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Space Environment Engineering and Science Applications Workshop Roadmaps

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Abstract

On the 5th through the 8th of September 2017, NOAA, SWPC, and NCEI hosted the Space Environment Engineering and Science Applications Workshop (SEESAW). The workshop was sponsored by the IEEE Nuclear and Plasma Sciences Society and by the National Science Foundation. It had approximately 70 attendees from the US and international institutions. As part of the workshop, the attendees constructed a set of roadmaps, addressing surface charging, internal charging, single event effects, total dose, nowcast/ forecast and special topics. These roadmaps have been collected and edited into a brief report for use by the scientific and engineering communities in moving forward with research and applications to further improve the design and operation of space and launch vehicles.

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1. Introduction

On the 5th through the 8th of September 2017, NOAA, SWPC, and NCEI hosted the SEESAW. The workshop was sponsored by the IEEE Nuclear and Plasma Sciences Society and by the National Science Foundation. It had approximately 70 attendees from the US and international institutions. As part of the workshop, the attendees constructed a set of roadmaps, addressing surface charging, internal charging, single event effects, total dose, nowcast/forecast and special topics. These roadmaps have been collected and edited into a brief report for use by the scientific community in moving forward with research and applications to further improve the design and operation of space and launch vehicles.

Most SEESAW presentations can be found on-line at: https://cpaess.ucar.edu/meetings/2017/seesaw-presentations.

SEESAW was organized by: Paul O'Brien, Justin Likar, Eamonn Daly, Véronique Ferlet-Cavrois, Bob Johnston, Mike Xapsos, Janet Barth, and Robert Reed.

The lead contributing editor of the roadmaps was Paul O'Brien. Additional contributing editors were Justin Likar, Mike Xapsos, Juan Rodriguez, and Eamonn Daly. The editors acknowledge review and input from Stu Huston, Hugh Evans, Piers Jiggens, Alex Hands, Insoo Jun, Scott Messenger, Mike Bodeau, Rick Quinn, Dan Allred, and Dan Clymer.

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The five roadmap documents follow hereafter.

2. Nowcast/Forecast

General Background on Nowcast and Forecast

A space weather nowcast represents a near-real-time specification of conditions in the space environment, while a forecast represents specification at some future time. Notionally, a forecast allows a space or launch system operator to prepare for hazardous conditions, while a nowcast provides high confidence that hazardous conditions do or do not exist.

While it is rare to put some or all systems on a spacecraft into safe mode, there are several routine uses of forecasts. A ground control team may add extra staff or put senior team members on notice for possible short re-call. A space operations team may elect to postpone a risky on-orbit operation, such as conducting a station-keeping maneuver or initiating an extravehicular activity (EVA). A science mission can use a forecast to plan when and how to take observations.

Nowcasts have their own uses as well. Space weather launch commit criteria are generally based on nowcasts (usually direct near-real-time observations). A critical period in a satellite lifetime is the launch, separation, and early deployment of a satellite. During this phase, an interruption in operation due to a processor reboot or mode switching can result in an unrecoverable condition such as loss of power, thermal, or attitude control balance, or failure to perform a one-time function in sequence. Also, a small number of orbital vehicles have employed partial safing procedures during observed severe space weather, after repeated observed critical space weather impacts.

In practice, very few satellite or launch operators change system configuration or take other tangible mitigation actions based on a forecast, instead waiting for the higher confidence nowcast to make a decision. In many cases, even a nowcast of an extreme hazard only results in a heightened level of preparedness. This reluctance to take preventive action arises from the fact that both launch and space systems are designed to function even during extreme space weather, and nearly always do so successfully. Nonetheless, it is reasonable to expect that quantitative improvements in forecast performance and lead time will lead to more use of forecasts, at least where nowcasts are currently used. Whether high quality, long-lead forecasts become widely used to improve spacecraft operations depends on the (unknown) future rate of design/test/fabrication escapes that introduce space environment susceptibilities, coupled with sufficiently improved forensic anomaly analysis capabilities to relate environmental conditions to anomaly risk.

Launch Operator Needs

Launch is a uniquely high-risk activity in the lifecycle of a space system, and so the many hazards to launch are carefully monitored during the countdown. Space weather launch commit criteria are often part of the countdown and launch decision process. While launch holds are typically based on observations, such as solar protons at geostationary orbit or at the L1 Lagrange point, some launch holds are based on nominal precursors to hazardous conditions (e.g., solar flares precede solar energetic particle events).

For the most part, such criteria are based on known, accepted susceptibilities of the launch vehicle to the space environment – susceptibilities that were allowed on condition that launch could be delayed in order to avoid exposure to hazardous space weather. However, sometimes legacy criteria get propagated to new systems without a positive determination that the new system has the susceptibility. (This implies that some delays can potentially be avoided through better analysis of vehicle susceptibilities to the space environment.) The evaluation of space weather launch commit criteria begins as early as four days prior to launch. During this pre-launch phase, the criteria are distilled into a forecast probability of GO or NO-GO conditions. As the launch countdown reaches its final stages, the evaluation changes to a nowcast, and the space weather criteria are designated GO or NO-GO based on observed conditions.

In terms of a forecast, an “all clear” or its probability is needed as early as four days prior to launch. The primary hazard being addressed is solar energetic particles, particularly energetic heavy ions, which cause single event effects (SEE). SEE can disrupt the launch vehicle’s control systems potentially leading to catastrophic mission loss. Because of this catastrophic risk, some launch commit criteria are based on solar flares which are not, by themselves, hazardous to the mission, but which are seen by some as harbingers of the energetic particle events that pose the real SEE risk (the utility of using flares to predict SEP is disputed, e.g., [1]). Once a solar particle event has begun, launch operators need to know how long the hold will last—a hold reduces risk while increasing cost by remaining in a launch-ready configuration for hours or days while a solar particle event fades away. If the duration of the delay is known in advance, cost can be reduced by standing down to a lower level of launch readiness.

Observationally, the new energetic heavy ion capability from NOAA’s GOES-R series of vehicles promises to provide an exception to proton-based launch commit criteria: if the protons exceed the launch threshold, but heavy ion data are present and below their own hazard threshold, launch may yet be safe.

Related to this SEE consideration is the need to be able to evaluate whether an active solar particle event can even influence the launch vehicle or early operations of the space vehicle. A trajectory analysis tool is needed that can account for the best available nowcasts or forecasts of the severity and location of solar energetic particles and other in situ hazards to determine whether they apply to the specific trajectory of an individual launch campaign. For example, a sufficiently low-inclination orbit might not be exposed to the solar energetic particles at all, on account of shielding provided by Earth’s own magnetic field, but this depends on the solar particle event’s energy spectrum and heavy ion abundances. Further, the SEE impact is higher during burn and separation phases, as opposed to the coast phases, and knowing where these events occur relative to the SEE environment can improve risk assessment.

More tenuously, some [4] have hypothesized that, because a launch campaign may depend on multiple on-orbit assets (e.g., for out-of-view communications), launch commit criteria may be needed to avoid a broader range of hazards, including charging to the launch vehicle and satellites on which it will depend. This “abundance of caution” approach sets the launch commit criteria at a high percentile, such as 99 percent, to limit outages, while avoiding launching into the most extreme space weather. Based on the tenuous nature of the risk, however, it seems this broad approach is not yet mature enough to drive nowcast/forecast needs on its own. It can be captured as a variant of the “all clear” mentioned above.

Across the range of launch needs, the highest priority is a forecast of the onset or all-clear for solar particle events, especially those with abundant energetic heavy ions.

Risky On-Orbit Operations Need

Risky on-orbit operations have some of the same considerations as launch, although they tend not to be captured as formally as launch commit criteria. For example, a software upload, a solar array or antenna deployment, or a maneuver could all be jeopardized by space weather hazards. However, most of these do not have the intense level of scrutiny a launch has, and, according to design requirements, they are all nominally allowed even under the most extreme space weather. For these activities, the “abundance of caution” approach mentioned above represents a reasonable approach, and these activities can be supported by some of the situational awareness capabilities that will be discussed below. One special consideration of note is that when structures, solar arrays, or antennae are deploying they transition through unusual geometries that may make them especially susceptible to vehicle charging. These kinds of risky operations need a high confidence “all clear” forecast.

Human spaceflight missions have a unique perspective on space environment hazards. Extravehicular activity (EVA) for human spaceflight missions represents a tangible, and well-documented space weather hazard to risky on-orbit operations. Spaceflight crews are susceptible to space weather, especially radiation dose caused by solar particle events. For sufficiently intense solar particle events, crew inside the spacecraft may also need to take shelter. Because the concern is crew dose, the operators need both a forecast of solar particle event onset time, and its expected duration or fluence. Under sufficiently severe conditions, ground staffing may be enhanced to support detailed investigation of the environmental conditions and contingency planning should they worsen. As with launch, a high confidence “all clear” would be very valuable.

For risky on-orbit operations, the highest priority is a high confidence “all clear” forecast, followed by a forecast of the onset and duration for solar particle events, especially energetic proton events that can cause substantial crew dose.

Space Situational Awareness and Anomaly Triage Needs

Space situational awareness (SSA) can be defined broadly to include many hazards and threats beyond space weather, but we are addressing only the space weather aspects of SSA. Anomaly triage refers to the rapid, initial decisions that are made following an anomaly to determine the broad category of the cause, such as space weather, human error, or vehicle aging. As with medical emergency triage, these decisions are made so rapidly that there is little or no time to obtain data or research relationships between data and anomalies. Thus, a forecast prepares the triage team through situational awareness, and a nowcast facilitates their rapid decision making should an anomaly occur.

To be truly valuable, SSA must be accurate and timely, it must apply to the subject vehicle, and it must put the observed/forecast conditions in the context of the vehicle’s history and expected performance.

The SSA priority, then, is a tool that provides seamless integration of forecast, nowcast, and vehicle history for any Earth orbit. At a minimum, such a tool can identify when conditions are unusually hazardous (by hazard) in common obit regimes. A more robust tool would accept any orbital ephemeris and compute hazards along the vehicle’s orbit or trajectory.

Improving How We Communicate Nowcast and Forecast Hazards

Scientists view the radiation and plasma environment in terms of particle populations and magnetic coordinate systems. Satellite and launch vehicle operators are concerned with orbits and trajectories and hazards to their vehicles. Although the transforms between these two views is generally well defined, there are surprisingly few tools that present the outputs of radiation and plasma models in terms the operator can understand and exploit. For models, this involves projecting the model output from its coordinates onto user’s vehicles or trajectories, and then converting from particle fluxes into hazard indicators: current behind shielding, single event effect rate in a reference part, dose at depth, or a surface charging index like >10 keV electron flux or electron temperature. Likewise, observations in low Earth orbit may provide valuable information to all orbits, but there are only limited capabilities to exploit these observations, even for other LEO vehicles, let alone higher altitude orbits. Physically, it is very difficult to map from LEO to high altitudes, but empirically it has been shown to work due to statistical correlations [2].

As a first step, we recommend a nowcast/forecast that is broken out by common orbit regimes. Table 1 shows how one might present the four primary space weather hazards to vehicles for a common set of orbits. It is intended to show how the current (or forecast) conditions compare to typical conditions in each orbit. The final selection of orbits to address depends on the user base. While this is not a detailed projection onto a user’s orbit, it is an excellent starting point for any user to gain insight into whether their vehicle may be at risk. A working variant of this concept is available at http://www.risk.spacestorm.eu/.

The table is interactive so that a user can click on a cell to obtain more detailed information for that hazard and orbit.

Based on the papers cited above, it is highly plausible the LEO observations can be used to identify hazardous internal charging conditions for all orbits and trajectories. The same is likely true for other hazards, with some notable limitations (e.g., local time coverage for surface charging hazard, or field-line dependence of solar energetic particle access.)

