Intuitive Space Weather Displays to Improve Space Situational Awareness (SSA)

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ABSTRACT
Making definitive attributions concerning satellite anomalies proves to be a challenging endeavor given the dynamic space environment, the threat of adversarial actions, and unanticipated system failures. Further, decision makers are usually contending with performance shaping factors such as time pressure and the knowledge that errors can be extremely costly. Significant consequences can emerge with erroneous conclusions, whether it's failing to thwart an adversary's attack against our space assets, or misconstruing an environment effect for a hostile action that drives a response. Although accurate and reliable measurements of the disturbances in the earth's magnetic field and the flux of high energy protons and electrons have been available for decades, it remains challenging to translate these data into actionable information concerning the potential threat to on-orbit assets. Even though satellite operators actively monitor these hazards, until very recently there has been limited statistical relationship between the measured radiation environment and the likelihood of an anomaly to the on-orbit asset [5]. To address this need, the Air Force Research Laboratory (AFRL) is supporting work to make space environmental effects information more accessible and actionable for users in the operational community. The tool under development leverages O'Brien's "hazard quotients" (which are derived from historical records of on-orbit anomalies) to relay the potential effect by presenting anomaly likelihood information related to surface charging, internal charging, single event effects, and the total accumulated particle dose.

1. Introduction

Making definitive attributions concerning satellite anomalies proves to be a challenging endeavor as analysts are confronted with the dynamic space environment, the threat of adversarial actions, and unanticipated system failures. Accurate assessment of space weather effects is a valuable capability that can help guide the attribution process. Other researchers, including Reeves [1] at AMOS 2010, advocate the need for a rapid assessment tool that can provide an estimate of space weather's role in an anomaly. However, the physics behind space weather phenomena is extremely complex and requires extensive training to master. The discipline has tended to produce reports and findings that are more suited for expert consumption and less comprehensible to the operational community. We therefore are striving to deliver actionable space weather information, available at the appropriate level of detail that supports operationally-driven workflows. Taking a human-centered approach, Aptima constructed an intuitive, interactive interface through which to convey space weather effects and support data exploration. The tool is crafted from a mission perspective and is intended to provide a first order assessment pertaining to space weather's potential for causing anomalies at specified locations and times.

2. Understanding User Needs

The team employed components of the Applied Cognitive Task Analysis (ACTA) as described by Militello & Hutton [2] to interact with space weather experts and operational personnel. Evidence emerged early in the process suggesting these two groups did not speak the same language nor share similar interests on many levels. More than a half dozen distinct operational user groups were engaged with interests ranging from satellite operations for defense, intelligence, and scientific study.

The ACTA method employs three tasks to engage users and delve into the critical cognitive factors. The first is a *Task Diagram* which provides a broader overview of the task but drives toward the more difficult cognitive elements involved in the task and results in decomposed task elements. This step is one that provides improved efficiency over conventional CTA methods as the information gained in the task diagram is utilized to probe more directly in the next two steps of ACTA. The second step is the *Knowledge Audit.* The purpose of the knowledge audit is to examine how expertise is utilized in the domain and provides concrete examples from the subject matter experts (SMEs) direct experience. This technique draws heavily on the well-established expertise literature (see Chi & Glazer for an overview [3]). The knowledge audit uses a set of probes to elicit types of skills and domain savvy central to the task as well as encourage the interviewee to provide relevant examples.

Task diagram and simulation interview results showed divergence between the user groups, indicating a bridging application could be beneficial. Thus, this investigation was bifurcated to gain a better understanding of the science behind space weather phenomena, and the information required for operationally relevant decision making. Success would depend on how well the two could be integrated and portrayed to operators.

