How Open Data and Interdisciplinary Collaboration Improve Our Understanding of Space Weather: A Risk & Resiliency Perspective

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Synopsis

Space weather refers to conditions around a star, like our Sun, and its interplanetary space that may affect space assets, ground-based assets, and human life. Space weather can manifest as many different phenomena, often simultaneously. It can create complex and sometimes dangerous conditions. The study of space weather is inherently trans-disciplinary, including subfields of solar, magnetospheric, ionospheric, and atmospheric research communities, but benefiting from collaborations with policymakers, industry, astrophysics, software engineering, and much more. Effective communication is required between scientists, the end-user community, and government organizations to ensure that we are prepared for any adverse space weather effects. With the rapid growth of the field in recent years, the upcoming Solar Cycle 25 maximum, and the evolution of research-ready technologies, we feel that space weather deserves a reexamination in terms of a risk–resiliency framework. By utilizing open data science, cross-disciplinary collaborations, information systems, and citizen science, we can forge stronger partnerships between science and industry and improve our readiness as a society to mitigate space weather impacts. These ideas fit into a broader space weather “risk–resiliency framework” that can be used to further assess areas of improvement in the field.

1 Introduction

Space weather is a term that refers to the conditions around a star, like our Sun, the dynamics of its solar wind, and the interactions with the planets in that solar system that can affect the performance and reliability of space- and ground-based technology as well as any life (Temmer, 2021). The field of space weather is growing rapidly and is recognized as a severe source of risk by national and international governmental agencies and corporations. As our understanding of space weather increases, so does the realization that answering the field's toughest questions requires a new scientific approach that values convergence: The merging of innovative ideas, approaches, and technologies from a wide and diverse range of sectors and expertise. In this white paper, we reflect on the current state of space weather. We then make recommendations as to what needs to be done to advance the field during the next decade and beyond, specifically by formulating space weather in a *risk and resiliency* framework.

The grand challenges in heliophysics and space weather, especially those that involve complexity precluding unidisciplinary analyses, may require new frameworks to further the multidisciplinary understanding necessary to make significant progress. A risk and resiliency framework (Scheffer et al., 2001; de Bruijn et al., 2017; Angeler et al., 2018, see Figure 1) provides a solid foundation for the evolution of our sciences over the next decade. Within this framework, a system is treated as a complex entity that can be defined by whether or not it can accommodate changes and reorganize itself while maintaining its unique characteristics (Scheffer et al., 2001). The framework is built on two important principles: 1) Consideration of the holistic Sun-to-*society* system, and 2) Quantification of the uncertainty that arises from coarse-graining and statistical simplification (McGranaghan, 2022). If space weather is approached through the lens of risk and resiliency, the domain could share a common framework with other risks such as terrestrial weather (e.g., hurricanes). This would allow researchers to conduct trans-disciplinary research into the convolved and compounding effects of space weather.

Space weather currently affects four main industry domains: ground infrastructure, high-frequency (HF) communications, near-Earth space assets and services, and aviation. Our modern-day society has become increasingly vulnerable to space weather. Our nearest star creates five main space weather disturbances discussed in this white paper:

1. Coronal mass ejections (CMEs; e.g., Webb & Howard, 2012) are large-scale eruptions that carry millions of tons of plasma material and magnetic fields into interplanetary space, occasionally in the direction of Earth.
2. Solar flares (e.g., Benz, 2017) are intense bursts of electromagnetic radiation, often orders of magnitude above background levels.
3. Solar energetic particle (SEP; e.g., Reames, 2013) events are associated with CMEs and flares. They cause large fluxes of high-energy relativistic protons and electrons to travel through the solar wind along the interplanetary magnetic field.
4. (Coronal-hole) high-speed streams (HSSs; e.g., Cranmer et al., 2017) are flows of fast solar wind that originate from open magnetic field lines in the Sun's corona.
5. (Co-rotating) stream interaction regions (SIRs; e.g., Richardson, 2018) occur when HSSs overtake slower solar wind, producing regions of enhanced density and magnetic field strength.

In Section 2 of this white paper we provide a background of space weather as well as highlight current shortcomings in science and forecasting. Then, we share possible solutions using the concepts of open data and data science (Section 3.1), cross-disciplinary science and information systems (Section 3.2), and citizen science (Section 3.3). Our concluding thoughts and general recommendations are summarized in Section 4.

