

1 **International Coordination and Support for SmallSat-enabled Space Weather Activities**

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3 Teresa Nieves-Chinchilla¹, Bhavya Lal², Robert Robinson³, Amir Caspi⁴, David R. Jackson⁵,
4 Therese Moretto Jørgensen⁶, and James Spann⁷

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6 ¹NASA Goddard Space Flight Center, Greenbelt, MD, USA.

7 ²IDA Science and Technology Policy Institute, Washington, DC, USA

8 ³The Catholic University of America, Washington, DC, USA.

9 ⁴Southwest Research Institute, Boulder, CO, USA.

10 ⁵Met Office, Exeter, UK

11 ⁶University of Bergen, Bergen, Norway.

12 ⁷NASA Headquarters, Heliophysics Division, Washington, DC, USA.

13
14 Corresponding author: Teresa Nieves-Chinchilla (teresa.nieves@nasa.gov)

15 **Key Points:**

- 16 • Space weather science and SmallSat technology have matured in parallel, but better inter-
17 national communication and coordination is needed
- 18 • International agreements must address orbital debris, spectrum management, export con-
19 trol, launch opportunities, data access, and more
- 20 • Challenges described in this commentary point to the need for a permanent international
21 working group to coordinate efforts

22
23 **Abstract**

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

33

34 **1 Introduction**

35 Addressing the science and societal challenges related to space weather is a global
36 enterprise, not only because the impacts can be worldwide, but also because the observations
37 required for effective forecasting and specification have international implications (National
38 Science and Technology Council, 2019). This is particularly true as small satellite (“SmallSat”)
39 technologies are increasingly being applied to the space weather priorities of many countries.
40 While some international coordination is happening bilaterally between government agencies of
41 individual states, and while such initiatives are important in promoting the utilization of small
42 satellites, there is need for larger, global-scale, multi-lateral coordination. Just as international
43 coordination and cooperation have been adopted for maritime and air transportation systems,
44 similar policies and agreements must now be formulated for space-based observing platforms.

45 SmallSats are a class of spacecraft with masses typically below 200 kg (with some
46 exceptions), including CubeSats with masses of ~1–10 kg and volumes measured in “units” of
47 ~10×10×10 cm³ cubes. There is rich literature describing SmallSat capabilities (e.g., National
48 Academies of Sciences, Engineering and Medicine [NASEM] 2016; Lal et al., 2017; Millan et
49 al., 2019). A recent report noted, “these lower-cost satellites’ expendability, faster refresh, and
50 simultaneous deployment in large numbers—to enable lower-cost spatially or temporally
51 distributed data collection—enables greater risk-taking, experimentation, and creation of new
52 applications not feasible with larger satellites” (Lal et al., 2017). As a result, SmallSats have
53 made forays in almost every area of space, including science and exploration. Multiple prior
54 missions exemplify the feasibility of using SmallSats for high-quality space weather-related
55 research (Spence et al., 2020), while new missions promise to further expand these capabilities
56 (Caspi et al., 2020).

57 Per NASEM (2016), one of the most promising potentials for CubeSats in science is that
58 they enable launching “low-cost constellations and swarms comprising hundreds or even
59 thousands of data collection platforms,” thereby introducing “entirely new architectures and
60 ways to conceptualize space science.” A COSPAR-sponsored international study had similar
61 findings (Millan et al., 2019). Because of the vast domain over which space weather occurs,
62 spanning from the Sun to the Earth’s surface and beyond, extended SmallSat constellations are
63 particularly desirable for space weather research and monitoring.

64 Accurate terrestrial weather prediction achieved great advances through deployment of a
65 comprehensive observation network, and the same strategy is required to realize significant
66 advances in space weather prediction capabilities.

67 Here, we identify several significant challenges posed by the blossoming deployment of
68 SmallSat constellations that require international coordination and policy responses. We briefly
69 summarize each challenge and conclude with recommendations on how the international space
70 weather community may begin to address them. Whereas we focus here on issues requiring
71 international coordination, other papers in this special issue highlight technological challenges
72 and opportunities in applying SmallSats to achieve space weather goals (e.g., Caspi et al., 2020;
73 Verkhoglyadova et al., 2020).