3. Space Weather from the Operational Perspective

Despite the considerable data available from space-based observations and ground-based sensors [4], daily space operations often fail to leverage environmental data to any observable benefit. Investigation reveals two primary barriers to integrating space environment information. First, the expertise is not sufficient at the operational level to assimilate the raw environmental data for mission objectives. While there are numerous environmental measures scientists can produce to characterize the space environment, understanding their implications for mission-based tasking proves quite challenging. For example, conveying particle flux measures of five megaelectron volt (MeV) protons does not embody an intuitive, meaningful quantity relating to mission impact. Figure 1 provides a sample of space weather data that are available, but of little interest at the operational level.

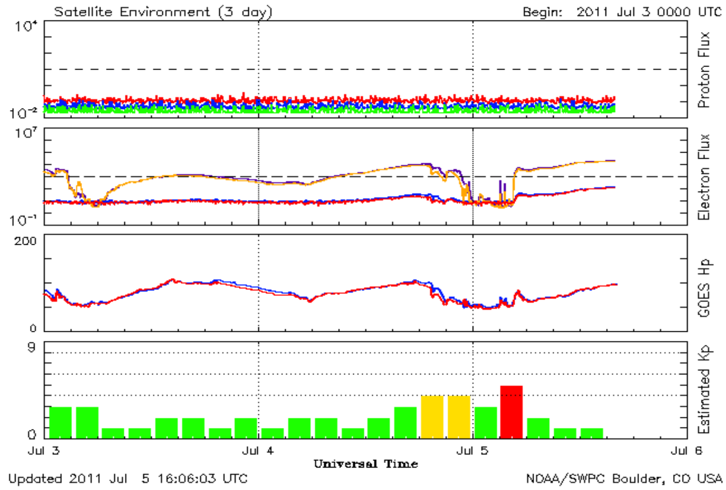

Figure 1. Space environment data available via http://www.swpc.noaa.gov/today.html.

The second obstacle is that little effort has been put forth to devise a better way of presenting space weather information to users. A thorough understanding of the operators, missions, and work domain is needed to transform the environmental data from the space physics observations to mission relevant inputs for the operational community.

Current practices at the operational level generally include distilling all the available data down to a universal assessment that space is green (good), yellow (potentially hazardous), or red (disturbed) for a given period of time. The time may vary from a few hours to a 24 hour period. Of course, global assessments also assume that all locations are essentially identical and offer no specificity in terms of asset position. With a space environment characterization so stripped of information, operators conducting particular missions with geographic constraints find it difficult to apply.

The user investigations we performed reveal that in contrast to the physicists, the operational users find little use in receiving particle fluxes or magnetometer readings collected by the scientific community. Fortunately, another group of scientists also arrived at this conclusion and have developed methods for quantifying a *Hazard Quotient* relating space environment readings to operationally relevant input. Paul O'Brien [5] at the Aerospace Corporation devised a set of algorithms for the Spacecraft Environmental Anomalies Expert System for geosynchronous orbits (SEAES-GEO) model. Using a collection of historical anomalous events, it employs recorded data from the space environment to determine the ratio of the instantaneous anomaly likelihood to the mission-averaged anomaly likelihood.

Using these models, Aptima constructed an application that collects the publicly available data pertaining to particle fluxes and magnetic indices (http://www.swpc.noaa.gov) to compute hazard quotients. Values can be computed for each degree of longitude (the operators' preferred means of describing position in geosynchronous orbits). The application marshals these data and then computes hazard quotients for four space environment threats (surface and internal charging, single event upsets and total dose) which are displayed in the familiar red/yellow/green stoplight fashion. These calculations lend themselves to a more operationally relevant translation for those with space situation awareness (SSA) responsibilities.

But the question of how the information should be delivered to the operator remains. The lines of data in Figure 2 are uninspiring and largely a presentation of excessive noise with little signal from an operator's perspective. We needed to probe the mental models of the space analysts and better understand their diagnostic procedures and workflows to make a useful application.

