Space Domain Awareness Advanced Radiation Awareness Technology: Hosted Payloads

Dr. Joseph Mazur
The Aerospace Corporation
Capt George Eberwine
Space Systems Command, United States Space Force
Mr. Donn Murray
Space Systems Command, United States Space Force

ABSTRACT

As the warfighter becomes ever more reliant on space assets, and as the space environment grows increasingly contested, the United States Force (USSF) must have accurate, reliable, and timely Space Domain Awareness (SDA) capabilities. When a USSF satellite experiences an anomaly, the operator needs the ability to rapidly make a distinction between anomalies resulting from natural (i.e. related to the space environment) or non-natural phenomena. The USSF and its partners have developed and prototyped a family of in-situ sensors including Energetic Charged Particle (ECP) prototypes such as ECP-Lite, as well as Catcher, for local monitoring of radiation and other potential causes of satellite anomalies. The data flowing from such sensors can not only inform the space vehicle operator on real-world environmental and man-made effects, but also can inform the overall space weather and operational picture.

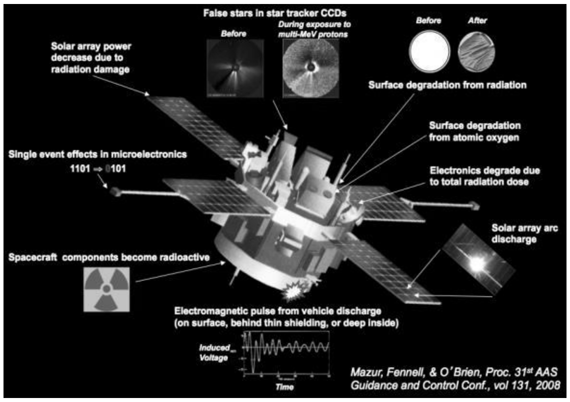
1. INTRODUCTION

Satellites operate within a background of interactions with the natural space radiation environment. By describing the results as a background, we mean that the interactions are usually not the primary focus of system design or operations. When satellite design specifications accurately capture the orbital environment and the vehicle and payload engineering adequately mitigates susceptibilities, it's less likely that anomalies will appear on orbit.

Our goal in this discussion is to explain a practical approach to account for the unexpected as it relates to space weather and other environmental drivers. It is practical because it is rooted in empirical experience and focused on an attribution mission. We want to eliminate the unexpected because space operations today require rapid decision-making in an increasingly contested background. We got to this place because of experience in mitigating the risk of space weather and analyzing its effects when risks became reality.

The primary way that the combined communities of satellite engineering and space environment experts have learned about what happens to satellites in space is through investigation of anomalies. This sounds like backwards logic: we should design, analyze, and test before flight to remove the risk, and then sharpen the mitigation techniques after problems occur. In practice, learning through experience is the most direct route. The space environment area isn't unique in this flow. For example, the launch vehicle community learned lessons about the complex interactions between vehicle hardware and the vibroacoustic launch environment as well as all the physics of high-pressure fuel flow from launch failures. The flow and generation of design rules isn't always clean and logical, but today we benefit from many lessons-learned related to space weather.

What kinds of effects are we discussing? Fig. 1 summarizes the primary space environment effects as learned from observations of on-orbit performance and, in some cases, followed-up with theory and ground and space laboratory research.



Mazur, Fennell, & O'Brien, Proc. 31st AAS Guidance and Control Conf., vol 131, 2008

Fig. 1. The full range of possible space radiation environment interactions with satellite hardware [1].

Space weather is the common term for the drivers of these effects: from plasma energies to relativistic electrons and ions, the space environment is a complex field with few terrestrial analogues. The term space weather became popular in the early 1990s [2]. Calling it 'weather in space' has benefits for communication with non-experts: it sounds better than 'space environment interactions' or 'radiation effects' but at the same time the simplicity suggests that the phenomena can be understood using weather approaches. This is one area where the space weather community struggles, especially when it is the interaction between the space environment and the space hardware that is the real problem and the physical properties of those interactions have few analogues with life on Earth.