Building a regional warning table may not require a complete global space weather model, but moving beyond such a table certainly would. Therefore, the roadmap endorses the ongoing development of global space weather models that address the radiation belt and energetic plasma populations that pose hazards to vehicles. We note that these hazards are, specifically:

- Solar energetic particles, including their penetration into the magnetosphere (responsible for single event effects and event total dose)
- The keV electron ring current (responsible for surface charging)
- Trapped proton and electron radiation belts (responsible for single event effects, event total dose, and internal charging)

These particle populations are listed in approximate priority order because the first two exhibit the shortest dynamic timescales, meaning a forecast/nowcast is most demanding. Because the radiation belts typically take hours to days to grow from benign to hazardous, they are a lower forecast and nowcast priority, but they are of equal priority for anomaly triage and anomaly resolution.

Table 1. Regional Warning Paradigm (Notional Example)

	Surface Charging	**Internal Charging**	**Single Event Effects**	**Event Total Dose**
GEO	🟥	🟨	🟥	🟥
High Inc LEO	🟥	🟨	🟥	🟨
Low Inc LEO	🟩	🟩	🟩	🟩
ISS	🟩	🟩	🟩	🟩
GNSS	🟥	🟨	🟥	🟨
MEO	🟨	🟨	🟨	🟨
HEO	🟥	🟨	🟥	🟩
Tundra	🟥	🟨	🟥	🟥

The highest priority for how we communicate hazards is to tailor the information to the user's hazards and orbit regime or orbit itself. The highest priority hazard is solar energetic particles and their access to the magnetosphere, followed closely by the energetic electron plasma of the ring current, which causes surface charging.

We note that forecasting for scientific missions is a sufficiently narrow and idiosyncratic use case that we have assumed it is responsibility of the missions themselves to develop their own forecast tools.

Additional Points Brought Up at the Workshop

Workshop participants raised the following points which relate to the forecast/nowcast roadmap:

- Without adequate forensic anomaly analysis, and the tools that support it, forecasts will remain unactionable for most operations because there will not be high confidence in how the space weather forecast relates to actual mission risk. Forensic tools are part of the solution, but another common theme of the workshop was the need for an anomaly database. Anomaly databases are vital for understanding what kinds of forecasts are valuable and for making general assessments of what severity levels constitute real vehicle risk.
- When interpreting a nowcast or forecast, it is necessary to put it into context of the vehicle's entire history: how long has it been since the vehicle has seen a similarly severe environment, and how often does that happen?
- Some serious thought will be required to refine the government-industry relationship. As investment moves from fundamental science and environmental forecast to tailored tools and applications, the private sector has traditionally been relied upon to conduct and even invest in research and development. Workshop participants expressed concern that as this relationship evolves, it will be necessary to establish an appropriate intellectual property framework to maximize the return on government investment without creating a disincentive to private industry investment and participation.
- There is probably an under-investment in empirical, data-driven, and data-assimilative models relative to physics-based models (simulations). Machine learning is showing promise in spite of very limited funding opportunities for purely empirical modeling.

Special Topics

While most of the discussion at the workshop was focused on space vehicle anomalies, two special topics came up during the nowcast and forecast discussion: aviation and drag.

Aviation users need nowcast/forecast of dose levels at aircraft altitudes (caused by dynamic >500 MeV solar protons and stable GCR). Specifically, the D index [3] has been proposed as a more relevant scale than the commonly-used but less targeted NOAA SWPC S-scale for proton flux. However, as there is no widespread *in situ* measurement capability for the aviation environment, such an index relies heavily on speculative extrapolations from space- and ground-based data sources. Little confidence can be had in such methods until validation activities take place based on new observations. Of course, should such events occur and the models prove inadequate, then it will be too late to avoid the under or overreaction that will already have taken place based on spurious predictions. This dilemma means that the only approach presently able to provide aviation SPE warnings with high confidence is onboard monitoring with properly calibrated instruments.

It should also be noted that even with perfect nowcasting, certain categories of solar particle events are extremely hard to mitigate. Primary particles from impulsive hard-spectrum events, such as the worst ever directly-observed event from February 1956, travel to the Earth at close to the speed of light, and thus arrive without warning and potentially achieve peak intensity within minutes of being observed. As avoidance of such ground level enhancement (GLE) events is impossible rather than merely impractical, mitigation can only be achieved by ensuring that avionics systems exposed to these events are sufficiently resilient to tolerate the radiation environments they produce. On this point, the aviation industry can learn many lessons from the space industry in terms of good practice for radiation hardness assurance and testing. In terms of dose to aircrew and passengers, post-event calculations of exposure are only likely to be reliable if *in situ* dosimetry data are available, which again necessitates the need for proper inflight monitoring.

Satellite operators noted the need for a tool to convert space weather and solar cycle nowcasts and forecasts into a drag estimate for orbit determination and orbit decay calculations.

Summary of Highest Priorities

Table 2 provides a brief summary of the highest priorities identified in the prior sections.

Table 2. Summary of Highest Priorities

User Area	Highest Priority Need	Notes
Launch Operations	Forecast of the onset or all-clear for solar particle events	Particularly events with abundant energetic heavy ions
On-Orbit Operations	High confidence all clear forecast	Additional need for forecast on onset and duration of solar proton events that can cause substantial crew dose
SSA/Anomaly Triage	Tool that provides seamless integration of forecast, nowcast, and vehicle history for any orbit/common orbits	Start with regional nowcast/forecast tool. On the timeline, nowcast is currently most valued by operators.
Forecast Communication	Tailor nowcast/forecast to user's hazards and orbit	Top hazards are solar energetic particles and keV electron plasma
Aviation	Dose and SEE in avionics nowcast at aviation altitudes	>500 MeV solar protons
Satellite tracking/orbit decay	Tool to convert nowcast/forecast to short term and long-term satellite drag estimate	General issue with solar cycle forecasts: how to use?

References

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3. Surface Charging

Note: References made herein to SEESAW talks are noted as [Author; SEESAW] while other references are noted in numerical order with a reference list provided at the end of this document.

General Background on Surface Charging

Spacecraft surface charging is the accumulation of net electric charge, and therefore potential, on the exterior surface(s) of a spacecraft due to the incidence of particles with energies of ~1 keV to 50 keV [26][27].

It is often convenient to describe surface charging in two forms:

- “Absolute charging” or “frame charging” is the development of a potential between the spacecraft frame to the surrounding space plasma (or “ground”). Absolute charging may interfere with scientific payloads, increase surface contamination, or exacerbate effects related to electric propulsion (EP) plumes.
- “Differential charging” is the development of a potential between adjacent or nearby spacecraft surfaces or features. Differential charging is highly spacecraft dependent and often the cause of electrostatic discharges (ESD) once breakdown thresholds are reached.

Ref. [1] offers an effective review of historical perspectives on spacecraft surface charging. In its simplest form surface charging may be described by a current balance equation,

$$I_T(V) = -I_E(V) + (I_I(V) + I_{SE}(V) + I_{SI}(V) + I_{BSE}(V) + I_{PH}(V)), \tag{1}$$

where,

V	surface potential relative to space;
I_T	total current to spacecraft at V (0 at equilibrium);
I_E	incident negative electron current;
I_I	incident positive ion current;
I_{SE}	secondary emitted electron current due to I_E;
I_{SI}	secondary emitted electron current due to I_I;
I_{BSE}	backscattered electron current due to I_E;
I_{PH}	photoelectron current.

The solution to Eq. (1) may be quite complicated. However, it remains the fundamental relationship for determining the potential at an exterior spacecraft surface. A quick inspection of Eq. (1) enables one to identify the influences of the space plasma environment and material properties on the resulting potential.

Perhaps not unexpectedly it is the effects of, or phenomena resulting from, surface charging that captures the attention of the spacecraft community. Electrostatic discharges (ESD) resulting from the exceedance of breakdown thresholds may impact spacecraft operations with the magnitude of potential impacts ranging from “nuisance” to “catastrophic”. The breadth of undesirable effects resulting from surface discharges is quite large, as such, discharges may (an incomplete list):

1. Generate electromagnetic interference (EMI) which negatively impacts spacecraft (RF) communications or vehicle performance;

2. Couple into vulnerable electronics (e.g., via cables or temperature sensors) causing uncommanded mode changes to device (circuit/function) failure; phantom commands
3. Degrade EPS (power system) performance, should discharges occur in the vicinity of unfused power and/or solar cells, diode boards, or battery cells;
4. Damage material properties – thermal, optical, or electrical leading to premature aging of sensitive surfaces (e.g., thermal blankets or optical elements such as lenses, optical solar reflectors, or solar cell coverglasses).

Unsurprisingly surface charging, or in many cases the generalized "spacecraft charging" or "ESD", is a common root cause for satellite anomalies [2]. Credible or verified anomaly statistics are seldom published, however studies by [3] and [4] suggest spacecraft charging related anomalies represent between 25 percent and 50 percent of all anomalies attributed to the space environment. Also see [5] and the work of [Green, J.; SEESAW] summarized at SEESAW which captures, in detail, stakeholder comments relating to surface charging risks to spacecraft operations.

Indeed, the surface charging hazard depends on many parameters, such as detailed shape of the electron spectrum [4] and material properties (often a function of environmental conditions such as time, radiation dose, dose rate, temperature, and so on). However, the explicit coupling mechanism to vulnerable spacecraft electronics necessarily introduces additional spacecraft-specific design dependence. The characteristic time scales associated with surface charging effects are small (on order of minutes) [6]. Spatial and temporal correlation of surface potentials, absolute charging, and differential charging is challenging and includes both space environment variability and host-spacecraft design [7].

Discharges occurring somewhere on a satellite surface do not necessarily pose a risk unless the spacecraft design is itself vulnerable to the effects of discharges.

The now-widespread adoption of Electric Propulsion (EP) on a variety of spacecraft architectures has introduced a number of new accommodations and operations challenges resulting from use of EP engines for orbit-raising and station-keeping [8][9]. EP engines generate ionized plumes which possess ions of sufficient energy to modify the surface properties of exterior spacecraft surfaces as well as plasma of sufficient density to create a complex artificial (e.g., system generated) local plasma environment when combined with the natural, ambient plasma.

Ground based laboratory testing remains an integral part of surface charging verification efforts on modern spacecraft programs, in the assessments of on-orbit anomalies, and the verification/development of improved analytical tools and models. Laboratories may be generally described as addressing specific scientific or engineering needs:

1. Electron flood beams and/or combined effects (electron, proton, solar irradiance, or VUV) for characterization of material charge storage and surface potentials.
2. Materials characterization such as resistivity (bulk and surface), coefficients (e.g., secondary electron and Radiation Induced Conductivity (RIC)), and other electrical properties (such as time constants, dielectric constants, breakdown voltage, …) often as function of lifetime and temperature.
3. Electrostatic discharge characterization on representative spacecraft systems such as solar arrays (primary & secondary arcing); also plasma propagation, and EMI/radiation emissions.
4. Model verification.
5. Electric Propulsion (EP) thruster enabled; combined effects.

6. Spectral sources (such as Sr-90 or pelletron) which combine charge deposition and dose deposition effects.

Ground test methods, test environments, diagnostics, and processes are the subject of numerous international standards such as (not an exhaustive list) NASA-HDBK-4002A, NASA-HDBK-4006, ECSS-E-ST-20-06C, ISO 11221:2011, ISO/AWI 20584, …).

Roadmap Introduction

Results of the SEESAW proceedings may be distilled down to a total of 15 specific community needs. Each have been, tentatively, distributed by topical area and are discussed here under.