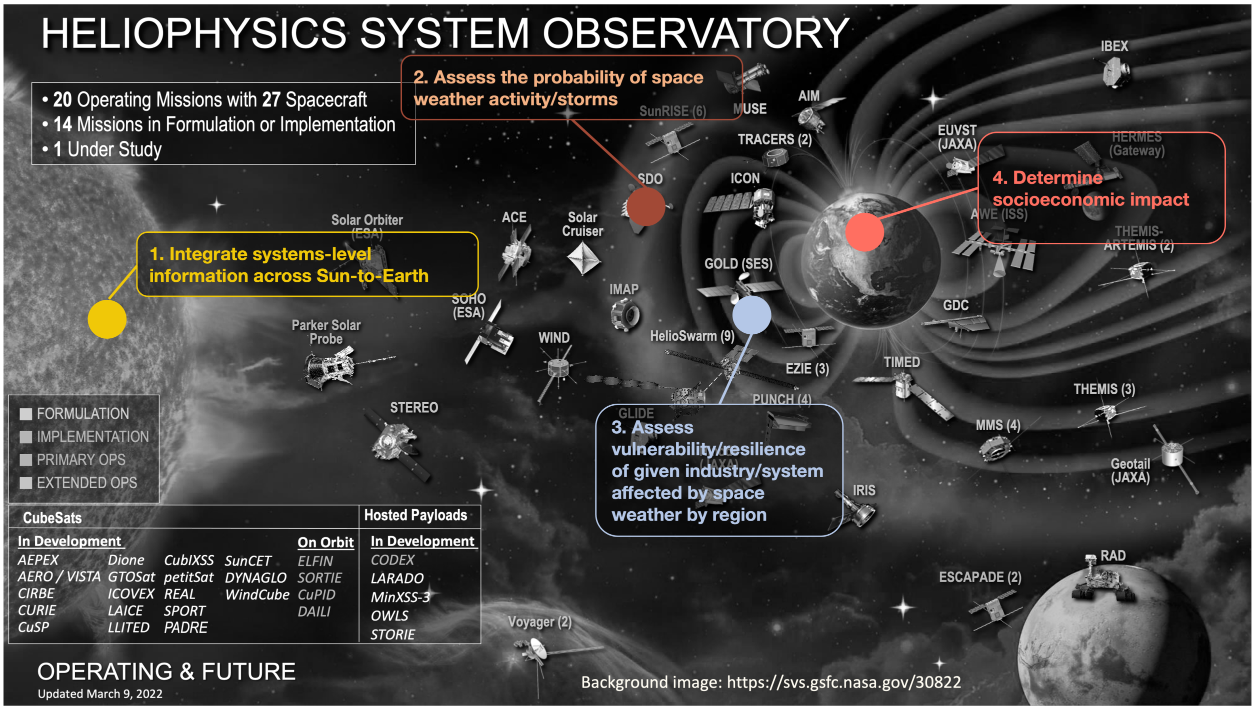

Figure 1: Overview of the Space Weather Risk and Resiliency Framework.

2 Space Weather's Effects on Industries

The disturbances from the Sun mentioned in the Introduction can manifest into three main categories of space weather effects at Earth: Geomagnetic storms and substorms, radiation storms, and radio blackouts[1]. At Earth, space weather can lead to damaging effects with varying time scales and spatial footprints (see Eastwood et al., 2017). Multiple space weather effects may also coincide, creating complex scenarios. So-called "Carrington-scale events" refer to extreme space weather events that cause widespread infrastructure damage (Tsurutani et al., 2003; Baker et al., 2013; Riley et al., 2018; Cliver et al., 2022; Hayakawa et al., 2022). For industries, Carrington-scale events often present a "worst-case scenario."

