Addressing Gaps in Space Weather Operations and Understanding With Small Satellites

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Abstract Gaps in space weather observations that can be addressed with small satellites are identified. Potential improvements in solar inputs to space weather models, space radiation control, estimations of energy budget of the upper Earth's atmosphere, and satellite drag modeling are briefly discussed. Key observables, instruments, and observation strategies by small satellites are recommended. Tracking optimization for small satellites is proposed.

1. Introduction

The updated National Space Weather Strategy and Action Plan formulates its Objective II as the task to develop and disseminate accurate and timely space weather characterization and forecasts, including regional and global characterization of space weather conditions (NSTC, 2019). Meeting the Objective requires space weather monitoring from ground and space (Knipp & Gannon, 2019). Due to continuing improvements in small satellite (SmallSat) technologies, SmallSat missions are gaining more interest as solutions to address long-standing scientific problems and operational needs (Moretto & Robinson, 2008; NASEM, 2016).

The World Meteorological Organization (WMO) produces (http://www.wmo-sat.info/oscar/application-areas/view/25) for observations of physical variables in support of all WMO Programs, including space weather. The requirements are rolling and are regularly reviewed by the WMO InterProgram Team on Space Weather Information, Systems and Services (IPT-SWeISS), whose members are experts typically representing national operational space weather centers. The requirements emphasize near-real time space weather operations. IPT-SWeISS assessments indicate that the WMO requirements are often poorly met by the existing observation network and gaps could be very effectively filled by observations from a SmallSat constellation.

The WMO requirements are a means by which improvements to space weather observations can be advocated, which requires good communication between forecasters, instrument developers, and researchers. However, much more work needs to be done to publicize the WMO requirements list, especially in the SmallSat community. By using the requirements as a focus for SmallSat design, we can work together more effectively to fill the gaps in the observational network, and to enable SmallSat observations to be increasingly useful for research and operational applications.

The First International Workshop on SmallSats for Space Weather Research and Forecasting (SSWRF), held in Washington, DC on 2017 August 1–4, brought together experts in heliophysics, space physics, space weather operations, and related fields to help identify how SmallSats could fill current gaps in space weather understanding and forecasting. Those findings are discussed here.

2. Current Gaps and Recommendations

SmallSats have a potential to enable cutting-edge heliophysics science (NASEM, 2016). A number of successful missions have already demonstrated such capability (Spence et al., 2020, unpublished data), and many future missions have been funded or proposed, including a number with direct relevance to space

weather science and operations (e.g., Caspi et al., 2020, unpublished data; Klenzing et al., 2019). Some of the key advantages of using SmallSats for progressing heliophysics science are their high-heritage technology, rapid replaceability, low cost, and constellation opportunities for distributed measurements. These advantages can be utilized to fill the important data gaps listed below. Table 1 lists several key observables that can be achieved with instruments launched on SmallSats, and additional advances in critical enabling technologies will further enhance SmallSat capabilities for space weather operations (Klumpar et al., 2020, unpublished data). Justification and additional considerations for the observables are provided below.

2.1. Solar Inputs of Space Weather Models

One of the ongoing concerns for space weather operations is the reliance of forecasting models on data inputs from research-type instrumentation. The inputs are of a critical nature, such as the key parameters of solar flares (e.g., spectral irradiance) and CMEs (e.g., occurrence, initial speed, and direction), which constitute the main drivers of space weather, and solar photospheric magnetic fields that are essential for establishing the background state of the heliosphere.

Solar telescope designs are mature with well understood measurement requirements. Many telescopes can be readily miniaturized without compromising their space weather value; some already have been. For example, MiniCOR (Korendyke et al., 2015), a 6U CubeSat-compatible version of the STEREO/SECCHI COR2 coronagraph, fulfills NOAA's operational requirements for a coronagraph, except for the extended lifetime requirement for operational payloads. The recently selected PUNCH Small Explorer will also include a miniaturized coronagraph and three wide-field imagers, all on SmallSat platforms (see Caspi et al., 2020, unpublished data). Soft X-ray spectrometers such as those flown on MinXSS (Mason et al., 2016; Woods et al., 2017), a 3U CubeSat, can provide detailed spectral irradiance diagnostics of flares and active regions for better modeling of Earth ionospheric reactions to solar soft X-ray forcing (see also Section 2.3).