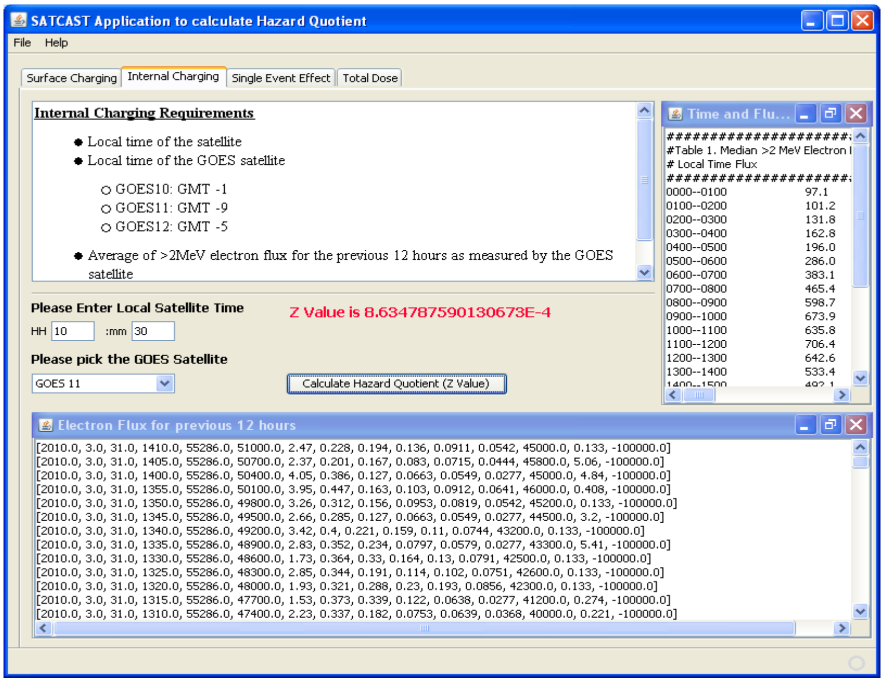

Fig 2. Computations for the Internal Charging Hazard Quotient.

More than a half dozen operational user groups were engaged with interests ranging from satellite operations for defense, intelligence, and scientific study. Even among the operator groups we discovered some surprising findings and differences between subgroups (for example, one group of operators almost never relies on geospatial information). Despite some divergence in the details of their needs, several opportunities emerged to improve the information delivered at the operational level that would cut across specialties.

4. Prototype Development

Operational users' frustration with current space weather information available was almost universal within our sample, resulting in a general dismissal of space environment data. The information they receive to inquiries characterizing historical space weather (as well as the daily briefing of current condition), as a global assessment undermined the reliability and usefulness of the reporting. Their experience as operators is such that anomalies occur on what are considered "good" days (i.e., little in the environment that should lead to anomaly) as well as "danger" days in which they saw no environmental effects at all.

One of the more robust findings among the operators was their belief that more defined, reliable space weather information could be valuable in their forensic investigation of known anomalies. That is, after an event has occurred (e.g., satellite X suffered degraded capabilities yesterday at 1700 UTC), it would be useful to know the environmental conditions around the event time to help make a preliminary assessment of the space weather's role in the anomaly.

With the forensic application as our first use case, the design specifically sought to make space weather effects information clear and accessible for this purpose. Using multiple visualization options, the user will be able to find time periods of interest and select an asset location(s) at GEO to create an envelope around the believed/known event. Each hazard quotient relates to one of four satellite threats corresponding to the SEAES-GEO model: surface charging, internal charging, single event upsets, and total dose. Discussions with operational personnel provided assurance that these concepts have meaning for them in terms of the threat to the asset and relevant mission-level effects that may be of concern. Figure 3 depicts the Space Awareness Toolkit for Calculating Anomalies to Satellite Tasking **(**SATCAST) application set to view four different satellites (each is represented by a vertical set of dots corresponding to the satellites longitude). Users can select the time of interest and the longitude (which corresponds to the asset under investigation in GEO), and may also create and save groups (of longitudes) that correspond to a constellation of interest (as is shown in Figure 3)

