should fund a scheme that ensures people from different domains come together regularly to share knowledge and explore research questions from different perspectives. The International Space Science Institute (https://www.issibern.ch) in Bern, Switzerland, holds regular meetings that enable this type of in-depth cross-disciplinary knowledge sharing. The UK Space Weather community finds those valuable and would like to see a similar approach taken in the UK.

PF32 There's limited collaboration between industry and atmospheric scientists. This poses challenges for understanding the atmospheric impacts of re-entry. There may be a role for UKSA in facilitating knowledge-sharing between the two communities. The view was expressed that developing shared good practice is more productive, and can more easily be kept up to date, than legal instruments. Satellite operators may feel regulations stifle innovation, and they are very resistant to adding extra mass to their satellites for data capture purposes.

PF33 There was general agreement that more robust scientific data on atmospheric impacts is needed to inform policy decisions and there needs to be better collaboration between space agencies, climate scientists, and policymakers on this issue. The trade-offs between impacts on Earth and impacts in space need to be better understood. The example was given of design for demise. Drag sails being incorporated into satellites may help them to de-orbit more quickly at their end-of-life. However, they also change a small object into a much larger object from the point of view of astronomy and involve additional materials being ablated during re-entry. The increased size of the satellite also increases its collision risk while de-orbiting.

PF34 There was also general agreement that greater investment was needed in human capital to address the challenges of space sustainability. More scientists, engineers and policymakers from diverse countries need to be engaged in plugging knowledge gaps and developing new methodologies, tools and technologies to address the issues. Knowledge sharing with those from other countries who might offer a different perspective is critical to building capacity to solve problems.

PF35 The agility and speed of science is not keeping pace with commercial developments. The question was raised of how to make the response and contribution of researchers more agile. Suggestions included regular international meetings to bring researchers together to examine specific issues and leveraging Marie Skłodowska-Curie Actions (MSCA) doctoral network funding to engage researchers from different parts of the world in a major collaborative project.

3.5 Raising Awareness

PF36 There's a benefit in policymakers having more readily available access to space environment models to inform their understanding of the rapidly evolving satellite and debris population. Massachusetts Institute of Technology and University College London have collaborated to create an open-source version of the MIT Orbital Capacity Assessment Tool (MOCAT) to contribute to a deeper and more widespread understanding of how the space environment is changing. (Brownhall et al. 2025)

PF37 ESA is currently carrying out a study for the European Commission to try to analyse the socio-economic benefit of Space Weather services - including for the defence sector. The researchers carrying out that study are finding that understanding the impact of Space Weather is growing increasingly complicated - due to how interconnected modern infrastructures are on Earth and in space. While challenging, it's important for policymakers to have this sort of evidence on which to base policy decisions.

PF38 There was a discussion about funding cycles and how the length of time it takes for funding decisions to be made creates gaps in long-term funding plans. This can result in long-term missions being "sunsetted" before other missions are available to continue the research. This undermines the study of phenomena that need to be monitored over very long time periods to begin to understand them, such as Space Weather and changes in particulate matter in the Earth's upper atmosphere. Raising awareness with policymakers and the public about the value of long-term research projects may help ensure continuity of funding.

4.0 Identified Knowledge Gaps and Research Priorities

Attendees highlighted the following as key areas where future research should be prioritised:

KG1 Orbit Propagation
SSA operators require more accurate and timely position data to perform more effective conjunction assessments.

- How can satellite operators collaborate to share more accurate ephemeris data?
- New orbital models and monitoring solutions are needed to manage proposed increases in cislunar traffic.

KG2 Space Object Catalogue
Improve the space object catalogue to provide a more complete and accurate set of base data for modelling the future evolution of the satellite and debris population; additional information could include: object brightness, rotation rate, attitude, mission profile.

KG3 Tracking
Study the inconsistencies between different sets of SSA data to identify improvements in both tracking and modelling. Look at the levels of agreement between various tracking systems and the reference data from precision tracking of specific objects to help assess the relative merits of different instruments/techniques, and identify solutions to plug the capability gaps.

