



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

Part 2

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Introduction

This document comprises the second part of the review document giving a summary of the views of researchers currently working on topics related to the evaluation and measurement of the sustainability of the space environment.

For a general introduction and an outline of methodology readers should refer to Part 1 of the review documentation.

This document provides the background material for the second of a 2-part Virtual Workshop examining research gaps which was held on 10 March 2025. It collates inputs on how Space Weather influences the satellite and debris population; atmospheric impacts arising from launch and de-orbit/disposal; and reflects researchers' views on the broader factors that need to be taken into account when considering the indicators/evidence that would be valuable for informing policy decisions and encouraging sustainable behaviours.

Space Environment Research Gaps - Part 2

Space Weather Impacts

The UK Government's National Risk Register assesses that severe Space Weather poses a significant risk to national security and resilience.¹ The more reliant we become on satellite services for economic growth and national security, the more vital it becomes to understand the impacts of Space Weather on the space (and Earth) environment.

Activity on the surface of the Sun - as measured by the number of observable sunspots - increases and decreases over a roughly 11 year cycle. The peak of the current cycle (Cycle 25) is expected to be reached in July 2025.²

Space weather can significantly impact satellites and debris by: causing increased atmospheric drag, making it harder to predict satellite trajectories; disrupting electronic

¹ <https://www.gov.uk/government/publications/national-risk-register-2025>

² <https://www.weather.gov/news/201509-solar-cycle>

systems through radiation exposure from solar particles; and causing scintillation in Earth's atmosphere which affects both communications links and the radars used for satellite tracking - resulting in increased risk of collision.

Large Space Weather events caused by Coronal Mass Ejections (CMEs) with sustained southward magnetic fields can deliver significant energy into the Earth's atmosphere. This can quickly move objects so far from their last-established orbital tracks that the Low Earth Orbit (LEO) catalogue becomes useless for conjunction analysis and has to be re-established by searching for and re-identifying "lost" objects.³

Space Weather impacts on satellites can include malfunction, loss of data and connectivity, reduced satellite lifetime and even complete loss of functionality - depending on the severity of the event. Elderly satellites which have already experienced some radiation damage are most at risk of failure.

As was widely reported at the time, SpaceX launched 49 Starlink satellites on 3 February 2022 into an area where orbital conditions were disturbed due to moderate Space Weather activity over several days. On 4 February 2022, many of these satellites started de-orbiting. Within a couple of days, 38 of them were lost since their propulsion systems had insufficient thrust to counteract the higher-than-expected drag environment. It has been shown that Space Weather played a large part in the demise of those satellites.⁴

During that event, poor understanding of the structure of the CMEs meant that geomagnetic storms happened at unexpected times; the increased atmospheric drag was double what was predicted by models, and the effects spread over a broader area than expected.⁵

In May 2024, increased solar activity resulted in a major geomagnetic storm (named the Gannon Storm) which was the largest to take place since 2003. The difference between the two events was that in 2003, there were around 1,000 satellites in orbit. In May 2024, there were more than 10,000 active satellites and some 37,000 pieces of debris larger than 10cm.⁶

A study conducted after the Gannon Storm showed that, in the period before the storm, approximately 300 of the nearly 10,000 active payloads in LEO appeared to be manoeuvring. After the storm hit, thousands of active satellites began to manoeuvre in response to the sudden increase in atmospheric density. This is mostly attributed to

³ <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019SW002373>

⁴ <https://doi.org/10.1186/s40623-024-02124-2>

⁵ https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220018/swsc220018.html

⁶ <https://spacenews.com/solar-flares-in-may-2024-revealed-earths-vulnerability-to-space-weather/>

autonomous station-keeping - which is a standard feature of the Starlink satellite constellation.⁷

The current approach to managing collision risks involves propagating every tracked object forward to identify potential conjunctions, then alerting satellite operators - hopefully, in sufficient time for collision avoidance manoeuvres to be planned and coordinated. When so many satellites manoeuvre at once, previous conjunction assessments are invalidated and the conjunction assessment process has to start again, once the new positions and velocities of the satellites are known.