Needed design/effect tools

The NASA/Air Force Spacecraft Charging Analysis Program (NASCAP2K) remains ubiquitous with surface charging analysis and verification within the United States. Ver. 4.1 is presently available for distribution to U.S. Persons only via the NASA Space Environments and Effects (SEE) portal at https://see.msfc.nasa.gov/. [12] presented an overview of present capabilities at SEESAW. Similar surface charging tools exist internationally (e.g., SPIS, MUSCAT, and COULOMB-2) and complementary tools available in the U.S. [Pothier McGillivray, N.; SEESAW]. Owing to largely US participation in SEESAW, community comments and needs associated with surface charging engineering design and effects tools tended to specifically reference NASCAP2K. The following represent specific needs identified by workshop participants.

1. NASCAP2K (including Ver. 4.2) assumes isotropic fluxes and users must accept this as being satisfactory. In capturing, and maintaining its role as the “industry standard” engineering tool for surface charging assessments in the US, NASCAP2K has made a number of simplifying assumptions in order to deliver scientifically credible results to satellite design engineers and analysts of varying degrees of technical competency. The user community is recognizing opportunities to apply NASCAP2K capabilities to increasingly complex systems and operational scenarios. *The ability to introduce non-isotropic particle fluxes and other, complex environment definitions, is identified as a user need.*
2. As an effective engineering tool NASCAP2K will generate “reasonable” looking results for “reasonably” well defined problems. An analyst need only do a reasonable job defining the geometric, grid, and environmental inputs to return results. This is indeed the goal of a rapid engineering design tool; however, modern/expert users may require additional fidelity on inputs and returned outputs. For example, the community is seeking *methods to identify the surface(s) and/or feature(s) driving charging results for specific calculations.* Spacecraft charging tools are heavily dependent on geometric and material properties, many of which may be defined by an analyst with proprietary or specialized properties. Tools which enable users to quickly determine which inputs drive the results are sought.
3. Surface charging engineering and design tools such as NASCAP, SPIS, MUSCAT, or COULOMB-2 generate, with relative ease, quantities such as differential charging potentials, absolute charging levels, particle tracks, collected currents, and so on. It is left to the designer/analyst to interpret these results in terms of specific effects, ascertain risk magnitude to the system under study, and develop mitigation (e.g., design or operational) as warranted. The user community recognizes that this presents opportunities to introduce effects-related results to the analyst to aid in risk assessments. Effects or tool deliverables

could include breakdown thresholds, ESD characteristics (rate, magnitude), propagation speed, and options to include coupling to pre-determined cables/harnesses or RF systems.

Needed quick turn anomaly analysis tools

The characteristic time scales associated with surface charging and the challenges related to spatial and temporal correlation [6][7] render extrapolation of available observations to the affected spacecraft difficult and/or uncertain (see SEESAW contributions from [Clymer, D.; SEESAW] and [Likar, J.; SEESAW]). Probabilistic approaches such as SEAES-GEO employ "hazard quotients" [10][11] derived from spacecraft (or architecture) past-performance as a means of directly connecting the space environment with anomaly likelihood. The utility of such an approach extends from real-time (or near-real-time) monitoring but also to reconstruction or event forensics.

Currently, GEO applications dominate surface charging discussions; however, it may not be the case indefinitely owing to the increasing number of long-duration All Electrical Propulsion (EP) transfer missions (or Electric Orbit Raising, EOR) and also constellations in Medium Earth Orbit (MEO). The following represent specific needs identified by workshop participants.

1. While engaged in on-orbit anomaly response activities, spacecraft operators and manufacturers often assess the comparative severity of current (real-time), recent (near-real-time), or historical space environment conditions relative to some known benchmark such as contract requirements or a statistical confidence level. *The user community has identified a need for statistical studies of the duration and severity of pertinent spacecraft charging environments at GEO*. Necessary imperatives related to any effective statistical studies are the identification of relevant (prioritized) environmental parameters such as temperatures [12][13] and/or Maxwellian parameters. Prior, related, work has considered observations from the Los Alamos National Laboratory (LANL) fleet [14], however these data are not easily obtained by many within industry. Other recent work by Meredith, et al [15][16] produced results using GOES >2 MeV and POES >30 keV, >100 keV, and >300 keV observations with data from both satellites proving useful in quick look internal charging assessments.
2. The user community has identified the need of for a statistical definition in terms of percentiles (e.g., 99 percent confidence level) for environment models, in order to make existing "worst-case" terminology statistically relevant. The rationale for such a request is that percentile confidence levels on environment specifications enable for cost and risk tolerance trade studies associated with design robustness and conservatism, accounting for mission lifetime and orbit. The availability of percentile confidence levels is enabled by the IRENE (AE9/AP9/SPM) model [Huston, S.; SEESAW] meets this need for radiation hazards, but not for surface charging. Benchmarking of low energy plasma (e.g., electrons and ions which contribute to surface charging) observations for GEO (and other orbits) is still needed.
3. Satellite operators, particularly those operating at GEO, rely almost exclusively on the GOES >2 MeV flux, 1-day, or 2-day fluence as an indicator of internal charging risk; see [Clymer, D.; SEESAW], [Likar, J.; SEESAW], and [Bodeau, M.; SEESAW]. Specific processes utilized by operators or manufacturers and the ultimate utility (e.g., "goodness score") of these methods are beyond the scope of this summary, however the widespread adoption of >2 MeV observations as an internal charging indicator is acknowledged [15][17] and real-time space weather web services such as those operated by NOAA (http://www.swpc.noaa.gov/) and the EU (http://fp7-spacecast.eu/) provide >2 MeV fluxes and fluences readily. *However, the user community recognizes the absence of – and need for – a well adopted proxy for surface charging*. A critical electron temperature

[12][13] and ground based magnetograms [18] have been well studied in recent years and offer candidate "rules of thumb" reference quantities or metrics for this purpose.

4. Models need to quantify differential potential (currently hard to extract).
5. *The user/stakeholder community has identified a need for real-time and historical auroral substorm mapping(s)* similar to that presently supported by AMPERE (http://ampere.jhuapl.edu/).
6. The absence of spatial and temporal correlations and the highly asset-dependent nature of surface charging often requires that analysts rely upon event occurrence times alone to establish a risk indicator. *The user/stakeholder community has identified a need for, at a minimum, a look-back tool that allows the user to enter in all the (candidate ESD) event dates, time, and locations and then provides an assessment for the combined dataset of events*. [Green, J; SEESAW] and [10] have discussed such efforts focused primarily at GEO however extensions to all earth orbiting regimes are highly desirable.

Needed in-situ observations

In situ observations of low energy charged particles are required for improved environmental models, improved nowcasting and forecasting, and as enablers for proper statistical-based or confidence level risk indicators. Opportunities exist for improvements in a variety of in-situ observation topics, including comprehensive environment monitoring instruments, low size, weight and power (SWaP) targeted sensors, and global data management, processing, assimilation, and distribution.

1. Electromagnetic Interference (EMI) assessments, considering RF generated during surface charging induced breakdowns, often rely upon a series of assumptions and/or extrapolations. Regardless of whether such assessments are performed as part of a system verification effort or in support of anomalous on-orbit conditions, surface charging induced EMI spectra seldom exist for specific materials and geometries of interest. *The user/stakeholder community recognizes that ESD RF spectra are based on old data and seek updates to it for modern materials and design practices*. Many published manuscripts date back decades to work performed for SCATHA and MILSTAR on a small number of material types [17][18]. Opportunities exist for high fidelity measurements – both ground based and on-orbit (e.g., discharge monitors) – for modern dielectric or semi-conductive materials, surfaces and satellite architectures.
2. User community familiarity with basic (targeted) detectors (e.g., transient pulse detectors or Charge Plate Assemblies) is somewhat fragmented owing to a lack of published data. Sharing of such telemetry data with the stakeholder community is strongly encouraged, and *the user/stakeholder community has identified an opportunity for review and analysis of previously unpublished targeted sensor observations*. The addition of scientific rigor may yield new insights and applications of such telemetry/observations.
3. A variety of flight instruments and sensors are useful in the development of environmental models and in assessing real-time or near-real time spacecraft charging risks. Energetic Charged Particle (ECP) sensors (e.g., telescopes) provide, in most cases, adequate charged particle measurements, however global surface charging risk indicators require correlated sensing at multiple locations throughout the magnetosphere. Further, owing to challenges associated with characteristic time scales, spatial and temporal correlations, and the dependence on spacecraft design (such as exterior materials), charging risk at specific locations or satellites is best assessed via on-board targeted sensing. *The user/stakeholder community has identified a need for increased in situ data (e.g., hosted payloads) to close the loop between charged particle observations and targeted (ESD/impact/differential charging/RF) sensors* – essentially linking the space

environment with the charging threat. Increased effectiveness of in situ measurements and sensing requires the following improvements:

   a. Improved/optimized sensors (simple with low SWaP and cost impact accommodations). ECP sensors as well as targeted "effects sensors" such as ESD detectors, RF detectors, differential charging detectors, et cetera.
   b. Increased numbers of host spacecraft in increasingly diverse orbits. Consider Co-located spacecraft at GEO, slot region, LEO constellations (e.g., OneWeb, Iridium NEXT, or LeoSat), and long(er) duration EOR spacecraft.
   c. Increased observational science and sensed data begets opportunities for Improved data management, processing, distribution, and/or dissemination to enhance the community value of the increased observational science and sensed data.

4. LEO missions, notably Freja and ISS, show that at higher latitudes surface charging has been observed on the day side, further illustrating the asset-specific and localized nature of the surface charging threat. "Rules of thumb" cannot be applied universally. The user community recognizes opportunities for increased study of surface charging at LEO: altitude and latitude dependences, auroral charging, et cetera. Opportunities exist for re-analysis of existing/historical data to as well as opportunities for new analysis afforded by CubeSats and hosted payloads.

Needed studies relating pre-flight effects estimates and on-orbit performance

The typical spacecraft lifecycle sees designers and analysts leading detailed verification analyses and/or ground testing to qualify a design for operation in the specified mission environment. The designer would use "best available/industry accepted" engineering tools, models, and testing only to, upon departure of the launch vehicle, have little to no contact with the satellite for the duration of the mission –except for anomalous performance. Further, many spacecraft operators or manufacturers eschew desires of the space environments community to host on-orbit sensors, making on-orbit verification of models or engineering tools challenging. The user/stakeholder community finds it highly desirable for positive verification (at best demonstration) of model predictions via on-orbit performance – good and bad.

Ground based laboratory testing remains an integral part of surface charging verification efforts on modern spacecraft programs, in the assessments of on-orbit anomalies, and the verification/development of improved analytical tools and models.

1. The user community recognizes that Freja data remain underexploited and offer opportunities for new discoveries upon rigorous analysis. Prior analyses identified charging in sunlight despite the spacecraft being designed not to charge [21][22]. Additional comparisons to DMSP observations may also be insightful.
2. Studies of charging observed on SCATHA, CRRES, DMSP, and Freja are literally decades old and, of course, relied upon models, engineering tools, and design practices that were state-of-the-art at that time. *The user community has prioritized the need to close the divide between modern state-of-art modelling and on-orbit observations via combined studies focused on recent on-orbit surface charging observations*. Recent examples include detailed studies of Van Allen Probes [23], POES [24], and even the HORYU microsatellites [25]. Studies of ISS charging are absolutely insightful but may be difficult to apply to non-ISS missions such as geostationary telecommunications spacecraft or navigation spacecraft. While all such studies are valuable, prioritization in such activities should be given to those missions which combine *modern* robust analytically modelling efforts with *current* on-orbit hosted sensors or instruments.