- How do YORP-induced spin changes affect debris evolution at different altitudes?
- Can optical polarization measurements be used to improve space debris tracking?
- What other sensing techniques/strategies could fill existing capability gaps?

KG4 Orbit Capacity
Define “safe carrying capacity” for different altitude bands in LEO. The nature of the population of small debris is probably the most uncertain aspect of developing an evolutionary model of the space environment. A lack of accurate knowledge about the number of fragments, their characteristics, and how they are changing over time can lead to many possible future states.

KG5 End-of-life Strategies
Evaluate the environmental impact of end-of-life strategies, including controlled re-entry and active debris removal.

KG6 RF Spectrum Sharing
Enable more use of the same spectrum while avoiding interference.

- How can active and passive services share RF spectrum?
- Can an active or passive identification system, such as those used for ships and aircraft, be designed and implemented for spacecraft.
- Do RFID tags cause RF Interference?
- Need to understand RFI and UEMR (unintentional electromagnetic radiation) and how to mitigate the impacts, including greater sharing of technical data and more routine monitoring
- Observations from radio astronomers could help identify which satellite electronics are responsible for the worst UEMR
- Passive spectrum monitoring - building on ESA THRIMOS project

KG7 Coatings/Shielding
Better models are needed to predict how reflective satellites will be in situ to enable an assessment of whether designs are compliant with standards prior to launch.

- Study the contribution of light reflected from satellites and debris to overall night sky brightness levels, to enable the potential ecological, cultural and human health impacts to be evaluated.
- Develop publicly available tools such as software for predicting brightness.

KG8 Space Weather and Atmospheric Variations
More research is needed to understand the effects of Space Weather and atmospheric variations on LEO satellites.

- How many satellite anomalies are actually caused by Space Weather? What fraction of satellite anomalies are due to Space Weather vs. internal failures?
- How do geomagnetic storms modify atmospheric density in different regions? How do they affect different types of spacecraft?
- How can Space Weather warnings be improved to give satellite operators actionable insights?
- How do solar storms modify satellite drag in real-time? Can we create a timely data assimilation system for thermospheric drag forecasts?
- How does density forecasting uncertainty affect satellite collision warnings?
- Can we build an in situ measurement network to improve data coverage? What is the optimal number of in situ measurement points needed to improve forecast accuracy? Can we use advanced data assimilation techniques to integrate in situ and remote sensing data?

- What are the long-term impacts of CO_2-driven thermospheric cooling on orbit stability? Current Space Weather and satellite/debris population models do not yet account for long-term CO_2 cooling effects, leading to errors in orbital decay predictions.
- How does prolonged solar radiation alter satellite materials?
- Can we develop better onboard sensors to diagnose Space Weather damage in a timely way?
- How do different satellite architectures respond to extreme Space Weather events?
- How does Space Weather influence fragmentation rates of spinning objects?
- How can we improve timely monitoring and prediction of Space Weather impacts on satellite operations? What role does increased private sector activity play in risk mitigation?

KG9 Atmospheric Re-entry

There are many knowledge gaps that make modelling the effects of re-entering satellites and debris on the atmosphere extremely challenging.

- Need to understand particle composition and size distribution, which affects how long they persist in the atmosphere and how they interact with other particles.
- To what extent does complete vapourisation occur?
- What fraction of re-entry material survives ablation and forms long-lived aerosols?
- Do metals form new mixed aerosols? How do mixed particles form and coagulate, and how do they behave compared to pure particles?
- How much of the metal oxides from re-entry accumulate in the atmosphere? Do current climate models accurately incorporate these effects? Are we already at a critical threshold where anthropogenic particles significantly affect atmospheric chemistry?
- Are the models used for natural meteoric ablation applicable to spacecraft materials?
- How does the different composition of anthropogenic vs. meteoric material affect atmospheric chemistry?
- What are the long-term atmospheric effects of increasing debris re-entry rates? How do different satellite materials interact with the upper atmosphere?
- What are the dominant atmospheric pathways for re-entry debris?
- Do different re-entry scenarios (equatorial vs. polar) lead to different atmospheric impacts?
- How do spacecraft-generated particles interact with the stratosphere.
- Do metals from re-entry enhance polar stratospheric cloud formation?
- What role do these metals play in stratospheric ozone depletion?
- How does aluminium hydroxide evolve chemically in the stratosphere?
- Does aluminium impact stratospheric sulphur chemistry?