The limited lifetime and/or robustness of SmallSats can be addressed by frequent unit deployment and replacement via rideshare, and/or multiunit deployment strategies. Small satellites can enable particularly novel inputs from EUV (information on the preeruptive structure and initial eruption stages) and soft and hard X-ray imagers (plasma composition and particle acceleration) from off-Sun-Earth line viewpoints (e.g., from L_5; Vourlidas, 2015). Although SmallSat-sized EUV and soft/hard X-ray imagers and imaging spectrometers, and Doppler magnetographs, have been discussed in the scientific community, no such instruments have yet been funded or flown. The development of such miniaturized designs would greatly benefit our understanding of space weather modeling inputs, with the ultimate goal of acquiring a standardized set of small satellite space weather sensors for rideshare deployment in Sun-synchronous polar orbits or interplanetary orbits (to L_4, L_5, or elsewhere).

2.2. Space Radiation Operational Control

Space radiation poses major hazards for satellites including spacecraft charging (surface and internal), radiation dose, and single-event effects (Schrijver et al., 2015). Continuous monitoring of energetic particle fluxes in geospace from solar energetic particles (SEPs), galactic cosmic rays, and radiation belt (RB) particles, as well as auroral low-energy particles, is crucial to mitigate space weather radiation risks in accordance with WMO directives. Increases of SEP or trapped energetic electron fluxes by 2–4 orders of magnitude can occur after solar flares or after passage of high-speed streams, respectively. Direct flux measurements are the most effective way to mitigate space weather risks. In situ SEP event detections by existing space weather services are now performed by spacecraft located in the solar wind (e.g., ACE) or at Geostationary Earth Orbit. Multisatellite observations by small satellites in low Earth orbit (LEO) can significantly improve SEP event detection and give information on the size of the polar area accessed by SEPs.

The outer (electron) radiation belt (ORB) is the most dynamical part of Earth's radiation environment. Relativistic and subrelativistic ORB electrons contribute to total ionizing dose and internal charging, leading to electrostatic discharge that can damage spacecraft or destroy instrumentation. Existing empirical models of Earth's RBs (Ginet et al., 2013; Vette, 1991) are unable to reproduce significant short-term variations of the energetic electron fluxes during magnetospheric disturbances and cannot be used in operational space weather services. Numerical models like VERB (Shprits et al., 2009) are not so fast for real-time services.

Table 1
Key Observables for Space Weather Science and Operations That Can Be Provided With SmallSat Missions

Observables	Instruments	Small-sat strategy
Solar flare occurrence and intensity	Soft X-ray spectrometer (0.5–15 keV, ≥64 channels)	Small-to-medium constellation, 3–6U bus, sun-pointed, 3-axis stabilized; LEO; real-time satcomm (e.g., GlobalStar) for low-latency alerts and light curve downlinks
Soft X-ray irradiance and variability (forcing of Earth ITM)	FOV: ∼1° [full disk + lower corona], spatially integrated, few-sec cadence	
CME occurrence	White light coronagraph (FOV: 3–20 R_S, spatial resolution: 30–60 arcsec; cadence: 15–30 min)	Adapt Mini-COR or CCOR design to a 6–12U bus. ESPA-compatible. Ruggedize for deep-space applications. Sun-Sync Polar or 1 AU drifting orbit
CME speed at 20 R_S		
CME direction		Same as above but deploy >30° from Sun-Earth line
Photospheric magnetic field	LOS magnetograph (FOV: full disk, spatial resolution: 2–4 arcsec)	12U bus. Adapt Solar Orbiter/PHI data reduction FPGA code for onboard analysis
Electron flux monitoring in the ORB and in auroral region	Particle detector (0.1–4 MeV) Particle detector (0.5–20 keV)	Altitude range: 600–2,000 km, access to $L > 10$, time resolution <10 s.; 3–4 energetic channels for each high-energy detector. 5–10 channels for low-energy detector
SEP flux monitoring in polar cap	Particle detector (1–100 MeV)	
Magnetic field in the Earth's ionosphere	3-component DC magnetometer, ULF frequency range from ∼1 mHz to ∼5 Hz	LEO high inclination orbit, altitude range of the ionospheric measurements: 100–600 km
Electric field in the Earth's ionosphere	Electric field sensor, the same frequency range, magnitudes up to 200 mV/m.	
Total ion density, ion/electron temperatures in the Earth's ionosphere	Langmuir Probe, Retarding Potential Analyzer	
Upper atmosphere parameters (total neutral pressure, temperature, mass composition, winds, total electron content, flux of molecular oxygen)	Neutral pressure sensors, neutral mass spectrometers, neutral wind meters, flux probe	Short-term missions to low altitudes (250–500 km), high-drag regime, ability to resolve from hundreds of km to global scales

