Satellite-Based EMI Detection, Identification, and Mitigation

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ABSTRACT

Commanding, controlling, and maintaining the health of satellites requires a clear operating spectrum for communications. Electro Magnetic Interference (EMI) from other satellites can interfere with these communications. Determining which satellite is at fault improves space situational awareness and can be used to avoid the problem in the future. The Rfi detection And Prediction Tool, Optimizing Resources (RAPTOR) monitors the satellite communication antenna signals to detect EMI (also called RFI for Radio Frequency Interference) using a neural network trained on past cases of both normal communications and EMI events. RAPTOR maintains a database of satellites that have violated the reserved spectrum in the past. When satellite-based EMI is detected, RAPTOR first checks this list to determine if any are angularly close to the satellite being communicated with. Additionally, RAPTOR checks the Space Catalog to see if any of its active satellites are angularly close. RAPTOR also consults on-line databases to determine if the described operating frequencies of the satellites match the detected EMI and recommends candidates to be added to the known offenders database, accordingly. Based on detected EMI and predicted orbits and frequencies, RAPTOR automatically reschedules satellite communications to avoid current and future satellite-based EMI. It also includes an intuitive display for a global network of satellite communications antennas and their statuses including the status of their EM spectrum. RAPTOR has been prototyped and tested with real data (amplitudes versus frequency over time) for both satellite communication signals and is currently undergoing full-scale development. This paper describes the RAPTOR technologies and results of testing.

1. INTRODUCTION

Commanding, controlling, and maintaining the health of satellites requires a clear operating spectrum for communications. Electro Magnetic Interference (EMI) from other satellites can interfere with these communications. Determining which satellite is at fault improves space situational awareness and can be used to avoid the problem in the future. The Rfi detection And Prediction Tool, Optimizing Resources (RAPTOR) monitors the satellite communication antenna signals to detect EMI (also called RFI for Radio Frequency Interference) using a neural network trained on past cases of both normal communications and EMI events.

Currently known potential RFIs have little or no effect on the schedule, much less newly detected or predicted electromagnetic interference (EMI)/RFIs. (EMIs can be predicted using the space catalog and known offender satellites as well as through other means). These should inform both the in-advance period and real-time scheduling. Furthermore, the EMI/RFI detection/prediction process should be utilizing the most up-to-date (and accurate) published and real-time schedules as well as the space catalog (both unknown and known offender objects). These EMI detections/predictions should also be displayed to high-level, strategic personnel in an intuitive, clear, and easy-to-understand form.

Satellites, their associated ground communications and control equipment, and their operations (highly trained manpower, etc.) are extremely expensive. It is therefore important to get the highest possible utilization of these limited resources. Typically, this has been achieved with highly centralized scheduling by highly trained and experienced personnel.

Other efforts, such as Stottler Henke's MIDAS project [1] [2], are addressing automatic scheduling and deconfliction. And another project by Stottler Henke is addressing satellite operations center (SOC) automation in the form of SOC local schedule optimization and transmission. What was needed was an architecture specifically designed to support distributed command, control, and communications. And cooperative, distributed scheduling is just one example of cooperative distributed reasoning. Once the distributed cooperative, intelligent architecture is in place, it can be easily utilized for additional applications such as SSA (specifically real-time and predicted status of antenna ground stations and operational areas.

Real-time changes will occur as EMI and RFI events are detected. These can be used as a basis for EMI prediction. Examples include inadvertent interference from satellites controlled by others (e.g., those on the known offender list); purposeful interference from adversarial satellites (found from other objects in the space catalog); and inadvertent or purposeful terrestrial interference (i.e., jamming) predictable in the sense of simply continuing, especially if located with a direction finding antenna and/or problematic directions for the satellite communication antennas. Scheduling around predicted EMI involves elevation, azimuth, and frequencies to be avoided or overcome with enough power (which is more likely with LEOs than GEOs). Typically in real-time, deconfliction must occur within seconds for the nearest supports and within minutes for the rest. Real-time deconfliction must strive to meet the most supports possible while minimizing disruptions to the published schedule.