74

75 **2 Challenges in SmallSat Development, Launch, and Flight Operations**

76 *2.1 Orbital Debris*

77 SmallSat use is growing quickly: in 2019 alone, almost 250 satellites with mass under
78 200 kg were launched, more than 5 times the number of SmallSats launched during 2012 (Bryce
79 Space, 2020). More than 1,100 CubeSats were launched during 2012–2019. While not all remain
80 in orbit, they add to the existing 900,000 pieces of orbital debris larger than a marble, with
81 34,000 larger than a softball (i.e., about the size of a 1U CubeSat), tracked by government
82 agencies (ESA, 2020). As the number of SmallSats in orbit increases, the concern is not just the
83 growing number of satellites occupying orbital space, but also that (depending on their altitude)
84 they will likely stay aloft as debris beyond their useful life, presenting a collision hazard for
85 human spaceflight and for other satellites and robotic missions (Berger et al., 2020). The
86 growing number of small objects in orbit can also threaten the integrity of ground-based
87 astronomical observations (Witze, 2019).

88 Despite the scientific, economic, and other benefits of SmallSat launch and use, these
89 threats from the growing number of SmallSat constellations represent a global problem. Going
90 forward, assuming that not all SmallSats can maneuver, international policies and restrictions
91 will be imperative to ensure that all SmallSats: (1) can be tracked, either actively or passively;
92 (2) cause no radio frequency interference (see next section); and (3) abide by stricter guidelines
93 to de-orbit after they stop functioning. For example, the United Nations Committee on the
94 Peaceful Uses of Outer Space (UNCOPUOS, 2019; see Annex II, Guideline B.8) has established

95 policies for tracking and de-orbiting of small satellites. However, international guidelines have
96 not been codified into law, and compliance rates remain low.

97

98 *2.2 SmallSat Communications*

99 Communications are a particular bottleneck for space weather operations, whether from
100 single SmallSats or from constellations (Hapgood, 2008). As discussed below, frequency
101 licensing for radio communications is a complicated and lengthy process even for highly-
102 experienced mission teams. Frequency licensing and coordination is necessarily international,
103 since many SmallSats transmit telemetry nearly continuously while crossing over dozens of
104 countries each orbit. Additionally, spectrum licensing agencies may impose bandwidth
105 restrictions for certain radio-frequency (RF) bands depending on the type of mission (e.g., Earth-
106 imaging versus celestial imaging or *in situ* measurements) regardless of the actual data volume
107 that mission may require. In low-Earth orbit (LEO), visibility of ground stations will limit
108 downlink capacity and hence data “timeliness” (latency). Adding ground passes to boost
109 downlink capacity or reduce latency may not be feasible or affordable, and other solutions must
110 be investigated.

111 While spectrum-related issues are qualitatively similar for SmallSats as for larger spacecraft,
112 the speed with which SmallSats, especially CubeSats, can be developed and launched is outpac-
113 ing current coordination processes for spectrum allocation and management. Procedures for re-
114 ceiving permission for spectrum use are long, complicated, and in many countries, spread across
115 multiple agencies. Many researchers deploying science-related CubeSats are unfamiliar with
116 these rules and regulations, and sometimes discover them late in the development process, risk-
117 ing denial of a license or, worse, launching without a license, as was the case with the American
118 startup Swarm Technologies (Harris, 2018). CubeSat developers have historically favored lower
119 frequencies (e.g., UHF or S-band), where equipment is less expensive and more readily avail-
120 able, but these are also the most congested parts of the radio spectrum. The growing use of Cube-
121 Sats and the accompanying explosion in data volume increases the need for higher bandwidth,
122 which has its own set of costs and challenges (as discussed earlier). Regulatory authorities also
123 prefer to know details of satellite orbits when spectrum filings are made, but these parameters
124 may be uncertain until late in the process, particularly for SmallSats launched as secondary pay-
125 loads where the primary may not be known until only ~12 months before launch. This challenge

126 is exacerbated for international and joint projects where spectrum allocations of multiple coun-
127 tries may need to be aligned.

128 In the next decade, if all proposed constellations are launched (an unlikely scenario but
129 worth considering), up to 20,000 satellites could be launched into LEO, most of them under 500
130 kg (Maclay et al., 2019). This rapid proliferation of SmallSats places increasing pressure on coor-
131 dination in UHF, S, and X bands as well as other space-allocated bands, since many commercial
132 operators use the same spectral bands as university or federal government agencies. As more
133 satellites are launched, the competition for bandwidth will intensify, not just among satellites in
134 LEO but also in GEO, and in some situations between GEO and LEO satellites. As RF interfer-
135 ence becomes more of a problem, enforcement of national and international regulations to pre-
136 vent interferences will increase, challenging the science community to continually stay apprised
137 of changes. The International Telecommunications Union (ITU) has implemented procedures
138 specifically aimed at regulating bandwidth for SmallSat communication and telemetry (von der
139 Ohe, 2020).