Although there are many affected industries, within this paper we will discuss how space weather currently disrupts five main technologies and infrastructures:

2.1 High-Frequency Communications

During radio blackouts and radiation storms, increased ionization in the atmosphere and ionosphere impact high-frequency (HF) radio communication, which relies on ionospheric propagation for signal transmission and integrity. Signals either become degraded from distortion and scintillation or completely absorbed by the ionosphere (Kintner et al., 2007). HF radio

[1] https://www.swpc.noaa.gov/noaa-scales-explanation

communication is used by the aviation and shipping industries, as well as by emergency responders, the amateur radio operator ("ham") community (Frissell et al., 2022, 2019), and the military (Balch et al., 2004; Kelly et al., 2014). Mobile phone networks and global navigation satellite system (GNSS) timing services can be affected and debilitated by solar flare radio noise (Kintner et al., 2009; Cannon et al., 2013). During minor-to-moderate space weather events, regional and global gaps in HF radio bands occur, but most critical infrastructure is designed to be resilient, i.e. capable of using multiple bands of communication or operating under expected noise. However, some infrastructure is not resilient enough: Even minor radio blackouts have caused airplanes to lose contact with ground controllers, especially over the North Atlantic (Fiori et al., 2022). Intense and prolonged radio blackouts caused by severe space weather (i.e. Carrington-scale events) may cause degraded HF communication performance for several days (Cannon et al., 2013; Frissell et al., 2019).

2.2 Geomagnetically-Induced Currents

During geomagnetic storms, substorms, and sudden impulse compression events, geomagnetically induced currents (GICs) in the ground may damage and cause wear and tear on infrastructure, particularly power transformers, and may offline certain power surge protection and fault-detection systems (Cannon et al., 2013; Tsurutani et al., 2003). These effects are most intense at high latitudes and in the vicinity of the auroral ovals that surround Earth's magnetic poles. GICs have also been observed at mid and low latitudes due to the effects of ionospheric current systems (Carter et al., 2015). Consequently, GIC power grid impacts are widespread and have been observed in the United Kingdom (Erinmez et al., 2002; Thomson et al., 2005), Finland (Juusola et al., 2015), Sweden (Pulkkinen et al., 2005), Spain (Torta et al., 2012), the United States and Canada (Bolduc, 2002), South Africa (Lotz & Cilliers, 2015; Matandirotya et al., 2015), Japan (Watari, 2015), China (Wang et al., 2015), and Brazil (Trivedi et al., 2007).

2.3 Satellite Infrastructure

During geomagnetic storms, the ionosphere often expands beyond its normal boundaries and changes the neutral density of low-Earth-orbit altitudes (Danilov & Laštovička, 2002; Oliveira et al., 2020). Satellites flying at these altitudes experience increased drag, causing a deceleration and lowering of their orbit as they fly through this increased density. Manual intervention often must be taken to ensure the nominal orbit of the spacecraft is maintained (Capon et al., 2019; Smith et al., 2019). A notable recent example of this phenomenon was in February 2022, when 38 SpaceX Starlink satellites re-entered Earth's atmosphere after a space weather event (Dang et al., 2022; Hapgood et al., 2022). During geomagnetic storms and substorms, energetic electrons become trapped in Earth's radiation belts, causing electrostatic charging and discharging on spacecraft, which can damage sensitive electronic equipment and solar panels (Koons et al., 1998; Wrenn et al., 2002; Hapgood, 2004; Choi et al., 2011; Loto'aniu et al., 2015). Over time, a satellite's performance may degrade due to radiation events. Many satellite providers use our current understanding of the climatology of the radiation environments to determine the expected total dose over their satellite's lifetime and include a safety margin to ensure resiliency. Complete satellite losses are rare.

2.4 Humans Working in the Atmosphere and in Space

Earth is constantly bombarded by high-energy charged particles (MeV to TeV) known as cosmic rays. These cosmic rays can originate from the Sun or interstellar space. During radiation storms, a sudden enhancement in the cosmic ray flux is sometimes observed at the ground, known as a ground level enhancement (GLE; e.g., Nitta et al., 2012). The highest-energy particles penetrate the magnetosphere and are seen at the ground as secondary particles. Due to open magnetic field lines at Earth's poles, particle fluxes are highest at high latitudes, as compared to the equator (Compton, 1933). Thus, during these radiation storms, the radiation environment at high latitudes and altitudes also becomes enhanced (O'Brien et al., 1996; Mertens et al., 2010). Due to this radiation causing ionization, such storms have biological impacts on aircrew (Dyer & Truscott, 1999; Lindborg et al., 2004). While unlikely, during severe space weather events crew radiation dose limits may be reached and airlines may choose not to fly at high latitudes to avoid adverse effects (Jones et al., 2005). Changes to flight plans have commercial and operational impacts on airlines, causing delays and increasing fuel use (Cannon et al., 2013). In geospace, humans lose radiation protection from the atmosphere, receive higher overall dose rates (Dachev et al., 2017), and are greatly affected by radiation storms (Berrilli et al., 2014). These may lead to adverse health effects over time (Cucinotta, 2014). In interplanetary space and on the Moon, humans lose all magnetic or atmospheric shielding and are exposed to higher radiation levels (Reitz et al., 2012). On Mars, due to the planet's thinner atmosphere and weaker magnetic field, dose rates are much higher than on Earth (Guo et al., 2021). The space radiation environment will present challenges to upcoming crewed lunar and martian missions.

