Assessing Space and Satellite Environment and System Security (ASSESS)

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ABSTRACT

Satellites and other spacecraft serve as critical assets in our communication, surveillance and defense infrastructure, and as such, they require constant, real-time environmental and security data monitoring for optimum performance. Some efforts have addressed this challenging effort by fusing the information gathered from ground, air and space-based sensors to detect and categorize anomalous situations. The aim is to provide decision support for space situational awareness (SSA) and defensive counterspace (DCS). Most results from the efforts have not yielded estimates of impact and cost of a given situation or suggested courses of action (level 3 data fusion). Assessing space and satellite environment and system security (ASSESS) is an effort to provide high level data fusion for SSA/DCS though two complementary thrusts: event scenario simulation with Automated Red Teaming (ART), and historical data warehousing and mining. ART uses stochastic search algorithms (e.g., evolutionary algorithms) to evolve strategies in agent based simulations. ART provides techniques to formally specify anomalous condition scenarios envisioned by subject matter experts and to explore alternative scenarios. The simulation data can support impact estimates and course of action evaluations. The data mining thrust is focused on finding correlations between subsystems anomalies on MightySat II and publicly available space weather data. This paper describes the ART approach, some potential correlations discovered between satellite subsystem anomalies and space weather events, and future work planned on the project.

1. INTRODUCTION

Space Situational Awareness (SSA) and Defensive Counterspace (DCS) planners lack the necessary tools to help them glean insights from the mass of potentially relevant data. Current approaches require highly skilled people to essentially manually gather and correlate a necessarily limited subset (given time and resource constraints) of the available data in pursuit of SSA and informed decisions.

While there has been significant progress on statistical approaches to generating the lower level data fusion products for SSA [1,2], the progress on higher level data fusion has not kept pace. Two factors contribute strongly to the difference—data and goals. There is a massive amount of historical data pertaining to normal satellite operations, and an operational low level fusion goal is to recognize abnormal or anomalous situations. This data and constrained goal open the door to statistical methods to recognize normal historical data and flag any outliers. This type of low level anomaly detection technology is extremely valuable in a data rich environment because it can enable an operator to focus their attention on situations that are most likely to require action.

In contrast, there is very little event scenario data relevant to intent and impact estimation (level 3 data fusion) [18,19]. The lack of historical data and the relatively ambitious goal of estimating specific outcomes combine to make level 3 data fusion a complex challenge. For example, a system might be tasked to determine whether an increase in a certain type of anomaly on a satellite subsystem is due to a space weather event, an internal malfunction, or externally-caused event. Each situation would be associated with different outcomes and would suggest different courses of action. Given the importance of space assets and the complexity of the relevant data, data fusion technology that can help gather, process, and analyze the data will play a crucial role for space asset operators and planners. ASSESS (assessing space and satellite environment and system security) has the ultimate goal of providing data fusion technology to generate high level estimates of situational impact and hostile intent (level 3 data fusion).

The ASSESS effort is a Phase I Small Business Innovative Research (SBIR) project funded by the Air Force Research Laboratory (Air Force Research Laboratory's (AFRL) Space Vehicles Directorate, Kirtland Air Force Base, N.M). ASSESS seeks to build on satellite and space environment data feeds and data fusion results at level 0 (L0, feature), level 1 (L1, entity/event), and level 2 (L2, situation) to explore methods of generating level 3 (L3, impact and intent) estimates for decision support [18,19]. ASSESS has pursued two complementary approaches to supplying L3 data fusion results: historical data analysis focusing on Space Weather (SPWX) data integration and Automated Red Teaming (ART). ART is a rigorous and relatively formal method to synthesize the "missing" historical threat and outcome data via simulations and stochastic search [3,4].

The following sections discuss some potential correlations discovered between satellite subsystem anomalies and space weather events, as well as the ART approach, and future work planned on the project.

