

LA-14381

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LA-14381
Issued: January 2009

Targeted and Comprehensive Space-Environment Sensors: Description and Recommendations

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Targeted and Comprehensive Space-Environment Sensors: Description and Recommendations

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ABSTRACT

We discuss the roles of the two classes of space-environment sensors on operational space systems: (1) *Targeted* sensors capable of measuring the environment and effects at a level sufficient for providing situational awareness for the host spacecraft and (2) *Comprehensive* sensors capable of providing detailed environment measurements that can be mapped to a broad region of near-Earth space, providing global situational awareness and quantitative characterization of the environment. Our purpose is to show the usefulness of a heterogeneous architecture with both classes of sensors for the near-term and long-term needs of National Security Space.

INTRODUCTION

Energetic particles and plasma in the space environment can be hazardous to space systems, causing system outages, shortening mission lifetimes, reducing functional capabilities, and potentially masking hostile actions. Effects include the degradation of electronic components resulting from total ionizing dose and dose rate, arcing between surfaces induced by warm plasma, electrical breakdown of dielectric materials caused by energetic electrons, and corrupted data and spurious commands driven by energetic ions through single-event effects. Table 1 summarizes the space-environment hazards and the responsible particle populations that are the background of this paper.

Table 1. Space-Environment Hazards

Environmental Hazard	Particle Population	Particle Dynamics Timescale
Surface Charging	0.01–100 keV e^-	Minutes
Surface Dose	0.5–100 keV e^- , H^+ , O^+	Minutes
Internal Charging	100 keV–10 MeV e^-	Hours
Total Ionizing Dose	>100 keV H^+ , e^-	Hours
Single Event Effects	>10 MeV/amu H^+ , Heavy ions	Days
Displacement Damage	>10 MeV H^+ , Secondary neutrons	Days
Nuclear Activation	>50 MeV H^+ , Secondary neutrons	Weeks

We classify the sensors that have been used to measure these space environments and their effects on operational vehicles into two broad categories: (1) *Targeted* sensors that are capable of measuring the environment and effects at a level sufficient for providing situational awareness of specific effects for the host spacecraft and (2) *Comprehensive* sensors that are capable of providing detailed environment measurements for a wide variety of effects and to map those

measurements to a broad region of near-Earth space, providing global situational awareness and quantitative characterization of the environment climatology for the design of future space systems. Table 2 lists several examples of each sensor type that have been flown or are manifest for flight.

Our general classification refers to the primary mission of the sensor. We recognize that there are cases in which other uses of the sensor data might blur the distinction between Targeted and Comprehensive. For example, Comprehensive sensors typically provide situational awareness for the host vehicle as well as comprehensive measurements that can be mapped to a larger volume of space. Likewise, the data returned from Targeted sensors hosted on many vehicles has been used for global space situational awareness through integration into assimilative environment models and for validation of climatology models needed for spacecraft design.

Table 2. Examples of Space-Environment Sensors for Operational Vehicles

Sensor Name	Type ¹	Mass (kg)	Telemetry Rate (bits/s)	Platform(s)	Orbit	Hazards	Provider	Ref.
CEASE CEASE-II	T	1.0	1.3	TSX-5 DSP-21	LEO GEO	Dose, Charging, SEE	AFRL	Di98 Co04
BDD CXD	T	6.8 3.5	0.5	GPS	MEO	Dose, Dose Rate, SEE	LANL	Ca98 Tu04
CPA	T	0.15	10	Intelsat	GEO	Charging	Lockheed Martin	Bo95 Ta07
Merlin	T	1.0		Giove-A	MEO	Dose, Charging, SEE	Qinetiq	
ADS02 chip dosimeter	T	0.02	0.13	LRO (launch Nov 2008)	Lunar	Total Dose	Aerospace	Ma07
DOS+ SCM+ HILET	C	8.9 total mass	45,000	Classified platform	HEO	Dose, Charging, SEE	Aerospace	Ma04
SEM	C	15.0	96	NOAA/POES	LEO	Dose, Charging, SEE	NOAA	
SEM	C		~0.5	NOAA/GOE S	GEO	Dose, Charging, SEE	NOAA	An96
CPA+SEE MPA+SO PA+ESP	C	3.5 per box	1,500 per box	LANL	GEO	Dose, Charging, SEE	LANL	Mc93; Me96 Be92
SSJ4/5	C	3.2	360	DMSP	LEO	Charging	AFRL	SC88
SABRS ZEP+ZPS	C	~9 total mass	Up to 20 kbps	Various	Various	Dose, Charging, SEE	LANL	