The difficulty of forecasting the impacts of solar storms on environmental conditions, coupled with the growing autonomous station-keeping capabilities of LEO constellation networks, raises clear questions about the efficacy of existing conjunction assessment procedures during geomagnetic storms.⁸ A greater understanding of the station-keeping strategies used by the constellation operators would assist the Space Situational Awareness (SSA) community to anticipate changes to satellite orbits.

It is worth noting that the increase in atmospheric density has a similar effect on both operational satellites and debris objects. However, debris objects aren't able to equilibrate the effects. In the aftermath of the Gannon storm, debris objects and rocket bodies were both observed to experience a period of substantial altitude decay - hastening their demise through the atmosphere.⁹ While this can be seen as a beneficial impact of Space Weather - helping to "declutter" LEO - it also gives rise to re-entry impacts on the Earth's atmosphere - which will be discussed in the next section of this document.

In addition to increased collision risk, Space Weather can also impact the operational reliability and accuracy of sensitive radio communication and navigation systems. Space Weather effects can include; anomalous reflection, refraction, delay, diffraction, and absorption of radio waves propagating through the ionosphere; or more directly by interference from solar radio bursts.¹⁰

Space Weather effects in the ionosphere include disruption to communications, Earth Observation, geodesy and radio astronomy - affecting a broad range of critical activities, for example; civil aviation, maritime transport, time synchronisation, space exploration, in-orbit operations and autonomous navigation.¹¹

Enhanced ionisation in the ionosphere leads to disturbances that can affect high frequency (3–30 MHz) radio wave communication. These frequencies are used mainly

⁷ <https://arc.aiaa.org/doi/10.2514/1.A36164>

⁸ <https://arc.aiaa.org/doi/10.2514/1.A36164>

⁹ <https://doi.org/10.2514/1.A36164>

¹⁰ <https://www.sciencedirect.com/science/article/pii/S0273117724000863>

¹¹ <https://www.sciencedirect.com/science/article/pii/S0273117724000863>

for military, government, maritime sea-to-shore/ship-to-ship, and aviation air-to-ground communications. Propagation of radio signals is strongly dependent on ionospheric electron density and enhanced ionisation can result in signals being absorbed by, or passing entirely through, the ionosphere, rather than being reflected back toward the target receiver on the ground.¹²

Our increasing dependence on satellite services strengthens the case for ensuring new engineering solutions are incorporated into satellite design - to withstand major solar eruptions comparable to the Carrington Event of 1859 (the most intense geomagnetic storm in recorded history). Many satellites could fail simultaneously in the event of a storm of that magnitude, and it is not well understood how long disruptions to communications through the atmosphere may last.

Critical knowledge gaps relating to Space Weather impacts, as reflected in the information gathered through this project, include:

- The impact of a Carrington-level Space Weather event on the current and future satellite population.
- How electric currents in the magnetosphere and ionosphere are characterised - spatially, temporally, and in intensity.
- Understanding Space Weather impacts over short, medium and longer timescales and what this means for planning, engineering design and standards and operations.
- Understanding modifications to the atmospheric composition (specifically the creation of novel isotopes); impacts on the ionosphere (and, by extension, Beyond Line of Sight radio propagation); and the thermosphere (which has implications for LEO satellite orbit decay).
- Better understanding of impacts on debris and the relevance of Space Weather events to collision/conjunction avoidance and re-entry characteristics.
- Understanding the impact of human activities on Earth's radiation belts.
- Linkage of thermospheric Space Weather models to Space Surveillance and Tracking orbital analysis and exploration of drag variability - comparing model predictions to tracking results during Space Weather events.
- Better understanding of the impacts of minor events on satellites that are potentially due to Space Weather or meteor damage.

¹² https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220003/swsc220003.html

- Long term monitoring of the full spin state (in all 3 axes) of inactive objects in the geostationary belt (and graveyard). For many objects it is difficult to get data from satellite builders on the properties of the materials used. Some form of a curated archive of these properties (including the reflection characteristics of the satellite surfaces), would be very useful.