- What is the full chemical composition of modern satellites and how do they behave during re-entry?
- How can the space industry be incentivised to share material composition data for sustainability research? Are there regulatory approaches that could ensure greater transparency?
- What is the full climate impact of rocket launches, particularly from black carbon emissions? How do different propulsion types compare in their environmental impact?

KG10 Policy Solutions
Research in areas of law, economics, ethics and governance to inform policy solutions for environmental impact assessment, and to set standards.

- What policies should be in place to regulate atmospheric impacts of space debris?
- How does space debris evolve post-collision, and what factors influence its long-term dispersion? Can improved modelling help mitigate risks to operational satellites?
- Can existing space governance institutions (COPUOS, ITU, IADC) be strengthened to address sustainability issues? What legal instruments could be applied to enforce environmental responsibility in space?
- How can a multi-dimensional sustainability framework be developed to assess trade-offs in space activities? What metrics should be prioritised in such an evaluation?
- What proportion of increasing night sky brightness is due to satellites versus terrestrial sources? How can policy interventions mitigate the impact on astronomical observations?
- What financial mechanisms could encourage space companies to adopt more sustainable practices? How can sustainability be embedded into commercial space models without stifling innovation?
- How can space sustainability research move beyond Western-centric economic models to include diverse global perspectives? What interdisciplinary approaches could yield the most effective solutions?
- Can we develop a "net sustainability" measure for space activities?

5.0 Recommendations

This project has highlighted that there are many knowledge gaps and unanswered questions relating to the environmental impacts in space and on Earth arising from human space activity. The recommendations below are intended to help inform the UK government's future space sustainability strategy and potential future research programmes. They're an attempt to synthesise the views of project participants into a number of concrete, actionable recommendations, and do not purport to offer any relative evaluation nor prioritisation of the knowledge gaps in the previous section.

The recommendations relate to specific environmental impact topics explored by this project, as well as some more general cross-cutting recommendations.

Where possible, estimates have been suggested of the timeframe within which recommendations could/should be actioned: "Short-term" falling within the next 1-3 years; "Medium-term" in the 3-5 year timeframe; and "Longer-term" in 5-10 years.

Clearly, longer-term research would need to build on earlier preparatory work, such as consultations or feasibility studies. Those preceding steps have not been set out.

R1: Satellite and Debris Population Indicators

There's a pressing need to improve understanding of the satellite and debris population, especially with respect to indicators of orbital carrying capacity and collision risk. Specific recommendations for UK government action include:

Short-term actions:

- Encourage and facilitate greater collaboration between satellite operators, SSA providers and the research community to improve modelling to better understand the current population and enhance techniques for orbit propagation to refine conjunction analysis.
- Undertake a study to compare data from different SSA sources to identify discrepancies and propose methods for resolving those.
- In partnership with STFC, work with astronomy research facilities to identify existing sources of data gathered for astronomical purposes that could help inform population modelling and analysis. Identify and remove barriers to accessing that data.
- Help identify and remove barriers experienced by non-astronomy researchers seeking to undertake new studies involving telescope observations to deepen understanding of the satellite and debris population.

- Investigate the potential to use precision-tracked objects in GEO as reference points for improving tracking of other satellites and debris.

- Commission a study to identify whether robust evidence can be found of Kessler Syndrome already taking place at some orbital altitudes.

- Encourage improvements to the data standards used in the SSN catalogue.