In addition to scheduling to avoid, predicted and real-time detected EMIs can be mitigated by several techniques depending on their classification. If the ground antenna is in Auto-Track mode during a GEO support and the interference is from a LEO known offender, the antenna can be Frozen to prevent tracking the LEO, and, since the GEO contact will angularly move very little, this will likely provide an acceptable link. If the support is for a LEO satellite, the antenna can be Slaved to the originally predicted satellite track. In both cases, since it is a LEO object causing the interference, it will be very temporary. If the interference has been classified as intentional jamming, usually based on the many channels affected and required power output, depending on the specific angles involved, a LEO contact will likely be able to power through it. The situation may be more hopeless for a GEO contact and the antenna may be best utilized by performing some other task.

As mentioned above, we have developed and are fielding the Managed Intelligent Deconfliction And Scheduling (MIDAS) system, which automates the very large majority of the scheduling/deconfliction process. MIDAS was developed in close cooperation with the satellite communication schedulers. Stottler Henke is also currently developing a MIDAS variant, which automates SOC operations and automatically creates (schedules) their satellite support requests.

2. PREVIOUS PROTOTYPING EFFORTS

As an initial step in RAPTOR's software development process, we developed a geographically distributed prototype that performed the entire multi-SOC and global scheduling and deconfliction process. It included the operational version of MIDAS for global scheduling, the existing MIDAS-variant for SOC scheduling and generating requests, and geographically distributed communication protocols. It was tested and demonstrated using an actual set of schedule requests as background and realistic support requests from several distributed SOCs, converging on a realistic and acceptable schedule after just three total cycles (one cycle of initial scheduling followed by two cycles of updates).

Prototype improvements were made to the abnormal support detection and classification neural network (ASDCNN) and its clustering/classification and other post-processing. This improved ASDCNN was applied to actual satellite communication signal data where it discovered 4 previously known abnormal signals but also detected another 31 abnormal events as well as a previously unknown timing pattern of EMIs. ASDCNN had previously been applied to actual operational satellite communication signal data in a semi-operational setting to independently find signal abnormalities. These were used along with the space catalog (manually) to compile a list of 150 known offenders.

ASDCNN was used to detect real abnormal behaviors to include discovered sun interference, unexpected EMI, and abnormal support signatures. ClassCat component of ASDCNN was modified to visualize abnormality detections over many days and expose abnormality patterns by hour of day and day of week. ClassCat was used to show historical times where similar abnormal signatures occurred. ClassCat was modified to name abnormality detections and store in variables files for use by ASDCNN. ASDCNN was used to name new abnormality detections that have similar signatures with the name from ClassCat. A named and channel event hybrid EMI event activity tracking capability was added.

ASDCNN's NNs were trained to learn support behaviors using actual operational data. All antenna signal data provided was tested with these NNs. NNs learned normal site-specific supports and background. Truth EMI events provided by the customer were detected with these NNs plus additional sun broadband, EMI over supports, sporadic

EMI, and new support behaviors. Abnormality detection scores per roughly 20000 frequency bins were clustered into common abnormality behaviors.

ClassCat was used to investigate and characterize abnormal satellite communication antenna signal detection cluster types. Abnormality type names were used to track EMI and other abnormal activities. When type names were not available, abnormal antenna channels were used to track abnormal activities. Detection sensitivity and event activity track parameters are adjustable to improve performance based upon performance assessments. New support detections can be used to automatically retrain the system.
The resulting satellite antenna event detection and tracking performance on 2011/2012 selected historical data sets are described in Table 1. In summary, our team reduced the risk for on-line operational abnormal activity characterization during the prototyping stage.

Table 1. Abnormal Activity Track Summary

Data Set	# of Records	# Distinct EMI Events	# Known EMI Events	# New Distinct EMI Events	# Total Separate Channel Events
1	890,231	11	Unknown	11	39
2	1,197,314	20	Unknown	20	48
3	108,708	4	4	4	4

We also developed and demonstrated a near real-time SOAP interface to an antenna signal data storage server, which could display the current actual status for supported antennas and retrieve recent detected abnormal signals. A design was also developed for low- and high-side versions and interfaces between the antenna signal data storage server and other system components.

3. SYSTEM DESCRIPTION

3.1 High Level Overview

Appropriate RAPTOR schedule agents interface to the signal data server and ASDCNN, sending them the published and current real-time schedules and receiving from them detected and predicted RFI and EMI. RAPTOR agents at the antenna ground stations receive attack warnings and predictions. The antenna station agents, in a manner similar if somewhat simpler than the SOC agents, work with the antenna operators to confirm, reject, and/or implement suggested COAs/schedule changes. The antenna station agent also includes an interface to display real-time detected and predicted EMI events along with recommended actions to respond to them, such as freezing the antenna for GEO contacts, slaving it for LEO contacts, possibly increasing power for LEO contacts to respond to jamming, etc.