Reproduction of fluxes over the whole ORB requires in situ monitoring of all magnetic L-shells. This can be done by polar LEO satellites (e.g., POES, Jason, SAC-D, and Meteor M), but particle flux distributions are quite complex: one needs simultaneous spatially distributed measurements. Multiple measurements performed by identical low-cost SmallSats at different longitudes and L-shells provides knowledge of locations of high radiation risk areas and electron flux values.

Simultaneous multipoint observations provide excellent opportunities for early detection of the both SEP and ORB radiation event onsets as well as strong auroral particle precipitation. Radiation events can continue from several hours to several days. Early detections of SEP and ORB events give more time to protect satellite electronics against environment factors. SmallSat constellations could thus improve data coverage in a cost-effective, yet comprehensive, way not available via existing, more conventional methods. Data assimilation RB models (see Bourdarie et al., 2007) depend strongly on data volume and SmallSat data would be useful for overcoming deficiencies in such modeling.

Key parameters needed for space radiation monitoring are listed in Table 1. Several detectors with different orientations can measure pitch-angle distributions and reconstruct the particle fluxes in the whole inner magnetosphere. This is the approach of the Moscow State University "Universat-SOCRAT" project to develop a system of SmallSats for operational monitoring of radiation conditions in near-Earth space (Panasyuk et al., 2017).

2.3. Constraining the Energy Budget of the Earth's Upper Atmosphere

The Earth's ionosphere and upper neutral atmosphere are driven from above (solar wind and magnetosphere) and from below (middle and lower atmosphere). First-principles models of the coupled ionosphere-thermosphere (IT) system are the foundation of many forecasting efforts and rely on accurate driver

specifications (Mannucci et al., 2016). Since the IT system is highly sensitive to driving (e.g., Siscoe & Solomon, 2006) uncertainties in energy inputs and energy budget drive large errors in modeling of IT state (Deng et al., 2013; Verkhoglyadova et al., 2017) and potentially its forecasting (Verkhoglyadova et al., 2020). Mannucci et al. (2020) emphasized the need for continuously available low-latency observations directly relevant to space weather. There is growing observational evidence that without considering energy transport at multiscales, energy input into the ionosphere may be underestimated (Chaston et al., 2005; Huang et al., 2017; Miles et al., 2018; Ozturk et al., 2020; Zhu et al., 2018).

There is a need for dedicated mission focused on understanding magnetic and electric field variability and providing energy inputs at mesoscales that will improve accuracy of first-principles models and their predictive capability. A SmallSat (or CubeSat) constellation targeting the high-latitude ionosphere between 100 and 600 km altitude and employing in situ (see Table 1) or remote sensing measurements (e.g., Yee et al., 2017) would provide an integration of SmallSat-based information and quantitative improvement of the space weather modeling framework.

Moreover, there is a lack of understanding of the solar soft X-ray spectral irradiance that is both variable (Rodgers et al., 2006) and strongly impacts the Earth's ionosphere-thermosphere-mesosphere (Sojka et al., 2013, 2014). Moderate-resolution measurements (e.g., Caspi et al., 2015; Moore et al., 2018) at both short (flaring) and long (solar rotation) timescales are needed to understand this critical energetic input to the Earth's upper atmosphere. Several suggested key observables are listed in Table 1.