Notes:

1. T = Targeted; C = Comprehensive.

More detailed information on a subset of the sensors in Table 2 and examples of their on-orbit utility are provided below.

Targeted Space Weather and Effects Sensors

Targeted sensors measure space-environment hazards to the host vehicle with a focus on a specific effect or set of effects (e.g., dose, single event effects, etc.). In some cases, information about the details of the particle environment (e.g., energy spectrum; angular dependence) outside the vehicle can be derived after the fact. However, the primary benefit of targeted data, such as the total accumulated dose, or the instantaneous potential of a surface relative to the spacecraft frame, is for the situational awareness and health and safety of the host vehicle.

CEASE

Successful operation of the Compact Environment Anomaly Sensor (CEASE) has demonstrated the utility of small on-board space weather sensors. CEASE is a 10 cm × 10 cm × 8.2 cm, 1 kg, and 1.5 Watt box made up of five separate sensors capable of measuring a wide range of the energetic particles responsible for spacecraft hazards [Di98]. Successful test flights of CEASE on the low-Earth orbiting Space Test Program satellite Tri-Service Experiment Satellite #5 (TSX-5) and CEASE-II (an upgraded version of CEASE) on the geosynchronous orbiting Defense Support Program satellite DSP-21 have validated performance through more than seven years of combined operation. Several anomalies on TSX-5 were resolved quickly using CEASE data [Di01]. CEASE-II on DSP-21 was an Advanced Technology Demonstration (ACTD). As a result of a Military Utility Analysis conducted as part of the ACTD, Air Force Space Command (AFSPC) recommended to the United States Strategic Command (USSTRATCOM) that they “support CEASE-II requirement on all future spacecraft.” [Co04].

CXD/BDD

Some targeted sensors are routinely flown on all satellites in a system. An example is the Global Positioning Satellite (GPS) constellation. Initially targeted Burst Detector-Dosimeter (BDD) instruments were flown on at least one satellite in each of the six GPS orbital planes with operational X-ray sensors on the remaining spacecraft. With improvements in instrument design and greater understanding of the GPS environment, a new generation of Combined X-ray/Dosimeter (CXD) instruments was developed. CXD performance exceeds BDD performance considerably while using fewer than half the resources, thus enabling combining X-ray and Dosimeter functions into a single instrument and the ability to provide both functions to every vehicle in the constellation with no additional impact on the host vehicle.

CPA

Developments in even more targeted, lower-impact sensors can provide information on specific space weather effects without necessarily measuring or analyzing the populations that cause them. An excellent example of a space weather effects sensor is the Charged Plate Analyzer (CPA) flown on several commercial satellites [Bo95; Oz01]. This simple sensor provides a real-time estimate of surface charging occurring on a surface patch representative of the host vehicle. Although it is not possible to deduce the incident particle radiation environment from such a sensor, the CPA’s output is simple to understand and process automatically. A high CPA voltage is a straightforward indication that the vehicle is at risk of surface charging, which can lead to electrostatic discharge and various negative consequences thereof.