The central scheduling RAPTOR agent receives the inputs described above from the RAPTOR agent community and cooperatively generates a new schedule (for both the pre-real-time and real-time periods), taking into account SOC requests, confirmations, rejections, special cases/constraints, and suggestions; detected and predicted EMI (including jamming) to be avoided; commander SSA (e.g., detected/predicted antenna status, discerned attack patterns, warnings regarding specific satellites and regions of space, etc.) and suggested COAs; and confirmations, rejections, and suggestions from antenna station agents. The scheduling component of the central scheduling agent uses the operational version of MIDAS. What should be readily apparent from this description is that all of the data, information, and knowledge related to EMI and scheduling originating from anywhere in the RAPTOR community will be available to all the agents in the RAPTOR community and, via them, to any decision-makers in the SOCs, command and control organizations, antenna ground stations, etc., realizing a much more net centric architecture.

The High-Level Communication Architecture is shown below corresponding with the agent communications described above and currently implemented.

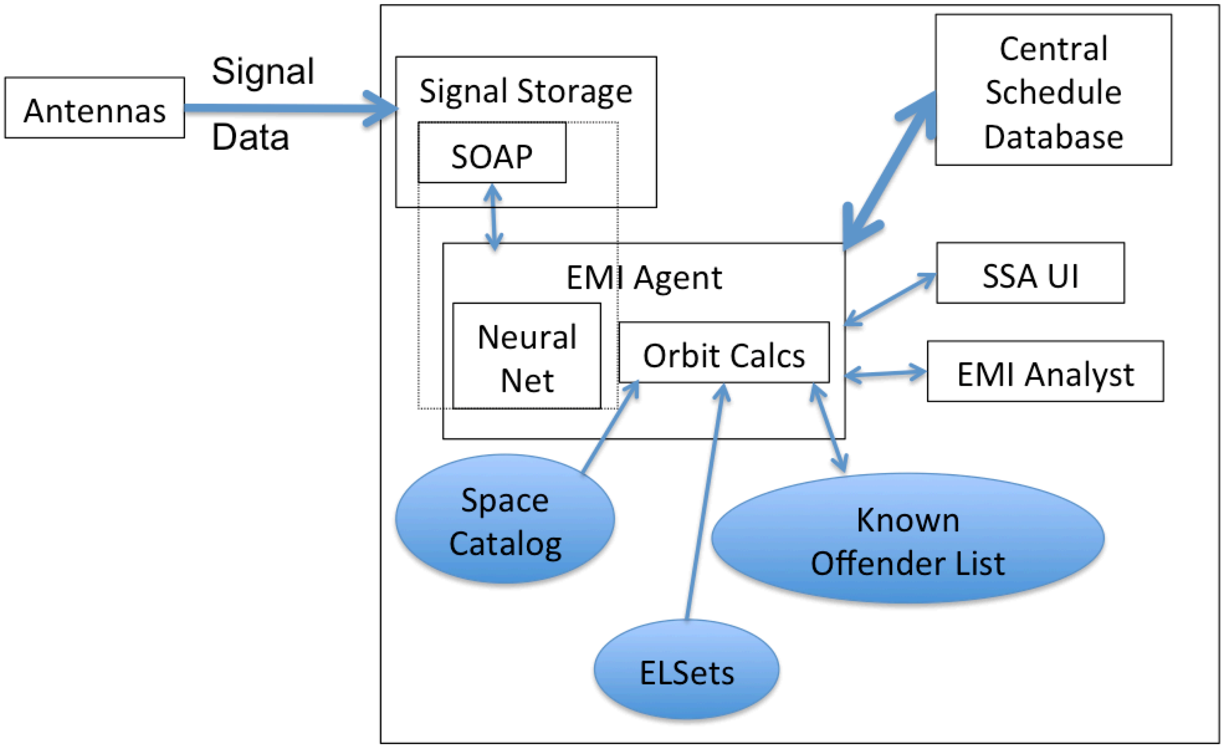

Fig. 1. High-Level Communication Architecture

The full-scale RAPTOR system under development consists of a distributed architecture with cooperating heterogeneous agents located at a central command and control location, the SOCs, and the antenna locations and includes interfaces with the antenna signal data storage server, ASDCNN, and the satellite communication schedule distribution system. Agents at the SOCs also incorporate technologies developed in previous projects, including MIDAS and SOC automation software (a MIDAS variant).