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

- Space Weather indicators (e.g. those modulated by the solar cycle) and a better understanding of how these affect satellites and debris.
- Orbital sensitivity to drag and the solar wind - and the dependence of these effects on satellite and debris shape and orientation.
- Intensity of currents in the magnetosphere and the indices describing this, e.g.: Auroral Electrojet Lower Index (AL) - which measures the strength of westward electric currents in the auroral region; Auroral Electrojet Upper Index (AU) - which measures the strength of eastward electric currents in the auroral region; and the Symmetric Horizontal Index (Sym-H) - which quantifies the intensity of the symmetric ring current around Earth.
- Radiation environment - Platform anomaly/electronic upset or damage risk.
- Atmospheric disturbance - Signal degradation/denial risk.
- Ground-level disturbance - Power-supply risk, electronic upsets/anomalies in ground-based infrastructure.

Atmospheric Impacts

This is a relatively new field of research – given that human activity in space was fairly limited over the first half century between the launch of Sputnik and the later growth of commercial satellite operators. As the frequency of launch increases and the numbers of artificial objects passing through the Earth’s atmosphere continue to grow, this is rapidly becoming a research area of greater importance.

Rocket launches and re-entering satellites and upper stages emit gases, aerosols, and particulates into every layer of the atmosphere from the Earth’s surface to LEO. These emissions potentially affect; climate, ozone levels, mesospheric cloudiness, ground-based astronomy, and thermosphere/ionosphere composition.

It has been estimated that the many planned large LEO constellations will require an increase in launch tonnage from the current 3,500 t/yr to over 30,000 t/yr by 2040 - and

launch emissions will increase along with payloads. In the absence of regulatory constraints, re-entry emissions from space debris and spent rocket stages are projected to increase from 1,000 t/yr currently to over 30,000 t/yr.¹³

By 2040, it is estimated that the total global flux of launch and re-entry particulate (Black Carbon and metal oxides) emissions into the stratosphere from planned LEO constellations will be comparable, in terms of mass, to the natural meteoritic background flux. Those estimates exclude plans for new satellite systems in Medium Earth Orbit (MEO), Geostationary Orbit (GEO) and future Moon/Mars exploration missions, so the actual level may be higher.¹⁴ However, there are concerns that the materials used in satellite construction (e.g. aluminium), may be significantly more harmful to the atmosphere than naturally occurring materials.

Research modelling the impact of rocket launches on loss of ozone has found that the planned future regular cadence of space tourism launches may undermine progress made in reversing ozone depletion in the Arctic springtime upper stratosphere. Black Carbon particles from rockets are almost five hundred times more efficient at warming the atmosphere than all other sources of soot combined.¹⁵

There are efforts underway to develop rockets that use alternative fuels which produce less soot. In July 2023, Land Space, a private Chinese company, launched the world's first methane liquid oxygen rocket into orbit.¹⁶ SpaceX's Raptor and the European Space Agency's Prometheus engine have also been designed to use liquid methane as a fuel, because it offers higher performance and lower costs. Methane is controversial, however, because it is one of the worst gases as far as global warming is concerned - causing around 80 times more warming than carbon dioxide over its lifetime.¹⁷

Recent research shows that about 10% of the aerosol particles in the stratosphere contain aluminium and other metals from de-orbiting satellites and rocket stages. The planned increases in the number of LEO satellites within the next few decades could result in up to 50% of stratospheric particles containing metals from re-entry. The influence of this level of metallic content on the stratosphere is unknown.¹⁸

Additionally, very little is known about the radiative impact from aluminium aerosols in the stratosphere.¹⁹

¹³ <https://ntrs.nasa.gov/api/citations/20240013276/downloads/NASA-TM-20240013276-V6.pdf>

¹⁴ <https://ntrs.nasa.gov/api/citations/20240013276/downloads/NASA-TM-20240013276-V6.pdf>

¹⁵ <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002612>

¹⁶ <https://www.fortunebusinessinsights.com/industry-reports/space-launch-services-market-101931>

¹⁷ <https://www.bbc.co.uk/future/article/20220713-how-to-make-rocket-launches-less-polluting>