2.4. Improvement of Satellite Drag Models

Another area of space weather that can benefit from SmallSats is satellite drag estimation. Changes to the exospheric temperature, the local composition of neutral species, and to their net motion modify the atmospheric density, hence the drag on satellites. Errors in the modeling of drag have important consequences on missions, particularly in terms of collision avoidance (Bussy-Virat et al., 2018) and mission lifetime. However, these parameters have hardly been measured since Atmospheric Explorer and Dynamics Explorer. Global measurements of the neutrals and winds are missing, which affect the calibration of the models and the fidelity of predictions (e.g., Vallado & Finkleman, 2014). A WMO analysis of the existing observations network rated it in general to be poor for operational use.

Semiempirical thermosphere models, such as the Drag Temperature Model (Bruinsma, 2015), are already used widely for operational calculations of satellite drag. While the results are reasonably good, there are questions regarding the consistency of the accelerometer observations on which they are largely based (e.g., March et al., 2019). Measurements of total neutral pressure, temperature, mass composition, and winds would therefore be useful in constructing the next generation of satellite drag models. These new data can also be added to data assimilation systems (e.g., Elvidge & Angling, 2019; Murray et al., 2015) which are being developed to run in conjunction with physics-based models and which potentially can supply better thermospheric analyses than semi-empirical models. The development of miniaturized instruments—such as neutral pressure sensors (Bishop et al., 2019), neutral mass spectrometers (Rodriguez et al., 2016), neutral wind meters (Kordella et al., 2018), and Fabry-Perot Interferometers (Harlander & Englert, 2020)—can provide multiple opportunities to capture new information about the neutral atmosphere (see Table 1). Short-term missions to low altitudes (250–500 km) in the high-drag regime become more feasible as the relative cost of these platforms drops. Additionally, constellations of measurements can help capture the complex spatiotemporal reaction of the thermosphere to magnetic storm inputs, ranging from hundreds of kilometers up to global scales.

Constellations of SmallSats equipped with GPS receivers can also improve the estimation of atmospheric density. By applying filtering techniques (Chen & Sang, 2016) to the ephemerides of each member of the constellation, small scale features and short temporal variations in the density can now be detected. For example, the CYclone Global Navigation Satellite System (CYGNSS) mission (Ruf et al., 2013), a constellation of eight SmallSats whose primary goal is to measure winds in cyclones, is used to estimate the density at ~500 km. In addition, high-drag maneuvers are carried out to control the trajectories of the CYGNSS satellites. These maneuvers imply different magnitudes of the drag force, thus the differing effects on the satellite trajectories can be used to improve the accuracy of the density estimation in the filtering algorithms.

2.5. The Role of Ground Support in Tracking Optimization for SmallSats

Since the beginning of the CubeSat era around the year 2005, the platform capabilities and the mission coverage are the two main critical points which need to be addressed in the system communication design for LEO missions. In addition, spectrum congestion areas around ground station (GS) facilities should be considered for tracking optimization of a successful mission.

Increasing telemetry volume and decreasing data latency can enhance the use of SmallSats in LEO for space weather applications. Some improvements can be achieved through optimized site selection when deploying or choosing GSs. For any single GS, the antenna elevation mask (i.e., view to the sky), customized for a mission's radio frequency band, is the most relevant and impactful parameter. Recently developed 3-D tools and techniques can accurately determine the elevation mask based on surrounding view obstruction and RF interference sources. This enables determination of optimal antenna placement, taking into account mission performance requirements and facility constraints, and can increase satellite visibility by up to 50% in built-up, urban environments (J. Nieves-Chinchilla et al., 2017, 2018). Utilizing a network of distributed GSs provides significant additional benefit, increasing available downlink by 5–10 times when the longitudinal distribution of the stations is optimized to minimize overlap and maximize visibility. For example, SatNet can help to construct the necessary telecom infrastructure to enable the sharing of radio amateur GSs between CubeSat operators (Tubío-Pardavila et al., 2016). Alternatively, some recent SmallSats have made use of real-time satellite-to-satellite communications (e.g., GlobalStar, Iridium) to enable real-time downlink separately from GS visibility, albeit at relatively low data rates. T. Nieves-Chinchilla et al. (2020) discuss relevant issues that must be considered for international coordination, for example, for frequency licensing and/or deployment and use of widespread GS networks.