2.5 Single Event Upsets

Single event upsets (SEUs) occur when ionizing radiation changes the internal voltages in electronics, leading to the corruption of stored or transmitted data (Dodd & Massengill, 2003; Oates, 2015). During radiation storms, highly energetic particles can cause increased rates of SEUs in electronics (Campbell et al., 2002; Lohmeyer & Cahoy, 2013). SEUs affect electronics from outer space to the ground. During the 2003 Halloween storms, about 10% (47 out of 450) of satellites experienced anomalies, one scientific satellite was lost, and 10 satellites were non-operational for over one day (Balch et al., 2004). Effects from these events were observed even at Mars, the most dramatic outcome being the loss of one instrument (ironically, a radiation monitor) aboard the 2001 Mars Odyssey satellite in orbit (Zeitlin et al., 2010). SEUs also affect avionics instruments (Taber & Normand, 1993), but almost all commercial aircraft contain mitigation techniques to limit disruptions[2]. SEUs also affect ground electronics, but in most cases, critical electronics have error-correcting mechanisms (Normand, 1996).

2.6 The Current State of Space Weather

Space weather may simultaneously affect these five domains and create complex and challenging situations for forecasters and industry managers. Our scientific understanding of these industry-specific risks to space weather is growing, but are we fully prepared for a Carrington-scale event? The answer to this question depends on who is being asked, and information regarding the ways in which industries respond to space weather is not readily publicly available. As we prepare for the next decade of space weather, including the solar cycle 25 maximum, there is a multitude of avenues by which we can improve forecasting and research to achieve clearer scientific understanding and more closely-knit collaboration.

3 Open-Data and Cross-Disciplinary Efforts in Space Weather

Adopting a new systems-science approach for space weather, utilizing citizen science and open data, will cultivate cross-disciplinary collaborations that help solve challenging problems in unique ways.

[2] https://www.faa.gov/aircraft/air_cert/design_approvals/air_software/media/TC-15-62.pdf

3.1 Open-Data and Data Science

As the amount of space weather data increases, data science projects and principles will enable new scientific discoveries via open access and collaboration.

As the number of models, data, and model–data fusion products increases with the growth of the space weather field, so does our recognition that powerful new opportunities for scientific discovery are made possible by utilizing data science principles on the increased volume and complexity of these data. Data science in regards to space weather refers to scalable architectural approaches, techniques, software, and algorithms that alter the paradigm by which data are collected, managed, analyzed, and communicated (McGranaghan et al., 2017).

Data science-driven transformation in related fields such as Earth science (Yue et al., 2016) and climate research (Carleton & Hsiang, 2016) is a testament to the immense potential of leveraging these new ideas, and similar efforts are beginning to take root in space weather. The NSF EarthCube project, Assimilative Mapping of Geospace Observations (AMGeO; Matsuo et al., 2021)[3] demonstrates the potential of implementing data science best practices. The project deploys a collaborative data science platform to investigate the constantly changing conditions of high-latitude ionospheric electrodynamics. AMGeO connects geospace observational datasets from NSF-funded facility programs (e.g. SuperDARN, AMPERE, and SuperMAG) to form a coherent specification of ionospheric electrodynamics. AMGeO does this through open-source Python software and an online interface that facilitates data acquisition and pre-processing. The project streamlines data access, collection, and integration and its software is designed to be transparent, expandable, and interoperable to encourage collaboration and engagement within the geospace science community. By shifting the way we access, describe, and share data, we enable new scientific collaborations and solutions.