¹⁸ <https://www.pnas.org/doi/10.1073/pnas.2313374120>

¹⁹ <https://ams.confex.com/ams/105ANNUAL/meetingapp.cgi/Paper/451972>

In the coming decades, the ablation of re-entering satellites and debris may lead to contamination of specific masses of not only aluminium, but also lithium, iron, nickel, copper, titanium and germanium. There is a case to be made for more research into magnetospheric and ionospheric metallic ions - before these metallic ions of space debris origin start to dominate over the natural contribution.²⁰

For some time, it has been assumed that intentionally de-orbiting objects at the end of their operational life - designing them in such a way that they disintegrate and “burn-up” in the atmosphere, or survive re-entry to be deposited in the ocean - was a practical way of avoiding adding to the risks of debris chain reactions in orbit. The recently published ESA Zero Debris Technical Booklet²¹ sets out a large set of key enablers intended to help operators minimise the creation of debris in orbit - with a strong emphasis on designing spacecraft for de-orbit/demise.

The document acknowledges that debris re-entering the atmosphere could have adverse environmental effects which are not yet understood, nor quantified. It also touches on the idea of creating a circular economy in space, through the reuse/recycling of parts and materials, but points out that this concept presents several technical challenges.

A 2023 study by University of Southampton calculated that the reuse of space junk could have a net value of between \$570 billion and \$1.2 trillion and concluded that a future circular economy for space may be financially viable.²²

While this could alleviate the atmospheric impacts of de-orbiting objects; to make this concept a reality, more research is needed in areas such as: suitable orbit assessment; reusable materials; design and engineering for reuse; robotics and other relevant technologies.

Critical knowledge gaps relating to atmospheric impacts, as reflected in the information gathered through this project, include:

- The impact of de-orbiting metals (including Al, Cu, Li, and Pb) on Earth’s atmosphere, including on the ozone layer and on the Earth's albedo.
- Long-term effects in the upper atmosphere, including chemical changes due to satellite ablation, and cooling of the upper atmosphere due to climate change.

²⁰ <https://link.springer.com/article/10.1007/s11214-024-01114-w>

²¹ https://esamultimedia.esa.int/docs/spacesafety/Zero_Debris_Technical_Booklet.pdf

²² <https://doi.org/10.1016/j.wasman.2022.10.024>

- The chemistry of the interactions of debris as it burns up on re-entry in the upper atmosphere and long-term atmospheric chemistry changes, especially for catalytic species.
- Understanding how variations in atmospheric density, including the effects of solar activity and extreme Space Weather events, affect satellite ablation.
- Understanding the high-speed interactions between debris and the atmosphere.
- Understanding the emission products from the destructive re-entry of satellites/upper stages/debris.
- For many objects it is difficult to get data from the satellite builders on the properties of the materials used. This information is critical to assessing likely atmospheric impacts of re-entry.
- Studying whether re-entry debris can nucleate cirrus or polar stratospheric clouds.
- Measuring the impacts of the substances and emissions from space debris in the laboratory - to understand what greenhouse gases could be affecting the upper atmosphere.
- Assessing the impact on the environment from both launching rockets and reentering space objects relative to other factors, i.e., natural effects such as volcanic eruptions, reentering meteoroids, etc, and other existing man-made contributors such as aviation.
- Assessing the comparative impacts of design for demise (i.e. disintegrate in atmosphere to reduce collision risk to aviation and ground property/people) versus design for non-demise (i.e. discourage hardware disintegrating upon re-entry to avoid leaving micro-particulates in the atmosphere).
- Further research on how re-entering objects burn up - to create models and tests that are closer to realistic effects of atmospheric ablation.
- Understanding the effects of space debris on the oceans and marine life.

The views on what information should be included in a standard set of environmental indicators relating to atmospheric impacts can be summarised as:

- Launch impacts on the ionosphere.
- Atmospheric impact from launch activity including upper stage disposal, use of green propellants, nozzle erosion effects.