Advances in CubeSat technology, design of constellation formations such as the LAICE CubeSat mission (Westerhoff et al., 2015) and the QB50 project (Gill et al., 2013), and utilizing a network of distributed GSs such as the SatNet project (Tubío-Pardavila et al., 2016) have positioned CubeSats as an alternative for space weather exploration. Feasibility of both real-time and nonreal-time telemetry technology for SmallSat platforms needs to be explored. Low-latency or constant downlinking is critical for time-sensitive observations, for example, alerts for solar flares, CMEs, and SEPs, while less critical, but more detailed, information can be downlinked in a traditional manner with higher latency. The need of data volume and the need to support SmallSat missions, tracking and control operations, has given rise to a major relevancy on GS locations and design in urban environments. The tracking optimization could maximize the satellite access times and therefore enhance space weather operations and understanding with SmallSats platforms.

3. Summary

We have identified several current gaps in space weather understanding and operational needs that can be addressed with SmallSats. We recommended key observables, instruments, and observations strategies that can enhance space weather operations in several domains.

Data Availability Statement

No new data were used in preparing this manuscript.

References

Bishop, R. L., Walterscheid, R., Clemmons, J., Barjatya, A., & Gunter, L. O. (2019). The low-latitude ionosphere/thermosphere enhancements in density (LLITED) mission. *Proceedings of the 33rd Annual AIAA/USU Conference on Small Satellites, Upcoming Missions, SSC19-WKV-05*. Retrieved from https://digitalcommons.usu.edu/smallsat/2019/all2019/101/

Bourdarie, S., Maget, V., Friedel, R., Boscher, D., Sicard, A., & Lazaro, D. (2007). Complementarity of measurements and models in reproducing Earth's radiation belt dynamics. In J. Lilensten (Eds.), Space weather. Astrophysics and space science library (Vol. 344, pp. 219–229). Dordrecht, The Netherlands: Springer. https://doi.org/10.1007/1-4020-5446-7_20

Bruinsma, S. L. (2015). The DTM-2013 thermosphere model. *Journal of Space Weather and Space Climate*, *5*, A1. https://doi.org/10.1051/swsc/2015001

Bussy-Virat, C. D., Ridley, A. J., & Getchius, J. W. (2018). Effects of uncertainties in the atmospheric density on the probability of collision between space objects. *Space Weather*, *16*(5), 519–537. https://doi.org/10.1029/2017SW001705

Caspi, A., Woods, T. N., & Warren, H. P. (2015). New observations of the solar 0.5–5 keV soft X-ray spectrum. *The Astrophysical Journal*, *802*(1), L2. https://doi.org/10.1088/2041-8205/802/1/L2

Chaston, C. C., Peticolas, L. M., Carlson, C. W., McFadden, J. P., Mozer, F., Wilber, M., et al. (2005). Energy deposition by Alfvén waves into the dayside auroral oval: Cluster and FAST observations. *Journal of Geophysical Research*, *110*(A2), A02211. https://doi.org/10.1029/2004JA010483

Chen, J., & Sang, J. (2016). Thermospheric mass density measurement from precise orbit ephemeris. *Geodesy and Geodynamics*, *7*(3), 210–215. https://doi.org/10.1016/j.geog.2016.05.004

Deng, Y., Fuller-Rowell, T. J., Ridley, A. J., Knipp, D., & Lopez, R. E. (2013). Theoretical study: Influence of different energy sources on the cusp neutral density enhancement. *Journal of Geophysical Research: Space Physics*, *118*(5), 2340–2349. https://doi.org/10.1002/jgra.50197

Elvidge, S., & Angling, M. J. (2019). Using the local ensemble Transform Kalman Filter for upper atmospheric modelling. *Journal of Space Weather and Space Climate*, *9*, A30. https://doi.org/10.1051/swsc/2019018

Gill, E., Sundaramoorthy, P., Bouwmeester, J., Zandbergen, B., & Reinhard, R. (2013). Formation flying within a constellation of nano-satellites: The QB50 mission. *Acta Astronautica*, *82*(1), 110–117.