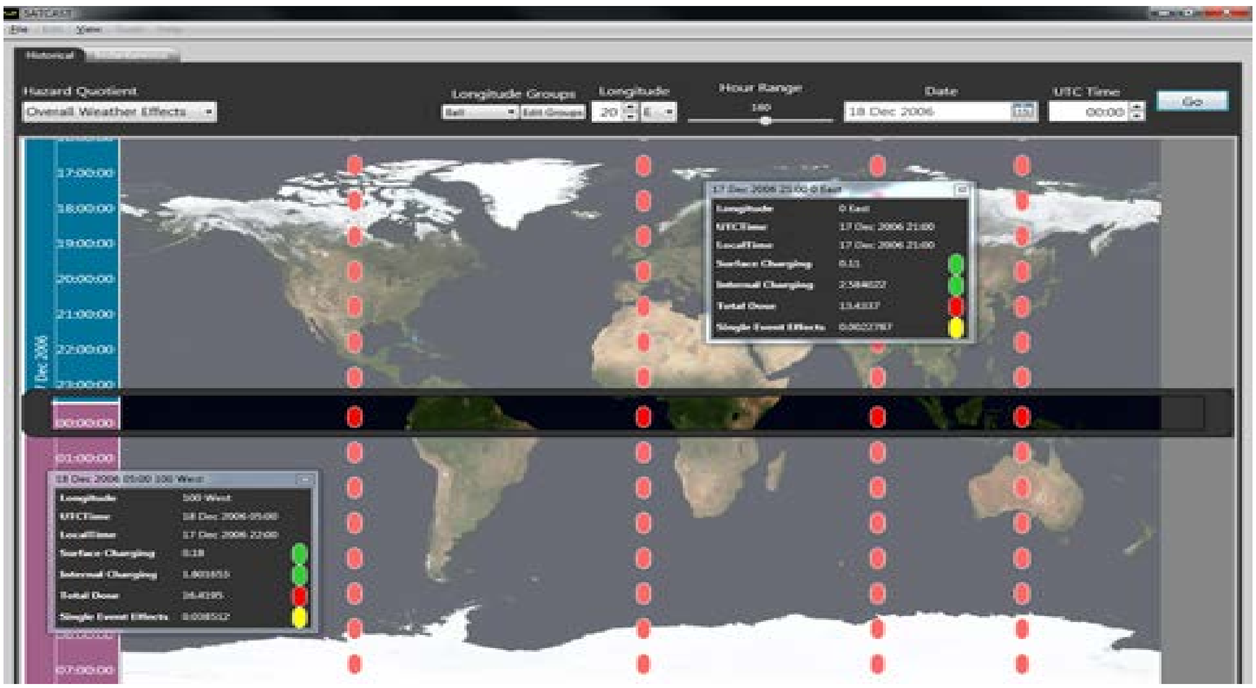

Fig 3. SATCAST showing four satellites on a vertical timeline.

The vertical timeline was a critical feature (opposed to the more widely used convention in the western world which is a horizontal timeline in which the past is to the left) to preserve the proper location of a satellite at a given longitude. With a vertical timeline, the selection of 0 longitude remains in place as one scrolls up/down to go forward or backward in time. Further, it retains the directional mapping of the scrolling motion to the change in values. A horizontal timeline (with a slider for example while keeping the map still) would require the user to make an orthogonal mental rotation which is likely to induce errors [6] because the mapping is not as natural.