- Atmospheric re-entry rates (if possible, together with the metrics that would reflect the level of atmospheric pollution caused by these reentries)
- Re-entry impacts on the stratosphere and mesosphere.
- Atmospheric impact from re-entry including toxicity from high-temperature reactions.
- Fragmentation of debris after collision and during atmospheric re-entry.
- A quantitative inventory of the materials ablated from reentering spacecraft and boosters, with input from industry.
- Composition and configuration of satellites and rocket bodies, to better understand atmospheric effects on burn up.
- Composition of satellites and rocket bodies, to better understand if they burn up in the first place - otherwise they create a casualty risk.
- Refining re-entry predictions as far as possible to help support decision making regarding, for example, airspace closures.

Other Aspects of Environmental Indicators

A recent (August 2024) systematic literature review of research into space industry environmental impacts identified more than 250 relevant papers and articles - nearly 100 published in just the four years between 2020-2024.²³ The rapid growth of the industry, and the critical role it has come to play in everyday life on Earth, is elevating the importance of research in this area.

Many of the contributors to this project have commented on the challenges of developing indicator frameworks and the need for a more holistic approach to understanding space environmental impacts. Several research institutions in the UK and elsewhere have begun to bring together interdisciplinary space research groups to facilitate discussions on the subject.

There are multiple initiatives seeking to address the challenges to sustainability through a variety of frameworks. The Earth and Space Sustainability Initiative²⁴ has collated a database of nearly 2,000 documents of current space sustainability standards and guidelines. In one recent example, an article published in February in the journal *One Earth* proposes a new United Nations Sustainable Development Goal (SDG) to

²³

https://auckland.figshare.com/articles/dataset/Supporting_data_for_a_systematic_literature_review_of_space_industry_environmental_impact/28004864

²⁴ <https://www.essi.org/>

safeguard Earth's orbits - drawing from the example of SDG14, which aims to safeguard the marine environment.²⁵

Many different indicators are being developed, most are focused only on a few aspects of environmental impact - for example, the risk of collisions or creation of debris. Only a few connect the sustainable use of space with other aspects of space sustainability, like the impact on the Earth environment or sustainable development on Earth. Developing models to assess the interdependencies and feedbacks between currently isolated domains would allow for a more holistic evaluation of the overall sustainability of space activities.²⁶

Current models are based on multiple assumptions and rely on historical data. Given the radical changes in the way the space economy has been developing over the past few years, historical data may be of limited utility.

There is little understanding of the complexity of the relationships between/amongst objects in space and the interaction with other environmental factors such as Space Weather events. Secondary effects that can propagate across the environment and over time are not clearly measured, nor captured by most existing models. This means that concepts like orbital carrying capacity or space environment stability might provide only a partial view or be unreliable as indicators.

Space is a complex ecosystem, and it's not clear that a standard set of indicators would be feasible or of any practical use. A more integrated approach, accounting for all aspects of sustainability, could be more effective in informing policy decisions and influencing behaviour.

However, this implies the use of multi-hazard/multi-risk approaches and modelling the complex interaction between objects, their services and functionality; interactions with natural (still largely unpredictable) changes in the space environment; and the relationship between sustainability on Earth and the sustainable use of space.

Alternatively, a set of composite vulnerability indices could be developed, as has been done for other critical environments such as marine reserves and urban coastal areas or territories at risk. Examples might include the Global Conflict Risk Index²⁷ or the Sendai Framework for Disaster Risk Reduction²⁸. Such an index would need to include socio-economic, socio-political, technical, and security-related components.

The scope of this project has primarily focused on exploring research gaps in our understanding of key environmental indicators for the use of space for civil purposes,

²⁵ <https://doi.org/10.1016/j.oneear.2024.12.004>

²⁶ <https://doi.org/10.1016/j.jsse.2024.05.007>

²⁷ <https://drmkc.jrc.ec.europa.eu/initiatives-services/global-conflict-risk-index#documents/1435/list>

²⁸ <https://www.undrr.org/implementing-sendai-framework/what-sendai-framework>

rather than defence. However, the importance of space for national security and defence cannot be ignored, and any vulnerability index would also need to take this aspect into consideration.