Ginet, G. P., O'Brien, T. P., Huston, S. L., Johnston, W. R., Guild, T. B., Friedel, R., et al. (2013). AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment. *Space Science Reviews*, *179*(1–4), 579–615. https://doi.org/10.1007/s11214-013-9964-y

Harlander, J. M., & Englert, C. R. (2020). Laboratory demonstration of mini-MIGHTI: A prototype sensor for thermospheric red-line (630 nm) neutral wind measurements from a 6U CubeSat. *Journal of Atmospheric and Solar-Terrestrial Physics*, *207*, 105363. https://doi.org/10.1016/j.jastp.2020.105363

Huang, C. Y., Huang, Y., Su, Y.-J., Hairston, M. R., & Sotirelis, T. (2017). DMSP observations of high latitude Poynting flux during magnetic storms. *Journal of Atmospheric and Solar-Terrestrial Physics*, *164*, 294–307. https://doi.org/10.1016/j.jastp.2017.09.005

Klenzing, J., Davidson, R. L., Jones, S. L., Martinis, C., Zawdie, K. A., Earle, G. D., et al. (2019). The petitSat mission: Science goals and instrumentation. *Advances in Space Research*, *66*(1), 107–115. https://doi.org/10.1016/j.asr.2019.12.013

Knipp, D. J., & Gannon, J. L. (2019). The 2019 National Space Weather Strategy and action plan and beyond. *Space Weather*, *17*(6), 794–795. https://doi.org/10.1029/2019SW002254

Kordella, L. J., Earle, G. D., Roth, G., Moel, S., Robertson, R. V., Davidson, R. L., et al. (2018). A neutral wind instrument for nano-satellite platforms. *Review of Scientific Instruments*, *89*(9), 095001. https://doi.org/10.1063/1.5054097

Korendyke, C. M., Chua, D. H., Howard, R. A., Plunkett, S. P., Socker, D. G., Thernisien, A. F. R., et al. (2015). MiniCOR: A Miniature Coronagraph for Interplanetary CubeSat. *Proceedings of the 29th Annual AIAA/USU Conference on Small Satellites, Science/Mission Payloads, SSC15-XII-6*. Retrieved from http://digitalcommons.usu.edu/smallsat/2015/all2015/82

Mannucci, A. J., Berger, T., Bortnik, J., Cherniak, I., Gulyaeva, T., Hoeg, P., et al. (2020). Recommendations for the community. *Proceedings of the Chapman Conference on Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes*. https://doi.org/10.5281/zenodo.3986940

Mannucci, A. J., Hagan, M. E., Vourlidas, A., Huang, C. Y., Verkhoglyadova, O. P., & Deng, Y. (2016). Scientific challenges in thermosphere-ionosphere forecasting. *Journal of Space Weather and Space Climate*, *6*, E01. https://doi.org/10.1051/swsc/2016030

March, G., Doornbos, E. N., & Visser, P. N. A. M. (2019). High-fidelity geometry models for improving the consistency of CHAMP, GRACE, GOCE and Swarm thermospheric density data sets. *Advances in Space Research*, *63*(1), 213–238. https://doi.org/10.1016/j.asr.2018.07.009

Mason, J. P., Woods, T. N., Caspi, A., Chamberlin, P. C., Moore, C., Jones, A., et al. (2016). Miniature X-ray Solar Spectrometer: A science-oriented, University 3U CubeSat. *Journal of Spacecraft and Rockets*, *53*(2), 328–339. https://doi.org/10.2514/1.A33351

Miles, D. M., Mann, I. R., Pakhotin, I. P., Burchill, J. K., Howarth, A. D., Knudsen, D. J., et al. (2018). Alfvénic dynamics and fine structuring of discrete auroral arcs: Swarm and ePOP observations. *Geophysical Research Letters*, *45*(2), 545–555. https://doi.org/10.1002/2017GL076051

Moore, C. S., Caspi, A., Woods, T. N., Chamberlin, P. C., Dennis, B. R., Jones, A. R., et al. (2018). The instruments and capabilities of the miniature X-ray solar spectrometer (MinXSS) CubeSats. *Solar Physics*, *293*(2), 21. https://doi.org/10.1007/s11207-018-1243-3

