



Review of Existing Research Initiatives relating to Key Environmental Indicators for Space

Part 1

Katherine Courtney¹,

Theresa Harrison^{1,2}, James Blake^{1,2}, Stuart Eves^{1,3}

¹ *GNOSIS Network*

² *University of Warwick*

³ *SJE Space Ltd.*

Review of Existing Research Initiatives relating to Key Environmental Indicators for Space - Part 1

Introduction

This document provides a summary of the views of researchers currently working on topics related to how to evaluate and measure the sustainability of the space environment. It provides background material for a 2-part Virtual Workshop examining research gaps which was held on 28 February and 10 March 2025.

This is not intended to be a comprehensive research review, rather a high-level summary of the views of members of the Global Network on Sustainability in Space (GNOSIS) and wider space sustainability research community.

GNOSIS¹ was launched in late 2019 with funding from the UKRI Science and Technology Facilities Council, it has subsequently continued to expand with support from the UK Defence Science and Technology Laboratory, UK Space Agency, The University of Warwick, and corporate sponsors. The GNOSIS mission is to facilitate knowledge-sharing and promote collaboration across disciplines, borders and sectors to accelerate progress in tackling the challenges of keeping space safe, secure and sustainable. GNOSIS now numbers over 1,000 members across more than 45 countries, with a split of 45% researchers, 45% industry, and 10% policy makers.

This first part of this review document records the inputs we have received relating to research gaps in understanding the satellite and debris population and how it is likely to change over time; radio frequency spectrum usage and interference; and optical impacts on astronomy and the night sky. The Survey brief and questions posed are given in Appendix A.

The second part of the review document collates inputs relating to understanding how space weather impacts on the satellite and debris population, as well as atmospheric impacts arising from launch and de-orbit/disposal. The final part of the document reflects researchers' views on broader factors that need to be taken into account when considering the indicators/evidence that would be valuable for encouraging sustainable behaviours and informing decisions, such as those made by licensing authorities and satellite system designers.

¹ <https://gnosishnetwork.org/>

Methodology

GNOSIS conducted a short online survey² of members between 24-31 January requesting respondents' 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, plus some additional direct contributions. The organisations of contributors were based in 9 different countries – although a majority (70%) were from UK-based organisations. As a result, it should be understood that the views reflected in this document are skewed towards European and North American perspectives.

It is clear from the contributions to this exercise that most researchers share the view that attempting to understand the sustainability of the space environment is a multi-dimensional problem and it isn't feasible to identify a simple set of key indicators. Indeed, some respondents questioned whether a standard set of environmental indicators would be desirable or could risk leading to poor decision-making and unintended adverse consequences. This is a topic we will explore further in the Workshop.

It is also clear that agreeing standard indices and adopting thresholds for space environmental management, at the international level, requires political leadership and engagement with a significant number of states and stakeholders. However, as international fora turn their attention to this issue, the research community has valuable contributions to make, which in turn should strengthen the case for compliance with sustainability requirements.

Space Environment Research Gaps - Part 1

Active Satellite Population

There are a number of models used to predict future trends in the space environment, for both the quantity and distribution of active satellites and debris. Several space agencies have developed software for this purpose, such as NASA's LEGEND simulator, ESA's DELTA, CNES's MEDEE, CNSA's SOLEM, and JAXA's NEODEEM. There are also models from academia such as MOCAT from MIT and ISOC from Politecnico di Milano.³

² <https://gnosishnetwork.org/survey-key-environmental-indicators-for-space/>

³ <https://amostech.com/TechnicalPapers/2024/Poster/Wu.pdf>

A recent paper in the Journal of Astronomy and Space Sciences provides a review of 11 existing models and makes the point that effective modelling requires data sharing to supplement the catalogue published by the US Space Surveillance Network (SSN).⁴

The SSN catalogue is the primary source of free public data, however it does not provide a complete picture of the satellite and debris population. It only contains objects which are at least 10 cm in size and have an accurately determined orbit.

The increasing frequency of “batch” launches of satellites into LEO orbits creates difficulty for identification and tracking. When satellites are deployed close together in space and time it can be hard for tracking radars to distinguish individual satellites, making it difficult to correlate which satellite is in which orbit.