Terrestrial weather drivers like wind and rain are familiar; most people have direct experience with weather and climate interactions with physical systems like roads, roofs, as well as operations like automobile and airline travel. The benefits of relating space environment to terrestrial weather are certainly there in the context of public affairs and general communication but in critical satellite operations the terminology matters. We'll discuss this disconnect in the context of space domain doctrine later, but here it's important to note that cognition of what happens in space radiation is no different than the study and prediction of satellite orbits and maneuvers: you can't drive a satellite like a car, nor can you imagine space weather affecting a satellite like rain on the road or atmospheric turbulence affecting an aircraft.

2. ROLE WITHIN DOCTRINE

Operating in the space domain and engineering what that means throughout a system's lifetime is not new. Commercial, civil, and national security have played often intertwined roles since early 1958. We only have to look at a snapshot in the early 1965 to appreciate the early and earnest adoption of space for many applications.

In May 1965, the commercial sector achieved a milestone with the first operational Early Bird communications satellite that provided telecommunications within Europe and between Europe and the US and the first television demonstration. In the same year, civil space marched on the roadmap to the moon with two flights of the Gemini crewed program. What we would now call space weather and environmental research included flights of the Orbiting Solar Observatory-2 to measure solar photon radiation and Pegasus-1 and -2 micrometeoroid detectors with almost seven hundred square feet of collecting area. DoD systems also targeted space weather with multi-payload Orbital Vehicles-1 and -3 as well as approximately eight ride-along small satellites for targeted technological studies. The US even performed an on-orbit test of the first nuclear reactor power supply in space with the Snapshot project. All of these activities occurred just in the first 6 months of 1965.

Turning to today, we face fewer unknowns about how satellites will fare in space, but the pace of change in some aspects is just as fast as it was in 1965. For example, proliferated low-Earth orbit constellations for commercial and defense applications involve new aspects of space-based networking that were not components of early space architectures. Testing and fielding of anti-satellite weapons was also not a prevalent driver of early system operations.

We refer to the 2020 Space Capstone Publication (Spacepower – SCP, [3]) for a defined structure of what these and other challenges mean for the USSF. The SCP describes three dimensions of space operations within which space environment (we'll still refer to it as space weather here) play a defined role as shown in Fig. 2.

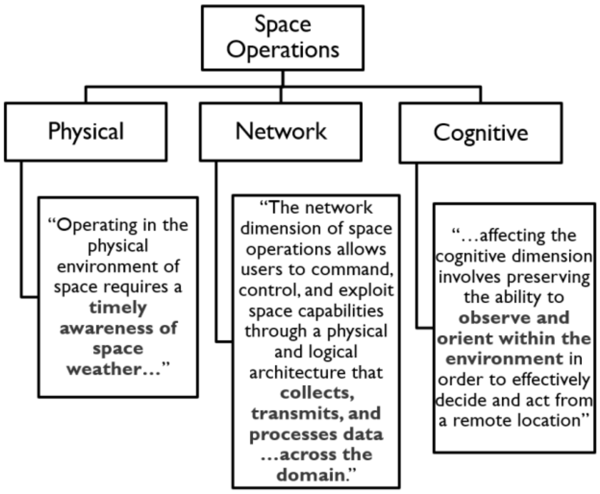


Fig. 2. These are the three dimensions of space operations described in the 2020 SCP. The highlighted text indicates the role of space weather awareness within each dimension; refer to the SCP for more context and detail.

Taking these in turn, the physical dimension makes sense as space weather is an unavoidable component of space, whether we consider low-Earth orbit or cislunar. The details are different depending on where we are operating, and there are unknowns related to time and propagation of hazards, hence the requirement of having a timely awareness. This discussion can't provide a full review of space weather as it relates to space-based systems; see [4] and references therein for more detail.