Moretto, T., & Robinson, R. M. (2008). Small satellites for space weather research. *Space Weather*, *6*(5), 05007. https://doi.org/10.1029/2008SW000392

Murray, S. A., Henley, E. M., Jackson, D. R., & Bruinsma, S. L. (2015). Assessing the performance of thermospheric modeling with data assimilation throughout solar cycles 23 and 24. *Space Weather*, *13*(4), 220–232. https://doi.org/10.1002/2015SW001163

National Academies of Sciences, Engineering, and Medicine. (2016). *Achieving science with CubeSats: Thinking inside the box*. Washington, DC: The National Academies Press. https://doi.org/10.17226/23503

National Science and Technology Council. (2019). *National space weather strategy and action plan*. Washington, DC: Executive Office of the President (EOP). Retrieved from https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf

Nieves-Chinchilla, J., Farjas, M., & Martínez, R. (2017). Measurement of the horizon elevation for satellite tracking antennas located in urban and metropolitan areas combining geographic and electromagnetic sensors. *Measurement*, *98*, 159–166. https://doi.org/10.1016/j.measurement.2016.11.030

Nieves-Chinchilla, J., Martínez, R., Farjas, M., Tubio-Pardavila, R., Cruz, D., & Gallego, M. (2018). Reverse engineering techniques to optimize facility location of satellite ground stations on building roofs. *Automation in Construction*, *90*, 156–165. https://doi.org/10.1016/j.autcon.2018.02.019

Nieves-Chinchilla, T., Robinson, R., Caspi, A., Jackson, D. R., Moretto Jørgensen, T., Lol, B., & Spann, J. (2020). International coordination and support for SmallSat-enabled space weather activities. *Space Weather*, *18*, e2020SW002568. https://doi.org/10.1029/2020SW002568

Ozturk, D. S., Meng, X., Verkhoglyadova, O. P., Varney, R. H., Reimer, A. S., & Semeter, J. L. (2020). A new framework to incorporate high-latitude input for meso-scale electrodynamics: HIME. *Journal of Geophysical Research: Space Physics*, *125*(1), e2019JA027562. https://doi.org/10.1029/2019JA027562

Panasyuk, M. I., Podzolko, M. V., Kovtyukh, A. S., Brilkov, I. A., Vlasova, N. A., Kalegaev, V. V., et al. (2017). Optimization of measurements of the Earth's radiation belt particle fluxes. *Cosmic Research*, *55*(2), 79–87. https://doi.org/10.1134/S0010952516060071

Rodgers, E. M., Bailey, S. M., Warren, H. P., Woods, T. N., & Eparvier, F. G. (2006). Soft X-ray irradiances during solar flares observed by TIMED-SEE. *Journal of Geophysical Research*, *111*(A10), A10S13. https://doi.org/10.1029/2005JA011505

Rodriguez, M., Paschalidis, N., Jones, S., Sittler, E., Chornay, D., Uribe, P., & Cameron, T. (2016). Miniaturized ion and neutral mass spectrometer for CubeSat atmospheric measurements. *Proceedings of the 30th Annual AIAA/USU Conference on Small Satellites, Instrument/Science Missions*. Retrieved from https://digitalcommons.usu.edu/smallsat/2016/S8InstSciMis/9/

Ruf, C., Unwin, M., Dickinson, J., Rose, R., Rose, D., Vincent, M., & Lyons, A. (2013). CYGNSS: Enabling the future of hurricane prediction [remote sensing satellites]. *IEEE Geoscience and Remote Sensing Magazine*, *1*(2), 52–67. https://doi.org/10.1109/MGRS.2013.2260911

Schrijver, C. J., Kauristie, K., Aylward, A. D., Denardini, C. M., Gibson, S. E., Glover, A., et al. (2015). Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS. *Advances in Space Research*, *55*(12), 2745–2807. https://doi.org/10.1016/j.asr.2015.03.023

Shprits, Y. Y., Subbotin, D., & Ni, B. (2009). Evolution of electron fluxes in the outer radiation belt computed with the VERB code. *Journal of Geophysical Research*, *114*(A11), A11209. https://doi.org/10.1029/2008JA013784