3. All spacecraft charging engineering tools such as, but not limited to, DICTAT, NUMIT, and NASCAP2K yield results that are strongly dependent upon material properties; the same is true for real-time risk indicators such as SatCAT [Green, J.; SEESAW]. Material properties such as dielectric constant, bulk resistivity, and surface resistivity may be reliably measured using international standards. However, such properties may also exhibit dependencies on temperature, radiation dose, and dose rate. The user/stakeholder community is seeking a database of high quality empirical test data for materials which includes complex dependencies such as temperature, dose, and dose rate. The immediate applications for such data are as inputs into common engineering tools and properties such as bulk resistivity, secondary electron emission constant, photoemission constant, RIC constants, and dielectric constant represent high priorities (at beginning and end of life). Current NASA/MSFC efforts to collect existing data into a managed repository reflect the value placed upon this need.

Needed environmental models

Well validated and benchmarked environmental models are likely to find greater adoption within the engineering and analyst communities if they yield outputs which are directly useable in industry standard engineering tools or comparable to common design standards (e.g., NASA, ECSS, or other). For example:

1. The user community is seeking environment models which generate outputs in formats used by common engineering tools (e.g., NASCAP2K). Specifically, one may consider Fontheim distribution for Auroral charging assessments and Maxwellian distribution for GEO charging assessments [Minow, J.; SEESAW] as both may be directly input into the NASCAP2K software.

Table 3. Summary of User/Stakeholder Community Comments and Initial Attempt at Prioritization and Difficulty Assessments

Need	Rationale	Difficulty
Non-isotropic and/or other, complex environment definitions into surface charging engineering tool[1]	Assumptions of isotropy may not be appropriate; desirable to study complex, transient, environmental conditions	Medium / High
Engineering tools[1] which identify surface(s) or feature(s) which drive results	Provide assistance to analysts seeking to validate analysis/study results, troubleshoot, or develop mitigation measures	Low
Extensions of engineering tools[1] to include effects	Aid analysts in risk assessments and in developing mitigation measures	High
Statistical studies of duration and severity of pertinent spacecraft charging environments at GEO	Aid in real-time on-orbit assessments and anomaly attribution; also for use in cost/risk trades in new mission planning and spacecraft design	Medium
Statistical definition (e.g., 99 percent confidence level) for environment models	Aid in real-time on-orbit assessments and anomaly attribution; also for use in cost/risk trades in new mission planning and spacecraft design	Medium
A proxy or reliable metric for surface charging	Establish an observable or derived space environment property (e.g. spacecraft design independent) to serve as indicator of surface charging risk	Medium
Models need to quantify differential potential(s)	This is the actual voltage that causes ESD	Low
Real-time and historical auroral substorm mapping(s)	Highly localized nature of spacecraft charging at LEO often requires analysts to ID instances or auroral passage	Medium / High
Assessment tool(s) based upon candidate event based entries	Specific threats to system performance are often not known *a priori*; ability to diagnose a surface charging sensitivity based upon observed event dates	High
ESD generated RF spectra for relevant materials/architectures	RF spectra for ESD are quite dated	Medium
Analysis of previously underutilized (unpublished) targeted sensor data/observations	Many on-orbit housekeeping or targeted sensor telemetry/observations unpublished and/or under-analyzed	Low
Increased in situ observations; low SWaP targeted sensors, hosted ECP sensors; global data management	Short characteristic time scales; poor temporal/spatial corrections; dependence on host spacecraft architecture necessitate need for more on-orbit sensing	Medium
Increased studies at LEO; dependences on altitude and latitude	Under-sampled, heavily used orbit regime	Medium
Rigorous analysis (re-analysis) of Freja data	Previously published analysis of Freja observations revealed daytime charging; opportunities for deeper investigations of valuable dataset exist	Medium / High
Surveys/re-reviews of recent examples of surface charging	Application of current state-of-art tools & methods in assessments of on-orbit charging observed on modern (current) spacecraft architecture(s)	Medium
Well controlled materials properties measurements (database)	Critical materials properties properly characterized for inputs into engineering tools and effects models (resistivities, RIC constants, SEE constant, photoemission constant, …)	Medium / High

Need	Rationale	Difficulty
Environment model outputs in formats compatible with common engineering tools (software codes)	Reduced errors/uncertainty when “good” models offer outputs readily compatible with industry-accepted engineering tools (Fontheim for auroral charging; Maxwellian for GEO charging)	Medium
Note: [1] Such as NASCAP2K, SPIS, MUSCAT, COULOMB and similar.		

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4. Internal Charging

Introduction

Internal charging (IC) is the phenomenon whereby environmental radiation (usually relativistic electrons) penetrates space vehicle shielding and collects in ungrounded dielectrics or conductors, building up until critical potential is reached. The resulting internal electrostatic discharge (IESD) is the hazard rather than the charging itself. (Formerly referred to as 'deep dielectric charging,' the more general term used here has gained currency in recognition of the role of ungrounded conductors in the hazard.) This discharge can cause damage directly, and it can radiate a signal that itself is damaging or at least communicates a spurious command to a nearby subsystem. Several years after surface charging was recognized, internal charging was identified by Meulenberg [17] as a cause of discharges in dielectrics in space. Spacecraft anomalies in the late 1970's and early 1980's particularly in geosynchronous orbit were correlated with observations of increased MeV electron fluxes, some measured by targeted instruments and others by instruments launched for other reasons [23][9]. Carrying both environmental sensors and instrumentation designed to detect charging and discharges, the SCATHA and CRRES missions contributed greatly to the understanding of internal charging. In 1995, the predecessor of the NOAA Space Weather Prediction Center (SWPC) started issuing alerts when the fluxes of >2 MeV electrons observed by GOES exceeded 1000 electrons/(cm^2 sr s). Environmental specifications have been developed based on observations [11]. Despite all this work resulting in the adoption of better practices, internal charging continues to pose a hazard to spacecraft. During the declining phase of Solar Cycle 24, a solar cycle generally lacking (so far) in the dramatic solar flares, solar energetic particle events, coronal mass ejections, and geomagnetic storms of the previous solar cycle, one of the dominant characteristics of 'space weather' has been the recurrent build-up of the radiation belts resulting from the interaction of high-speed solar wind plasma streams emitted from solar coronal holes, and the associated interplanetary magnetic fields, with the Earth's magnetosphere. For example, in 2016, numerous anomalies observed on 37 operational satellites in geosynchronous orbit have been attributed to IESD [16].

The purpose of the Internal Charging Roadmap coming out of SEESAW is to identify community needs in the areas of environmental and effects modeling, quick-look and deep-dive analysis tools, and *in situ* measurements, to estimate the relative difficulty faced in meeting these needs, and to prioritize future efforts toward these ends.

References to talks given at the workshop are in square brackets without a date. Published references are in parentheses.

Needed Environmental Models

Apart from the observation that increased pre-release testing will help avoid erroneous internal model changes (same input, different output) that decrease user confidence in models, there was not much commentary on the AE9/AP9 environmental models as they pertain to internal charging. Rather, the focus was on real-time and long-term assimilative models, derived products (such as integral fluxes and charge accumulation), and a modified approach to specifying severe environments. Because these needs are relevant to multiple categories, they are discussed in subsequent sections.

There is a need to go beyond "worst-case spectra" (as, e.g., in NASA Handbook 4002) to occurrence rates, percentile environments, and durations for electron fluxes relevant to internal charging [5]. For the near-earth radiation environment, the U.S. National Space Weather Action Plan recommends establishing benchmarks (at a minimum) for "an occurrence frequency of 1 in 100 years" and "an intensity level at the theoretical maximum for the event" (section 1.2). Extreme value analysis has been used to determine 1 in 50 and 1 in 100 year >2 MeV fluxes at GEO (Koons, 2001) and upper flux limits at multiple energies throughout the outer zone [20]. More recently, the 1 in 10, 1 in 50, and 1 in 100-year electron fluxes have been determined for >2 MeV electrons at GEO [14] and for multiple energies in LEO and MEO-GEO [15][16] using extreme value analysis. Thus, there is already a wealth of published information that should be worked into specifications and handbooks and, where there still are gaps, supplemented with additional research. This work should be refreshed at least every solar cycle as the set of observations grows.

Needed Design and Effects Tools

In interviewing ten organizations that either manufacture or operate satellites [12], found a wide range of practice in specifying designs for reducing the hazard posed by internal charging: "Spacecraft charging related requirements are more difficult to quantify and are often less consistent [than those for single event effects (SEEs) and total dose] with respect to each company's design and verification methods. The specifications may give the maximum external flux and duration, or the allowable internal flux as a means to reduce internal charging hazards. Or they may give the maximum resistivity of materials to be used in order to reduce the chance of charge build up in dielectric materials. While these are sensible guidelines, they do not guarantee that a system will be impervious to charging, or how it will respond should a discharge occur." Reliance on qualitative guidelines is one symptom of the gap that exists between knowledge of the radiation environment and the ability to predict internal charging effects. Also, [12] noted that many anomalies categorized as SEEs may in fact be due to ESDs and are categorized incorrectly because the investigations are not always performed. The gap between environmental information and internal charging effects models may contribute to this misattribution of anomalies. In general, a translation layer between environmental models and spacecraft effects is absent. Therefore, there is a need for improving the use of existing environmental models in effects modeling. Part of the solution is to make it easier to communicate the outputs of environmental models to effects models [5]. Adoption of a common export/ingest formats, coordinate systems, etc. would reduce the development burdens on both sets of models.

A lack of understanding of how certain common insulators such as Teflon [11][10] may contribute to internal charging also contributes to the difficulty of attributing anomalies to internal charging. Materials use is in part an education issue, especially as to why some materials should not be used (especially those with large electrical time scales, aka "RC time constants" or "charge bleed-off time"). Challenges include complexity in materials modeling, including the modeling of time-varying electrical properties of materials. Time "constants" are not constant over long periods and varying environmental conditions; electrical time scales vary with temperature, aging, and radiation-induced conductivity (RIC) (i.e., a sensitivity to dose rate). The laboratory measurement of electrical properties of materials is an evolving area that requires close attention. Bulk resistivity of materials measured in vacuum can be orders of magnitude greater than the resistivity measured in air [4][10]. More and improved testing is needed that better reproduces on-orbit conditions such as vacuum and aging.

Moreover, there is the "Rolodex problem": information on materials is very "expert friendly" whereby experts with connections in the community can get information while others cannot. Relatively new entrants to the field either may not be aware of materials issues or may not have ready access to experts or materials data. A means should be developed for new users (new suppliers, designers, builders and operators of small sats or nanosats, such as university student projects) to obtain the information they need, in an orderly and efficient manner. Some combination of a publicly-available materials property database and guidelines for choices of materials would go a long way toward mitigating this problem.

Existing organizations could help bridge the gap between those studying environment and building models of it, and those designing, launching and operating space missions. IEEE Nuclear & Plasma Sciences Society (NPSS) is one such organization. Conferences such as the IEEE Nuclear and Space Radiation Effects Conference (NSREC) (run by NPSS) and the Spacecraft Charging and Technology

Conference might add workshops on surface/internal charging materials data, like that NSREC has for parts testing compendia [22].

Needed Quick-Look Anomaly Analysis Tools

Perhaps the most commonly-used quick-look tools at present are ‘canned’ plots and files of fluxes and indices from the operational weather satellites (GOES, POES, MetOp). However, there have been recent changes in NOAA websites that have not been sensitive to the expectations of users long accustomed to pre-existing collections and formats. In general, it is difficult for even seasoned experts to access real-time data for quick environmental information. This situation introduces another “Rolodex problem.”