The network dimension of space weather may be less clear but is central to awareness. Space is not one physical place and the intersection between a given orbit and a radiation hazard depends on time and location. At geostationary orbit (GEO) for example, the surface charging hazard at one local time is not necessarily the same at a location even a few thousand kilometers away [5]. A network of monitors could provide warning for satellites about to enter a hazardous region. While other radiation effects can affect multiple orbit regimes almost simultaneously (for example, intense solar particle radiation throughout GEO and high-latitude low-Earth orbit - LEO), it is only through a network approach of information moving at machine speed that a complete picture forms for space domain awareness.

Space weather interactions with satellites is a component of observing and orienting within the environment in order to decide and act. Ruling in or out the role of environment in an anomalous state is on the checklist for decisions, whether they are made autonomously or by a human on the loop. How the machines or humans cognitively handle whatever space weather information and assessments they have is critical. Up to now, initial estimates of probabilities of effects have not been uniform in quality. Common perceptions based on terrestrial cause and effect are not relevant to what happens on orbit.

Cognition not only affects operations, but also acquisition. If, for example, there is a perception that growing commercial space has few issues with space weather, other system acquirers may take risks in design and procurement that aren't really knowable and only based on perceptions of commercial success. If system Y appears to be working just fine, then given all the unknowns and the complexity of dynamic commercial activities, is it reasonable that a similar approach would yield similar results?

The same question applies to operations when a space weather event appears in the public news. If that is the latest source of information an operator has when they come on station, how accurately would they assess a system upset that then occurs on their shift?

3. VALUE PROPOSITION

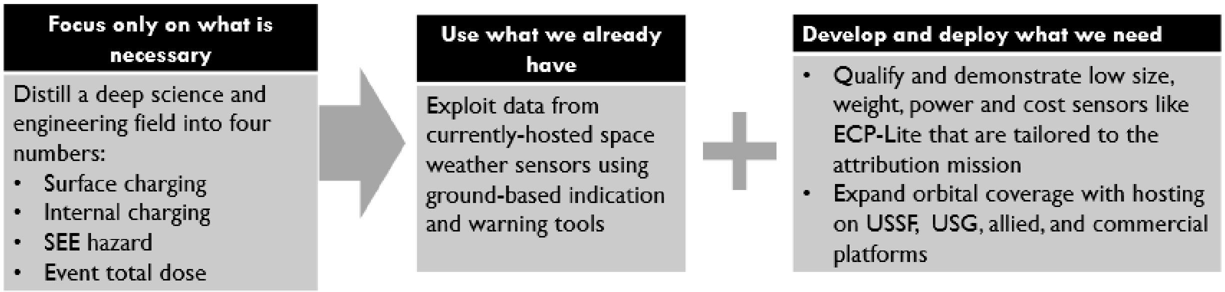
It is too costly to use traditional engineering approaches of analysis and test and inspection to eliminate all space weather risk to satellites. It is increasingly the case that the primary unknowns are on the hardware side: whether it is a new thermal control paint or an advanced electronic component, being able to forecast how the material or an electronic component will behave on orbit and how that behavior could affect a larger system depends on having ground-truth data on space environment exposure. With state-of-the-art system on a chip microelectronics, the required single-event effects testing would require too much time and cost for most acquisitions [6], and that's just one electronic component from potentially hundreds that are critical for operation. There are simply too many new technologies and too few testing laboratories to adequately test everything.

Fig. 3 lays out the basics of our value proposition. Timelines for decisions are faster today than they were twenty years ago. We don't want to rely on deep-dives for the cognitive layer. We require the information at machine-speed.

Problem	**➢ Space weather can cause anomalies for spacecraft and payloads** **➢ Most systems lack the capability to rapidly and accurately identify space weather impacts** **➢ Result is prolonged and uncertain attribution**
Proposition	**Know within minutes if space weather caused or did not cause a satellite anomaly**

Fig. 3. Problem statement and value proposition for space weather awareness.

Fig. 4 describes the methods to achieve the value proposition. While the logic flows in the diagram from left to right, it was the recognition that accuracy and in some cases the phenomenology would require some kind of measurement at every system of interest. In fact, the localized nature of the surface charging hazard was one of the primary drivers of the 2015 US Secretary of the Air Force policy memo for 'energetic charged particle' detection on every pre-milestone-B satellite system [7].