Siscoe, G., & Solomon, S. C. (2006). Aspects of data assimilation peculiar to space weather forecasting. *Space Weather*, *4*(4), S04002. https://doi.org/10.1029/2005SW000205

Sojka, J. J., Jensen, J., David, M., Schunk, R. W., Woods, T., & Eparvier, F. (2013). Modeling the ionospheric E and F1 regions: Using SDO-EVE observations as the solar irradiance driver. *Journal of Geophysical Research: Space Physics*, *118*(8), 5379–5391. https://doi.org/10.1002/jgra.50480

Sojka, J. J., Jensen, J. B., David, M., Schunk, R. W., Woods, T., Eparvier, F., et al. (2014). Ionospheric model-observation comparisons: E layer at Arecibo incorporation of SDO-EVE solar irradiances. *Journal of Geophysical Research: Space Physics*, *119*(5), 3844–3856. https://doi.org/10.1002/2013JA019528

Tubío-Pardavila, R., Diaz, J. E. E., Rohling, A. J., Ferreira, M. G. V., Dos Santos, W. A., Puig-Suari, J., & Aguado-Agelet, F. (2016). Integration of the INPE ground station into the SATNet network for supporting small satellites programs in Brazil. *Proceedings of the 1st IAA Latin American Symposium on Small Satellites, IAA-BR-10-01*. Retrieved from https://www.researchgate.net/publication/331045064_Integration_of_the_INPE_Ground_Station_into_the_SATNet_Network_for_Supporting_Small_Satellites_Programs_in_Brazil

Vallado, D. A., & Finkleman, D. (2014). A critical assessment of satellite drag and atmospheric density modeling. *Acta Astronautica*, *95*, 141–165. https://doi.org/10.1016/j.actaastro.2013.10.005

Verkhoglyadova, O. P., Meng, X., Mannucci, A. J., Mlynczak, M. G., Hunt, L. A., & Lu, G. (2017). Ionosphere-thermosphere energy budgets for the ICME storms of March 2013 and 2015 estimated with GITM and observational proxies. *Space Weather*, *15*(9), 1102–1124. https://doi.org/10.1002/2017SW001650

Verkhoglyadova, O. P., Meng, X., Mannucci, A. J., Shim, J.-S., & McGranaghan, R. (2020). Evaluation of total electron content prediction using three ionosphere-thermosphere models. *Space Weather*, *18*(9), e2020SW002452. https://doi.org/10.1029/2020SW002452

Vette, J. I. (1991). *The AE-8 trapped electron environment. NSSDC/WDC-A-R&S 91-24*. Retrieved from https://ntrs.nasa.gov/citations/19920014985

Vourlidas, A. (2015). Mission to the Sun-Earth L5 Lagrangian point: An optimal platform for space weather research. *Space Weather*, *13*(4), 197–201. https://doi.org/10.1002/2015SW001173

Westerhoff, J., Earle, G., Bishop, R., Swenson, G. R., Vadas, S., Clemmons, J., et al. (2015). LAICE CubeSat mission for gravity wave studies. *Advances in Space Research*, *56*(7), 1413–1427.

Woods, T. N., Caspi, A., Chamberlin, P. C., Jones, A., Kohnert, R., Mason, J. P., et al. (2017). New solar irradiance measurements from the miniature X-ray solar spectrometer CubeSat. *The Astrophysical Journal*, *835*(2), 122. https://doi.org/10.3847/1538-4357/835/2/122

Yee, J. H., Gjerloev, J., Wu, D., & Schwartz, M. J. (2017). First application of the Zeeman technique to remotely measure auroral electrojet intensity from space. *Geophysical Research Letters*, *44*(20), 10134–10139. https://doi.org/10.1002/2017GL074909

Zhu, Q., Deng, Y., Richmond, A., & Maute, A. (2018). Small-scale and mesoscale variabilities in the electric field and particle precipitation and their impacts on Joule heating. *Journal of Geophysical Research: Space Physics*, *123*(11), 9862–9872. https://doi.org/10.1029/2018JA025771