Daily indices are an important starting point for quick-look environmental data in support of anomaly resolution [2]. However, daily electron fluences have become difficult to find at NOAA SWPC and NCEI, and when found the format is too detailed to be suitable for a quick look at key environmental parameters [1][2]. Daily GOES fluences and POES/MetOp belt indices should be continued, but the uninterrupted production of useful products should not be taken for granted. Daily LEO flux maps (including the old SWPC ‘tiger’ plots) were discontinued when POES/MetOp processing switched from SWPC to NCEI. It is easy for such needs to fall through the cracks when there is a block change; for example, a requirement for calculating daily electron fluence from GOES-R measurements has not been communicated to NCEI, which is responsible for developing such higher-level products. Production of the POES/MetOp belt indices is running thin on human resources; all POES/MetOp SEM activities (five spacecraft) are supported by approximately 0.10 FTE at NCEI [6]. A strategy for the replacement of POES/MetOp with other LEO sources such as REACH in the generation of belt indices should be developed, since the last SEM-2 was launched on MetOp-C in 2018.

Changes in processing need to be noted wherever the affected data are used. For example, the switch in the processing of the GOES >0.8 MeV electron channel (E1) starting with GOES-13 in 2010 that reduced fluxes by about a factor of 10 [2] was announced by SWPC but not noted in the Daily Particle Data (DPD) file header. When such changes occur, pre-existing indices and fluxes should be reprocessed.

While some operational satellites are now flying instruments that provide improved energy- and angular resolution, this introduces the problem of a gap between the scientific-quality measurements and the reduced quantities needed by many in the community. For example, it was generally agreed that, while pitch-angle measurements are of scientific interest, current effects models assume isotropic fluxes. Therefore, omnidirectionally-averaged fluxes should be produced routinely, in real time if possible. Additionally, there are different needs for how the electron observations are processed. Some users wish to have the electron differential energy spectrum (albeit omnidirectional), which itself requires some sophistication to derive accurately from real observations [7]. The electron differential spectrum is necessary as an input to codes that transport electrons through realistic models of the vehicle. Others prefer to take advantage of a higher level of processing, either a product containing integral fluxes above multiple energies corresponding to a fixed set of shielding thicknesses, or a tool to calculate integral flux for user-selected shielding.

Where available, severity metrics (such as percentiles or the frequency of a given flux level), as discussed above under ‘Environmental Models’, should be indicated on canned plots. Such severities will be based on general assessments. However, canned plots are not sufficient for all quick-look needs. Real-time assimilative models can provide information tailored to a specific satellite location. As addressed below, real-time observations in MEO are currently only provided by Van Allen Probes, which does not have a planned follow-on mission. An empirical mapping of REACH data [4] to MEO could contribute toward addressing the real-time coverage in MEO. Radial diffusion data assimilation models such as the Versatile Electron Radiation Belt (VERB) code [3] or LANL DREAM can be used to specify relativistic electron radiation belt fluxes at and inside GEO in near-real-time.

Needed Deep-Dive and Whole-Mission Analysis Tools

For anomaly analysis, there is a need to understand the complete internal charging history of the spacecraft, perhaps all the way back to launch. The mission history is needed for an accurate accumulated charge estimate, under several shielding thicknesses, particularly for dielectric materials with very long dielectric time constants in vacuum (i.e., hundreds of days). Mission-tailored tools for this purpose are by definition 'deep dive'. Deep dive tools tailored to a specific mission can provide severity metrics (e.g., flux percentiles) for that mission based on observations/model results since launch. Long-term data assimilation models such as VERB, LANL DREAM, and ONERA Salammbô have potential for deep-dive analyses over the history of a mission. For example, the VERB-3D model is currently used in the Satellite Charging Assessment Tool (SatCAT, [12]) to estimate fluxes and accumulated charge following the method of Bodeau [10] at a user-selected satellite location. Future accumulated charge tools should also include effects such as radiation-induced conductivity that reduce charge bleed-off times. The workshop identified a need for common input and output formats (time, location, energy) for such data assimilation models, which would reduce the development burden.

Deep dive analyses require access to the most recent, real-time data as well as to the historical record. Even in a quick-look analysis, understanding real-time data or forecasts requires being able to place these contemporary data in the context of the entire mission history of a vehicle. This presents a problem when the former and the latter are available at different locations in different formats. Data providers should work towards seamless provision of real-time and historical data. Analysis tools, whether performing a deep-dive charging analysis, or simply contextualizing recent, current, or forecast conditions, need to be able to estimate conditions at the subject vehicle all the way back to its launch.

Needed In-Situ Observations

Particle observations are needed for (near)-real-time situational awareness as well as for retrospective deep dives and model development. There are many multi-decadal data sets from LEO (e.g., DMSP, POES/MetOp) and GEO (e.g., GOES, LANL) that still receive attention for improved reprocessing and availability. Recently, data coverage in MEO at electron energies associated with internal charging has received a great boost from LANL GPS [18], INTEGRAL [16], and of course Van Allen Probes. However, of all of these, only GOES and Van Allen Probes data are available to the public in real time, and there is no planned operational follow-on to Van Allen Probes (whose mission life is expected to be fuel-limited by the end of 2019). Long-term, real-time data from MEO is a gap that needs to be addressed. The processing of the POES and MetOp data is delayed by about an orbital period. This kind of latency problem from LEO has been addressed by the Responsive Environmental Assessment Commercial Hosting (REACH) mission architecture [4]. There are some environmental modeling approaches to addressing this coverage gap (discussed above).

While the missions mentioned above are indispensable, there is no substitute for in situ observations on a satellite that has suffered an anomaly. It is USAF policy to fly an Energetic Charged Particles (ECP) sensor on every vehicle [13]. Ideally, this would be emulated by other agencies and governments, and even commercial satellites. Inclusion of environmental monitors on all Class A (high national importance, high priority, minimum risk, high complexity, high redundancy) spacecraft (as a standard) would greatly improve ability to assess the link between anomalies and environments [1]. However, policy is not a guarantee of success. There was such a policy 20 years ago regarding the CEASE sensor that had very limited effectiveness; only a few CEASE sensors were flown. Satellite programs are very sensitive to the additional cost and accommodations burden of even a very small sensor (field-of-view requirements can be some of the most difficult), especially if it is unclear before launch whether the benefit outweighs the cost. Requirements can be waived. The satellite engineering community needs to advocate for such sensors; they need to be viewed as necessary as thermistors and current and voltage monitors (and need to be about as cheap and reliable) [4]. Success stories from CEASE and other simple environmental monitors need to be documented and publicized, in which the *in-situ* observations were invaluable to anomaly resolution, could not be reproduced by models or extrapolations from other satellites, and led constructively to change in satellite design or operations.

Not only environmental measurements are needed. New sensors and missions dedicated to measuring anomalies are needed. Past examples include SCATHA and CRRES, which had comprehensive environmental and anomaly measurements. Particular attention was drawn to the need for measuring RF waveforms from discharges on-orbit, and better distributing characteristics from such waveforms from laboratory measurements and past missions.

Anomaly databases are included under this category since they require the collection of satellite data (both technological and environmental). General support for anomaly databases was expressed at the workshop. (Of course, this is relevant to all effects, not just internal charging.) An anomaly database is an action assigned to the Departments of Commerce and Defense under the U.S. National Space Weather Action Plan (4.2.8): "DOC and DOD will create and support a satellite-anomaly database to enable secure collection and analysis of satellite-anomaly data related to space weather; Deliverable: Complete development of a satellite-anomaly database in a secure format at DOC." Such a database could start with the content and format recommended by O'Brien et al. (2011) and adopted by the international Coordination Group for Meteorological Satellites (CGMS) for reporting anomalies on weather satellites. Anomaly databases have been discussed at the Spacecraft Anomalies and Failures Workshop, a yearly meeting of recent origin held in Chantilly, Virginia; the SEESAW community should consider leading constructive discussions of paths forward at this forum in the future.

During the workshop, there was feedback that the current >2 MeV electron alerts (based on GOES observations in geostationary orbit) issued by SWPC are too low. This is not a universal sentiment. However, it is reasonable to consider whether the current alert level (1000 electrons/(cm^2 sr s)), first issued by SWPC in 1995, is obsolete and needs to be reevaluated. It can be traced to the work of Wrenn and Smith (1996), which was based on anomalies observed during the early 1990s and attributed to IESD. NOAA would not initiate such a change, relying instead on the community to provide such concrete feedback. If this happens, both the energy threshold and the associated flux level should be reconsidered. Also, orbits besides GEO should be considered.

Summary

In addition to the major points raised above, the workshop participant contributed several other ideas for topics that need further attention.

Needed Studies Relating Pre-Flight Effects Estimates and On-Orbit Performance: In order to relate pre-flight effects estimates to on-orbit performance, the pre-flight analysis needs to provide predictions that are testable, given the instrumentation on the satellite in question. Satellite data should include telemetry data, which is a very valuable source of data the analysis of which is not published as much as it should be. Soft effects that do not cause manual intervention or other changes in operations should be analyzed to provide context for harder/disruptive effects.

Comments on Funding and the Role of Government vs. Private Industry: The historical trend is for less and less government-internal support for tool development. Government-funded efforts such as AE9/AP9 need to ensure products are openly available both contractually and as regards export control. Third-party providers may need to fill gaps. A consortium of the community could prioritize its needs and provide funding for common, open models to be developed and maintained by third parties.

Revival of the NASA SEE Branch: It was suggested that a NASA-SEE branch would be beneficial as a mechanism to engage the hybrid public-private research workforce.

Table 4. Internal Charging Roadmap

EM	DE	QL	DD	IS	PF	Need	Rationale	Priority	Difficulty
X		X	X	X		Fluxes below GEO esp. MEO: climatological, mission and near-real-time (same day) observations, e.g. Van Allen, LANL GPS	Important especially for NASA needs and electric orbit raising. Issue with Van Allen Probes is projected limited mission duration. Issue with LANL GPS is no public access to data in real time.	2	MEDIUM / HIGH
X		X				A model that maps LEO (POES/MetOp, REACH) electrons empirically up the field line to MEO	Specific example of a possible MEO model. Empirical, not physical.	19	MEDIUM
X		X				Near-real-time environment everywhere, including vehicle locations (e.g. VERB, DREAM)	Needed to fill in gaps for unusual and transfer orbits	18	MEDIUM
X			X			Long-term data assimilative reanalysis (VERB, LANL/DREAM, ONERA/SALAMMBO)	Helpful, especially for internal charging design.	5	MEDIUM
X		X	X			A tool to calculate integral flux above multiple energies in real-time and over mission duration	Place conditions at time of anomaly in mission context. Need integral flux corresponding to multiple shielding thicknesses. GOES 2 MeV electron data is good enough only as a quick look, and adequate for GEO only	9	LOW
			X			A tool to calculate internal charge accumulation (for multiple energies /shielding thicknesses/ materials) over mission duration, accounting for effect of environmental variability on materials properties	Place conditions at time of anomaly in mission context. Existing tools do not account for environmental effects such as radiation-induced conductivity.	10	LOW / MEDIUM
X			X			A tool to calculate electron spectrum from channel data	Pre-determined integral fluxes may be inadequate. This enables people to calculate their own integral fluxes well as use it as input to transport models.	8	LOW
X						Establish environmental spectra with occurrence rates, confidence levels and durations	Move away from ‘worst-case’ spectra	3	MEDIUM

EM = Needed environmental models, **DE** = Needed design/effects tools, **QL** = Needed quick-look anomaly analysis tools, **DD** = Needed deep-dive analysis tools, **IS** = Needed in-situ observations, **PF** = Needed studies relating pre-flight effects estimates and on-orbit performance