In addition, the focus of this project has largely been on the use of space in Earth orbit. The ambitious plans for expansion of human activity into cis-lunar space and beyond being pursued by many space agencies and the private sector will give rise to further complexities and challenges for assessing environmental impacts.

It would be helpful to clarify the purpose of environmental indicators for space - are they for specific purposes such as the safety of current and future missions, or for more general assessment of both the safety and the broad sustainability of global space activities? Decisions on licensing (at both national and international levels) must be informed by these indicators, enabling action to be taken to mitigate future risks.

If the purpose is to support global sustainability, space environmental impact assessments should be integrated with whole life cycle sustainability assessments. This is a complex process. For example, attempting to include economic and socio-political aspects might drive the assessment towards financial or socio-political sustainability. The use of global indicators with a holistic view of other impacts can risk diluting the understanding of direct impacts on the space environment.

Creating meaningful indicators requires a global approach, involving wide stakeholder engagement. No single nation can impose indicators on the global space community. However, it is clear from this high-level review that significant knowledge gaps remain and there could be considerable value in the UK research community contributing to filling those.

Key knowledge gaps identified through this project include:

- Understanding the interconnectedness of the processes and activities in the orbital environment (such as de-orbit times, collision risk criteria, spacecraft reliability, launch cadence).
- Understanding, in a more sophisticated way, how Space Weather and other factors may impact over short, medium and longer timescales, and what this means for planning, engineering design and standards and operations.
- Understanding, in a more holistic way, the connections between sustainable use of the space environment and sustainability on Earth.

Acknowledging the points reflected above about the need for more complex, whole life cycle or whole ecosystem frameworks, the suggestions from respondents for key indicators that should be included in any framework can be summarised as follows:

- Regardless of the purpose of indicators, a critical priority is a sufficiently complete and trustworthy catalogue of space objects currently around Earth and a robust means of forecasting future changes to that catalogue.
- Debris, Space Weather, cyber-related risks, pollution and uncontrolled orbit occupation should be included in the metrics.
- Adherence to a zero debris standard - missions should not contribute to the space debris population at any stage, from launch to end-of-life.
- Sustainable sourcing of materials for missions (including both launchers and satellites).
- Carbon footprint and other environmental effects arising from mission planning, manufacture and transport.
- Ground casualty risk assessment.
- Transparency about the metrics and thresholds that operators are actually using. Derived accuracy requirements that must be met in order to operationally support and sustain those metrics and thresholds. Evaluation of how well we are doing in terms of meeting these derived requirements.

Appendix C

Sources and Wider Reading

Space Weather Impacts

Analysis of the impact of atmospheric models on the orbit prediction of space debris:
<https://www.mdpi.com/2549136>

Data assimilation modelling of the thermosphere:
<https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/271>

Operational Space Weather forecasts to support satellite operations:
https://amostech.com/TechnicalPapers/2024/Atmospherics_Space-Weather/Elvidge.pdf

Revealing Orbital and Atmospheric Responses to Solar activity (ROARS) CubeSat swarm concept (Warwick-led consortium): <https://activities.esa.int/4000142470>

Using the local ensemble Transform Kalman Filter for upper atmospheric modelling:
<https://www.swsc-journal.org/articles/swsc/abs/2019/01/swsc180038/swsc180038.html>

Space Weather as main source of uncertainty in LEO:
<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019SW002373>

Influences of Space Weather forecasting uncertainty on satellite conjunction assessment: <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023SW003818>

Probabilistic Space Weather modelling and its impact on Space Situational Awareness:
<https://amostech.com/TechnicalPapers/2023/Poster/Paul.pdf>

Extreme Space Weather: Impacts on engineered systems and infrastructure:
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf

Summary of Space Weather worst-case environments:
<https://epubs.stfc.ac.uk/work/51273983>

A spacecraft environmental anomalies expert system for geosynchronous orbit:
<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009SW000473>

Statistical Analysis of LEO and GEO Satellite Anomalies and Space Radiation:
<https://www.mdpi.com/2226-4310/11/11/924>

