International Coordination and Support for SmallSat-enabled Space Weather Activities

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Key Points:

- Space weather science and SmallSat technology have matured in parallel over the past, but better communication and coordination are needed.
- Areas of improvement are: orbital debris; communication protocols; export regulations; launch opportunities; data policies; and education.
- The challenges described in this commentary point to the need for a permanent international working group to coordinate efforts.

Abstract

Advances in space weather science and small satellite (SmallSat) technology have proceeded in parallel over the past two decades, but better communication and coordination is needed among the respective communities contributing to this rapid progress. We identify six areas where improved international coordination is especially desirable, including: (1) orbital debris mitigation; (2) communication protocols and spectrum management; (3) export regulations; (4) launch opportunities; (5) data policies; and (6) education. We argue the need for internationally coordinated policies and programs to promote the use of SmallSats for space weather research and forecasting while realizing maximum scientific and technical advances through the integration of these two increasingly important endeavors.

1 Introduction

Space weather is a global enterprise, not only because the technological impacts can be worldwide, but also because the observations required for effective forecasting and specification have international implications (National Science and Technology Council, 2019). This is particularly true as the use of small satellite ("SmallSat") technologies are increasingly being applied to the space weather priorities of many countries. Just as international coordination and cooperation have been adopted for ocean and air transportation systems, the time is rapidly approaching when similar policies and agreements must be formulated for space-based observing platforms.

SmallSats are a class of spacecraft with masses typically lower than 200 kg (with some exceptions), which include CubeSats that weigh ~1–10 kg with volumes measured in "units" of ~10×10×10 cm^3 cubes. There is a rich literature that describes SmallSat capabilities (e.g., National Academies of Sciences, Engineering and Medicine [NASEM] 2016; Lal et al., 2017; Millan et al., 2019). A recent report noted that "these lower-cost satellites' expendability, faster refresh, and simultaneous deployment in large numbers—to enable lower-cost spatially or temporally distributed data collection—enables greater risk-taking, experimentation, and creation of new applications not feasible with larger satellites" (Lal et al., 2017). As a result, SmallSats have made forays in almost every area of space, including science and exploration. Indeed, a number of prior missions have already shown the feasibility of using SmallSats for high-quality space weather-related research (Spence et al., 2020), while current and upcoming missions promise to further expand these capabilities in just the next few years (Caspi et al., 2020).

Here we identify several of the greatest challenges that will be faced with the blossoming deployment of SmallSat constellations. We briefly summarize each of these and conclude with recommendations on how the international space weather community may begin to address these challenges.

2 Challenges in SmallSat Development, Launch, and Flight Operations

2.1 Orbital Debris

As stated in NASEM (2016), one of the most promising potentials for CubeSats (a specific group of SmallSats) in science is that they may be used to "launch low-cost constellations and swarms comprising hundreds or even thousands of data collection platforms," thereby introducing "entirely new architectures and ways to conceptualize space science." An international study on small satellites sponsored by COSPAR had similar findings (Millan et al., 2019). Because of the vast domain over which space weather occurs, spanning from the Sun to the Earth's surface and beyond, large constellations are particularly desirable for space weather research and monitoring.

Just as great advances in accurate weather prediction over the last many decades were achieved through deployment of a comprehensive observation network, the same strategy will be required to realize significant advances in space weather prediction capabilities. Thus, just during 2019 alone, 326 SmallSats (1,200 kg and smaller) were launched, more than 17 times the number of SmallSats launched during 2009[1]. This amount adds to the already existing 900,000 pieces of orbital debris larger than a marble, with 34,000 of them larger than a softball (i.e., about the size of a 1U CubeSat), being tracked by government agencies[2]. As the number of SmallSats in orbit increases, the concern is not just the increasing number of satellites occupying orbital space, but also the fact that they will likely stay in space as debris for longer than their useful life and will be a collision hazard to other objects in space, for human spaceflight, and for robotic missions (Berger et al., 2020). Thus, the probability of collisions increases, especially if satellites are not able to be tracked well or are not maneuverable[3]. Going forward, international policies and restrictions will be imperative in three areas to: (1) ensure all SmallSats can be tracked, either actively or passively; (2) ensure no radio frequency interference; and (3) abide by stricter guidelines to de-orbit after SmallSats stop functioning. On the last point, it is worth noting that international guidelines that recommend satellites de-orbit within a 25-year period after their operational period ends not only have low compliance internationally, but are also arbitrary, and may need to be revised.