Focus only on what is necessary

Distill a deep science and engineering field into four numbers:

- Surface charging
- Internal charging
- SEE hazard
- Event total dose

Use what we already have

Exploit data from currently-hosted space weather sensors using ground-based indication and warning tools

Develop and deploy what we need

- Qualify and demonstrate low size, weight, power and cost sensors like ECP-Lite that are tailored to the attribution mission
- Expand orbital coverage with hosting on USSF, USG, allied, and commercial platforms

Fig. 4. Problem statement and value proposition for space weather awareness.

Anticipating that the community would need an affordable yet accurate means of monitoring the hazards led us to develop the system that we describe in section 5. That development started with distilling a complicated scientific and engineering field into four numbers for the four main hazards [8] so that not only was the monitoring technology constrained to respond to the hazards themselves, but also that the integration and operations did not require a team of PhDs and dedicated engineers.

The next step is to exploit on-orbit capabilities; these include shorter-term science missions like the NASA Van Allen Probes [9] and other future civil and commercial systems, but more importantly the longer-duration NOAA terrestrial weather systems at GEO and in LEO [10]. The main question is how adequate are those individual point monitors for the entirety of the space domain. That leads to the next brief discussion of alternatives to these methods.

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4. ALTERNATIVES TO LOCAL MONITORING

We have already mentioned that full-scope mission assurance to minimize all space weather risk is not in scope for most of the new systems today. One alternative to hosting/integration of local sensing of the hazards is reliance on physical or empirical modeling, perhaps driven by existing point measurements or by first-principles and boundary conditions between the Earth and Sun. The models could allow for forecasting of the driving environments and fill in all the measurement gaps that exist in the domain. In fact, a large portion of the space weather research community develops these kinds of tools with the aim of specifying the environment external to any satellite [11].

Why isn't modeling enough to rapidly decide on the role of space weather in an anomaly? Ideally, it would be, but the dependences that translate physical quantities (for example, plasma density and temperature; energetic electron flux) into relevant hazards are complicated and often unknown themselves. Even if the community specified flux, density, temperature, and composition of everything outside of a satellite, it would require another set of tools to translate the quantities into relevant effect probabilities. There are many auxiliary hypotheses involved in translating environment into effects for a specific subsystem as illustrated in Fig. 5.