Benefits of a Centralized Anomaly Database and Methods for Securely Sharing Information Among Satellite Operators:

https://www.rand.org/content/dam/rand/pubs/research_reports/RR500/RR560/RAND_RR560.pdf

Space weather impact on radio communication and navigation:

<https://www.sciencedirect.com/science/article/pii/S0273117724000863>

Implications of ionospheric disturbances for precise GNSS positioning in Greenland:

https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220013/swsc220013.html

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<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JA027681>

The Influence of the Lower Ionospheric Disturbances on the Operating Conditions of Navigation Satellite Systems: <https://www.intechopen.com/chapters/68567>

Solar Storm Risk to the North American Electric Grid:

<https://assets.lloyds.com/assets/pdf-solar-storm-risk-to-the-north-american-electric-grid/1/pdf-Solar-Storm-Risk-to-the-North-American-Electric-Grid.pdf>

Geomagnetically Induced Current Mitigation in New Zealand:

<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023SW003533>

Space Weather Forecasts of Ground Level Space Weather in the UK: Evaluating Performance and Limitations:

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024SW003973>

A risk assessment framework for the socio-economic impacts of electricity transmission infrastructure failure due to Space Weather:

<https://www.jbs.cam.ac.uk/wp-content/uploads/2020/08/wp1801.pdf>

Analysis of the Ground Level Enhancement GLE 60 on 15 April 2001, and Its Space Weather Effects:

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023SW003488>

Single-Event Effects in Ground-Level Infrastructure During Extreme Ground-Level Enhancements: <https://ieeexplore.ieee.org/document/9007497>

Impact of Ground-Level Enhancement (GLE) Solar Events on Soft Error Rate for Avionics: <https://ieeexplore.ieee.org/document/9020117>

Successive Interacting Coronal Mass Ejections: How to Create a Perfect Storm:

<https://spiral.imperial.ac.uk/server/api/core/bitstreams/0cb1b6c5-0279-4b57-9cd9-33cf8d364308/content>

Spacecraft Charging of the Morazán MRZ-SAT Satellite in Low Earth Orbit: Initial Results on the Influence of Energetic Electron Anisotropy on Differential Charging:
<https://arxiv.org/abs/2310.11803v1>

Atmospheric Impacts

Physics of Fluids Research Article: [Atmospheric pollution from rockets](#)

Space Waste: An update on the natural vs human-made mass influx to the atmosphere:
<https://www.researchgate.net/publication/388504095>

Worldwide Rocket Launch Emissions 2019 - An Inventory for Use in Global Models:
<https://doi.org/10.1029/2024EA003668>

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<https://doi.org/10.1073/pnas.2313374120>

Modelling the atmospheric transport and possible radiative impact of alumina aerosols emitted from the projected increase in annual satellite re-entry emissions:
<https://ams.confex.com/ams/105ANNUAL/meetingapp.cgi/Paper/451972>

Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate:
<https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002612>

Heavy Molecular and Metallic Ions in the Magnetosphere:
<https://link.springer.com/article/10.1007/s11214-024-01114-w>

Potential Perturbation of the Ionosphere by Megaconstellations and Corresponding Artificial re-entry Plasma Dust: <http://arxiv.org/abs/2312.09329>

Cooling of the upper atmosphere by enhanced greenhouse gases — modelling of thermospheric and ionospheric effects:
<https://www.sciencedirect.com/science/article/pii/S003206339290141A>

Exceptional stratospheric contribution to human fingerprints on atmospheric temperature: <https://www.pnas.org/doi/10.1073/pnas.2300758120>

Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth: <https://www.nature.com/articles/s41598-021-89909-7>

Global 3D rocket launch and re-entry air pollutant and CO₂ emissions at the onset of the megaconstellation era: <https://www.nature.com/articles/s41597-024-03910-z>

Airspace closures due to re-entering space objects:

<https://www.nature.com/articles/s41598-024-84001-2>

Unnecessary risks created by uncontrolled rocket re-entries:

<https://www.nature.com/articles/s41550-022-01718-8>

ESA Zero Debris Technical Booklet:

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

Viability of a Circular Economy for Space Debris:

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