- Encourage operators to share GPS-based Ephemeris data to improve accuracy of satellite population monitoring.

Medium-term actions:

- Investigate new/non-traditional sensing techniques to improve methods of gathering more accurate data for timely identification and monitoring of the satellite and debris population.

- Invest in new methods to gather more accurate data on the <1 cm debris population, distinguish meteoroid flux from debris, understand how it behaves in orbit and measure how quickly the population is being replenished.

- Undertake a research programme with international partners to explore technical options for an automated satellite identification and tracking system, similar to maritime AIS or aviation ADS-B systems.

- Commission a study to identify requirements for accurate cataloguing and monitoring of objects in lunar and cislunar space and evaluate existing and alternative methodologies.

- Develop a process for sharing anonymised data of satellite design characteristics to improve population modelling.

Longer-term actions:

- Work with the Department for Science, Innovation & Technology (DSIT) and Civil Aviation Authority (CAA) to consider implementing a requirement to log satellite characteristics as part of the UK licencing process.

- Lead efforts in multilateral fora to agree best practice standards and work towards binding legal requirements to register objects in a timely and accurate way and to keep registration information updated.

- Promote international collaboration to develop accurate cataloguing and timely monitoring of objects in lunar and cislunar space.

R2: Indicators of Radio Frequency and Optical Impact
While UKSA does not directly hold the policy levers necessary to address the RF and optical impacts highlighted through this project, it has an important role to play in providing evidence to inform government policy relating to these areas. Specific recommendations include:

Short-term actions:

- Sponsor a project in partnership with the UK Science and Technologies Facilities Council (STFC) to explore how more coordinated, consistent and systematic measurement of optical and RF impacts on astronomy could be implemented across multiple sites.
- Encourage DSIT and the UK Office of Communications (OFCOM) to build on the ESA THRIMOS project to develop low-cost passive monitoring of spectrum usage to provide evidence to inform future policy on spectrum sharing and interference.
- Consider commissioning a study to explore how spectrum conjunction alerts could be developed and incorporated into the NSpOC monitoring services provided to operators.
- Encourage OFCOM to lead efforts within the ITU to speed up spectrum allocation processes and develop enhanced approaches to spectrum sharing.

Medium-term actions:

- Work with STFC and the Engineering and Physical Sciences Research Council (EPSRC) to commission cross-disciplinary studies between satellite operators, astronomers, electrical engineers, material scientists and other relevant researchers to identify sources of UEMR and design improved systems to mitigate the effects.
- Encourage DSIT, CAA and OFCOM to develop a process for evaluating potential RFI impacts as part of the licencing process.
- Encourage DSIT and OFCOM to implement a programme of cross-border research collaboration to develop spectrum sharing proposals.
- In partnership with STFC and the Natural Environment Research Council (NERC), commission a study to assess night sky brightening attributed to the increasing satellite and debris population (as opposed to terrestrial sources) and evaluate ecological impacts.

Longer-term actions:

- Encourage DSIT, CAA and OFCOM to consider implementing a requirement to demonstrate RFI avoidance as a condition of UK licencing.

R3: Indicators of Space Weather Impacts

The UK is a world leader in Space Weather research and has well-established operational monitoring and forecasting capability. There are opportunities to build on this by encouraging greater collaboration between the Space Weather science community, satellite operators and other researchers working on aspects of environmental impacts from space activities. Specific recommendations include:

Short-term actions:

- Commission a project, potentially through NSpOC, into how satellite and debris population estimates and conjunction forecasts currently take account of Space Weather forecasts and propose how that could be improved.

- Partner with STFC to raise awareness of Space Weather research across the wider space sector through workshops and knowledge exchange events, with the aim of deepening understanding of potential impacts and forging new research collaborations.

- Explore the potential for an innovation programme designed to stimulate entrepreneurial interest in developing commercial applications that would embed timely Space Weather information into operational systems.

- Establish a research programme with industry participants to explore how to better operationalise Space Weather models into the design and testing stages of spacecraft manufacture and, importantly, into operational and end of life stages.