Those objects therefore cannot be added to the catalogue until the orbit has been determined, which can take weeks or months to resolve, if ever. Clearly, with objects missing from the catalogue, operators of other satellites in nearby orbits may be unaware of close approaches, hindering their ability to mitigate risks of collision.⁵

Historically, space surveillance and tracking capabilities used to monitor and catalogue the satellite population were owned and operated largely as part of military operational structures - with a heavy reliance on US Space Situational Awareness (SSA) capabilities for sharing data to manage potential collisions.

Civil satellite monitoring capabilities are now also being established around the world - for example; US Traffic Coordination System for Space, UK National Space Operations Centre, German Space Situational Awareness Centre, European Union Satellite Centre. A number of rapidly growing, well-funded, private sector SSA providers have also been expanding their services - primarily providing supplementary monitoring capabilities for satellite operators in LEO and GEO.

Existing SSA systems produce different results regarding the current and future location of individual spacecraft. These differences can cause significant issues for operators needing to make decisions about whether or not to manoeuvre and then how to plan those manoeuvres without creating further risks. New partnerships and data-sharing arrangements are being developed - allowing for better shared understanding of the space environment.⁶

In April 2024, the US Office of Space Commerce released its “Global Space Situational Awareness Coordination” document, outlining a vision for a future of globally

⁴ https://www.janss.kr/archive/view_article?pid=jass-41-4-209

⁵ <https://www.nasa.gov/smallsat-institute/sst-soa/identification-and-tracking-systems/>

⁶ <https://www.sciencedirect.com/science/article/abs/pii/S0265964621000369>

coordinated SSA services. That document called for international alignment on SSA data standards and data and information sharing best practices.⁷

Data sharing has become a key topic for the space sustainability community. There is a lot of information held by satellite operators (mass, configuration, attitude, ballistic coefficient, etc.) that could be fed into models to improve accuracy, but much of that has historically been viewed as commercially and strategically sensitive information, so is not widely shared.

Implementing better tracking and orbit propagation is a multi-parameter problem that requires coordination across national boundaries to succeed. Current geopolitical tensions make that extremely challenging.

Critical knowledge gaps relating to the active satellite population reflected in the information gathered through this project include:

- A sufficiently complete and trustworthy catalogue of space objects currently in earth orbit - including improvements in identifying activity status of objects - and, of growing importance, objects in cislunar orbit.
- A common framework for assessing orbital carrying capacity.
- Model of orbital environment evolution over a +25 year time horizon, assuming accelerating growth in launch and data on the expected lifetime of satellites and constellations.
- Long term monitoring of the full motion state (in all 3 axes) of inactive objects in the geostationary belt (and graveyard).
- Bidirectional Reflectance Distribution Functions (BRDFs) of satellite materials – together with a satellite configuration model BRDFs can help with accurate assessments of the brightness of a satellite and determining orientation.
- A comprehensive economic model of optimal space traffic levels - to assess the critical economic threshold, when risks outweigh the benefits of operations in orbit.
- More robust cost-benefit analysis of Active Debris Removal.
- Threats to satellite population and the vulnerability of large LEO constellations to disruptions (cyber, anti satellite kinetic weapon, electromagnetic pulse, coronal mass ejection, etc.).

The views on what information should be included in a standard set of Environmental Indicators relating to the active satellite population can be summarised as:

- Measures of catalogue quality - including accuracy and completeness.
- The number of satellites that are visible to the naked eye.

⁷ <https://www.space.commerce.gov/wp-content/uploads/Global-Space-Situational-Awareness-Coordination-Vision-March-2024.pdf>

- The number of post-mission satellites remaining in orbit.
- Number and severity of conjunction events (definition of severity based on probability of collision, and other relevant factors such as mass of objects)
- Fraction of orbital carrying capacity occupied (assuming carrying capacity has been defined) by active satellites and uncontrolled objects.
- Information on collision avoidance and re-entry control capabilities (and/or lack thereof) of satellites and constellations.
- Instantaneous alerts of spacecraft failures or uncontrolled behaviour, made accessible to all providers, harnessing the potential to acquire diagnostic data.
- Identification signals for active satellites.
- Metrics and thresholds that operators are actually using.
- Risk of collision with lethal-non-trackable objects as a function of time.
- Residual risk of collision of active satellite systems, to be defined and measured.
- Simplified (but space-specific) Life Cycle Assessments of space system(s).