2. HISTORICAL DATA WAREHOUSING AND ANALYSIS

Data efforts in ASSESS have focused on warehousing a wide variety of space weather (SPWX) data sources and correlating them with L0 anomalies generated by Satellite as a Sensor (SAS) algorithms [20] run on satellite subsystem data streams[1] from the AFRL's testbench satellite, MightySat II (MS2). The time periods and data correlated were largely guided by the data made available through the grant sponsor (Paul Zetocha, AFRL's Space Vehicles Directorate). This data includes:

- MS2 subsystem anomaly data
    - Timeperiod: 7/01 through 9/01
    - SAS L0 anomalies and primary measurand and subsystems responsible, L1 anomaly tracks
    - Measurand and subsystem decodes of the primary anomaly causes

This MS2 data has been well studied by the sponsor's lab and provides some SPWX events and MS2 anomaly spikes that can be used for data analysis and algorithm development. Relevant space environment data was downloaded from the National Geophysical Data Center (NGDC) and Space Environment Center (SEC) archive servers for the same time period and loaded into a database for analysis. The goal was to mine the data for interesting correlations. This data includes:

- Space Environmental Monitor (version 2) on the Polar Operational Environmental Satellites (POES)
    - Proton and electron flux for POES-15 and POES-16
    - SAS L0 and L1 reports for POES-15
- Space Environment Monitor on the Geostationary Operational Environment Satellites (GOES)
    - X-ray flux from GOES-8 and GOES-10
- GeoMagnetic Indices collected from ground stations and averaged at intervals of an hour to a day.
- Solar Radio Burst Events from NGDC
    - L1 event reports from ground stations.
- Latitude/longitude/altitude information via orbital elements downloaded from www.space-track.org and run through a stand-alone propagator.

In addition, day exposure and multi-orbit visualization for the LEO satellites was generated with the System Effectiveness Analysis Simulation (SEAS) simulator sponsored by Air Force Space Command, Space and Missile Systems Center, Directorate of Developmental Planning (SMC/XD).

Results

The historical data analysis yielded the negative result that spikes in proton and electron fluxes, geomagnetic indices, and some measures of solar activity are not tightly correlated with MS2 subsystem anomalies. The analyses are summarized in Figs. 1 through 3.

[1] Output from the SAS algorithms was provided by Chris Tschan of the Aerospace Corporation. [20]