AMGeO and other projects are at the forefront of a wave of new data science initiatives. Given the breadth of the space weather field—which spans from solar physics to geology—inter-disciplinary science connecting phenomena from the Sun to Earth may require datasets from many organizations, spacecraft, and agencies. Making observations and science data open source reduces the barrier to start research and can help accelerate needed discoveries—the "democratization" of science. While the needs of specific industries may vary from country to country, these specific perspectives help scientists understand why these regional variations exist. Making these data available, translatable, and accessible to a worldwide audience will help foster international collaboration, a critical step in reacting to and developing technology for the regional and global nature of space weather phenomena.

3.1.1 Recommendations

- Provide sufficient funding to operational centers (e.g. NASA's CCMC[4]) to transition space weather science models and tools into forecasting.
- Provide funding to replicate communities that successfully govern their data commons—e.g., the Pangeo Big Data Ecosystem (Hamman et al., 2018) and Pangeo Forge[5], which use analysis-ready, cloud-optimized (ARCO) data (Stern et al., 2021).

3.2 Cross-Disciplinary Science and Information Systems

Understanding space weather from a broad perspective is important for industries to communicate their needs to scientists, and vice-versa. Common scientific understanding improves the utility of discovery and unifies efforts.

[3] https://amgeo.colorado.edu
[4] https://ccmc.gsfc.nasa.gov
[5] https://github.com/pangeo-forge and https://pangeo-forge.org/

An information system is a technology that provides the structure to collect, store, process, and integrate data. These systems structure data in ways that elevate the information content and knowledge. The Sun-to-industry information system is an important part of creating industries resilient to space weather, and coordinating collaboration across disciplines improves scientific knowledge. Specifically, information currently flows mainly in one direction: from space weather to industry, but this should not be the case. Bidirectional communication improves scientists' understanding of what industries need (e.g. real-time maps of GICs used by power grids). Communication also improves trust in space weather models, which helps clarify risk. Additionally, coordinating across scientific communities is an important step in developing a "systems science" approach to space weather. Space weather comprises a broad field with many disciplines and focuses; during space weather events, disciplines from the surface of the Sun to the currents on Earth are all involved. In order for the observation, forecasting, and modeling of space weather to improve, a knowledge commons shared between disciplines should be created. This sharing of information will standardize the glossary and semantics of space weather, fostering collaboration without current communication barriers. More importantly, gathering and sharing knowledge across groups prevents the duplication of effort. Optimizing the information flow "from Sun to mud" means that we can create more refined and polished plans for how industries respond and prepare for space weather.

3.2.1 Recommendations

- Promote space weather end-user surveys to facilitate bidirectional communication between the industry and research communities.
- Target a tight integration of scientific communities along the Sun-to-industry connection: solar, heliospheric, interplanetary, magnetospheric, ionospheric, etc.
- Identify and eliminate incongruities between industries and scientific disciplines.
- Facilitate communication, collaboration, and partnerships between industry and science organizations.
- Target multi-level and multi-scale forms of communication and connection.
- Encourage studies that assess the risk and resiliency of industries following a systems science approach.

3.3 Citizen Science

Citizen science connects scientists with the public to help solve some of the most challenging space weather mysteries.

Citizen science is a rapidly growing, recently formalized, field that is fueled by the concept of cognitive surplus, i.e. that small amounts of volunteered time by many people can contribute to a larger scientific goal (Shirky, 2010). Specifically, it involves "organized research in which members of the public engage in the processes of scientific investigations by asking questions, collecting data, and/or interpreting results" (Citizen Science Central[6]). Projects that incorporate citizen science have the potential to engage and motivate broad audiences from around the world to drive new scientific discoveries, while still maintaining data quality. Citizen science also centers around creating open-data frameworks, making data accessible to a wide range of audiences, while educating the public. Citizen science projects are frequent and well-established in astronomy (e.g. Globe at Night), and within the past solar cycle, a number of projects have emerged to study space weather. One such project, Aurorasaurus (MacDonald et al., 2015), utilizes manual reports as well as aggregate Twitter sightings of aurora to develop a more accurate nowcast prediction of the auroral ovals. In some instances,