Debris Population

The same models used to track the active satellite population are also used to simulate the paths of debris objects by modelling the forward evolution of the debris environment. Space object catalogues, as generated and maintained by space surveillance networks, are limited to larger objects, typically greater than 10 cm in Low Earth Orbits (LEO, below about 2000 km) and greater than 0.3–1 m at Geostationary Orbits (GEO, about 36 000 km). These sensitivity thresholds are a compromise between system cost and performance.^{8,9,10}

In LEO, the catalogue of such objects is known to be incomplete because some of the objects in this size range are not very radar-reflective (and most of the LEO tracking is done by radar).¹¹

In higher orbits, as well, the catalogue is probably incomplete because some of the objects are very dark and most of the tracking is done optically. Recent anomalies exhibited by satellites and rocket bodies have highlighted that a population of faint debris exists at GEO altitudes, where there are no natural removal mechanisms. Regular monitoring of faint sources at GEO is challenging, so knowledge remains sparse.¹²

⁸ https://www.esa.int/Space_Safety/Space_Debris/Scanning_and_observing2

⁹ Blake et al., 2023, <https://amostech.com/TechnicalPapers/2023/Poster/Blake.pdf>

¹⁰ Buzzoni, 2024, <https://doi.org/10.1093/rasti/rzae065>

¹¹ <https://ntrs.nasa.gov/api/citations/20160011226/downloads/20160011226.pdf>

¹² Blake et al., 2021, <https://doi.org/10.1016/j.asr.2020.08.008>

There are fundamental omissions in our understanding of the debris population; eg. density as a function of altitude, orbital information, shape distribution, tumble rates, etc. Most of the population is statistically inferred with no/little observational characterisation.

Research to improve this situation is underway, and includes using space-based sensors to get above the atmosphere and closer to the target objects¹³. Novel wide-area sensors on the ground, backed up with innovative processing techniques will also help with detection¹⁴.

Keeping these detected objects in the catalogue may prove more difficult. Better propagation tools and improved force models would be desirable in order to achieve this improved catalogue, since it is easy to “detect and then lose” small objects.

A key gap is being able to detect and track debris down to 1 cm in LEO and around 20 cm in GEO, since at the closing velocities that are seen in these orbital regimes, such objects have the potential to disable a satellite.

Even smaller debris in LEO (mm) and GEO (cm) has the potential to cause damage. We know even less about this very small debris population. Models suggest that very small objects are more likely to be influenced by solar radiation pressure, so small debris created in collisions is unlikely to be in similar orbits to the larger fragments.

This process is not well understood, and the estimated number of debris objects larger than 1cm is highly uncertain, (500,000 according to NASA; 900,000 according to ESA). We need to improve this situation as it is not clear that existing conjunction tools would work well with a catalogue of this size.

Debris objects in the mm size range are large enough to cause critical damage to assets, generate more debris, etc.¹⁵ - but the measured flux of this debris population is very poorly constrained.¹⁶ It cannot be measured from the ground, only in situ. The flux may be growing, but if we do not know what it is now, we cannot tell if it is changing.

There is also a need to measure and understand the natural small particle meteoroid flux and its effects. This is a baseline against which to check the debris flux, but there are clear issues in separating the two sources for mm-sized objects.¹⁷ More research into the natural particle rates would help to resolve this - the Moon is a potential source of this information. The intensity of meteor showers is also notoriously hard to predict at present.