- Support researchers in making the case to government for continuity of research funding to improve monitoring, modelling and forecasting of solar events. This should include funding to support data from satellite operations and SSA systems being fed back into Space Weather models.

- Work with DSIT and the Civil Contingencies Secretariat to implement annual reviews of the space-related risks on the UK National Risk Register, to ensure that deeper understanding of Space Weather impacts on the rapidly evolving satellite and debris population is reflected in risk assessments and mitigations are identified to build rapid response capabilities and resilience.

Medium-term actions:

- In partnership with MetOffice and STFC, commission a programme to enable open source access to Space Weather data sets through standard APIs.
- Fund a collaborative project to test how satellite operators could potentially gather data to improve understanding of Earth's magnetosphere.
- Establish a research programme to understand how Space Weather impacts debris, to improve debris modelling and forecasting.
- Work with STFC and EPSRC to commission cross-disciplinary studies between Space Weather scientists, satellite operators, engineers, material scientists and other relevant researchers, to identify ways to improve satellite resilience to Space Weather and optimise autonomous manoeuvring in the face of Space Weather events.

Longer-term actions:

- Work with STFC, ESA and other international funding bodies to commission a research programme to measure in situ storm-time atmospheric density variations and make that data available to improve SSA modelling and forecasting.

R4: Indicators of Atmospheric Impacts of Launch and Re-entry
This is a nascent area of research in which only a small number of studies have been published to date. There's a real opportunity for UKSA to drive progress and develop globally impactful expertise. This is an area that cuts across traditional research boundaries and in which international collaboration is essential to raise awareness and achieve impact. Specific recommendations include:

Short-term actions:

- Issue a call for expressions of interest for novel uses of existing research facilities to better study atmospheric impacts of re-entering space objects.
- Working with NERC, establish an awareness-raising initiative to attract more atmospheric scientists to study these questions.
- Develop a process for sharing anonymised data with atmospheric scientists about satellite "design for demise" approaches and the materials used.
- Devise and fund a programme of international knowledge-sharing events to build a network of researchers with interests in this area.

- Raise awareness with UK government environmental policy leads about the issue of atmospheric impacts of launch and re-entry and advocate for a formal agenda item to be adopted by the UN to develop multilateral policy solutions.

Medium-term actions:

- Encourage NERC to commission research to set a more accurate baseline for particles in the atmosphere.

- Develop proposals for a multi-year, cross-disciplinary, multi-national research programme to deepen knowledge about atmospheric impacts of launch and re-entry – and support consortia to bid into cross-border funding such as Horizon Europe.

Longer-term actions:

- Work with NERC to develop testing facilities that more closely replicate atmospheric conditions.

- Work with NERC and STFC to develop novel approaches to gathering ground-based and in situ observations of re-entry processes and material dispersal.

R5: Holistic Indicator Framework
There was clear consensus across participants in this project that a more holistic approach is needed with respect to developing an environmental indicator framework for space, if unintended consequences are to be avoided. UKSA has been progressing research in this area and this should continue to form an important strand of any future sustainability strategy. Specific recommendations include:

- Sponsor a cross-disciplinary knowledge-sharing event to engage researchers from outside the space community with this topic.
- Ensure a broad range of diverse stakeholders are involved in UK-led standards development.
- Support UK researchers to engage proactively with international LCA initiatives.
- Consider how more holistic evidence of impacts might be gathered through existing mechanisms such as the annual Size and Health survey or National Risk Register review process.
- Consider whether to propose that a Specialist Group be formed under the UNCOPUOS Science and Technology Subcommittee to develop a holistic environmental indicator framework.
- Consider whether to propose that this topic be included in the agenda of the 2027 UN Conference (UNISPACE IV) which is being contemplated by UNCOPOUS members.