RAPTOR also includes a high-level SSA interface to receive detected (and potentially predicted) EMI, RFI, and satellite events from the EMI agent. It also receives the published, deconflicted and current real-time schedules. These are displayed in an intuitive, easy-to-understand graphical manner.

3.2 ASDCNN Functional Flow and Design

Perhaps the most important component, and one that can drive the rest of the process is the ASDCNN which uses neural network technology to detect and classify EMI. Its functional flow is shown below.

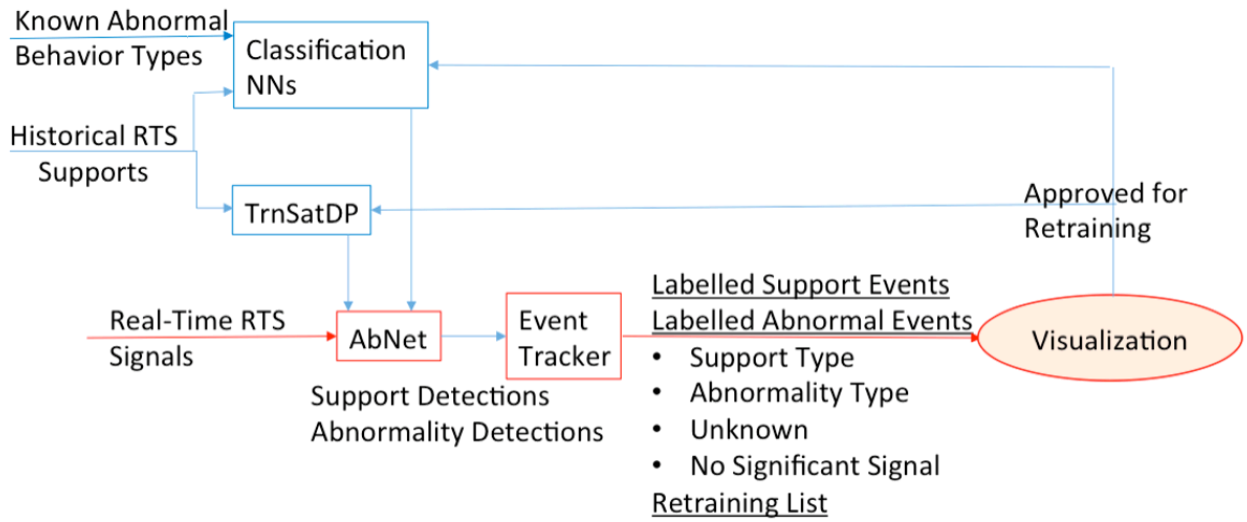

Fig. 2. ASDCNN EMI Detection, Characterization, and Event Activity Track Functional Flow

The ASDCNN operational functional flow is shown in Fig. 2. The real-time or historical signals are ingested and normalized for presentation to ASDCNN. ASDCNN contains the NN models learned from normal real supports and in some cases known RFI. ASDCNN provides detections of unknown unexpected abnormal EMI in the antennae output signals. ASDCNN also clusters these detections and provides cause names (either from user-assigned names or default channel names) to the abnormal event activity tracker. These resulting detections, names, and abnormal event tracks have been historically output to the NN viewer for the user. However, in this effort, we are providing an additional layer of reasoning and logic to process these outputs to provide automatic determination of space object culprits and predictions of future EMI resulting from these and previously known culprits.