¹³ Davis et al., 2022, <https://amostech.com/TechnicalPapers/2022/Space-Based-Assets/Davis.pdf>

¹⁴ Bowler, 2025, <https://academic.oup.com/astrogeo/article/66/1/1.20/7991402>

¹⁵ Cornwell et al., 2025, <https://doi.org/10.1016/j.asr.2024.06.058>

¹⁶ Wozniakiewicz and Burchell, 2019, <https://doi.org/10.1093/astrogeo/atz150>

¹⁷ Kearsley et al., 2024, <https://doi.org/10.1098/rsta.2023.0194>

It should also not be forgotten that our debris populated region of space now extends to the Moon, so research into the cis-lunar debris environment is of great value.

Critical knowledge gaps relating to the debris population reflected in the information gathered through this project include:

- Detection, tracking, and cataloguing of objects < 10 cm.
- Real-time (high-cadence) view of the changing debris situation.
- How the micrometeorite flux compares with the debris population in LEO.
- Size-frequency distribution of the small debris population.
- Orbit evolution of small debris - how objects of different sizes evolve in their orbits.
- Small Near Earth Objects down to about 150 m in size - at present we don't have many of those in our catalogue.
- What is happening in GEO graveyard orbits.
- Understanding the factors that contribute to changes in debris rotation behaviour over time (a topic relevant to ADR missions)
- Certain aspects of identifying activity status of objects, so as to distinguish whether active or debris.
- Understanding the consequences of impact on current and future space structures.
- Bidirectional Reflectance Distribution Functions (BRDFs) of satellite materials is not well researched and can be used in determining the face of the satellite or debris facing the Earth, which is useful when assessing tumble rates of objects for active debris removal.
- The fragmentation of different materials under different conditions is poorly constrained when impacted by mm to cm sized projectiles and hypervelocity. Tracking fragmentation of these particles in the near-Earth environment is a significant knowledge gap. There is insufficient understanding of how different materials respond to the space environment.
- Evidence for minor events on satellites (i.e. not significantly disabling) that are potentially due to space weather or meteor (there is plenty of data, the gap is in creating a commercially safe place to make it available for research).
- There is a large body of work on the risk of a Kessler syndrome in LEO. Still missing is a comprehensive, holistic model with realistic assumptions that can assess the relative aggregate risk of large LEO constellations on the debris population, and risk of denying LEO orbits.
- Understanding the gap to achieve zero debris. ESA's Zero Debris Charter¹⁸ asks for 99% Post Mission Disposal, however the current failure rate for satellites is 4%.

¹⁸ https://esamultimedia.esa.int/docs/spacesafety/Zero_Debris_Technical_Booklet.pdf

- Number of debris objects that need to be removed to maintain sustainable thresholds in the context of increasing cadence of launch.
- Attempts to calculate “the most dangerous debris objects” do not necessarily generate consistent lists, as the states of such objects evolve over time. This represents a gap and a more robust approach is needed for deciding which objects to prioritise for removal.

Views from contributors on what information should be included in a standard set of Environmental Indicators relating to the debris population can be summarised as:

- Growth of debris population (trends in distribution by size/altitude).
- Total risk of collision between derelict hardware (i.e., fragments, rocket bodies, and non-operational payloads) as a function of altitude.
- The flux of debris in the critical 0.1 to 10 mm range should be measured and monitored continually in real time.
- Space debris density levels for every orbital region.
- Current density profile of the Earth's atmosphere vs altitude.
- Debris population density as a function of altitude down to 1 cm in size.
- Debris population mass as a function of altitude.
- Debris mass by country.
- Dynamical evolution of debris and satellite population vs orbital carrying capacity.
- Observed characteristics of individual debris over time e.g. rotation rates, likely deviations from spherical structures, brightness, altitude, etc.
- The background sky brightness (this can be an indicator of the increase in small debris over time instead of performing in situ measurements).
- Percentage of operators attempting Post Mission Disposal and success rates.
- Factors relevant to determining the most dangerous debris, including:- mass/size and configuration, orbit, expected natural lifetime, rotational motion, volatiles (fuel) on board, centre of mass, constituent materials, ownership, and in a few cases, whether it is radioactive.