Two windows are open that contain detail on the time/location of the asset the user selected (clicking a dot opens the window). The window contains the longitude and time information, local and UTC time, and the high level indicator (red/yellow/green) for each hazard quotient. This window provides a quick look at the potential threats at a glance for each of the four hazard quotients for the time frame selected. The value is that it shows the operator which hazard quotient is driving the top-level assessment of red/yellow/green. In Figure 3, all dots are red, and until a window is opened, it is not clear which type of hazard is exceeding that threshold. By opening two windows, both show that total dose is the dangerous hazard. Selecting dots that are separated by location (right to left in GEO longitude) and time (top to bottom separates them in hours), it is seen that Total Dose is in the red and single event upset is yellow. The consistent pattern across time and location may suggest a robust environmental effect. These items may warrant further investigation.

From within the first drill-down windows, an operator can click directly on one of the hazard quotients to open a more detailed look at what is driving the value of that hazard quotient. Figure 4 below shows drill-down windows for Single Event Upset and Total Dose hazard quotients.

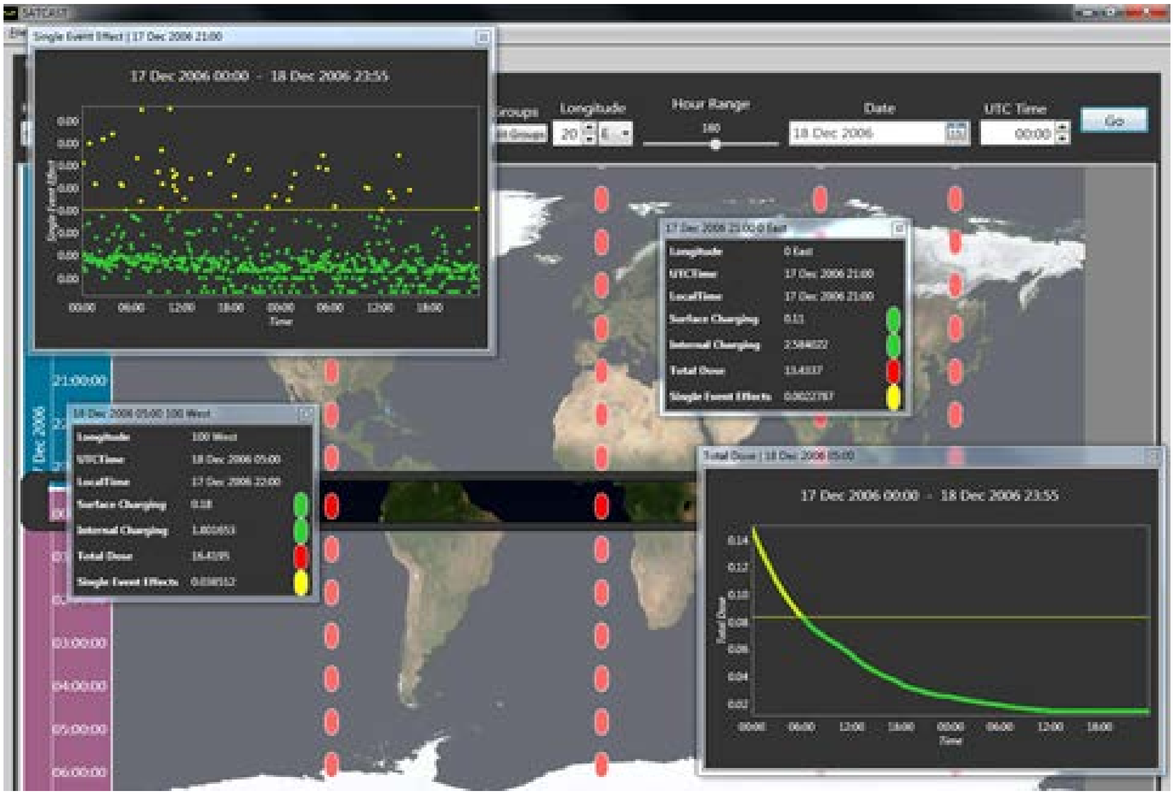

Fig 4. Drill-down information for Single Event Upset and Total Dose which seem to be driving the warnings for this constellation of assets.