R6: Data Sharing
More accurate data, more transparently shared, was highlighted as a key requirement for better understanding of environmental impacts across all the topics considered as part of this project. While the UK cannot address all the challenges on its own, it can proactively support the development of best practice. Specific recommendations include:

Short-term actions:

- Undertake a consultation with manufacturers, launch operators and satellite operators to understand their reluctance to share data and identify ways to address their concerns.

- Identify mechanisms to make anonymised and historical data procured with public funds available to researchers working on understanding the space environment.

- In partnership with NERC, commission studies to develop quantifiable metrics relating to key environmental impacts and create a secure data sharing environment where appropriately vetted researchers are able to access more detailed data that isn't publicly available. This would need to be done in collaboration with a number of manufacturers and operators willing to share precise information, some of which may need to be anonymised.

- Commission a study to examine how best practice data sharing approaches from other high-value, high-risk domains can be applied to the space domain.

- Commission, together with STFC, a joint research project between a UK-licenced constellation network operator and a wide field observatory to explore how timely data could be shared to develop mitigations for optical and RF interference. This should be fully-funded by government to impose no costs to the operator. This would signal that the UK takes the astronomy community's concerns seriously and encourage a more collaborative approach to identifying mitigations.

Medium-term actions:

- Work with researchers and industry to develop data sharing solutions that would give operators confidence they can trust the fidelity and accuracy of the information they are given and that their own data won't be mishandled nor used to benefit competitors. To be effective, data sharing solutions need to include data verification and protection measures to build trust - this may involve a non-military independent data custodian.

- Implement international bilateral data sharing arrangements to improve the accuracy, timeliness and integrity of data used to drive operational and policy decisions.

Longer-term actions:

- Work with DSIT and CAA to consider mandating that UK-licensed operators share relevant data on satellite specifications, timely updates of planned and unplanned automated manoeuvres, and credible disposal plans for end of life.

R7: Research Funding Coordination
There is an important role for UKSA to play in helping to facilitate and coordinate cross-disciplinary funding streams within the UK funding landscape - to fill some of the knowledge gaps identified through this project. To be effective, the government's space sustainability strategy and long-term research roadmap must demonstrate a joined-up approach across currently siloed research responsibilities and budgets.

To implement that strategy, the government should consider establishing, in partnership with relevant research councils and industry, a cross-disciplinary National Space Environment Centre of Expertise to act as a hub for knowledge-sharing and fostering collaboration between disparate research groups around the country. Such a centre should promote holistic approaches to assessing and tracking environmental impacts and serve as a focal point for knowledge-sharing and fostering collaboration – helping researchers navigate the funding landscape and providing expertise to policy makers to inform future government policy and investment.

This could facilitate collaborative research in key cross-cutting areas identified through this project, such as: engaging satellite operators to gather evidence of Space Weather impacts on the satellite and debris population and applying that to improve conjunction estimates; and bringing expertise from materials science, engineering, and chemistry to work with atmospheric scientists to design novel ways to gather evidence of atmospheric impacts and develop mitigations.

R8: International Research Collaboration
On the international front, UKSA should seek to incentivise and facilitate significant cross-border research collaborations in the priority knowledge gap areas identified through this project - e.g. MSCA doctoral network projects under Horizon Europe.

R9: Knowledge Sharing and Awareness Raising
A key theme from the participants in this project was the need for greater collaboration between the research community and satellite operators. In the short-term, UKSA should harness existing networks to support knowledge sharing and awareness raising and facilitate collaboration between satellite operators and

researchers as a key element of its space sustainability strategy. In the medium-term, the National Space Environment Centre of Expertise mentioned in R7 could fulfil this function.

Knowledge sharing and awareness raising for government officials, political decisionmakers and the general public is also important, to build understanding around the trade-offs between the benefits of human activity in space and the environmental impacts. This should be a plank that runs right through the space sustainability strategy, with clear communication objectives for key stakeholder groups and audiences.

Sharing knowledge to build international capacity should also be included in the UK's space sustainability strategy, to support emerging space nations to strengthen their voices in multilateral fora. For consensus building to succeed, there's a perceived need to increase the number of countries that share the UK's perspective.