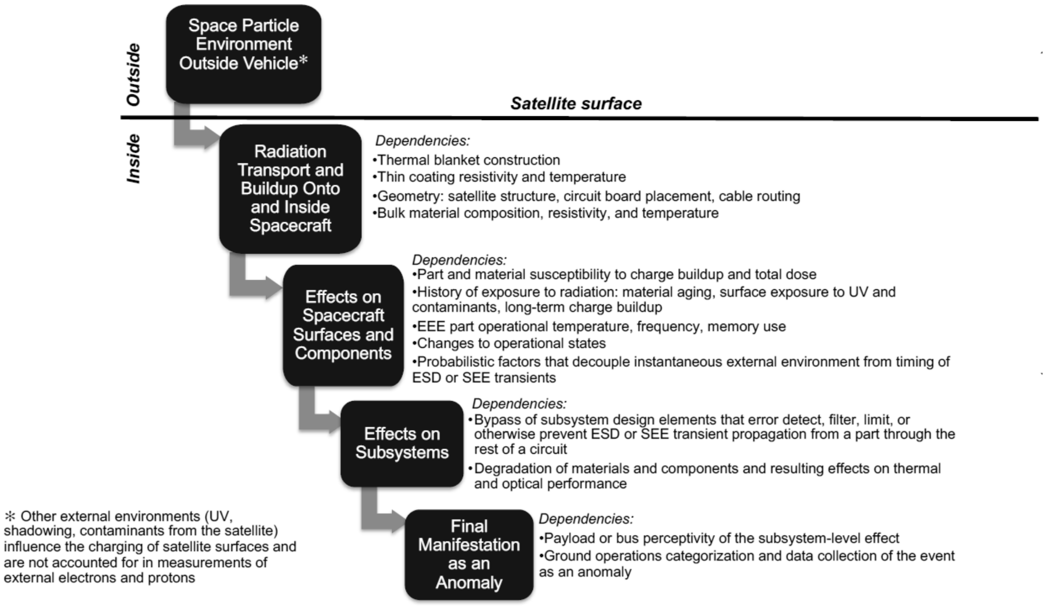


Fig. 5. Flow of external space weather environment into a satellite. The fundamental process is the transport and deposit of charged particles into satellite material, with resulting charge separation and material damage. Whether or not the interactions between charge transport and deposit effects and the material functions yield an observable anomaly are highly dependent on a long chain of events.

The IRENE climatological model [12] is the community's best repository of knowledge of those driving particle and plasma environments with the addition of empirical uncertainties and statistics of natural variability. Those currently do not have a real-time mode and are focused on the design stage. For acquisition, the bulk of the space weather risk assessment is now on the hardware side, not the environment. The same is true for operations.

Sometimes environmental modeling is all we have especially for forecasting, and that modeling, coupled with past system performance in the same environments, could provide actionable warnings or all-clears because there are no viable alternatives [13].

One step towards all domain monitoring using an off-board system is the REACH project [14] in low-Earth orbit. REACH is a commercially-hosted small payload that targets the total dose and single-event effects environments on thirty-two satellites in the Iridium-Next system. Six of those vehicles include a monitor for lower-energy electrons that are closer in energy to the main drivers of surface charging. Fig. 5 illustrates the contrast between the daily coverage of a single satellite in LEO and the entire REACH network.

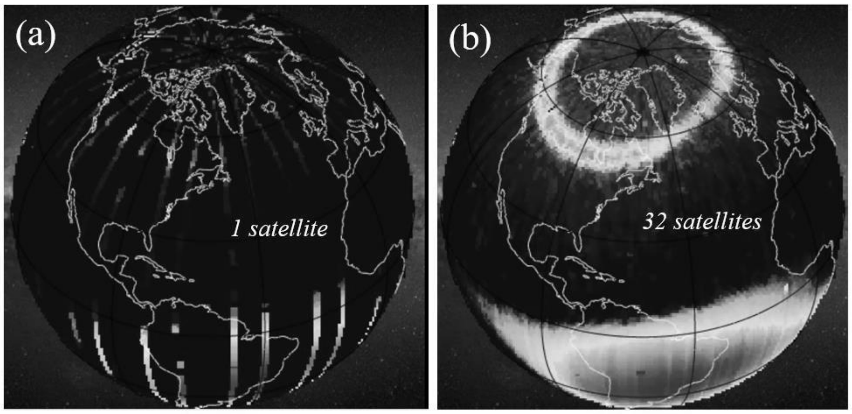


Fig. 5. Daily coverage of space weather hazards (in this case, total dose and internal charging) from one LEO satellite (a) and the REACH network (b). Color intensity (arbitrary units) is proportional to external particle integral flux. The graphics illustrate the spatial dependence of the intersections of LEO with the outer and inner van Allen radiation belts.

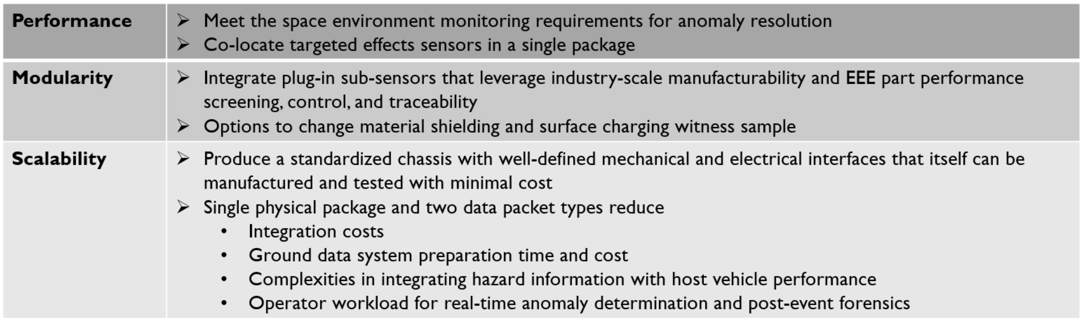
LEO is complicated because of the intersection of orbits with the many distinct trapped and precipitating particle populations. Add time dependence to the particles that are localized in these spatial regions and the result is increasing uncertainty in inferring the hazard at a distant location using local measurements. The near-real-time REACH system (space hardware, LEO data network, and ground-based processing) aims to minimize the uncertainty by flooding the domain with as many monitors as was possible given budget and schedule constraints. REACH was the pathfinder for the ECP-Lite system's development concepts as well as transfer to industry for manufacture that we discuss in the next section. It continues to be the pathfinder for options for ground-based exploitation and dissemination of space weather data, currently using the Unified Data Library as the data lake for higher-level processing and interpretation.