Now instead of a simultaneous, averaged value for a one-hour block, the user can view the data trending over a 48-hour period and get a sense of hazard fluctuations over time. Note again, that it is not just numbers and values given to the operator. A clear threshold line is indicated in the graph. Individual data points describing the hazard (and depicted in their appropriate colors) are plotted appropriately to indicate the level of concern over time. Operators are thus unburdened from needing to know or memorize a "goodness" range of values. The application offers a perceptual understanding that is consistent with many other systems employed at the operational level.

In Figure 5 we show another situation in which a single asset is being investigated. The first level window is seen in the middle of the screen, and by clicking the hazard quotients, it has opened a drill-down window for each. Starting in the upper left and moving clockwise, more detailed information is shown for Surface Charging, Internal Charging, Single Event Upsets and Total Dose. The use of color is intended to facilitate the interpretation of potential space environment hazard at a glance. The size of the oval is also determined by the hazard index with red producing the largest object, yellow smaller, and green smaller still. The reduced size is less salient and is appropriate because of its reduced need to call the operator's attention.

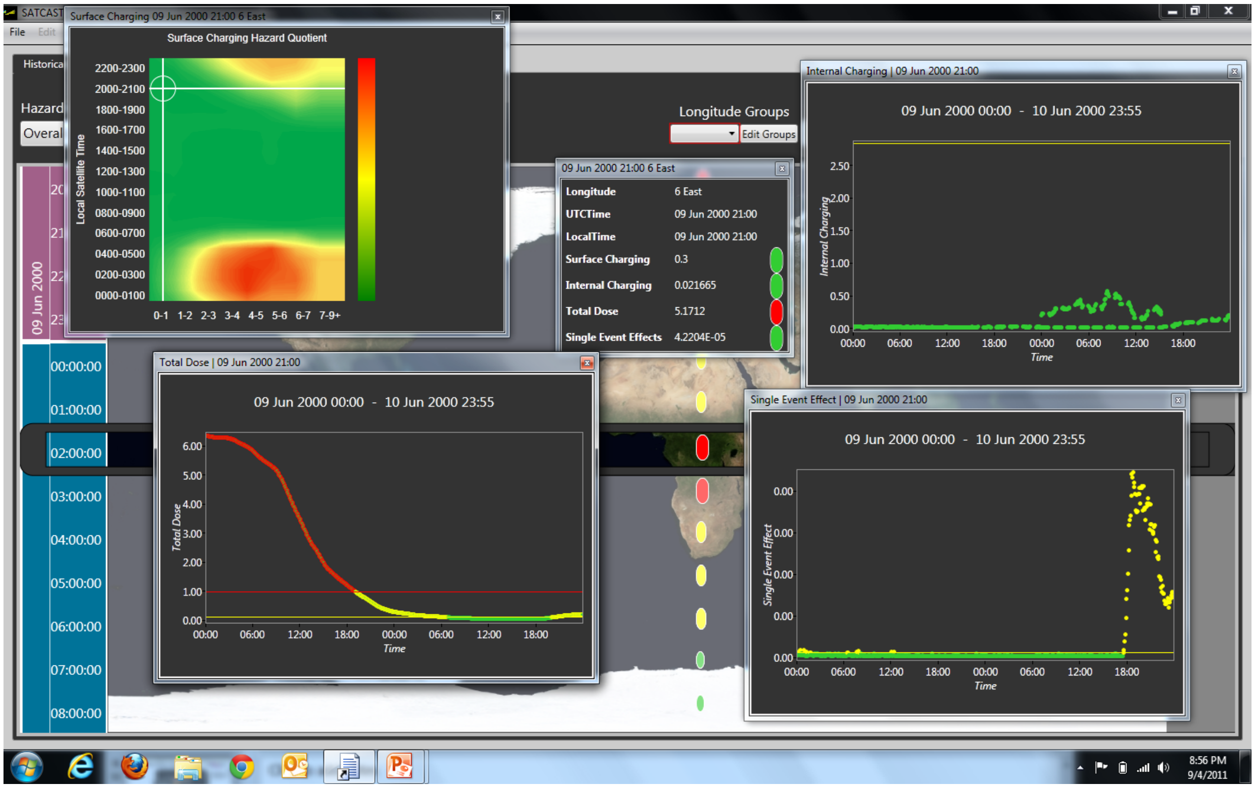

Fig 5. SATCAST with drill-downs shown for (clockwise from top left) Total Dose, Surface Charging, Internal Charging, and Single Event Upsets.

5. User Influence

Any tool with low reliability, clumsy interactions, and latent utility faces tremendous resistance to adoption. To prevent such labels from plaguing this design, we have engaged the operational community, for whom this is intended to support, to understand their needs, decision processes, and work context. With these data, we needed to take great care in not alienating the user population we were determined to serve. Again, they are not space physicists. Though a few conceded some of this detail was beginning to approach their limit of space weather understanding, most assured us that the hazards identified had meaning for their space operations. The drill-downs were developed with and vetted by several operators stating this level of detail was still of use to them.

The value of user participation cannot be overemphasized. A specific design element pertaining to the top-level display serves to illustrate their value. From the point of the four hazard quotients, we received strong input that a roll-up or aggregate would be needed in the final design. Speaking with Paul O'Brien and others indicated there was no easy way to craft a mathematical function that could bring together all four quotients. Their properties were not conducive to aggregating with a simple function.