140 Optical laser communication is an emerging technology with over 100,000 times more fre-
141 quency bands than traditional RF, operates at lower power levels, can achieve much higher data
142 rates, and can potentially be lighter and smaller (Klumpar et al., 2020). The main problem for
143 laser communication is cloud cover that can block transmissions, but it may also be a valuable
144 capability for communications between spacecraft.

145

146 *2.3 Export Controls*

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

155 New technologies are under development to enable large SmallSat constellations,
156 particularly ones requiring interaction between spacecraft, and to improve both data speeds and

157 latency. Some of these are discussed in the companion paper by Klumpar et al. (2020). For
158 example, miniaturized propulsion technology provides station-keeping capabilities for SmallSats,
159 whether to combat orbital decay to improve mission lifetime or to enable large constellations
160 whose constituent spacecraft must maintain a known and constant configuration/separation.
161 Many options are becoming commercially available, including cold gas thrusters and ion
162 propulsion, but have not yet been commonly adopted. These innovative technologies represent
163 intellectual property subject to control by individual nations, potentially impeding the
164 international partnering that is the hallmark of many SmallSat missions.

165 While export control regulations typically exclude general scientific, mathematical, or engi-
166 neering principles in the public domain (e.g., basic and applied research), they are often hard to
167 interpret by scientists. In some countries, concepts such as “deemed exports” – items or informa-
168 tion provided to a foreign individual – are often difficult to understand and follow, and responsi-
169 bility for complying with these laws often resides with researchers and students not trained in
170 such matters. There is ongoing debate between government and academia regulated by export
171 controls regarding the extent to which these restrictions harm scientific activity. Institutions of
172 higher education in the United States argue that overly hawkish export control regulations inhibit
173 the best international students from studying in the U.S. and prevent cooperation on international
174 projects. Over time, export control-related laws and regulations have become more complicated
175 and more aggressively enforced by government agencies. In the U.S., where enforcement infor-
176 mation is publicly available, university personnel have been prosecuted for breaches. Despite re-
177 cent changes to U.S. policy that now place many export controls for “pure research” missions
178 under the Department of Commerce rather than the State Department, this remains a driving con-
179 cern. Harmonizing international collaborations while ensuring export control compliance of their
180 research has become a precarious balancing act for scientists.

181

182 *2.4 SmallSat Launch Opportunities*

183 SmallSat developers globally are increasingly looking for low-cost launch opportunities
184 wherever they can find them (e.g., Frick & Niederstrasser, 2018). Nearly 150 small launchers ei-
185 ther already exist or are being developed for launching SmallSats (Niederstrasser & Madry,
186 2020). Historically, however, it has been more economical for SmallSats to launch as rideshares
187 on larger rockets. In 2017, India’s PSLV rocket launched over 100 satellites developed by the

188 U.S., the Netherlands, Israel, Kazakhstan, and Switzerland. International cooperation and coordi-
189 nation will facilitate future efforts and expand available options for SmallSat deployment and op-
190 eration. For instance, the Access to Space for All initiative of the United Nations Office for
191 Outer Space Affairs (UNOOSA) connects established and emerging space actors to ensure the
192 benefits of space are available to non-spacefaring and emerging space-faring nations.

193
194 *2.5 Data Policies*

195 An open data policy is desirable to maximize the scientific and operational impact of new
196 SmallSat data (e.g., on space weather forecasts). For operational applications, it may be worth-
197 while to follow the World Meteorological Organization (WMO) and other bodies (e.g., European
198 Organisation for exploitation of Meteorological Satellites [EUMETSAT]) in defining a list of
199 “essential” data and products that would be made available world-wide on a free and unrestricted
200 basis. UNCOPUOS has also established policies for sharing of space weather data
201 (UNCOPUOS, 2019, Annex II). Standardization of space weather data products will facilitate
202 data exchange and ease of use. However, data sharing should allow researchers to retain prefer-
203 ential access to more innovative observations and ample opportunity to exploit those data via
204 peer-reviewed publications. As with most missions, there should be a period immediately after
205 launch reserved for calibration when data need not be shared and, clearly, the instrument devel-
206 opers should own Intellectual Property Rights for the data they create. To provide further incen-
207 tive for this open data policy, funding agencies should require a meaningful “pathway to impact”
208 for SmallSat data and can develop frameworks to facilitate these pathways by, for example,
209 funding near-real-time downlinks for operational use, or supporting missions that are demonstra-
210 tors for future operational missions.