X					X	Determine significance of flux anisotropy to anomaly resolution, especially below GEO	Analyses assume it is not important. Much skepticism – expectation is it's not important. Is there an example in which isotropy was assumed pre-launch and anisotropy was deemed to be important on-orbit?	24	HIGH
	X					Establish a materials property database, preferably with associated anomalies when available. Even a database of “good or bad” is better than nothing.	Addresses “Rolodex problem.” May mitigate the risk of less-experienced/informed users using high-time constant materials. Are there ways to verify/validate ways that people are properly testing/working with materials? Recommend a community database to store property test results.	1	MEDIUM
	X					More and improved materials testing, including under on-orbit conditions (e.g., vacuum, aging)	Dielectric properties can vary by orders of magnitude from air to vacuum.	4	HIGH
	X					Develop guidelines or standard for how to choose a time constant for prediction/evaluation of internal charge accumulation	Complex problem involving ageing, radiation-induced conductivity (RIC), temperature, as well as wide variety of materials	6	LOW
		X	X			Routinely calculate omnidirectionally-averaged fluxes from pitch-angle-resolved measurements	There are no codes that work well with non-isotropic data, so designers just assume isotropic. ‘Ditch the steradian.’	14	LOW
		X	X			Create a seamless interface to data from GOES and other satellites, bridging real time and archive: daily averages, short (days) time history, mission history since launch	Current data interface too rich/complex for non-scientific users. The NOAA data are split between SWPC (latest, some archive) and NCEI (most of the archive) and are scattered within each site. This poses another “Rolodex problem” for most users.	15	MEDIUM
		X	X			Revive/continue daily (weekly, monthly) flux indices from GOES and POES/MetOp	Ease of use by non-scientists	7	LOW
		X	X	X		Develop a strategy for achieving continuity in LEO belt indices between NOAA (POES/MetOp) and new/future (e.g., REACH) monitors	Final SEM-2 launches on MetOp-C (~October 2018). No NOAA plans to replace.	21	LOW

EM = Needed environmental models, **DE** = Needed design/effects tools, **QL** = Needed quick-look anomaly analysis tools, **DD** = Needed deep-dive analysis tools, **IS** = Needed in-situ observations, **PF** = Needed studies relating pre-flight effects estimates and on-orbit performance

X	X		X			Develop an interface control document (ICD) for 5-D (time, location, energy) data cubes for re-analyses. Energy range and LEO resolution need special attention.	Long term model runs will be more broadly useful if they are stored in a consistent data format.	17	LOW
X	X		X			Develop an interface control document (ICD) between environmental datasets/models and effects models, including specifying the spatial coordinate grid	Will facilitate broader use of datasets and models.	16	LOW
				X		More on-orbit sensors and missions dedicated to measuring anomalies. The design should allow anomalies to take place, and provide a means to monitor the cause and effect simultaneously	More sensor data and a dedicated effects mission will improve future pre-flight anomaly rate estimation and anomaly impact mitigation methods.	12	HIGH
				X		Small environmental sensors on multiple missions: USAF/SMC is doing Energetic Charged Particles (ECP), and would like to extend that to other USG organizations, commercial hosting	Local environmental observations pertinent to anomaly resolution on as many missions as is feasible	13	HIGH
				X		More information about ESD waveforms: on-orbit measurements of RF transients (at a minimum, counting them with a first-circuit filter), making RF characteristics from on-orbit measurements or lab test more widely available to the community.	Current pre-flight testing is based on old and limited in situ RF waveform data.	11	MEDIUM
				X		Anomaly database: aggregating historical data and sharing results	Important, has international (e.g., CGMS) interest.	22	HIGH
				X		Develop and recommend updated real-time alert levels based on current spacecraft susceptibilities.	GOES >2 MeV alert levels are too low. Current alert level based on c. 1990 situation. Spacecraft susceptibilities have changed.	20	MEDIUM
					X	More studies closing the loop between preflight estimates and on-orbit behaviors/performance	Could reduce margins, or lead to more stringent requirements.	23	MEDIUM

EM = Needed environmental models, **DE** = Needed design/effects tools, **QL** = Needed quick-look anomaly analysis tools, **DD** = Needed deep-dive analysis tools, **IS** = Needed in-situ observations, **PF** = Needed studies relating pre-flight effects estimates and on-orbit performance

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5. Single Event Effects

Introduction

Single event effects (SEE) are caused primarily by energetic protons and heavy ions that deposit energy in the form of ionization in solid state electronics. Only very energetic (10's of MeV) electrons, such as those found in Jupiter's magnetosphere and (under certain conditions) in the Earth's radiation belts, can cause SEE. The conventional way to describe a heavy ion's capacity to cause SEE is through its linear energy transfer (LET), which is the energy it deposits per unit length travelled through matter. Typically, LET increases with the square of charge and decreases with increasing energy. Therefore, as a particle loses energy, its LET increases, until it reaches what's called the Bragg peak, below which its LET decreases with decreasing energy. For protons, the SEE capacity is often related to the proton energy: protons themselves, being singly charged, have low LET, but they can knock loose nuclei in the ambient matter, which become high LET heavy ions. Neutrons are mainly secondaries in the atmosphere and inside vehicles, and, while they have zero primary LET, they interact with nuclei analogously to protons, producing heavy ions.

Galactic cosmic rays (GCR) are a low-intensity source of heavy ions. GCR have some solar cycle modulation, anticorrelated with the sunspot number. GCR also exhibit Forbush decreases associated with magnetic activity. For the GCR component that causes SEE, these are not large dynamic effects. The far more dynamic source of heavy ions, and protons, for space missions is solar energetic particle (SEP) events. During these events, the SEE hazard to satellites can increase many orders of magnitude over GCR levels. Finally, trapped protons contribute to the SEE risk for satellites, especially those that traverse the inner Van Allen belt or its low-altitude edge, the South Atlantic Anomaly.

The Earth's magnetic field strongly controls access of GCR and SEP to a given point in near-Earth space. Typically, more energetic particles penetrate deeper into the magnetosphere than less energetic particles. The location and energy of the access boundary is referred to as the geomagnetic cutoff. The cutoff varies with geomagnetic activity, allowing deeper access during geomagnetic storms.

For the most part, satellites mitigate SEE through prudent design and pre-flight testing. However, some missions accept down-time due to SEE, and others discover susceptibility once on orbit due to various kinds of design and test escapes.

Background

There are several kinds of SEE:

Single event upset:	Non-permanent change of state of a "bit" caused by creation of free charge by passage or interaction of radiation (heavy ion, p, n, e, γ);
Latchup:	Permanent (but protectable) damage to a component through creation of parasitic current path by passage or interaction of radiation (heavy ion, p, n);
Burnout, Gate rupture:	Catastrophic electrical breakdown in power MOSFETs through creation of parasitic current path by passage or interaction of radiation (heavy ion, p, n);
Functional interrupt:	In complex logic devices (e.g., ASICS) a strike inducing a logic change can disrupt the program execution in unpredictable ways;
Single event transients:	Single strike on a logic element can induce a pulse on output line that may not be adequately filtered and so propagate, introducing logic errors;

Stuck bits:	Displacement damage in the “bit” quasi-permanently fixes its state. Can reverse;
Sensor background:	Sensors for detection of signals, e.g., from infrared (IR) to gamma, other signals can be affected by radiation. Pixelated sensors can “see” particle impacts as noise.

The effects result from various particle interactions:

Direct ionization:	The particle track generates a trail of electron-hole pairs in material. The particles are usually heavy ions but in sensitive devices proton direct ionization can lead to SEE.
Nuclear interactions:	The primary particle interacts with a nucleus in the sensitive volume and induces breakup, the products of which create sufficient local ionization to cause a SEE. Historically this has related mainly to protons and neutrons, but recently electrons and gamma rays have been seen to induce SEE via electro-/photo-nuclear reactions. In space the neutron flux is generally lower than ion fluxes so that neutrons are not normally an issue. However, it is important for aircraft and heavily shielded locations (on ISS, within lunar or Martian habitats, etc.).
Displacement damage:	One or more atoms are displaced from their location by collisions with the primary particle.

Current State of the Art and Needs

From the above, careful evaluation of all sources and effects is clearly necessary as part of spacecraft development, and is normally done via a radiation hardness assurance processes (e.g., ECSS-ST-Q-60-15c, …).

The de-facto standard methodology for evaluating the probability or rate of direct ionization SEE is the integrated rectangular parallelepiped (IRPP) model of CRÈME-96. Here, the sensitive volume is assumed to be a parallelepiped “box”.

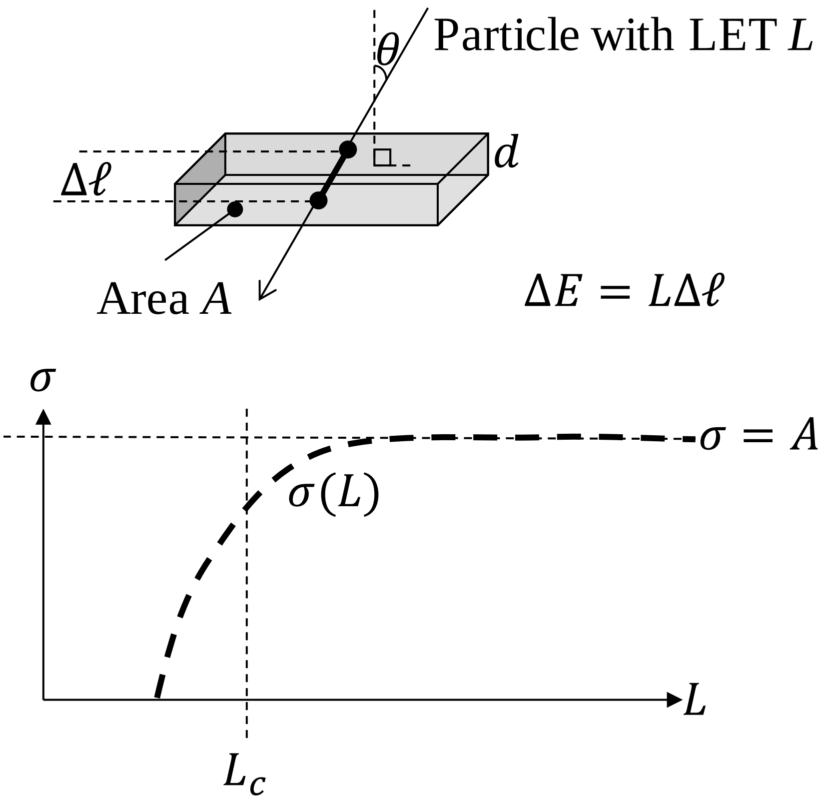

Figure 1. An illustration of the rectangular parallel piped (RPP) model of sensitive volume, and how its parameters relate to upset cross section σ.

The method relies on characterizing the environmental fluxes on the basis of a particle's linear energy transfer (LET) which allows the combination of ions that are of differing species and energy, but having the same energy loss[1] rate in the material (LET), and so in principle generate the same free charge on a particular path through the box. Then the combination of path length and LET allow determination of created free charge, and, if this is above a device-specific threshold, a SEE will result. Irradiation tests with heavy ions help establish the threshold (Lc) and the size of the box (σ, A) (see Figure 1.). The saturation cross section seen in testing the SEE as a function of particle LET is in principle the box cross section A. The onset LET Lc reflects the critical energy and charge.

In a sense, protons and neutrons are easier to deal with. The probability of nuclear interaction is proportional to the path length (d/cosθ) through the sensitive volume, but the directional flux also follows a cosine law. One "only" needs to perform a test of the proton/neutron SEE cross section as a function of energy and fold this with the expected spectrum to compute the rate.

The electron/photon induced SEE is more complex in the sense that the photonuclear[2] interaction follows after the transport of the e or γ, and so the electromagnetic transport is important. Again, the probability calculation leans heavily on testing.

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[1] More accurately, it is the energy transferred to ionization, rather than loss; some energy goes elsewhere.

[2] Electronuclear is almost the same, acting via a virtual photon.