In contrast to the complex modeling driving this element of design in our approach, the benefit of working with the operators again emerged with their parsimonious offering. After engaging several mathematicians and space physicists to devise valid computational formulas for aggregating the four hazard quotients to a meaningful roll-up, the operators assured the best approach for them would be to always show the worst case of the four hazard quotients. This would of course provide an alert when at least one parameter was out of normal without any averaging effects that might yield a failed detection. Further investigation will determine if such a method results in too many false alerts. Nonetheless, this will likely be one of the display modes (and perhaps the default) on their home screen.

Another intriguing design challenge the team is devoting significant resources to is determining the thresholds for indicating green-yellow-red status. These thresholds are required for each individual hazard quotient as well as the summation status. As Figure 3 depicts the four hazard quotients in a single artifact representing the aggregation of space weather hazards (the single bar in the upper right), in order for it to be reliable, must be calculated with a rigorous and robust function. Given the individual hazard quotients are derived from different phenomena, affect satellites differently, and have varying mission impacts, a simplified weighting approach fails to provide a meaningful result. This stems from each quotient having differing and non-Gaussian distributions (these are left bounded at 0) making them difficult to combine along a common scale.

In the current iteration, we are taking design inputs from the operators pertaining to particular interactions they requested. This includes functions such as specific viewing settings, selecting temporal bounds, and tracking spacecraft. By providing a flexible platform to provide information at the appropriate level for operator expertise, work domain context, and mission needs, we believe we can provide an enhanced capability supporting improved understanding of the environmental component for SSA.

Work with space weather scientists will continue to verify the best science available, but more importantly, the iterative design processes with operational users will shape the final product. It is hoped this application can become a trusted tool for operators with interests in managing assets in geosynchronous orbit, as that is where the science has been most vetted. Operators at other orbits have also expressed interest which may provide paths of additional development.

6. Conclusion

Environmental factors are persistently capable of affecting a satellite's performance and survivability which ultimately impact U.S. space superiority and the capabilities delivered to the warfighter. These space assets are used daily to support numerous missions by relaying communications, to ensuring precision targeting. The men and women in the military, whose expertise is crafted for mission specialties, are unlikely to also have expertise in space physics. We therefore are striving to deliver actionable information, available at the appropriate detail, and conformant to their workflow.

7. Acknowledgements

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