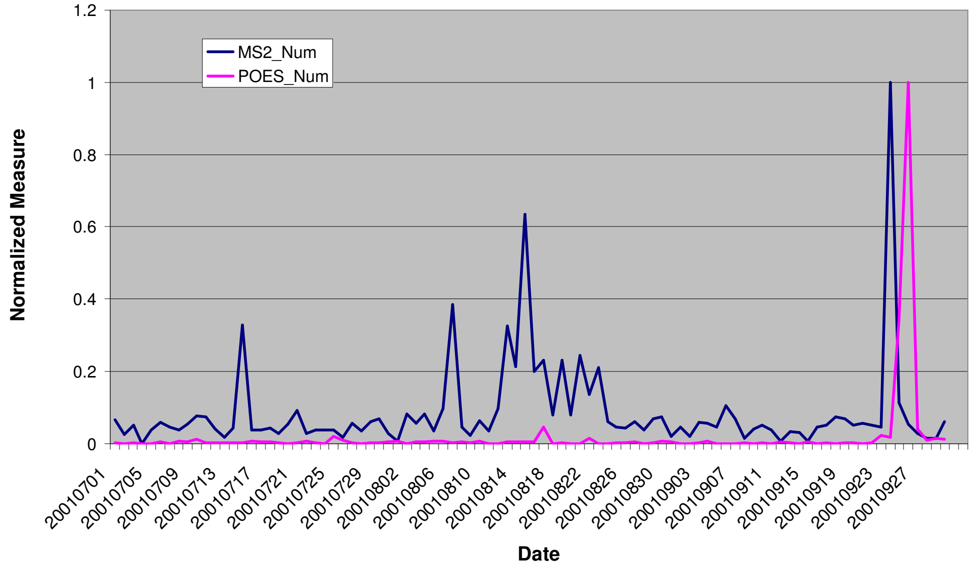

Fig. 1. MS2 L0 subsystem anomaly counts by day (MS2_Num) plotted with NOAA POES-15 satellite Space Environment Monitor (SEM) anomaly counts by day (POES_Num). For plotting purposes, all counts are normalized to be percentages of the maximum number of anomalies for the given satellite in a single day during the three-month data window. The data streams used for anomaly detection on the POES-15 satellite are those publicly available through NGDC[2], including proton and electron flux, total energy, and location. Note that the spike in MS2 L0 subsystem anomalies (on 9/24/01) was not correlated with anomalous space environment data from POES-15 (the POES-15 anomaly spike was on 9/26/2001). Direct analysis of the POES-15 SEM data streams yields similar negative results, despite the very high electron and proton fluxes observed in the auroral regions on 9/26/2001.

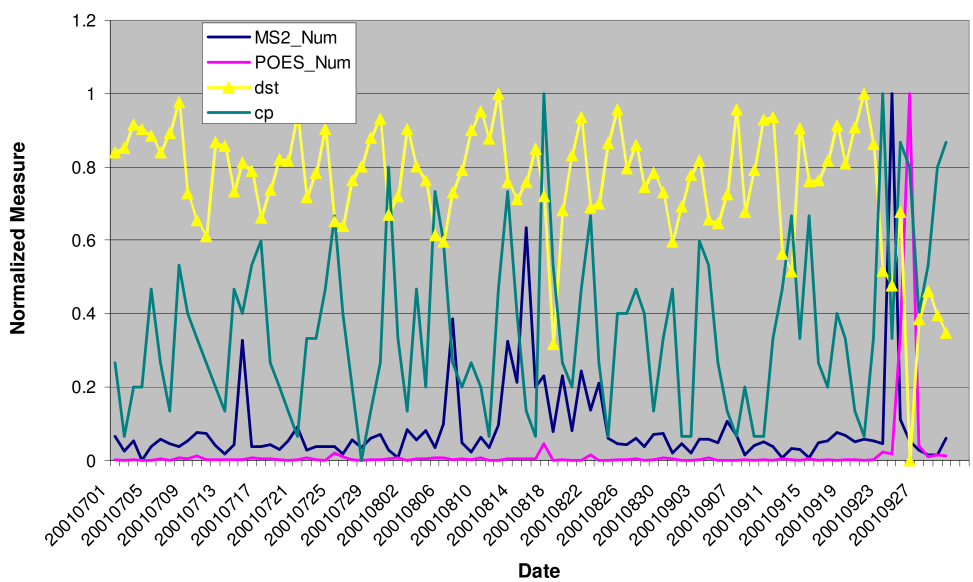

Fig. 2. MS2 (MS2_Num) and POES-15 (POES_Num) anomaly counts as described in Fig. 1. plotted with normalized daily averages for representative geomagnetic indices measured at multiple ground stations[3]. Note that the geomagnetic indices are not clearly correlated with the

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[2] Description of the POES data is available at: http://poes.ngdc.noaa.gov/data/readme.txt

[3] Description of geomagnetic index data is available at: http://spidr.ngdc.noaa.gov/spidr/help.do?group=geomInd#cp

MS2 subsystem anomaly spikes. While dst does indicate heightened activity (low figures indicate heightened activity) around both the MS2_Num and POES_Num spikes, dst also indicates higher activity on many days during the end of the period that are not associated with higher anomaly counts.