2.2 SmallSat Communications

Communications are a particular bottleneck for space weather operations, whether from single SmallSats or from constellations. As discussed below, frequency licensing for radio communications is a complicated and lengthy process even for highly experienced mission teams. Adding to the complexity is that frequency licensing and frequency coordination is necessarily inter-

[1] Per the UCS Satellite Database (https://www.ucsusa.org/resources/satellite-database#.W60XF_lRfIU)
[2] Per ESA's Space Debris Office at ESOC, Darmstadt, Germany as of February 2020 (https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers)
[3] See discussions by NASA's Orbital Debris Program Office (https://orbitaldebris.jsc.nasa.gov/quarterly-news/)

national since many SmallSats transmit telemetry packets nearly continuously while crossing over dozens of countries each orbit. Additionally, spectrum licensing agencies may impose bandwidth restrictions for certain radio-frequency (RF) bands depending on the type of mission (e.g., Earth-imaging versus celestial imaging or *in situ* measurements) regardless of the actual data volume that mission may require. In low-Earth orbit (LEO), visibility of ground stations will also limit downlink capacity and hence data "timeliness" (latency). Adding ground passes to boost downlink capacity or reduce latency may not be feasible or affordable, and thus other solutions must be investigated.

While spectrum-related issues are not qualitatively different for SmallSats compared with larger spacecraft, the speed with which SmallSats, especially CubeSats, can be developed and launched is outpacing the ability of the current coordination process for spectrum allocation and management. Furthermore, the procedure for receiving permission for spectrum use is long, complicated, and in many countries, spread across multiple agencies. Most researchers working on science-related CubeSats are typically unfamiliar with these roles and regulation, and sometimes discover them too late in the development process, risking denial of a license. CubeSat developers have historically favored lower frequencies (e.g., UHF or S-band), where equipment is less expensive and more readily available, but lower frequencies are also the most congested parts of the radio spectrum. The growing use of CubeSats may increase the need for higher bandwidth, which has its own set of costs and challenges (as discussed earlier). Regulatory authorities also prefer to know details of satellite orbits when spectrum filings are made, but these parameters may be uncertain for many researchers until late in the process, particularly for SmallSats launched as secondary payloads where the primary may not be known until only ~12 months before launch. The challenge is exacerbated for international and joint projects where spectrum allocations of multiple countries may need to be aligned.

There are other challenges as well. The expected rapid proliferation of CubeSats[4] will place increasing pressure on coordination in UHF, S, and X bands as well as other space-allocated bands, since many commercial operators use spectrum that is being used or could be used by university or federal government agencies. As more satellites are launched, the competition for spectrum would get even more intense, not just among satellites in LEO but also with satellites

[4] By some accounts (e.g., Aerospace Corporation reports) in the next decade, we may see up to 20,000 satellites launched into LEO, most of them under 500 kg. However, predictions vary widely: NSR predicts that fewer than 4,000 satellites are likely to be launched in this timeframe, while Euroconsult predicts more than 6,500.

in GEO (for example, LEO satellites crossing the equator will have to change bands to avoid interfering with GEO satellites, whose frequency rights generally take precedence). Also, as RF interference becomes more of a problem, enforcement of current national and international mechanisms to regulate radio frequencies to prevent interferences might ramp up, challenging the science community to continually stay apprised of changes to the system. A complementary option to traditional RF communication is optical laser communication, which has more than 100,000 times more frequency bands than traditional RF communication, can achieve much higher data rates, and can potentially be lighter and smaller (Klumpar et al., 2020). The main problem for laser communication is cloud cover that can block transmissions.