It is possible that a future space domain state would include a set of data-assimilative or other models that adequately specify the relevant space weather drivers everywhere with good-enough resolution and fidelity. Two of the hazards in Fig. 4 (charging and the resulting electrostatic discharge; single-event effects) would still be a complication because they are probabilistic. The same external environment may or may not yield an electrostatic discharge or upset. This is why we landed on the position that ultimately it is the space system itself, coupled with monitors of the hazards at the vehicle and not the external drivers, that would yield the best indicator of impacts from space weather hazards.

Even for low-risk and carefully designed systems, their probabilistic nature of these significant effects means that a space weather nowcast or forecast would guarantee a system outage if the mitigation was to take a system offline or otherwise degrade its operations [15], while the actual upset had a low probability of occurring and the system would likely have worked through the hazard without any problem. Combining the monitoring of effects with the performance of the satellite itself was the main design logic for the ECP-Lite system that we describe next.

5. PHYSICAL AND COGNITIVE APPROACHES

We focused on performance, modularity, and scalability in the development and eventual technology-transfer of the ECP-Lite concept. Fig. 6 outlines these key attributes:

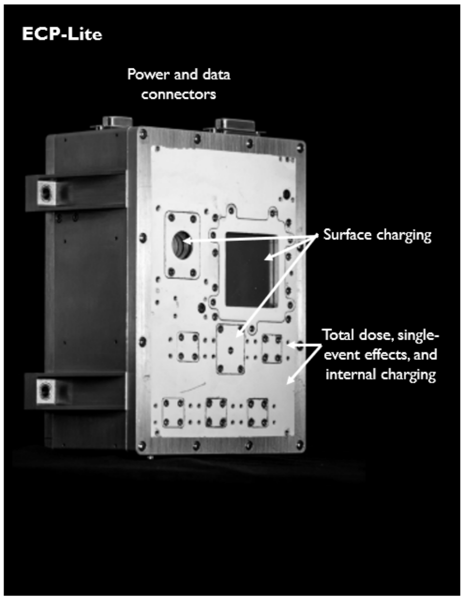


Performance	➢ Meet the space environment monitoring requirements for anomaly resolution ➢ Co-locate targeted effects sensors in a single package
Modularity	➢ Integrate plug-in sub-sensors that leverage industry-scale manufacturability and EEE part performance screening, control, and traceability ➢ Options to change material shielding and surface charging witness sample
Scalability	➢ Produce a standardized chassis with well-defined mechanical and electrical interfaces that itself can be manufactured and tested with minimal cost ➢ Single physical package and two data packet types reduce • Integration costs • Ground data system preparation time and cost • Complexities in integrating hazard information with host vehicle performance • Operator workload for real-time anomaly determination and post-event forensics

Fig. 6. Key attributes for the ECP-Lite sensor and related operations.

The ultimate goal was an affordable and scalable solution for local hazard monitoring. We kept in mind the issues the community had seen regarding the role of space weather in SDA and the three SCP domains, even though the ECP-Lite development that started in early 2015 predated the USSF and its doctrine.

Fig. 7 summarizes the technical attributes of the sensor as well as general information about accommodation on a host satellite. There are many ways to characterize performance in this context but we show the fundamental observables and map them to the technologies as well as the information that we can infer about the external charged particle environment.