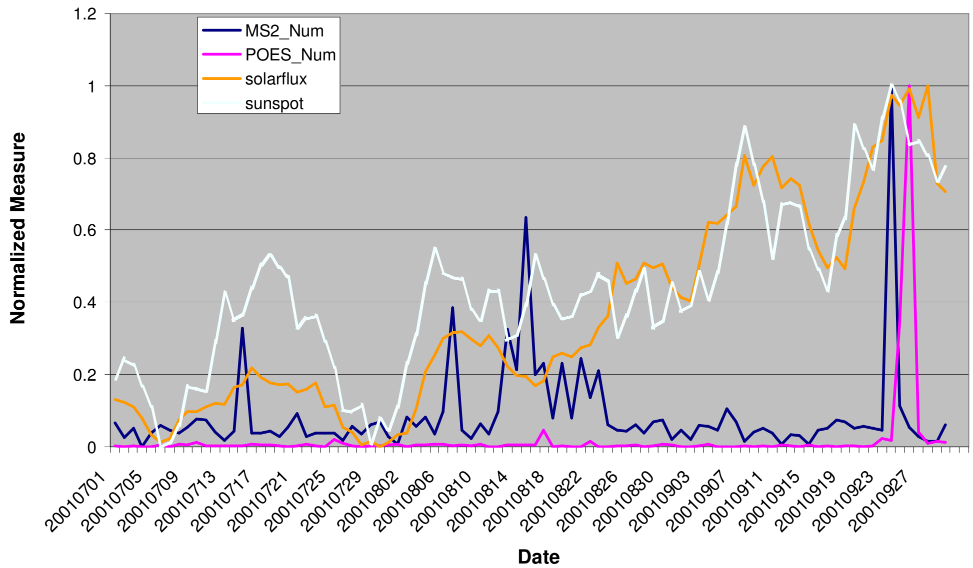

Fig. 3. MS2 (MS2_Num) and POES-15 (POES_Num) anomaly counts as described in Fig. 1 plotted with normalized daily averages for solar radio flux (2800 Mhz) and number of sunspots as measured from ground stations. As with the geomagnetic indices in Fig. 2, note that these solar activity measures are not clearly correlated with the MS2 subsystem anomaly spikes. While the measures do indicate heightened activity around both the MS2_Num and POES_Num spikes, they also indicate higher activity toward the end of the time period not associated with heightened anomaly counts.

Additional data integration and analysis[4] revealed some potentially causal relationships between MS2 anomalies and solar x-ray and radio bursts.

[4] Analysis of these data sources was suggested by Chris Tschan of the Aerospace Corporation and Kevin Scro of the Technology Application Division of the Space and Missile Systems Center (SMC/WXT).

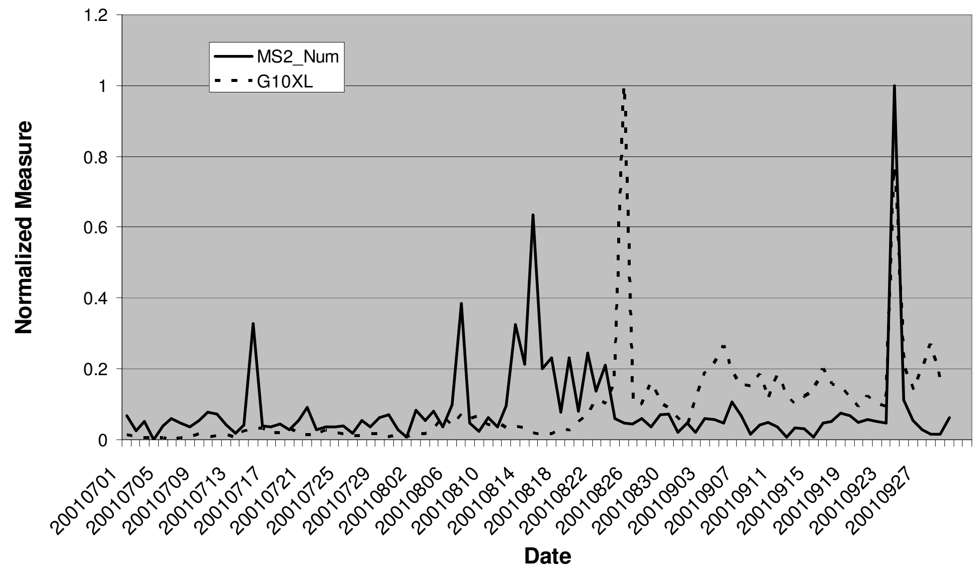

Fig. 4. MS2 L0 Anomaly counts by day (MS2_Num) plotted with average daily X-Ray flux as measured by GOES-10 (G10XL). Note that the X-Ray burst on 9/24/01 correlated strongly with a MS2 anomaly spike, but a seemingly similar burst on 8/25/2001 was not correlated with an increase in MS2 anomalies.