ADS02 (Chip Dosimeter)

Research programs are underway at Aerospace and Air Force Research Laboratory (AFRL) to further decrease the size and resource requirements of dose and charging effects sensors to levels well below CEASE-class sizes, i.e., to the level of “thermistors” where they ultimately become part of the bus infrastructure [Ma07]. A sacrifice in measurement resolution and dynamic range will be offset by the large number of sensors possible at a multitude of critical spacecraft locations and by leveraging the measurements from comprehensive sensors on a much smaller subset of platforms that enable global context and on-orbit cross-calibration of instrument responses.

Comprehensive Sensors for Weather, Effects, and Climatology

Comprehensive sensors also make measurements of one or more space-environment hazards but return detailed energy and angular resolution with a large dynamic range; the corresponding resource requirements are naturally larger than Targeted sensors (see Table 2). Typically, more comprehensive measurements are needed when the space weather effects on a particular host are not well understood or their causes are not known; when it is necessary to mitigate space weather effects such as background signals in space instruments; or when there is a need to extend the data to locations far from the host spacecraft through mapping of particle distributions in magnetic coordinates with a fair degree of accuracy. Thus, a single point measurement specifies a relatively large volume of the radiation environment at a broad range of energies.

GEO sensors: NOAA and LANL

Well-known examples of comprehensive space-environment sensors are the Geostationary Operational Environmental Satellite (GOES) and Los Alamos National Laboratory (LANL) particle sensors at Geosynchronous Orbit (GEO) [An96; Mc93; Be92; Me96]. Combined, these two constellations provide long-term measurements of the proton and electron environment for particles with energies from a few eV to hundreds of MeV. As a result, the geosynchronous environment is one of the best characterized for spacecraft design [e.g., Bo03, Si06].

LEO Sensors: NOAA TIROS and POES

Another well-known example of long-term space-environment sensors is the particle instruments on the NOAA TIROS or Polar Operational Environmental Satellite (POES) constellation, in sun-synchronous orbit at ~800 km. Although not as comprehensive as the GEO measurements, the POES/SEM package includes a set of proton measurements that have been used to quantify the long-term variability of the energetic protons in Low-Earth Orbit (LEO), including the motion of the South Atlantic Anomaly, a region of intense radiation in LEO [Hu02].

Orbital environments other than GEO and LEO/Sun-Synch are poorly monitored, leading to large uncertainties in anomaly assessment and spacecraft design specifications. A successful strategy for deploying comprehensive sensors would provide similar coverage for other widely used orbits while also preparing at least preliminary climatology information for arbitrary new orbits.

Roles of Targeted and Comprehensive Sensors

Targeted Sensors

Low-impact and inexpensive space weather sensors should be placed on all operational spacecraft to provide situational awareness for improved operations, rapid and accurate anomaly assessment, and, when integrated over constellations or fleets, to provide a global picture of the space-environment threat. An optimal space situational awareness package should contain monitors for directly measuring the environmental effects relevant to satellite subsystems, including dose deposition, single-event effect rates, surface charging, and internal charging. Without space weather sensors on a vehicle, the mission must rely on various interpolations and extrapolations in order to assess the environment hazard during operations or during an anomaly resolution. Currently, such extrapolated environmental specifications are time consuming to produce, inaccurate and of a low confidence level, although numerical tools are actively under development to enable future more-accurate mapping of local measurements to a global environment specification. Real-time, spatially accurate space-environment data from a targeted sensor are critical to determining whether a specific anomaly event might be the result of hostile activity rather than natural phenomena.

Targeted sensors will also provide databases that can be used to correlate environments with anomalous events and continuous degradation to improve satellite design ultimately enhancing capability while reducing acquisition and operations costs. Although there is as yet no mandate or central authority to guide the acquisition of such sensors (although a space-environment and effects-sensing requirements document is in draft at the Air Force Space Command), there is a growing consensus in the satellite operations and acquisition community that new technologies, new orbits, and new threats will continue to expand the need for space-environment sensors.