The UK has a strong track record of raising awareness of space sustainability issues at the most senior levels – for instance, securing the joint statement on space sustainability at the G7 Leaders' Summit in Cornwall in 2021 (Carbis Bay Communique 2021). In spite of current geopolitical uncertainties, the UK government should consider options for bringing world leaders together to raise awareness of the emerging evidence of the environmental impacts of human activity in space and seek to forge consensus for collective action.

R10: Space Traffic Management
Whilst this project was primarily concerned with identifying gaps in knowledge relating key environmental impact indicators for space, the topic of Space Traffic Management was raised many times during the workshops. Project participants shared the perspective that global STM is essential for the sustainability of the space environment. Many challenges were highlighted. The UK cannot address those alone, however, there is much that can be done to accelerate progress. Specific recommendations include:

Short-term actions:

- Continue to engage proactively in multilateral fora and seek to build consensus for agreements on STM.
- Coordinate cross-government stakeholders to develop a UK policy statement on future global STM.
- Encourage NSpOC to formalise bilateral cooperation and information sharing agreements with other national space operation centres.

Medium-term actions:

- Work with international partners to produce a roadmap for standardised interoperable STM technical systems - with the strategic aim that UK research institutions and industry are able to shape technical standards, innovate and supply products and services to the global marketplace.

Longer-term actions:

- Work through relevant UN bodies and deploy diplomatic efforts to develop proposals for an independent inter-governmental organisation with the necessary legal status and enforcement powers to oversee global STM. The UK's experience as a founding member of other bodies such as the International Civil Aviation Organisation, International Maritime Organisation and International Atomic Energy Agency can be brought to bear to help shape effective proposals.

- Encourage a programme of international collaboration to develop proposals for lunar and cislunar STM.

6.0 Conclusions

This project has highlighted that the rapid increase in human space activity has pushed past the boundaries of current understanding of the space environment and is giving rise to new risks and hazards that are poorly understood and difficult to mitigate.

This report has attempted to summarise the many detailed points raised by participants and draw out some key themes.

While there are no universally agreed indicators of the condition of the space environment, there's emerging evidence of adverse environmental impacts which all participants agreed would benefit from further development and international standardisation and collaboration.

Removing inconsistencies and improving the precision and timeliness of satellite and debris population metrics was seen as a high priority. Improved cataloguing, monitoring, modelling and forecasting of the satellite and debris population, including better and faster feedback loops between Space Weather and SSA systems, would help keep the space operating environment safer and more sustainable. It would also help to manage scarce resources such as orbital capacity and RF spectrum in a more optimised way.

Better measurement of the small debris population and improved understanding of how to mitigate impacts of that segment of the population on other space objects were also highlighted as priority knowledge gaps.

Tracking and mitigating RFI and UEMR in LEO were raised as areas where further research into impacts and mitigations should be prioritised, to minimise adverse impacts and optimise spectrum utilisation.

Better sharing of data about satellite characteristics (e.g. material composition, drag profiles, thermal dispersal properties, BRDF, etc.) would enable the research community to improve conjunction modelling and help develop mitigations for impacts on Astronomy and the Earth's atmosphere.

Very little is understood about the impact of launch and re-entry on the Earth's atmosphere. More observational data is needed to measure particles in the atmosphere; along with new ways of testing how materials are likely to react during launch and re-entry.

There was a shared view that more holistic measures of impacts, e.g.: ecological, economic, cultural, human health, etc. should be developed to ensure trade-offs are understood when operational and policy decisions are taken.

It isn't too soon to lay the groundwork to ensure that impacts of human activity on the lunar and cislunar environment are measured and understood. That will require different approaches to those being developed for Earth orbit environments.

During the discussions across the two workshops there were many calls for:

- An independent, international, civil reporting body to facilitate data sharing;
- An inclusive, democratic, international STM organisation, akin to ICAO, to coordinate the safe use of space and monitor compliance with agreed rules and norms; and
- Embedding mandatory data sharing and environmental impact assessments in licencing processes.