Given the above, the main requirements in terms of the environment, and the respective states of the art are:

Table 5. Single Event Effect Environment Status

Environment	State of the art
GCR ion energy spectra to be transformed into LET spectra	There are good stable models of the CR fluxes. Fluxes are in principle needed for all ions (but especially up to the Ni composition knee). They have been well-measured with many experiments over decades [1].
SEP ion energy spectra to be transformed into LET spectra	Although there has been a healthy evolution of solar energetic particle (SEP) proton models based on long time series data, the SEP data on ions is less complete, especially at higher energies. The ACE spacecraft is a key resource. Fluxes are in principle needed for all ions (but especially up to the Ni composition knee). However not all ions are measured, ion groups are often measured together (e.g. CNO), and some ions have poorer knowledge which necessitates extrapolations. GOES-R-series EHIS (starting with GOES 16) will be an important source of data over nearly 2 solar cycles.
SEP protons	There has been a healthy evolution of SEP proton models based on long time series data, efforts at cleaning, establishing reference datasets, and statistical techniques (e.g. King, ESP, MSU, SAPPHIRE, VESPER). However, for instantaneous particle fluxes the engineering models rely on historical “worst observed” events, rather than a more rigorous statistical treatment.
Geomagnetic cut-offs	The above 3 environments are modulated by the Earth’s magnetic field. Field models are mature and the methodology to calculate the effects on spectra are well established. Climatological tools are available and validated with data, but real-time tools, using real-time in situ data, are not available.
RB Protons	Secular variations in the magnetic field have to be considered since they alter the location and shape of the South Atlantic anomaly. Widely used traditional engineering models, such as AP-8, are static and do not include information on the dynamics of the proton belt, nor indication of the risk of exceedance.
Internal/planetary neutrons	Several tools exist with the ability to compute secondary neutron fluxes (Geant4, Fluka, MCNPX, …). These are needed for lunar and mars missions, and for human habitats
Electrons in severe cases (Jupiter, possibly GNSS)	The severe environments of Jupiter and GNSS have models available. Unfortunately, the high energy regime is based on relatively weak data because the instrument was never intended for this (i.e., at Jupiter – the Galileo EPD). Van Allen Probes and GPS electron measurements do not extend above 10 MeV. CRRES and SAMPEX have observed intense, transient >10 MeV electrons in the inner belt and slot region.
Solar cycle variations	All elements of the environment are affected by solar activity. The solar cycle variations of GCRs are well modelled. However, solar activity levels vary beyond the ranges used in modelling may cause problems. Similarly, the inner belt protons are affected by solar activity, but solar cycle predictions are very unreliable.

Related Discussions at the Workshop (Current Situation)

If device technology details are known, predictions are "reasonably good"
Underlying this statement is the fact that the main problem with the methodology that quantifies SEE probabilities is the need to obtain good and relevant data on the particular device to be flown.

In well-engineered s/c we should not be seeing destructive events – engineering needs improving, not modelling;

If destructive events are seen, then there has been some failure of the radiation hardness assurance process. In rare cases, the environment may have been inadequately defined but more likely is a problem in the component evaluation (testing, lot screening, inadequate testing, etc.).

Rare events – e.g., destructive strikes, single-event transients (SETs) or complex-system function errors – are difficult to predict since quality test data are difficult to obtain; databases of testing needed;

Complex systems are difficult to predict because the behavior depends strongly on the location of the hit and the execution of logic (timings of operations). In principle the best way to test is at system level which implies using facilities that can accommodate them, e.g., broad beam, heavy ions in air (so high energy).

COTS components are difficult to cope with; there are traceability issues; missing technology data;

COTS components are increasingly sought for space applications but although they have cost advantages, evaluation of the radiation hardness is difficult for several reasons. The technology within the components may be complex and not generally accessible from the vendor. The radiation screening is made difficult by the fact that there is low confidence that a device that is tested will be the same as one that is flown, even if the device batch is nominally the same. The devices can be manufactured in different fabrication facilities and may behave differently on exposure to radiation. However, other civil domains have active programs for procurement of COTS for high radiation environment applications (e.g., Large Hadron Collider (LHC), High-Luminosity LHC, International Thermonuclear Experimental Reactor (ITER),…) that the space community can cooperate with.

Risk may be identified late in a project;

While in principle the radiation hardness assurance (RHA) process should identify susceptibility to SEE of all components early in a project, experience shows that sometimes problems are found late in development. This makes for an expensive and difficult risk assessment and in the worst case, re-engineering.

Basic statistics explains apparent strange variabilities in observed rates;

In devices with low SEE rates, sometimes SEEs are observed clustered in time. While this may seem to imply an enhanced environment, such behavior is consistent with basic statistics and the probability of clusters is reasonably high.

Multiplicity of models is confusing for engineers and results in loss of confidence;

Manufacturers establish processes that over time provide heritage and confidence. In addition, it is commercially more efficient to establish standard product lines for units and (sub-)systems. As a consequence, changes in models that increase the radiation levels can potentially lead to problems with re-establishing processes and/or re-qualification of equipment. Of course, another way to look at this issue is to use the new models that provide better risk assessment to determine what the risk is that is assumed using the old models. For example, the use of JPL 91 with 90 percent is comparable to the ESP at 80 percent.

Table 6. Trends and Related Emerging Needs for Single Event Effects

<table>
<tr><td>EOR</td><td>Raising satellites to their final orbits (e.g., GEO, GNSS) from a lower orbit using electric propulsion (electric orbit raising – EOR) exposes the satellite to a harsher radiation environment during the (slow) transfer. Moreover, this exposure eats into the “radiation budget” for the mission. This aspect is not so problematic for SEE. Rather it is the fact that the spacecraft is possibly exposed to high fluxes of protons in the inner radiation belt, leading to enhanced SEE risk. The transfer may potentially occur during one of the occasional radiation belt enhancement and the design has to reflect this. Sensors should be flown to validate/record the environment.</td></tr>
<tr><td>Mega-constellations</td><td>The development of mega-constellations (see table below) poses problems for radiation hardness assurance both because some concepts place satellites at higher altitudes than a “standard” EO-like polar earth orbit (PEO), in “high LEO” (low Earth orbit) or medium earth orbit (MEO), but also because the paradigm relies on low-cost spacecraft. The latter implies extensive use of COTS and/or low-cost screening. One constellation will use “*16nm feature size ASICs/FPGAs”*- relatively advanced technology yet low cost. To avoid a space debris growth in the orbits, reliability has to be sufficient to de-orbit at end-of-life. The SEE susceptibility will be difficult to ascertain. The environment certainly needs better definition, along with variabilities over different timescales. Sensors should be flown to validate/record the environment.
<table>
<tr><th></th><th>*alt (km)*</th><th>*i*</th><th>N_{SATS}</th></tr>
<tr><td>**SpaceX**</td><td>1100</td><td>86.4</td><td>800+</td></tr>
<tr><td>**Globalstar**</td><td>1410</td><td>52</td><td>48</td></tr>
<tr><td>**Oneweb**</td><td>1200</td><td>?</td><td>800</td></tr>
<tr><td>**O3B**</td><td>8000</td><td>0</td><td>20</td></tr>
<tr><td>**Boeing ph.1/2**</td><td>1200</td><td>45-55</td><td>1396+</td></tr>
<tr><td>**Boeing ph.2**</td><td>1000</td><td>88</td><td>~1000?</td></tr>
<tr><td>**ViaSat-3**</td><td>8200</td><td>87</td><td>24</td></tr>
</table>
</td></tr>
<tr><td>Other hazardous locations</td><td>Apart from the mega-constellations and high PEO EO (e.g., Sentinel-6/Jason-CS) that will be operating in areas with higher radiation levels than maybe used for heritage equipment, locations with particularly severe environments are the GNSS orbits that pass through the heart of the electron belt and missions to Jupiter and Saturn. Most of the “abnormal” hazard is due to electrons so the additional concerns are for devices susceptible to electro/photo-nuclear induced SEE. Requirements for environment models will be similar to internal charging and dose needs, although it is the high energy population that is important in these nuclear reactions</td></tr>
<tr><td>Smarter spacecraft</td><td>EO missions have increased in complexity both in terms of the payload but also the extent of on-board processing. As a result, single event effects, especially in the SAA are a common feature of EO missions. The complexity trend is now seen in telecommunications satellites where extensive “digitalization” and on-board processing is done. In the latter this is accompanied by the need to keep costs down. This potentially opens the systems to more issues regarding single event effects.</td></tr>
<tr><td>COTS</td><td>COTS components are attractive for cost reasons, but are also used in high reliability applications (e.g., automotive) and even radiation environments (high energy physics facilities). Some space system manufacturers have established processes for using COTS. However, the difficulties related to testing, the obtaining of technology details needed for SEE evaluation, etc., remain.</td></tr>
</table>

Table 6. Trends and Related Emerging Needs for Single Event Effects (continued)

Device complexity	Complex device structure will become difficult to deal with, not just from the point of view of describing sensitive volumes, but also due to the presence of metallic features close to sensitive nodes which incident particles can have nuclear reactions in, generating SEE from the reaction products.
Drive to low cost and development time	This has been covered above: the mega-constellations are low-cost, there are commercial pressures on GEO systems, and space industry can respond to such pressures by standardizing product lines and families. This may however mean that a product (unit) flies in an orbit it was not designed for. It also makes it difficult for industry to cope with changes in models if the levels imply changes to the environmental requirements or associated margins.
High reliability in support systems for humans	Apart from radiation directly affecting humans, any life-critical system that crew may be relying on has to be of very high reliability. This implies high reliability designs, and especially strict RHA and extensive test/analysis with respect to SEE for electronics in those systems (e.g., life support, warning systems, propulsion, communications.
Atmospheric neutrons	Large solar particle events pose an SEE threat to avionics which, unlike space hardware, are not routinely hardened to such effects. As for planetary neutrons above, codes exist to calculate the neutron flux environment. However, almost no data are published on the vulnerability of avionics, especially at system level. Good practice would be to conduct ground level test campaigns at spallation neutron test facilities, in order to screen for susceptible components in elevated flux environments.

Related discussions at the workshop (trends and emerging needs)

With regard to the environment care needs to be taken in very low solar activity conditions with enhanced GCR and SAA protons at low altitudes;

Low solar activity results in enhanced GCR fluxes. The present solar cycle has had unusually low activity and the solar minimum GCRs unusually high. The elevated GCR levels are not predicted by models based on sunspot number, but the improved methodology of Matthiä et al. is able to cope with extremely low activity. Problems with the older engineering models include the reliance on phasing the solar cycle with solar minimum. The “older” CREME86 M3 environments provide a good upper bound on the experiences of the last solar cycle, however the ISO15390 model underestimated the solar minimum peak in 2010 by >25 percent.

There is also an important solar activity dependence of trapped protons. The fluxes of GCRs that interact with the atmosphere to feed the cosmic ray albedo neutron decay (CRAND) process are higher and, since the atmospheric density is lower with lower solar activity, atmospheric losses of protons are also lower. One has to bear in mind that the models (e.g., AP8MIN, AP9, TPM) are based on data obtained with particular solar activity conditions.

Higher than normal sun-synchronous orbit is less well known

As indicated above some missions will operate between a standard PEO and GNSS. In this region there is less experience and so greater uncertainty. In addition, it is known that the environment in this region can be temporarily enhanced. Van Allen Probes measurements in this region should help considerably, but it would also be useful to embark upon radiation monitoring on spacecraft flying in less well-known regions like this.

Trend to increasingly risk tolerant missions, e.g., CubeSats;

There is a large range of approaches to CubeSats ranging from very inexperienced teams of students to groups exploiting the CubeSat technology for operational uses. Nevertheless, if the objective is to implement missions with very low cost, the risks are inevitably high because of the savings on testing and analyses, along with use of COTS components.