Comprehensive Sensors

When integrated with data-assimilation algorithms, a small number of comprehensive sensors could provide global situational awareness throughout the entire near-Earth space regime. Resolution and utility will be further improved as better tools are developed to process targeted space weather sensors to levels that can be incorporated in data-assimilation models. As sensors proliferate, the assimilation of data can provide a global picture of the space-environment threat to all blue, red, or grey forces with the accuracy of the threat assessment in proportion to the number and distribution of sensors.

Comprehensive space-environment data also provide the long-term description of the average environment and its variation (space climatology). This type of information is critical for improving radiation design specifications, such as AE-8 and AP-8 [Ve91; Sa76]. Because the Solar Cycle has an 11-year activity cycle (22-year magnetic) and varies considerably in dynamic range, long-term measurements are essential. For example, the author of the standard AE and AP specification models remarked, “the inclusion of newer data at regular intervals is mandatory because our knowledge of the radiation belts increases as improved instruments are flown and new ideas are advanced” [Ve66]. In order to enable updates of the radiation specifications, comprehensive sensors should be flown in every critical, commonly used orbit (e.g., GEO, Highly Elliptical Orbit [HEO]/Molniya, Medium Earth Orbit [MEO] and LEO) and on path-finder missions. In addition, comprehensive sensors can be of high value when flown on

elliptical orbits, especially those with low inclination (e.g., Geosynchronous Transfer Orbit [GTO]).

SUMMARY

Individual satellite programs reap the benefits from enhanced situational awareness and reduced anomaly resolution time as a result of having space weather effects sensors on all of their assets. All of National Security Space benefits from comprehensive sensors through better situational awareness at points far away from the sensor platform and from the detailed climatology data gathered over long-duration missions.

ACKNOWLEDGEMENTS

The authors acknowledge contributions from: LTC Clark Groves (USAF); Michelle Thomsen, Marc Kippen, and Eric Dors (LANL); and James Clemmons (The Aerospace Corporation). ATR-2008(8073)-4.

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APPENDIX: ACRONYMS

ACTD	Advanced Technology Demonstration
AFRL	Air Force Research Laboratory
BDD	Burst Detector Dosimeter
CEASE	Compact Environment Anomaly Sensor
CPA	Charge Plate Analyzer (Intelsat surface charging monitor)
CPA	Charged Particle Analyzer (LANL energetic particle sensor at GEO)
CXD	Combined X-Ray sensor and Dosimeter
DMSF	Defense Meteorological Satellite Program (DoD weather satellite).
DoD	Department of Defense
DOS	Dosimeter
DSP-21	Defense Support Program satellite #21 (DoD operational satellite).
ESP	Energy Spectrometer for Particles
GEO	Geosynchronous Orbit
GOES	Geostationary Operational Environmental Satellite (NOAA weather satellite).
GPS	Global Positioning Satellite
GTO	Geosynchronous Transfer Orbit
HEO	Highly Elliptical Orbit (classified satellite)
HILET	High Linear Energy Transfer
LANL	Los Alamos National Laboratory.
LEO	Low-Earth Orbit
MEO	Medium Earth Orbit
MPA	Magnetospheric Plasma Analyzer
NOAA	National Oceanic and Atmospheric Administration
POES	Polar Operational Environmental Satellite (NOAA weather satellite)
SABRS	Space and Atmospheric Burst Recording System
SCM	Surface Charge Monitor
SEE	Spectrometer for Energetic Electrons (LANL instrument at GEO)
SEE	Single Event Effects (space-environment hazard)
SEM	Space Environment Monitor.
SOPA	Synchronous Orbit Particle Analyzer
SSJ5/4	Special Sensor J4 or J5.
TSX-5	Tri-Service Experiment satellite #5 (DoD experimental satellite).
USAF	United States Air Force
USSTRATCOM	United States Strategic Command
ZEP	SABRS Energetic Particle (LANL energetic particle sensor at GEO)
ZPS	SABRS Plasma Spectrometer (LANL plasma sensor at GEO)

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