RFI Detection Training Data Sets

- Trained on LEO, GEO, and other high orbit satellite supports, including pre-pass setup time for one (especially interesting) month of data
- 63 support types trained on by ASDCNN and classification NNs
- 3 specific known abnormal behaviors trained on by classification NNs
- Trained on 273K examples, tested on 553K examples in all data at 2 second rate
- 2070 inputs including sin/cos TOD, 20 skews, & roughly 2000 frequencies to abnormal detection and classification NNs
- ASDCNN NNs take about 12 hours to train
- Classification NNs trained on supports & known man-made and environment signatures. Have 45 hidden nodes so about 3 examples/weight.
- 3 min/classification NNs iteration with typically 500 iterations

Results/Performance

- 6 unknown abnormal behaviors detected
  - Similar abnormal behavior classified correctly
- 5 known abnormal behaviors detected/classified correctly
- 8 of the 10 medium events ID'ed by customer detected
  - other 2 events had no/little data above min. threshold
- 32 ASDCNN -only abnormal event tracks detected
  - 11 new abnormal behaviors documented
- Trained EMI events detected by classification NNs
- New support behavior detections classified as supports for retraining
- Performance will improve as new abnormal and support behaviors are classified, NNs retrained, and as tracking is added

3.3 Abnormal Signal Post Processing

Additional information was combined with ASDCNN's outputs and in the automatic post processing that occurs when abnormal signals are detected, including the list of known offenders, known live space catalog objects, (eventually all objects on the space catalog to determine if an object disguised as space debris is actually a jammer), and orbital calculations to determine which space objects are in the angular vicinity of the satellite being communicated with. ASDCNN and its post-processing now automatically identify new candidate known offenders from the live space catalog. Additional processing now automatically uses the orbital parameters of the known offenders to predict future EMIs based on the current satellite communication schedule (i.e. to predict when these same objects will cause the same type of interference on the same channels at different antennas and for different supported satellites), and these can be automatically scheduled around, or, alternatively used to inform the SOCs and ground antenna operations personnel of potential EMI problems with specific supports.

A final necessity for ASDCNN is an additional layer of reasoning and processing logic to take its many, many analog outputs and transform them into much more clear and concise classifications and recommendations. Any DF or satellite communication antennas that are supported by antenna data storage server will be supported by the new, improved ASDCNN and the entire RAPTOR architecture. As is clear from this discussion, the normal ASDCNN outputs will be highly processed and reasoned over to generate these predictions and detections for display in a clear, concise, and easily understood manner.

3.4 RAPTOR Scheduling

Using the SOC MIDAS variant, the SOC RAPTOR agent formulates requests from mission objectives, payload user requests, user input, downloaded maintenance and launch schedules, predicted EMIs, and from interpreting telemetry and data feeds and passes the requests along to the central RAPTOR agent, which will pass back a deconflicted schedule. The SOC agent, based on the constraints, special cases, and other SOC-specific knowledge, will accept or reject suggested resolutions as well as make its own suggestions. A similar process would occur for changes to the real-time schedule where changes could come from the SOC (in the case of vehicle emergency or suspected satellite attack or EMI), from the central command and control agent, or from a ground antenna site if EMI is detected in real-time and classified as a problem that the operators cannot solve. Detected and predicted EMIs not scheduled around are displayed to SOC personnel and include the classification, type, source, and likely channels for the interference. Based on this information, the SOC can contingency plan for if the EMI actually materializes. If the EMI source is a LEO space object, for example, they will likely just live with it and wait it out since it will be very short duration. Alternatively, they might consider using an alternative communication channel, if possible.

3.5 Display

An additional layer of processing looks at the Abnormal Signal Detections for the Direction Finding (DF) and satellite communication antennas at a specific site to provide higher-level fusion and understanding. For example, if many channels are being affected, that may indicate jamming and at least indicates a high power source. If the DF antenna is also picking up the signal, a range of azimuth angles can be determined. If the interference is occurring on multiple antennas at a single site, that should also be considered and used to determine azimuth and elevation limits of the interference as well as the location of the likely source.

The outputs of ASDCNN must be reasoned over, processed, and displayed in a clear, concise, and intuitive manner to different types of end-users, based on their specific tasking, decision processes, and needs. The different RAPTOR user interfaces include systems for the SOCs, central command and control, commanders, and the antenna stations.

The SSA User Interface displays current and predicted EMI in a global, graphical interface. This is currently based on a 2-D map earth projection but could also utilize a 3-D globe projection. Status of antenna stations are represented by graphical icons corresponding to their antennas and important equipment shown on the global map at their approximate locations. EMI detections from ASDCNN are processed into a Red/Yellow/Green status for the electro magnetic spectrum associated with each antenna. In general, each antenna icon represents the status of 4 items: EM spectrum, antenna, ground equipment, and links.