Performance	Event total dose Single-event effects Internal charging	- Six silicon detectors in physically-separate microdosimeters	Protons 2-20 MeV Ions 10-100 MeV Electrons 0.1-5 MeV
		- Surface current monitor	Electrons 0.1-40 keV
	Surface charging	- Low-threshold energy dosimeter - Surface current monitor	Electrons >50 keV Electrons 0.1-40 keV
		- Potential of dielectric witness sample - Electrostatic discharge threshold counter and digitized waveform - Photodiodes for visible illumination determination	Supporting measurements of surface potential, sunlight condition, and ESD rate and waveform
SWAP	- 17.53 x 15.51 x 7.56 cm - 2.9 kg - 3.1 W - 430 bps		
Interfaces	- Commanding and telemetry: differential RS422 with provision for MIL-STD-1553 - Power: nominal +28V (operating range +24V to +35V)		
Accommodation and operation	- Operational temperatures: -20 deg C to +50 deg C - Survival temperatures: -40 deg C to +80 deg C - 10mil flatness tolerance for mounting - No hard FOV obscuration threshold - Power-off during launch - Powered-on for as much as possible during host operations - Two CCSDC packet types (1Hz standard packet; adjustable output rate for transient event packet with digitized ESD events)		

Fig. 7. Photograph and technical summary of ECP-Lite.

Here is a brief overview of how the sensor works. All the component sub-sensors are always active when powered-on. The power-on sequence includes a 15-second interval of electronic stimulation of the dosimeter detectors, after which the sensor operates in its single mode. Charged particles from space deposit their charge onto the surface of the witness sample, leave free charge in the fully-depleted dosimeter detectors, and appear as a ~picoamp current in the surface dose faraday cup subsystem. In short, all the sensitive elements of ECP-Lite react to the environment in direct physical correspondence to how the materials of the satellite themselves react.

We also integrated supporting subsystems that are important to awareness of the charging hazard. The first was a 100 MHz sampling of ESD transients that are picked up on an integrated antenna. Satellite differential charging itself isn’t a hazard; any resulting ESD can be the trigger for neighboring systems effects and the details of the waveforms would be useful for anomaly forensics [16].

The second was a pair of visible-wavelength photodiodes in order to determine whether ECP-Lite is sunlit or in shadow. Sunlight will release any charge that has been deposited on surfaces via the photoelectric effect [17]. Sunlight state at ECP-Lite could be determined on the ground using satellite attitude information and a digital model of the hosting location, but instead we incorporated detectors in the sensor for a direct measurement of local lighting instead of pushing additional complexity on the ground data processing.

It's important to note that we refer to the microdosimeters [18] as dosimeters only because we designed the technology to address total ionizing dose and that is how they are currently marketed [19]. In the past our nomenclature has led to confusion because radiation dose is only one of the hazards and the technology name by itself doesn’t suggest utility for single-event effects or internal charging. The fact is that the sensitive element is a silicon detector backed by signal processing electronics that trigger from even single particles. The physical principles we use are identical to more capable and more complex traditional charged particle detectors and are directly applicable to other hazards besides radiation dose. We can and have described how to invert the dosimeter measurements to yield incident particle flux if required for other analyses [20].

The relative simplicity of operations decreases the workload prior to launch and during host operation, when combined with a ground-support decision tool as described in [21] and [22]. The ground element is critical for translation of the measurements into statistics, so that a human operator or another machine does not require deep physical insight into what the measurements mean. The statistics themselves quantify the current state of space weather at the satellite. Past system performance, anomalies or no issues whatsoever, increase the confidence in assessing the role of the environment in an ongoing anomaly or abnormality.