In order to better understand the possible role of this X-ray burst (and as described below, simultaneous radio burst) in causing the subsystem anomalies, the distribution of subsystem anomaly types as well as the timing of the subsystem anomalies relative to X-ray and radio bursts was investigated. The distribution of subsystem errors was strongly biased during the 9/24/01 spike compared to the overall distribution during the three-month period as shown in Fig. 5.

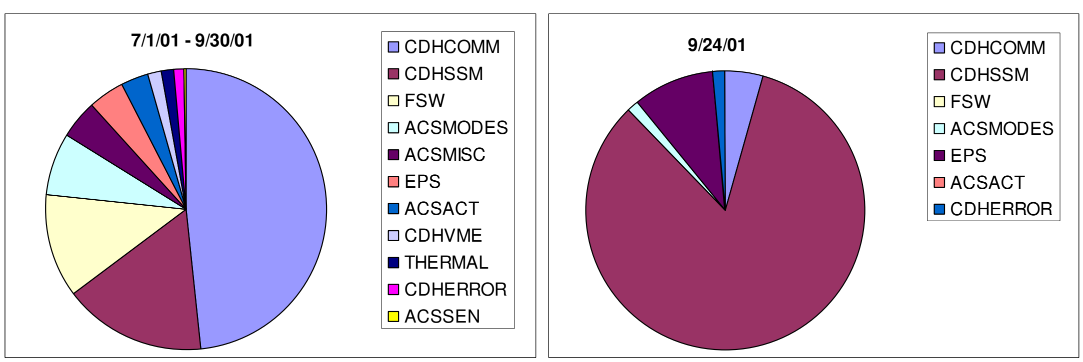

Fig. 5. MS2 L0 Anomaly type percentages for the period 7/1/01— 10/1/01 compared to the percentages for 9/24/01. Note that the proportion of Command Data Handling Solid State Memory Monitoring Subsystem (CDHSSM) anomalies on 9/24/01 is disproportionately high.

Of the 509 CDHSSM-caused anomalies seen on 9/24/01, all but one occurred after X-ray and radio burst events which ended approximately at 1330. Notably, these anomalies did not start to occur until 3–4 hours after the end of the X-ray and radio burst events (starting approximately at 1630).

The prevalence of a specific type of subsystem anomaly paves the path to using the correlation to predict the outcomes (e.g., systems downtime, data loss, etc.) associated with a particular scenario (L3 data fusion). These analyses suggest a causal link between the solar electromagnetic bursts and the subsystem anomalies recorded. However, given the limited amount of data any conclusions are preliminary.

Much of the data analysis tried to find event features that distinguished the two SPWX events: one that correlated strongly with MS2 anomalies (9/24/01) and one that did not (8/25/2001). The aim was to establish a stronger predictive link between environmental factors and satellite subsystem anomalies and to guide future data gathering efforts to validate and extend the current findings.

Analyses compared MS2 day exposure during the X-ray and radio burst events, as well as the profiles of the burst events. The findings are summarized in Fig. 6.