Optical and Radio Frequency Spectrum Impacts

As the population of satellites and debris expands, it is having an increasing impact on our ability to view and study the night sky. As of 2022, filings for radio spectrum for over one million satellites had been submitted to the International Telecommunication Union.¹⁹

¹⁹ <https://outerspaceinstitute.ca/osisite/wp-content/uploads/One-million-paper-satellites-Accepted-Version-.pdf>

Ground-based telescopes “see” satellites and pieces of orbital debris as streaks of various lengths and apparent brightness depending on their orbital parameters and physical characteristics, the observational conditions and timings. These streaks can often be as bright or brighter than the object(s) being studied, with consequences for astronomical data. There is a concern that the night sky is growing brighter in a way detectable by the human eye due to sunlight reflecting and scattering off orbiting materials.²⁰

Satellite operators are making efforts to mitigate light pollution through design modifications, but the overall impact is growing, not reducing. The Outer Space Institute’s recent Astronomy Strategy Report²¹ observes that while SpaceX has made some progress in brightness mitigation, it is also making larger satellites. AST SpaceMobile’s BlueWalker3 and five BlueBirds are among the brightest objects in the sky; and many other large satellites are planned.

Another phenomenon affecting optical astronomy is ionospheric holes resulting from both rocket launches and reentries. These create patches of sky with a red glow (dominated by emission at 630 nanometers). Plumes of gases and combustion products during launches, as well as venting of propellant later in the mission, can also affect astronomical observations.²²

Seven new \$Billion Earth-based astronomy facilities are in development:

- Vera Rubin Observatory: optical scope for all-sky survey, transient events
- Giant Magellan Telescope: optical scope for deep observations
- Thirty Meter Telescope: optical scope for deep observations
- Extremely Large Telescope: optical scope for deep observations
- ALMA 2030: microwave array
- Meerkat: radio array
- Square Kilometer Array: radio array

These were all designed in an era before satellite mega-constellations. There is a risk these important scientific facilities will face significant impacts from satellites, both during their mission lifetime and following post mission disposal.²³

Alongside optical interference, the growth in the satellite population is also creating adverse impacts on Radio Frequency spectrum usage.

²⁰ <https://academic.oup.com/mnras/article/504/1/L40/6188393>

²¹ <https://outerspaceinstitute.ca/osisite/wp-content/uploads/OSI-Astronomy-Strategy-Report-16DEC2024.pdf>

²² <https://skyandtelescope.org/astronomy-news/space-industry-adds-threats-to-astronomy-light-pollution-remains-a-big-problem/>

²³ <https://drive.google.com/file/d/1GQl11aaQXhiFAoBZpdQvVYcBHcGJcj2C/view>

An international team used the Low Frequency Array (LOFAR) telescope in the Netherlands to observe 68 Starlink satellites in 2022. The study detected “unintended electromagnetic radiation” (UEMR) emanating from the satellites' onboard electronics, most concerning within a protected band specifically allocated to radio astronomy by the International Telecommunications Union (ITU).²⁴

The study was repeated in 2024 and found that the second generation of Starlink satellites were observed to emit higher levels of UEMR over a broader frequency range compared to that emitted by the first generation of Starlink satellites. These newer satellites are larger and operate in lower altitude orbits and so are closer to Earth-based Telescopes.²⁵

An RFI measurement campaign conducted in October–November 2023 for the Sardinia Radio Telescope revealed several sources of RFI, including emissions from satellite communications.²⁶

RFI doesn't just impact astronomy however, it also impacts satellite operations. With the rapid growth of the satellite population, the US Space Force 19th Space Defense Squadron (19 SDS) - which performs conjunction assessment (CA) for global commercial, civil, military, and academic operators - is issuing approximately 600,000 Conjunction Data Messages (CDMs) per day, as of September 2024, an increase of 200 % over the daily rate from just three years ago.²⁷ So many close approaches between satellites leads to radio frequency interferences between spacecraft from different operators and orbital regimes.²⁸

Intentional RF interference through cyber attacks is also a known threat to satellite operations. Earth Observation satellites in LEO have experienced interference with RF communications as they pass over conflict zones on Earth.²⁹ It was reported that Russia was behind a massive cyberattack against Viasat's network that took tens of thousands of modems offline at the onset of the Russia-Ukraine war.³⁰

The inputs gathered through this project highlighted many critical knowledge gaps relating to impacts from orbital light pollution as well as RF interference; including:

²⁴ https://www.aanda.org/articles/aa/full_html/2023/08/aa46374-23/aa46374-23.html

²⁵ https://www.aanda.org/articles/aa/full_html/2024/09/aa51856-24/aa51856-24.html

²⁶

https://www.researchgate.net/publication/384742012_Measurement_Campaign_of_Radio_Frequency_Interference_in_a_Portion_of_the_C-Band_4-58_GHz_for_the_Sardinia_Radio_Telescope

²⁷ <https://www.sciencedirect.com/science/article/pii/S2468896724001150#bib0002>

²⁸ <https://conference.sdo.esoc.esa.int/proceedings/neosst2/paper/47/NEOSST2-paper47.pdf>

²⁹ <https://interactive.satellitetoday.com/via/november-2024/how-earth-observation-companies-stay-ahead-of-the-cyber-threat>

³⁰ <https://www.reuters.com/world/europe/russia-behind-cyberattack-against-satellite-internet-modems-ukraine-eu-2022-05-10/>

- There is a lack of critical information about the satellites themselves, which would enable more advanced studies to be carried out - this would ideally happen before the new satellite types are launched into space.
- Improving the position prediction accuracy for ground-based telescopes to avoid or remove satellite emission - this topic has many unknowns and new challenges arise with each new satellite constellation launched.
- What impact will satellite de-orbiting have on the atmospheric properties through which telescope observations are made?
- Aggregate interference from many constellations - it is not well understood how having several large constellations of satellites will affect radio astronomy observations.
- Bidirectional Reflectance Distribution Functions (BRDFs) of satellite materials are not well researched and can be useful in more accurately inferring the physical and attitudinal characteristics of the satellite or debris - important when assessing tumble rates of objects for active debris removal.
- Investigating the brightnesses of satellites across a variety of wavelength bands of the electro-magnetic spectrum.
- The actual use of allocated spectrum is not well monitored/understood.
- RF interference is difficult to predict - to anticipate operations or make adaptations in real time.
- Possibility of steering radio beams away from radio observatories and to shut down transmissions when the satellite is transiting the field of view (FOV) of the radio telescope. Sidelobes must also be considered.
- How to improve the efficient allocation of RF spectrum for ITU/Regulators.
- The effect of unintentional electromagnetic radiation has only recently been identified. There is a need for more studies, mitigation measures and potential standards for space radio emissions.
- Microwave RFI detection and mitigation techniques in the first stages of the data processing (i.e. raw/L0 before the RFI "propagates" to successive levels in which, although the detection may be easier, the mitigation would be more complex or impossible), with special emphasis in techniques that can be implemented in-orbit.

The views on what information should be included in a standard set of Environmental Indicators relating to optical and RF impacts can be summarised as:

- Measurements of light impacts on the night sky.
- Mitigations of optical reflectivity.
- RF jamming and interference indicators.

- The use of RF spectrum in LEO, MEO, GEO & Exploration - actual usage versus allocation.
- RFI Incident Statistics & Cases to assess spectrum use and update management of spectrum allocation.
- Control of unintentional emissions that can fall into radio astronomy bands, as a function of the number of satellites.
- Long-term trends to the use of spectrum in orbit (especially LEO) could include effects on ground-based optical and radio astronomy.
- RF interference probability of occurrence maps (per frequency band).
- RF sharing measures.

Appendix A

Survey Brief and Questions

Identifying Research Gaps in Key Environmental Indicators for Space

The UK Space Agency is seeking views of GNOSIS Members and the wider space community on the evidence base that underpins our collective understanding of how human activity in space is impacting on the space environment.

This short survey is seeking to answer the question of what research is currently available, or being planned, that measures:

- the magnitude of the debris catalogue, its size distribution, and its evolution
- the active satellite population and how that is changing over time
- light pollution from space activities
- Radio Frequency (RF) utilisation/interference relating to spacecraft
- atmospheric pollution attributable to launch and de-orbiting space objects
- the impact of space weather and the meteor population

Any additional areas of research relating to the impacts of space activity on either the space or terrestrial environments would also be welcomed.