2.3 Export Controls

Recent advances in miniaturization of critical spacecraft systems enable SmallSats as viable and cost-effective platforms for space weather research. These include high-precision attitude determination and control systems (ADCSs) for accurate three-axis stabilized pointing; high-powered and resilient processors for on-board data processing and sophisticated command and data handling, as well as increased mission lifetime; and high-speed, high-bandwidth communications using S- and X-band radio frequencies. Improved efficiency of space-rated multi-junction photovoltaic solar cells and innovations in miniature panel deployment and even articulation technology enable high power generation from a relatively small footprint.

New technologies are under development to enable large constellations of SmallSats, particularly ones that require interaction between spacecraft, and to improve both data speeds and latency. A number of these are discussed in the companion paper by Klumpar et al. (2020). For example, miniaturized propulsion technology is required to provide station-keeping capabilities for SmallSats, whether to combat orbital decay to improve mission lifetime, or to enable large constellations whose constituent spacecraft must maintain a known and constant configuration/separation. A number of options are becoming commercially available, including cold gas thrusters and ion propulsion, but have not yet been commonly adopted. These unique and innovative technologies represent intellectual property subject to control by individual nations, potentially impeding the international partnering that is the hallmark of many SmallSat missions.

While export control regulations typically do not apply to general scientific, mathematical, or engineering principles in the public domain (typically basic and applied research), they are often hard to interpret by university-based and other scientific researchers. In some countries, concepts such as "deemed exports" – which refer to items or information provided to a foreign individual – are often difficult to understand and adhere to, and the responsibility for complying with these laws often resides with faculty members and students not trained in such matters. There is ongoing debate between government and academia regulated by export control regimes regarding the extent to which these restrictions harm legitimate scientific activity. Institutions of higher education in the United States argue that overly hawkish export control regulations could inhibit the best international students from studying in the U.S. and prevent cooperation on international projects. Over the years, export laws and regulations have become more complicated and more aggressively enforced by government agencies. In the United States, where enforcement information is publicly available, university personnel have been prosecuted for breaches. Despite recent changes to U.S. policy that now place many export controls for "pure research" missions under Commerce rather than Defense, this remains a driving concern. Harmonizing international collaborations while ensuring export compliance of their research has become a precarious balancing act for scientists.

2.4 SmallSat Launch Opportunities

SmallSat developers globally are increasingly looking for low-cost launch opportunities wherever they can find them. In 2017, India's PSLV rocket launched over 100 satellites from the United States, the Netherlands, Israel, Kazakhstan, and Switzerland. International cooperation and coordination will facilitate these efforts and expand the number of options available for SmallSat deployment and operation. For instance, the Access to Space for All initiative from the United Nations Office for Outer Space Affairs (UNOOSA)[5] works to ensure that the benefits of space, are available to all, with special focus on non-spacefaring and emerging space-faring nations, by connecting the established and emerging space actors.

2.5 Data Policies

In order to grow the science and maximize the impact of new SmallSat data (e.g., on operational space weather forecasts), it is desirable to have an open data policy. With regard to using SmallSat data for operational purposes, it may be worthwhile to follow the lead of the World

[5] https://www.unoosa.org/oosa/en/ourwork/access2space4all/index.html

Meteorological Organization (WMO) and other bodies (e.g., European Organisation for exploitation of Meteorological Satellites [EUMETSAT]) in defining a list of "essential" data and products that would be made available to all users world-wide on a free and unrestricted basis. This still allows scope for researchers to retain preferential access to more innovative observations and allows them the maximum opportunity to exploit these data via peer-reviewed publications. As with most missions, there should be a period immediately after launch reserved for calibration when data need not be shared and, clearly, the instrument developers should own Intellectual Property Rights for the data they create. To provide further incentive for this open data policy, we should encourage funding agencies to insist on a meaningful "pathway to impact" for the SmallSat data. Funding agencies should also assist this pathway by, for example, funding near-real time downlinks for operational use, or supporting missions that are demonstrators for future operational missions.

2.6 SmallSat Educational Efforts

The educational aspects of SmallSats (and CubeSats in particular) are an intrinsic part of their heritage. The technology was created in 1999 at California Polytechnic State University (CalPoly) and the Space Systems Development Lab at Stanford University[6] with the goal of facilitating access to space for university students without an increase in cost. The National Science Foundation[7] advocated for this concept and served as a trigger to motivate the flow of new ideas from academia to the scientific community (Moretto and Robinson 2008).