[6]http://www.citizenscience.org

citizen science reports map the aurora more realistically in real-time than operational models (Case et al., 2016). The Aurorasaurus community have also contributed to discoveries relating to the STEVE (Strong Thermal Emission Velocity Enhancement) phenomenon, using citizen scientists' aurora photographs (MacDonald et al., 2018; Chu et al., 2020; Grandin, 2020; Hunnekuhl & MacDonald, 2020; Semeter et al., 2020). Other notable citizen science projects include Solar Stormwatch (Jones et al., 2017), Solar Jet Hunter (Musset et al., 2021), and NOAA's CrowdMAG (Nair et al., 2014), which has proven capable of detecting geomagnetic fields Robinson et al. (2021). Citizen science is often an overlooked sub-genre of science, but it works in tandem with initiatives focusing on systems science, open data, and international collaboration. Citizen science in space weather enables novel ways to monitor conditions on the ground in real time, and contributes to scientific endeavors that require the analysis of large datasets. Together with developing data aggregates and knowledge commons, citizen science projects may be developed to leverage the large amount of data linking industry and science (e.g. identifying patterns that link GICs to specific ionospheric or magnetospheric indices).

3.3.1 Recommendations

- Formalize citizen science as a crucial facet of modern space weather research.
- Develop citizen science projects that make use of preexisting open data, as well as new datasets made open under recent efforts.
- Create live-updating platforms including information from vetted sources of space weather as well as compatible citizen science projects.

4 Conclusions and Recommendations

Adapting a risk–resiliency framework for space weather is crucial for tackling heliophysics' grand challenges during the next decade and beyond. Utilizing open data and data science is one way to make existing data products, tools, and software more easily accessible and widely available. The "democratization of science" will only happen if we promote existing projects and develop new efforts to converge information into a knowledge commons that can be accessed by scientists, industries, the public, and other end-users. Robust and sustainable solutions will only happen with dedicated funding. Cross-disciplinary efforts will be crucial for advancing space weather. Specifically, adopting information systems where knowledge is shared between scientists, space weather forecasters, and affected industries will improve our readiness to space weather threats. Working towards this goal will require dedicated, funded efforts to convene scientists, community members, and industry representatives (e.g. cross-disciplinary workshops and industry testbed scenarios). Finally, citizen science takes these concepts and puts them into practice. Projects such as Aurorasaurus employ science–public partnerships, community-building, reciprocity efforts, data sovereignty and accessibility, and inter-disciplinary science to advance the field of space weather in unique ways. Most importantly, citizen science projects are able to quickly respond and evolve to answer emerging science questions. Funding should be supplied to increase the amount of citizen science.

Over the next decade, the challenge of the next solar cycle maximum coinciding with an increasingly technology-dependent society will demand new technologies, collaboration, and innovative research methods to bridge knowledge gaps in science, operations, and industry response to space weather. Funding the creation of a risk–resiliency framework for space weather will ensure we can approach these problems confidently and adapt to create resilient and responsive systems.