- Please indicate which areas of research, relevant to measuring impacts of human activity on the space environment, you are involved in.
- Are there critical knowledge gaps that would warrant further research? Please list these.
- What, in your view, should be included in a standard set of Environmental Indicators for Space? Please list these in order of importance.
- Please provide links to relevant papers, articles, websites.

Appendix B

Sources and Wider Reading

Satellite and Debris Population

Special report of the Inter-Agency Meeting on Outer Space Activities on developments within the United Nations system related to space debris:

https://www.unoosa.org/res/oosadoc/data/documents/2024/aac_105/aac_1051317_0.html/AC105_1317E.pdf

A holistic systems thinking approach to space sustainability via space debris management:

https://www.sciencedirect.com/science/article/pii/S2468896724000685?ref=pdf_download&fr=RR-2&rr=9089efcc9dbc79c0

Kessler's syndrome: a challenge to humanity:

<https://doi.org/10.3389/frspt.2023.1309940>

A&G review article on space debris, SST, ADR, and light pollution, collating many relevant research papers:

<https://academic.oup.com/astrogeo/article/63/2/2.14/6546993>

Warwick work on faint LEO target recovery in optical images:

<https://www.sciencedirect.com/science/article/pii/S0273117723003502>

Warwick survey of faint geosynchronous debris:

<https://www.sciencedirect.com/science/article/abs/pii/S0273117720305664>

Temporal analysis and quantification for space sustainability: [MOCAT on Temporal Analysis and Quantification for Policies in Space Sustainability](#)

Contrasting the Inflection Points and Efforts in Space Traffic Coordination and Management:

https://drive.google.com/file/d/18RJRC9E7QA9u6DEG2u_mAtOGqRM2Dl9o/view?usp=sharing

Website visualising future space catalogues, i.e., the results of a Future Space Population Model project: <https://ucl-sgnl.bitbucket.io/fspviz/fspviz.html>

Using precise orbits (cm-level accurate orbit solutions) for nowcasting of atmospheric density along the path of LEO satellites during geomagnetic storms:

<https://arxiv.org/abs/2408.16805>

Collaboration between UCL and MIT on source sink evolutionary models: [MOCAT-PYSSEM_An_Open-Source_Python_Library_and_User_Interface_for_Orbital_Debris_and_Source_Sink_Environmental_Modelling](#)

UCL work on improving catalogue accuracy: <https://app.cospar-assembly.org/2024/browser/presentation/34201>

Using complex systems and social-ecological systems approaches to study space debris accumulation: [Tipping Points of Space Debris in Low Earth Orbit | International Journal of the Commons](#)

Feasibility of using CubeSats and small detectors for in-situ space debris and cosmic dust flux measurement: <https://doi.org/10.1016/j.asr.2024.06.058>

Lack of flux data at critical small sizes: [Space dust and debris near the Earth](#)

Confusion between natural and debris particles at small sizes: <http://doi.org/10.1098/rsta.2023.0194>

Lunar dust flux problem: [A cosmic dust detection suite for the deep space Gateway - ScienceDirect](#)

New detector technologies for in-situ dust detection include: [A study on the capabilities and accuracy of Kapton based TOF space dust and debris detectors - ScienceDirect](#)

Developing a time of flight space dust and debris detector: <https://doi.org/10.1016/j.ijimpeng.2024.104897>

ESA Zero Debris Technical Booklet: https://esamultimedia.esa.int/docs/spacesafety/Zero_Debris_Technical_Booklet.pdf

NASA study examining the costs and benefits of active debris removal: [Cost and Benefit Analysis of Orbital Debris Remediation | NASA](#)

EPFL Publication: [Space debris mitigation guidelines for lunar orbits](#)

4th European Conference on Space Debris - proceedings: [a new look at nuclear power sources and space debris](#)

AMOS 2024 Paper on Fragmentation Events impacts on LEO Constellations: [Resilience of LEO Constellations to Accidental and Intentional Fragmentation Events Mark A. Sturza, Mark D. Dankberg, and William N. Blount](#)

Union of Concerned Scientists Blog: [Our Satellite Database Reaches a Milestone.](#)