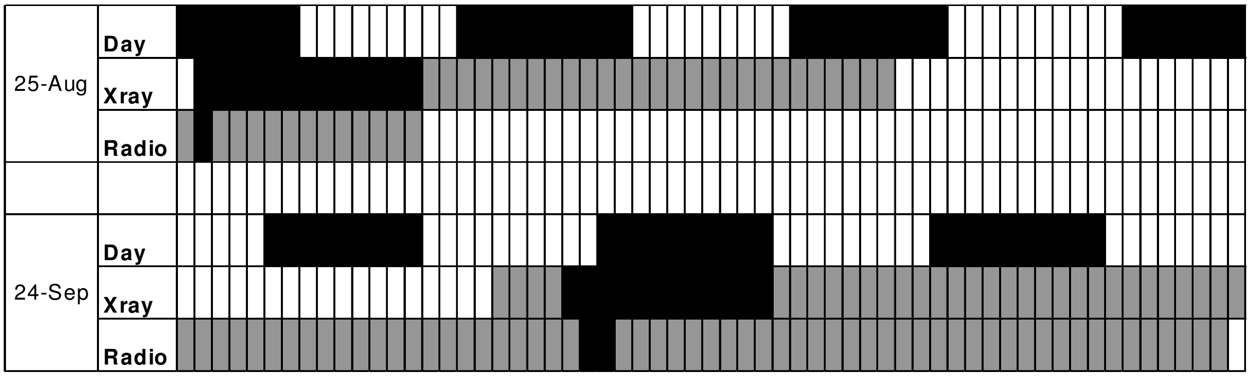

Fig. 6. Comparison of X-ray and radio bursts on 8/25/01 and 9/24/01. Time is shown on X axis increasing from left to right. Time span shown for each day is approximately 5 hours. Black is MS2 night side exposure, grey shows elevated X-ray flux, black shows peak X-ray flux, grey shows duration of radio burst event, black shows peak of radio flux.

Both of these events included X-ray and radio bursts, but the radio burst on 9/24/01 was significantly longer overall, had a longer period between onset and peak activity, and the peak radio activity overlapped MS2 dayside exposure.

3. AUTOMATED RED TEAMING (ART) SIMULATIONS

The second research thrust in ASSESS is to leverage ART to support high level data fusion and decision support. “Red” refers to assets or phenomena that are threatening and “blue” refers to friendly assets [3,4,14,15,16,17]. ART uses agent-based models coupled with stochastic search algorithms (e.g., evolutionary or swarm search algorithms [5,6,7,8,9,10]) to explore the space of possible threat (Red) scenarios, their likely outcomes and the (Blue) courses of action (COAs) that best mitigate the threat. The algorithms optimize an outcome (measure of effectiveness, MOE) or combination of outcomes measured in the agent-based models. The algorithms typically start by evaluating a random set of scenarios and based on the results evaluate a set of new scenarios similar to the previously explored scenarios which maximize the desired MOEs. This approach allows an operator or analyst to formally specify the potential friendly (Blue) assets, hostile or threatening (Red) assets, asset capabilities and behaviors, situational constraints, and hostile MOEs and then automatically search for the configuration of assets and their characteristics that optimize those MOEs.

For example, a Red team may want to optimally disrupt Blue communications over a given area without being detected. In this case, ART could potentially evolve a set of Red orbits that in combination provide many conjunctions with the Blue asset over the area of interest, such that no one Red satellite is present during jamming events, but in combination, the satellites jam the Blue satellite much of the time. Here the MOEs would be based on minimal detection probability and maximal jamming events. Similarly, if there is a given hostile Red scenario, the same technology can be applied switching Red for Blue and evolving a Blue COA that optimally disrupts the Red activities.

A goal of ASSESS is to develop and apply this technology to the SSA and DCS domains where scenarios are highly complex and there is very little historical data relevant to threat conditions. The goal is to generate ART data that samples a population of threat scenarios that are especially threatening to Blue assets and mission plans (e.g., jamming surveillance of a given region). This data can then potentially be used as proxy historical data and analyzed via statistical modeling so as to detect, identify, and categorize unfolding threat scenarios.