Finally, a key message from this project was that cross-disciplinary, cross sector (research institutions, industry and government), and cross-border knowledge sharing and collaboration is essential to accelerate progress in identifying, measuring and mitigating key environmental impacts for space.

UKSA's remit doesn't extend to all the areas covered in this report. Nonetheless, it has a vital role to play. It's hoped that the recommendations made above will be useful in informing the development of the UK's long-term space sustainability strategy and research roadmap.

APPENDIX A: Contributors

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APPENDIX B: Workshop Agendas 1 & 2

Workshop Agenda - Part 1, 28 February 2025

Time	Topic/Objective	Panel
12:00	**Welcome** Set UK Context and Objectives for Workshop	Ray Fielding/Katherine Courtney
12:10	**UKSA Context** Share UKSA Perspective	Jodie Howlett/Chris Young - UK Space Agency
12:20	**Satellite Population** Chair: Stuart Eves, SJE Space Explore Sources of Modelling Uncertainty and Barriers to Harmonisation	Peng Zhao, Global Satellite Operators Association Santosh Bhattarai, University College London Jonathan McDowell, Harvard-Smithsonian Center for Astrophysics Richard Linares, Massachusetts Institute of Technology Brian Gunter, Georgia Institute of Technology
13:20	**Optical and RF Interference** Chair: Robert Massey, RAS Explore Key Research Gaps	Federico di Vruno, Spectrum Manager SKA Observatory Aishling Dignam, NOIRLab Don Pollacco, Warwick University Andy Lawrence, Royal Observatory Edinburgh Martin Coleman, Satcoms Innovation Group Emma van der Wateren, Netherlands Institute for Radio Astronomy (ASTRON)
14:30	**Coffee Break**	
14:45	**Debris Population** Chair: Stuart Eves, SJE Space Explore Key Data gaps and Sources of Modelling Uncertainty	Holger Krag, Head of ESA Space Safety Programme Mark Burchell, University of Kent Massimiliano Vasile, University of Strathclyde
15:45	**Plenary Discussion** Identify Key Priorities	Facilitators: GNOSIS Team
16:30	**Summing Up and Next Steps**	GNOSIS Team
17:00	**Close**	

Workshop Agenda - Part 2, 10 March 2025

Time	Topic/ Objective	Panel
13:00	**Welcome** Key Messages & Objectives of Workshop	Ray Fielding/Katherine Courtney
13:10	**UKSA Remarks** Share UKSA Perspective	Jodie Howlett/Chris Young - UK Space Agency
13:20	**Space Weather Impacts** Chair: Ian McCrea, RALSpace Explore Key Research Gaps	Sean Elvidge, University of Birmingham John Coxon, Northumbria University Klaas Wiersema, University of Hertfordshire Ravi Desai, Warwick University Juha-Pekka Luntama, Head of ESA Space Weather Office
14:20	**Atmospheric Impacts** Chair: Katherine Robson Brown, University College Dublin Explore Key Research Gaps	Daniel Murphy, NOAA Chemical Sciences Laboratory Karen Rosenlof, NOAA ESRL Chemical Sciences Division Minkwan Kim, University of Southampton Leonard Schulz, Technical University of Braunschweig John Plane, University of Leeds Fionagh Thomson, Durham University
15:20	**Coffee Break**	
15:30	**Challenges / Value of Indicators** Chair: Katherine Courtney Designing an Effective Framework	Megan Perks, Southampton Karen Anderson, Exeter Emmanuelle David, EPFL Aaron Boley, Co-Director of Outer Space Institute Marek Zeibart, UCL/ESSI
16:15	**Plenary Discussion** Identify Priority Gaps	Facilitators: GNOSIS Team
16:45	**Summing Up**	GNOSIS Team
17:00	**Next Steps**	GNOSIS Team
17:15	**Close**	

APPENDIX C: References & Wider Reading

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