[We've Learned Much Along the Way - Union of Concerned Scientists](#)

Jonathan McDowell's Space Report: [Space Activities in 2024](#)

Politecnico di Milano ESA project on orbital capacity: [SME - Space Missions Engineering | Dipartimento di Scienze e Tecnologie Aerospaziali](#)

Politecnico di Milano COMPASS project: <https://www.compass.polimi.it/research/>

Space capacity allocation for the sustainability of space activities Workshop outcomes: [Space capacity allocation for the sustainability of space activities](#)

Study comparing EUSST and USTraCSS services: [Comparison of European Union Space Surveillance and Tracking and TraCSS](#)

SpaceNews Article: [To sustainably develop space, we must manage orbital capacity - SpaceNews](#)

AIAA SciTech Forum 2024 Conference Paper: [Modelling Future Launch Traffic and its Effect on the LEO Operational Environment | Strathprints](#)

13th IAASS Conference Paper: [ENVIRONMENTAL IMPACT OF LARGE LEO CONSTELLATIONS](#)

US Space-Track website: [Space-Track](#)

US TraCSS Website: [Traffic Coordination System for Space \(TraCSS\)](#)

COMSPOC Technical Library Website: [COMSPOC Technical Library](#)

eSpace Website: [Sustainable Space Hub – eSpace](#)

eSpace Publications: [Publications – eSpace](#)

Viasat Research: [Space sustainability research](#) and [Space safety research](#)

Optical and Radio Frequency Spectrum Impacts

Technical Summary of the SATCON2 Workshop:
<https://noirlab.edu/public/media/archives/techdocs/pdf/techdoc031.pdf>

Astronomical Journal Article: [Satellite Optical Brightness - IOPscience](#)

Imperial assessment of Bluewalker 3 prototypes : [Massive low earth orbit communications satellites could disrupt astronomy](#)

The impact of satellite trails on Hubble Space Telescope observations:

<https://www.nature.com/articles/s41550-023-01903-3>

Warwick work on LEO satellite platform machine learning classification:

<https://academic.oup.com/rasti/article/3/1/247/7673085>

Starlink satellites - Facts, tracking and impact on astronomy:

<https://www.space.com/spacex-starlink-satellites.html>

Satcoms Innovation Group (SIG): [Spectrum Sharing in a Contested Space Environment - Satcoms Innovation Group](#)

Experiments on different interference avoidance schemes for the Karl G. Jansky Very Large Array and the Green Bank Telescope: [Toward Spectrum Coexistence: First Demonstration of the Effectiveness of Boresight Avoidance between the NRAO Green Bank Telescope and Starlink Satellites](#)

Astronomy & Astrophysics Article: [Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz](#)

Astronomy & Astrophysics Article: [Bright unintended electromagnetic radiation from second-generation Starlink satellites](#)

IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference: [Protecting dark and quiet skies by SKA Observatory - Issuu](#)

Proposed work plan for Post-Mission Satellites working group in SatHub at IAU-CPS: https://drive.google.com/drive/folders/1hWW2F-M_yQeRyWugHiQPWazMdvniDDGF

Position paper by the IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference: [Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations](#)

IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference - database of publications: <https://www.zotero.org/groups/4501709/satcons/library>

Astronomy & Astrophysics Article: [Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains](#)

Nature Astronomy Article: [Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise](#)

Importance of Spectrum Management in Radio Astronomy: <https://doi.org/10.2478/lpts-2022-0022>

Next Generation Observatories At Risk of Reduced Science Output:

<https://drive.google.com/file/d/1GQl11aaQXhiFAoBZpdQvVYcBHcGJcj2C/view>

ESA RFI Monitoring & Information Tool:

<https://rfi.smos.eo.esa.int/rfimanager/publicindex.jsp>

Geoscience and Remote Sensing Society: [Frequency Allocations in Remote Sensing \(FARS\) Technical Committee](#)

Press Release - Spire Global: [Identifying Radio Frequency \(RF\) and GPS Interferences for Military Applications with Satellite Data from Spire Global](#)

Colem Engineering Resource Site: [Files – Resource Library](#)