In the last few years, the scientific community has been actively working to prepare the nation to reduce the vulnerability to space weather hazards. Among other roles, the scientific community advances the knowledge of the fundamental nature of space weather, contributes to developing a reliable space weather prediction and forecast system, and evaluates its effects on human beings and technological assets. A long-term plan requires a multidisciplinary approach and an effort to promote the flow of knowledge from the scientific community towards the academia. SmallSat capabilities and legacy are a key piece in both requirements.

Currently, there is a significant lack of space weather programs within U.S. universities and lack of a critical mass of students and faculty within existing academic departments at colleges

[6] http://www.cubesat.org
[7] Through the "CubeSat-based Science Missions for Geospace and Atmospheric Research" program

and universities. Space weather is inherently interdisciplinary, but those interested in space weather are typically trained in academic departments that lack the breadth and depth that the field demands. The cost to create a space weather program in universities is very high and the number of potential students is likely low. This scenario has created challenges in overcoming the scientific and technical complexities of space weather research, as well as in the practical problem of sustaining support for space weather-related infrastructure and human resources. Although significant effort is being made by the scientific community (see, e.g., CCMC, Community Coordinate Modeling Center), we believe that a trigger to ensure the transfer of knowledge is to create an international collaboration between academia, agencies, and international organizations to promote cooperative academic programs that minimize the cost and maximize the number of end-users.

3 Conclusions and Recommendations

As the market and demand for SmallSats grow and their use becomes more commonplace, these platforms become more capable for implementing space weather research and operations in regions of parameter space that can be entirely unavailable to traditional larger missions, and at lower cost. Much of this advancement has, to date, been driven by the commercial market, but typically sponsored by small business innovation grants from government agencies. These agencies should continue to recognize the need for innovation and sponsorship of opportunities in this growing market. However, sharing of these technological advancements between different nations is itself complicated by the challenges outlined above, which will also need to be overcome to enable increased international collaborations in SmallSat-driven space weather research and operations.

The challenges described in this commentary point to the need for a permanent international working group to coordinate efforts, produce and maintain a list of best practices for SmallSat developers, and recommend regulations that will guide future SmallSat operations. Schrijver et al. (2015) developed a space weather roadmap that included recommendations for future Smallsat-based space weather observations. Following from this, COSPAR commissioned an international study group to construct a SmallSatellite Roadmap (Millan et al., 2019). Recommendations were aimed at scientists, industry, space agencies, policy makers, and COSPAR, with an underpinning aim of increasing exploitation of Smallsats and increasing flexibly to ensure these

Smallsats could be exploited for space weather. They suggest COSPAR could facilitate International Teams to come together like the QB50 project (e.g., Gill et al., 2013) to meet large-scale science goals via Smallsat constellation missions. This is not inconsistent with our recommendation for an international working group, but misses our further aim of enabling Smallsats to ultimately benefit providers of operational space weather services and the end users of such services.

As indicated in the companion paper by Verkhoglyadova et al. (2020), the WMO produces requirements for space weather observations with an emphasis on near-real-time operations. The existing observational network is regularly assessed against these requirements to indicate gaps in provision and to advocate for developments in the network. These efforts need to be better coordinated with other groups of observation providers, such as the Coordination Group for Meteorological Satellites (CGMS), and the SmallSat community, especially since the gaps between provision and requirements are currently often very large.

Another goal of this improved coordination is to better publicize operational space weather observational needs. A longer-term aim is to strike a balance between the WMO requirements – designed to meet the needs of the users of operational space weather services rather than necessarily being linked to upcoming observational developments – and research into new observational methods being carried out by the SmallSat community and other researchers. This balance is essential to ensure a strong connection between research and operations, to enable a pathway for continual research-to-operations developments, and to minimize the risk of lack of engagement (e.g., via the researchers dismissing the WMO requirements as being too challenging). An effective a way of achieving this connection is for our proposed working group to organize a research-to-operations observations workshop, jointly sponsored by stakeholder agencies worldwide.

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