For example, the Antenna status might be green and the ground equipment yellow, indicating some degradation but still functional, and the electro-magnetic spectrum might be red, indicating significant EMI across all or most channels and in all or most directions (jamming). Similarly the comm. links to/from the antenna stations may indicate that some are up and some are down. This type of information would be replicated for all the antennas at a site (plus the DF antenna), and all sites could be displayed on the global map.

The color of the electro-magnetic spectrum would be indicative of the amount of unauthorized energy in the RTS or DF. If the EM spectrum representation had N lines, the color of each could indicate the status of that channel (out of 20 channels). Different positions in each line (channel) could represent different times and be colored based on the projected and predicted status of the corresponding channel at the corresponding time. The DF antenna icon should also indicate whether it is still moving or not (i.e., it has stopped rotating). All this information is useful to the SOCs.

A future RAPTOR agent for the strategic commander would receive the published deconflicted and current real-time schedules and detected (and potentially predicted) EMI and RFI events. These could be displayed to the strategic commander, presumably using existing 3-D JMS displays as well as additional but integrated RAPTOR time sequence displays for the satellite support schedule and future pass opportunities. The strategic commander could investigate the impact of various COAs, such as temporarily bringing down an antenna or site or skipping a scheduled pass. This impact would have to be calculated by rescheduling. For example, if the COA is to skip a support and it turns out that support was to upload the command to gather intelligence and there is no other pass before the intelligence gathering opportunity, the intelligence download support immediately after that opportunity can also be deleted (thus freeing up resources) and the impact will be to fail to gather that intelligence. Alternatively, if the command upload pass can be rescheduled in time, there may be no mission impact. Also, if the original pass was a routine health and status check, and the satellite is not in any danger, the mission impact to the missed pass may be negligible. The strategic commander, if he sees a pattern to the asset attacks and failures, can enter warnings about predicted future negative events regarding satellites, antennas, or regions of space and these will be sent to the appropriate RAPTOR agents and handled appropriately (including both human user notification and scheduling to avoid them).

3.6 Communication between sites

The various SOC sites and central command and control location will need to communicate information about their schedules and requests amongst each other and with planning and scheduling agents. Additional communication will be required with the antennas and strategic commander as well. All communication is required to be secure and quick using industry-standard protocols. The types of information include SOC schedules (satellite ID, StartTime, EndTime, StartTimeWindow, Site, Side, PrePassTime), orbital data such as Two-Line Elements (TLE) sets, requested changes to a schedule, and acceptance/denial of a requested change or suggested alternative.
We have implemented all SOC communication using Representational State Transfer[3] or REST. A RESTful communication interface is essentially a web service running on the same machine as the component. RESTful communication interfaces do not require special-purpose middleware and rely on simple HTTP or HTTPS connections. They provide a flexible API that can be accessed by a variety of different applications. In order to make our RESTful communication interface secure, we use an industry-standard, two-step approach. We encrypt the RESTful communications using SSL/TLS, thus adding the security capabilities of SSL/TLS to the HTTP interface (called HTTPS).

The information communicated between SOC sites needed to be represented in a language-independent format. We chose the JavaScript Object Notation (JSON), which is a lightweight data exchange format and a text format. Given the approximately 600 total SOC support requests per day and that each request consists of only simple text, the bandwidth requirements of using text for these requests is minimal. If bandwidth becomes an issue, various compression schemes are possible with any of the representations. Change requests will be even smaller and can also be easily handled with minimal bandwidth.

4. CONCLUSION

RAPTOR has been prototyped, demonstrated, and full-scale development begun. Halfway through development, this has created an initial RAPTOR version which was demonstrated and well received. The demonstration showed many benefits:

- RAPTOR improves operations by automatically detecting and classifying EMIs and making appropriate recommendations.
- RAPTOR improves schedule timeliness by automating the scheduling and deconfliction process.

- The current ASDCNN system has already been successfully used to detect over 150 EMI events. These detections improve the understanding of satellite support issues. However the current version of ASDCNN being used is more labor intensive than it needs to be, especially for training and retraining the neural networks. We are developing a turn-key ASDCNN abnormality detection and characterization system that automatically maintains its capability to detect, characterize, and fuse multiple sources of information to report satellite control network status to its users and support scheduling to avoid EMIs and recommendations to mitigate those that are not avoided.

Development work on the full-scale system continues.

5. References

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