To date, ART efforts have focused on developing infrastructure to support stochastic search over simulated scenarios. A survey of the simulation platforms found that the agent-based model offered in SEAS has a good range of features for supporting space environment scenarios. SEAS has high level programming support for simulating and capturing measures of effectiveness (MOEs), sensor streams, communication uploads and downloads, weapons attacks, orbital dynamics, geomagnetic coordinates, space environment areas of interest and solar effects. During Phase I, SEAS has been integrated with the stochastic algorithms, and a cluster-based framework has been implemented to reduce the time needed for an ART run. Representation schemes for the assets, asset characteristics and behaviors, space weather environment, and other scenario features have also been explored. Because stochastic search algorithms are crucially dependent on the representation of both the scenarios and the algorithm details, refining these aspects of ART will be a focus of future work.

The functioning of this framework has been validated with a simple debugging scenario, generating a Red satellite orbit to match a given Blue satellite orbit. In addition, several runs have attempted to optimize a Red orbit that maximizes conjunctions with three Blue satellites near a given geographical region, the putative intention being to jam multiple satellite communications or surveillance with a single Red asset. These multiple satellite runs have generated scenarios with interesting orbit matching behavior, but not the expected subtle and complex Red strategies. Future runs will refine the fitness function to reward scenarios with more subtle behaviors, e.g., those that would be harder to detect.

4. FUTURE WORK

At the time of writing, an invited Phase II proposal for this project has been submitted. There are two main research and development objectives for the Phase II effort:

- *Validate and extend the L3 data analysis* for SSA/DCS decision support by warehousing and mining historical SPWX and subsystem anomaly data.
- *Develop and demonstrate ART-based tools* for generation, understanding, detection and classification of satellite event scenarios.

Validate and Extend the L3 Data Analysis

The data gathering and analysis in Phase I yielded some of the first potential correlations between MS2 subsystem anomalies and SPWX events. These correlations were subtle and low confidence given minimal amount of subsystems anomaly data available (three months of L0 anomalies for approximately 5000 total). Future work will attempt to expand the data available for analysis, both in the realm of subsystems (e.g., longer time periods or more satellites) and SPWX. This expanded data set coupled with more extensive data mining could potentially raise the confidence in the correlations identified and discover other correlations useful for SSA/DCS decision support. For example, analysis of the particular characteristics of the 9/24/01 radio burst that differentiate it from the 8/25/01 burst allowed the identification of a radio burst on 04/09/01 that shares the profile of the 9/24/01 burst. Gathering MightySat II anomaly data during this time period would help test and validate the preliminary findings.

The integration of SPWX data sources can be considerably expanded as well. Several sources of data have been identified, especially SSJ4 data from the Defense Meteorological Satellite Program (DMSP) and "data assimilation" model-based data streams from Auroral models like the Ovation Auroral Oval Model [11,12] or the Hardy Auroral Oval Model available from AFRL through AF-GEOSPACE [13]. These models fuse space environment data and solar observations with physics-based models to generate state--the-best estimate space environment estimates.

Develop and Demonstrate ART-based Tools

Future work will attempt to build a toolset for generation, understanding, detection, and classification of satellite event scenarios. The ART technology is of interest to a wide variety of groups for support of mission planning, ConOps, situational awareness and COA analysis. It could potentially provide a capability to perform "what-if" analyses with an approach that is complementary to current expert systems techniques.

The difficulty with the technology will be making it flexible and intuitive enough that reasonably skilled operators and analysts can use it with a realistic amount of training. To achieve broad applicability and operational deployment of ART will require processes and technologies to support:

- Choosing or developing appropriate representations and algorithms for a given set of scenarios or tasks.

- Operator interfaces to the ART runs to manage the simulation process.
- Gleaning insights into the dynamics of the simulated scenarios from the mass of data produced by the ART runs.
- Leveraging the ART results to detect, identify and categorize unfolding scenarios.

A primary objective of the Phase II effort is to generate a roadmap to achieving these goals and to provide a template application of the technology in the SSA/DCS domain. This application will require domain expert validated ART results that include SPWX and that can be used to provide insight to analysts into a type or class of satellite threat scenarios. The Maui High Performance Computing Center (MHPCC) will help support future work by providing engineering expertise, cluster-based supercomputer resources and SSA/DCS expertise. Given the high computational demands of the ART approach, MHPCC's support will substantially aid the development process.

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