References

Angeler, D. G., et al. 2018, BECT, 101, 543
Baker, D. N., et al. 2013, SpWea, 11, 585
Balch, C., et al. 2004, NOAA, US Dep. of Commerce, Silver Spring, Md, 106, 1
Benz, A. O. 2017, LRSP, 14, 2
Berrilli, F., et al. 2014, JSWSC, 4, A16
Bolduc, L. 2002, JASTP, 64, 1793
Campbell, A., et al. 2002, ITNS, 49, 1340
Cannon, P., et al. 2013, Extreme space weather: impacts on engineered systems and infrastructure (Royal Academy of Engineering)
Capon, C. J., et al. 2019, AdSpr, 63, 2495
Carleton, T. A., & Hsiang, S. M. 2016, Sci, 353, aad9837
Carter, B. A., et al. 2015, GeoRL, 42, 6554
Case, N. A., et al. 2016, SpWea, 14, 198
Choi, H.-S., et al. 2011, SpWea, 9, 06001
Chu, X., et al. 2020, JGRA, 125, e2020JA028110
Cliver, E. W., et al. 2022, LRSP, 19, 2
Compton, A. H. 1933, PhRv, 43, 387
Cranmer, S. R., et al. 2017, SSRv, 212, 1345
Cucinotta, F. A. 2014, PLoSO, 9, e96099
Dachev, T. P., et al. 2017, SpWea, 15, 1475
Dang, T., et al. 2022, SpWea, e2022SW003152
Danilov, A., & Laštovička, J. 2002, IJGA, 7, 278
de Bruijn, K., et al. 2017, EnSP, 70, 21
Dodd, P. E., & Massengill, L. W. 2003, ITNS, 50, 583
Dyer, C., & Truscott, P. 1999, MICPRO, 22, 477
Eastwood, J. P., et al. 2017, RiskA, 37, 206
Erinmez, I. A., et al. 2002, JASTP, 64, 743
Fiori, R. A. D., et al. 2022, JSWSC, 12, 21
Frissell, N. A., et al. 2019, SpWea, 17, 118
Frissell, N. A., et al. 2022, GeoRL, 49, e2022GL097879
Grandin, M. 2020, AGUA, 1, e2020AV000268
Guo, J., et al. 2021, A&ARv, 29, 8
Hamman, J., et al. 2018 in EGUGA, 12146
Hapgood, M. 2004, Report on demonstration of correlation of spacecraft anomalies with environment data
Hapgood, M., et al. 2022, SpWea, 20, e03074
Hayakawa, H., et al. 2022, ApJ, 928, 32
Hunnekuhl, M., & MacDonald, E. 2020, SpWea, 18, e2019SW002384
Jones, J. B. L., et al. 2005, AdSpr, 36, 2258
Jones, S. R., et al. 2017, SpWea, 15, 1125
Juusola, L., et al. 2015, SpWea, 13, 49
Kelly, M. A., et al. 2014, SpWea, 12, 601
Kintner, P. M., et al. 2007, SpWea, 5, 09003
Kintner, P. M., et al. 2009, RaSc, 44, RS0A08
Koons, H. C., et al. 1998 in 6th SCT, 7–11
Lindborg, L., et al. 2004, RPD, 110, 417
Lohmeyer, W. Q., & Cahoy, K. 2013, SpWea, 11, 476
Loto'aniu, T. M., et al. 2015, SpWea, 13, 484
Lotz, S. I., & Cilliers, P. J. 2015, AdSpr, 55, 220
MacDonald, E. A., et al. 2015, SpWea, 13, 548
MacDonald, E. A., et al. 2018, SciA, 4, eaaq0030
Matandirotya, E., et al. 2015, SpWea, 13, 185
Matsuo, T., et al. 2021 in AGUFM, SA11A–08
McGranaghan, R. M. 2022, FrASS, 9, 951411
McGranaghan, R. M., et al. 2017, JGRA, 122, 12,586
Mertens, C. J., et al. 2010, SpWea, 8, S03006
Musset, S., et al. 2021 in AGUFM, SA32A–07
Nair, M. C., et al. 2014 in AGUFM, ED53A–3470
Nitta, N. V., et al. 2012, SSRv, 171, 61
Normand, E. 1996, ITNS, 43, 2742
Oates, A. 2015 in Reliability Characterisation of Electrical and Electronic Systems, ed. J. Swingler (Woodhead Publishing), 115–141
O'Brien, K., et al. 1996, EnvInt, 22, 9
Oliveira, D. M., et al. 2020, SpWea, 18, e2020SW002472
Pulkkinen, A., et al. 2005, SpWea, 3, S08C03
Reames, D. V. 2013, SSRv, 175, 53
Reitz, G., et al. 2012, P&SS, 74, 78
Richardson, I. G. 2018, LRSP, 15, 1
Riley, P., et al. 2018, SSRv, 214, 21
Robinson, J., et al. 2021 in AGUFM, ED35A–0556
Scheffer, M., et al. 2001, Natur, 413, 591
Semeter, J., et al. 2020, AGUA, 1, e2020AV000183
Shirky, C. 2010, Cognitive surplus: Creativity and generosity in a connected age (Penguin UK)
Smith, B., et al. 2019, JGCD, 42, 2590
Stern, C., et al. 2021 in AGUFM, U51B–13
Taber, A., & Normand, E. 1993, ITNS, 40, 120
Temmer, M. 2021, LRSP, 18, 4
Thomson, A. W. P., et al. 2005, SpWea, 3, S11002
Torta, J. M., et al. 2012, SpWea, 10, S06002
Trivedi, N. B., et al. 2007, SpWea, 5, 04004
Tsurutani, B. T., et al. 2003, JGR, 108, 1268
Wang, K.-R., et al. 2015, ChA&A, 39, 78
Watari, S. 2015, EP&S, 67, 77
Webb, D. F., & Howard, T. A. 2012, LRSP, 9, 3
Wrenn, G. L., et al. 2002, AnGeo, 20, 953
Yue, P., et al. 2016, IGRSM, 4, 84
Zeitlin, C., et al. 2010, SpWea, 8, S00E06