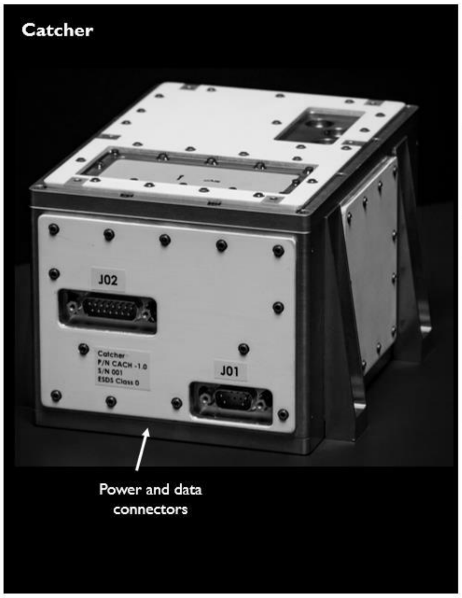
6. CURRENT STATE

There are currently two flight demonstrations of ECP-Lite underway in GEO that launched beginning in late 2021. Evaluation of performance continues and we expect to be able to provide details and examples in a future forum.

Teledyne Brown Engineering [23] is the commercial vendor for the ECP-Lite technology, referred to in their product line and the reference as the Space Radiation Sensor. The technology transfer successfully occurred during 2018-2019.

7. FURTHER DEVELOPMENTS

We used the design modularity and the engineering and qualification experience from ECP-Lite to develop a demonstration called Catcher [24]. In essence, Catcher incorporates a different set of sub-sensors while using the same power and data interface systems and the same mechanical footprint as ECP-Lite. Fig. 8 shows the Catcher prototype concept.



SWAP	• 11.1 x 15.5 x 18.2 cm • 3.3 kg • 5.6 W • 1015 bps
Interfaces	• Commanding and telemetry: differential RS422 • Power: nominal +28V (operating range +22V to +35V)
Accommodation and operation	• Operational temperatures: -30 deg C to +50 deg C • Survival temperatures: -40 deg C to +60 deg C • 10mil flatness tolerance for mounting • No hard FOV obscuration threshold • Power-off during launch • Powered-on for as much as possible during host operations • Two CCSDC packet types (1Hz standard packet; adjustable output rate for transient event packet with digitized events)

Fig. 7. Photograph and summary of the primary interface and host accommodations for the Catcher prototype.

We had to increase the height of the mechanical housing to accommodate a new set of sub-sensors but the basic approach is the same as ECP-Lite: provide a diverse set of awareness measurements from a co-located and integrated system and use statistics of the results in ground-based decision-support tools. Catcher launched into GEO in January 2023 and is currently undergoing evaluation and on-orbit assessment.

8. SUMMARY

Awareness of the space domain means more than tracking objects. Space weather exists everywhere in the domain. While the terminology sometimes introduces confusion, we continued the practice here and described the hard-learned ways that space weather may interfere with satellite technology. It is not always the primary cause of abnormalities or anomalies, but it will continue to be on the list of possible causes. All satellite systems interact with space weather but how and if the interactions result in perceptible effects depend on many, often unknown parameters.

Our value proposition assumes that this will always be the case and attempts to quickly determine if space weather played a role in an anomaly. We chose methods that distilled a complex field of study into four numbers, recognized the utility of existing space weather monitors, and developed a material solution that is as close as possible to the actual hazards that may manifest on orbit. Our approach addresses practical solutions to the three dimensions of domain awareness that the SCP describes: physical space and phenomena, networks of systems and data to cover the domain and all of its complexity, and a recognition of the cognitive demands on operators and the people that will structure and define the learning parameters of intelligent machines as part of space domain awareness.

We have successfully qualified and flown the ECP-Lite sensor and in parallel with its development, partnered with Teledyne Brown Engineering to make this solution commercially available. Together with innovative ground software tools and continued development of containerized software, we aim to make the integration of sensors like ECP-Lite affordable with minimal impact to the hosting system.

The experience allowed us to use ECP-Lite as a foundation to prototype other space domain awareness sensors like the Catcher prototype. All along we have kept the philosophy that co-located threshold detection may only provide 80 percent perceptivity of a more capable sensor suite, but the initial cost and longer-term ease of operations outweigh whatever technical compromises we may have made relative to gold-standard systems that target only the external satellite environment.

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