211
212 *2.6 SmallSat Educational Efforts*

213 The educational aspects of SmallSats (particularly CubeSats) are an intrinsic part of their
214 heritage. CubeSats, with their concomitant philosophy of standardization and containerization,
215 were created in 1999 at California Polytechnic State University (CalPoly) and the Space Systems
216 Development Lab at Stanford University to facilitate access to space for university students at
217 low cost (see <https://www.cubesat.org/>). The U.S. National Science Foundation (through the
218 “CubeSat-based Science Missions for Geospace and Atmospheric Research” program) advocated

219 for this concept and served as a trigger to motivate the flow of new ideas from academia to the
220 scientific community (Moretto & Robinson, 2008).

221 In the last few years, the scientific community has been actively working to prepare our
222 technologically advanced societies to reduce vulnerabilities to space weather hazards. Among
223 other roles, the community advances knowledge of the fundamental nature of space weather,
224 contributes to developing a reliable space weather prediction and forecast system, and evaluates
225 space weather effects on human and technological assets. Long-term planning requires a multi-
226 disciplinary approach, with efforts to promote the flow of knowledge from the scientific commu-
227 nity towards academia. SmallSat capabilities and legacy are key pieces in both requirements.

228 Currently, there is a significant lack of space weather programs within U.S. colleges and
229 universities and lack of a critical mass of students and faculty within relevant departments. Space
230 weather is inherently interdisciplinary, but researchers interested in space weather are typically
231 trained in academic departments that lack the breadth and depth that the field demands. The cost
232 to create a space weather program in universities is very high and the number of potential stu-
233 dents is likely low. This scenario has created challenges in overcoming the scientific and techni-
234 cal complexities of space weather research, and in the practical problem of sustaining support for
235 space weather-related infrastructure and human resources. Although significant effort is being
236 made by the scientific community (e.g., the Community Coordinated Modeling Center), ensuring
237 the transfer of knowledge requires creating an international collaboration between academia, in-
238 dustry, government agencies, and international organizations to promote cooperative academic
239 programs that minimize the cost and maximize the number of end-users.

240

241 **3 Conclusions and Recommendations**

242 As the market and demand for SmallSats grow and their use becomes more commonplace,
243 these platforms become more capable for implementing space weather research and operations in
244 regions of parameter space that can be entirely inaccessible by traditional larger missions, and at
245 lower cost. Much of this advancement has, to date, been driven by the commercial market, but is
246 typically sponsored by grants or contracts from government agencies. These agencies should
247 continue to recognize the need for innovation and sponsorship of opportunities in this growing
248 market. However, sharing technological advancements between different nations is complicated

249 by the challenges outlined above. These will need to be overcome to enable increased
250 international collaborations in SmallSat-driven space weather research and operations.

251 The challenges described in this commentary point to the need for a permanent international
252 working group to coordinate efforts, produce and maintain a list of best practices for SmallSat
253 developers, and recommend regulations that will guide future SmallSat operations. Schrijver et
254 al. (2015) developed a space weather roadmap including recommendations for future SmallSat-
255 based space weather observations. Following from this, COSPAR commissioned an international
256 study group to construct a SmallSat Roadmap (Millan et al., 2019). Recommendations were
257 aimed at scientists, industry, space agencies, policy makers, and COSPAR, with an underpinning
258 aim of increasing exploitation of SmallSats, and increasing flexibility to ensure their application
259 to space weather. They suggest COSPAR could facilitate international teams to come together
260 like in the QB50 project (e.g., Gill et al., 2013) to meet large-scale science goals via SmallSat
261 constellation missions. This is not inconsistent with our recommendation for an international
262 working group, but misses our further aim of enabling SmallSats to ultimately benefit providers
263 of operational space weather services and the end users of such services.

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

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

280 organize a research-to-operations observations workshop, jointly sponsored by stakeholder
281 agencies worldwide.

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287

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