New technologies are susceptible through particle transport features: delta-rays (track spread), secondaries from nuclear interactions, multiple scattering;

Component evolutions include very small feature sizes and complex metallic tracks and layers with complex geometries. When a heavy ion passes through or close to a sensitive region, it is becoming insufficient to consider the track as a line and the energy deposition as being along the line and simply the product of length and LET (see Figure 1). Rather, the higher-fidelity modelling becomes important, in which the track has lateral spread and some more energetic electrons are produced (“delta rays”) that can travel significant distances. Therefore, the energy deposition in small volumes is difficult to assess. In addition, particles interacting with metallization can generate secondary products that complicate the energy deposition evaluation.

Needs within a “quick look tool”: geomagnetic cutoff

From an SEE point of view a quick look tool should indicate whether or not there was an SEP event at a time of interest, the location of the spacecraft with respect to the proton belt, and the GCR and SEP flux as modulated by the geomagnetic shielding cutoff. The geomagnetic shielding tool should be fast and not require extensive computations.

Tool assumptions need documentation;

Beyond just referring to published data which are necessarily abbreviated, good documentation of the underpinning assumptions, data and their calibration/analyses are needed in order that the end-user and model development collaborators can evaluate the quality and confidence. This is especially import for adjudicating model/tool disagreements.

Difficult to definitively attribute anomaly to SEE – it’s only possible to indicate a probability;

Although some SEE are directly observable through monitoring (EDACs, latch-up protection, etc.), some anomalies occur with no clear evidence of the cause. It is often attributed to SEE or ESD with limited evidence. Greater on-board monitoring would clearly help reduce the ambiguity, leading to better future designs.

Testing: need standard beams;

Testing/characterizing component behavior with respect to SEE is not easy and the facility used has to be carefully evaluated with respect to its quality and relevance. Source characteristics (uniformity, energy accuracy, purity/contamination, dose effects, range, etc.) all need careful evaluation. It is clearly more reliable to use facilities that are frequently used and characterized by others.

System impacts important;

The severity of a SEE clearly depends on its effect on the system. It is often difficult to anticipate or test the system-level effects because of the complexity of the system logic. Facilities are becoming available that allow testing of large pieces of equipment, enabling system level testing to observe functional behavior.

The high priority is to have a combination of tools + testing + IOD on same device(s);

In orbit demonstration (experimentation)—IOD—provides the means to validate ground evaluation which is done through a combination of testing and application of models and analysis tools. Unfortunately access to space for IOD is limited and the effort to prepare IOD experiments is large. Retrievable experiments such as the NASA Long Duration Exposure Facility (LDEF) have been limited to relatively low-inclination, low altitude orbits accessible to the Space Shuttle, or the International Space Station. It would be highly beneficial to ease this access problem with routine/regular IOD opportunities; automation will be necessary for IOD in the most hazardous orbits. Like SCATHA and CRRES, future IODs will require a combination of environmental observations and effects experiments in order to properly validate the ground evaluations.

Conclusions/Way Forward

From the discussion above it should be clear that the main problem with respect to SEEs is not the definition of the environment but is rather the evaluation of the effects on the flight devices. The difficulties in establishing effects tools, the provision of the data needed to run them, and the difficulties in characterizing representative samples of devices should be apparent. Present methodologies are becoming invalid. Methodologies combining component technology evaluation, particle transport and track structures, effects prediction, and validation through ground and IOD tests need improvement.

Nevertheless, some areas of environmental knowledge can be identified for further work:

- Low altitude proton population and its "climatology" are needed, especially for higher LEOs where there's less heritage, and for abnormally low solar activity;
- The >10 MeV electron population needs to be characterized with dedicated spectrometers, with particular application to GNSS missions;
- Mega-constellation and GNSS orbits, and EOR trajectories need models that improve over the historical ones which appear inaccurate, and in these applications, the excursions from the mean need to be quantified (magnitude, probability). This will emerge from the inclusion of Van Allen Probes and GPS particle data in models;
- Geomagnetic cutoff: a real-time, dynamic cutoff tool is needed, especially one that incorporates in situ data.
- As with other areas, the general accumulation of SEP and radiation belt data and their assimilation into models remain useful; Our in-situ data only goes back 60 years, yet we are asked to plan for 15-year missions. Our sample size is effectively four for assessing error bars on environment specifications for such missions.
- There is a growing set of radiation measurements being undertaken on missions. There is clearly a need to capture these data in community "reference data" systems, with calibration documentation and quality assessments, so that they become resources for model improvement.

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6. Total Dose

General Background on Total Dose

Total dose effects in electronic and photonic parts is a cumulative, long-term degradation due to ionizing or non-ionizing radiation—mainly primary protons and electrons but secondary particles arising from interactions between these primary particles and spacecraft materials can also contribute. For the case of Total Ionizing Dose (TID), the concern is mainly its effects in insulating regions of metal-oxide semiconductors (MOS) and bipolar devices, most commonly composed of SiO_2. In MOS devices, ionizing radiation causes threshold voltage shifts due to exposure of gate oxides. The effect first appears as parametric degradation and can eventually result in functional failure. Ionizing radiation can also cause leakage currents in MOS devices due to exposure of field oxide regions used for isolation and result in increased power consumption. Eventually the effect becomes so pronounced the transistor cannot be switched to the off state. For bipolar devices loss in performance is caused by gain degradation and increased leakage currents. In addition, bipolar devices can also be subject to the Enhanced Low Dose Rate Sensitivity (ELDRS) effect, wherein the amount of total dose degradation at a given total dose level is greater at low dose rates than at high dose rates. This complicates extrapolating the effects observed in laboratory testing to the lower dose rates observed during space missions.

The effects of Total Non-Ionizing Dose (TNID) or displacement damage dose (DD/DDD) is also a cumulative effect caused when the incident radiation displaces atoms in a semiconductor lattice or optical material. This produces defects that result in material property changes such as carrier lifetime shortening, mobility decreases and degradation of optical transmission. Displacement damage effects are commonly observed in components such as solar cells, focal planes and optocouplers (often a component in power devices). Dose rate effects can present still more challenges, such as transients or hot pixels in imagers.

It is possible to reduce total dose effects in space to a limited extent with shielding material. This will have the greatest effect on electrons and low energy protons. However, the amount of shielding that can be used is limited by weight constraints. Furthermore, as the shielding is increased, its effectiveness decreases due to the difficulty of slowing down higher energy protons.

Needed Environment Models

The models required for total dose analyses are for trapped protons, trapped electrons and solar protons. These radiations contribute at least 90 percent of the total dose exposure for levels of shielding used with electronic and photonic components. The trapped particle models discussed in the workshop were AP8/AE8 [8], AP9/AE9-IRENE (S. Huston) and GREEN [1]. The AP9/AE9-IRENE model features new capabilities such as calculation of error bars and percentiles for mission fluences. It has the capability of doing “perturbed” and Monte Carlo simulations, the latter of which accounts for space weather variability. The new GREEN model, which is currently under development, may be regarded as an extension of AP8/AE8 by supplementing this global model with local models in the energy and L-space grid developed at ONERA. Attendees pointed out shortcomings of trapped particle models, particularly in Low Earth Orbit (LEO) and Medium Earth Orbit (MEO). There are data gaps in LEO and MEO that need to be filled in. There is no solar cycle effect for LEO, although AP8/AE8 includes an approximate one by dividing solar cycles into simplistic solar maximum and solar minimum time periods. In addition, the models do not directly include the East-West effect, although this can be accounted for using the SPENVIS program suite.

Solar proton models discussed included the established ESP/PSYCHIC model [16], the new SAPPHIRE model [6] and a model currently under development by Robinson and Adams [14]. The ESP/PSYCHIC model uses statistical methodology such as Maximum Entropy Theory and Extreme Value Theory. The SAPPHIRE model is a Monte Carlo based approach featuring an updated data base of events. The model of Robinson and Adams builds on the ESP/PSYCHIC model by incorporating a true solar cycle dependence and also includes an updated data base of events.

Needed Design/Effects Tools

A general topic that came up was the need to close the gap between pre-flight predictions and on-orbit performance. For the case of total dose this is a clear need due to the extreme conservatism of device selection for flight, which potentially limits system performance. One solution is to move away from the methodology of using radiation design margin for part selection and replace it with a confidence level based approach in which parts are selected by their probability of failure during a mission [17]. The advantages over the standard approach are that it is a better characterization of a device's radiation performance in space, is a more objective parameter, and is more amenable to reliability analyses. In addition, it uses the trapped and solar particle models in a consistent fashion, although this requires the use of AP9/AE9-IRENE.

Another design tool that may require further attention is three-dimensional ray trace/Monte Carlo simulations of radiation transport through complex shielding geometries such as heavily shielded electronics or instruments. This generally has the effect of bringing down total dose requirements that were calculated as a top-level number using a simple geometry such as spherical or planar shielding. Using such a tool (I. Jun) can also reduce the gap between pre-flight prediction and on-orbit performance. Also, it was pointed out (I. Jun) that pre-flight ground testing is very important to understand potential discrepancies between numerical simulations and in-flight data.

A needed tool is one capable of calculating dose deposited in small volumes of solid media such as thin films, coatings and sensitive volumes of highly scaled devices. It was pointed out by attendees that the standard tools often have difficulties with boundaries in such small volumes.

Finally, there was discussion of device test methodology. It was noted that there is no acceptable laboratory test method for the ELDRS effect in bipolar devices other than testing at low dose rates, although methods exist that bound the problem [13].

Needed Anomaly Analysis Tools

There were no attendee comments on anomaly analysis tools for total dose. This may well be due to the very conservative nature of selecting parts for total dose applications. Although total dose anomalies are rare, the TacSat-4 mission experienced accelerated displacement damage to its solar arrays due to a higher-than-expected proton environment [5]. This suggests a deficiency in the radiation environment models and the tools used to estimate displacement damage effects, at least in solar arrays. The models are in development [4][2], and at least one tool (SCREAM) shows promise [9] to correlate on-orbit detector data for both TacSat-4 [5] and GPS (SV41) [10].

Needed In-Situ Observations

There are a number of types of dosimeters that have flown in space but, until recently, they have not been standardized to a degree that they agree with each other better than a factor of two. One promising development is the Aerospace/Teledyne ionizing dose microdosimeters [11], which can be purchased like catalog parts, and which agree among themselves to within 20 percent.

Starting with GOES-R, NOAA's GOES satellites carry two dosimeters that measure dose behind 100 and 250 mils of Al shielding. Data from these dosimeters are included in the GOES real-time data stream.

Additionally, some dosimeters are specifically built to measure the displacement damage (DD) environment. The Optically Stimulated Luminescence (OSL) sensor developed in France [2] has been successfully used in space. Another DD sensor in development by NRL [15] – “Realtime Radiation Displacement Damage Dosimeter” (R2D3) promises to add DD data like the Aerospace/Teledyne microdosimeter does for total ionizing dose.

More robust sensor packages, like CEASE [3] and SREMS [12] provide more detailed measurements that can be used to reconstruct the dose and displacement damage environment at or within a vehicle.

Finally, solar arrays themselves can provide in situ data on their performance and degradation. AIAA Space Power Systems Standard (S122) indicates that 0.4 percent of the entire solar array are be devoted to a full current-voltage measurement system. This measurement can be accomplished with relatively simple circuitry, and can prove invaluable in diagnosing anomalous solar array degradation.

One satellite designer indicated the following high priority measurements to improve total dose and internal charging models: more proton and electron data at LEO (below 800 km), incorporation of existing POES and DMSP data into the models, and gyro-angle resolution (e.g., East-West effect).

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