Automated Terrestrial EMI Emitter Detection, Classification, and Localization

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ABSTRACT

Clear operating spectrum at ground station antenna locations is critically important for communicating with, commanding, controlling, and maintaining the health of satellites. Electro Magnetic Interference (EMI) can interfere with these communications so tracking down the source of EMI is extremely important to prevent it from occurring in the future. The Terrestrial RFI-locating Automation with CasE based Reasoning (TRACER) system is designed to automate terrestrial EMI emitter localization and identification, providing improved space situational awareness, realizing significant manpower savings, dramatically shortening EMI response time, providing capabilities for the system to evolve without programmer involvement, and offering increased support for adversarial scenarios (e.g. jamming). TRACER has been prototyped and tested with real data (amplitudes versus frequency over time) for both satellite communication antennas and sweeping Direction Finding (DF) antennas located near them.

TRACER monitors the satellite communication and DF antenna signals to detect and classify EMI using neural network technology trained on past cases of both normal communications and EMI events. Based on details of the signal (its classification, its direction and strength, etc.) one or more cases of EMI investigation methodologies are retrieved, represented as graphical behavior transition networks (BTNs), which very naturally represent the flow-chart-like process often followed by experts in time pressured situations, are intuitive to SMEs, and easily edited by them. The appropriate actions, as determined by the BTN are executed and the resulting data processed by Bayesian Networks to update the probabilities of the various possible platforms and source types of the EMI. Bearing sweep of the EMI is used to determine if the EMI's platform is aerial, a ground vehicle or ship, or stationary. If moving, the Friis transmission equation is used to plot the emitter's location and compare it to current flights or moving vehicles. This paper describes the TRACER technologies and results of prototype testing.

1. INTRODUCTION

The Satellite Control Networks are critically important for communicating with, commanding, controlling, and maintaining the health of satellites. Occasionally there are incursions at the satellite communication antenna locations into the electro magnetic spectrum (EMS) reserved for these communications. These incursions may interfere (Electro Magnetic Incursions (EMI)) with scheduled satellite communication supports, or they may simply be noticed. In either case, tracking down the source of these incursions is extremely important to prevent them from occurring in the future, perhaps with grave consequences. This importance, combined with the current state of the monitoring equipment and software, has created a labor-intensive process taking several hours per EMI or incursion, as described below.

When a satellite support has problems, initially the problem has to be localized. Is it a problem with the satellite? With the ground equipment? Or with the communication link? If the problem relates to the communication link, is the problem being caused by some unpredicted EMI or from a predicted source, such as another controlled satellite in the vicinity or a celestial event (e.g., the Sun, Moon, space weather, etc.)? If from an unpredicted source, then that source must be tracked down. Alternatively, this same process may be initiated, not by an EMI event, but from a detected incursion event, i.e., an external signal that was detected in the band of frequencies reserved for communications with satellites.

These reserved frequency bands are typically divided into a dozen or more channels which are monitored to detect abnormalities. Such detections cause highly skilled Radio Frequency (RF) Analysts to go through an involved procedure to track down the source using a variety of diverse data sets. Each ground antenna site consists of one or more large parabolic dish antennas for satellite communications and one Direction Finder (DF) antenna, used to help track down the source of electro magnetic (EM) intrusions/interference (hereafter referred to collectively as EMI). If the EMI is from space and was detected during an actual satellite support, then the direction at which the antenna was pointed at the time will be known. A list is manually maintained of satellites known to inadvertently intrude on satellite support channels. This list is checked along with the satellites' 2-line element set to determine if it was angularly close to the antenna's pointing direction at the time of the event. If no satellite on that list matches the angle and frequency of the problem, then the satellite catalog is checked to determine if any active satellites were angularly nearby, and additional websites are checked for technical data about each satellite, including what frequencies they use for various purposes, to determine if any of them could be the source of the problem. The DF Antenna is also checked for clues as to whether the interference is space-based or terrestrial in origin (the latter being the focus of this paper).

The DF antenna currently sweeps a full circle periodically. Many times per cycle it produces a plot of the magnitudes of thousands of frequencies along with the direction the DF antenna was pointing to at the time. Relative quick directional changes of the EMI source, as indicated by this data, typically imply an aerial emitter. Using the Friis transmission equation along with an estimate of the emitter's transmitter power and the direction provided by the DF antenna allows the emitter's path to be plotted for specific points in time on a 3-D map such as Google Earth. This can be compared to various public sources of flight patterns (which can also be plotted for matching purposes) and frequencies to try to determine the specific identity of the emitter. These sources will vary depending on which antenna site is involved because the satellite control networks (by design) span the globe.

For non-aerial sources, the DF-provided bearings and bearing rates are used, along with Google Earth to identify possible source candidates, which could be stationary or moving (as in the case of a ground vehicle or a ship (if the antenna is near water). If one of the other antennas also picked up the interference, the bearing it provides can be used to triangulate the source. In real-time, if an antenna is not being used for a support, it can be directed toward the source as indicated by the DF antenna to try to triangulate the source. Whether a bearing only from one antenna or triangulated bearings are used, a map of infrastructure, buildings, businesses, and structures is useful to identify candidates. In the case of hard-to-pinpoint recurring sources (determined by the frequency signature), past plots of previous EMI bearings may also be used.

Over time, as new types of EMI are tracked down, an experience base is built up and added to by the RF Analysts. Associated with each problem-solving episode and methodology are the specific EMI events, including the offending emitter and its characteristics. Thus these methodologies are constantly expanding and growing. Along with this expansion is the growth of new sources of data to help with this problem, mostly in electronic form but also in the form of human contacts that can be called. These electronic sources are usually reliable, but their availability, especially in a crisis, cannot be assumed.

The process described above, heretofore, has all occurred during normal operations. However, the US military must be prepared for conflicts of all kinds, and so it should engage in exercises to prepare for those. So in addition to the presumably inadvertent intrusions that have occurred to date, purposeful jamming and other adversarial scenarios must be prepared for and trained for. In these cases, the RF Analyst must provide situational assessment based on space domain understanding of threat conditions. If satellite supports are being interfered with, what types of satellites were they and what was the impact of the interference? What course of action is appropriate? Of course, the source should be investigated and the type of threat identified as quickly as possible, but what about the support that may be in progress and is being interfered with? This will depend on the specifics of the situation. Is the interference for this support inherently short-lived? Should the antenna be locked onto the satellite's projected path instead of tracking it (because the interference is not moving with the satellite, but the dish may track with the interfering emitter)? Should power be increased or a different channel used? (This would violate the electronic warfare principle of taking no action that can be discerned by the adversary because this indicates to him that he is having an effect.) And what about future already-scheduled supports? Which of these will likely be affected and should they be rescheduled in some way?

The process described above for dealing with detected EMI is labor-intensive during normal operations, but, furthermore, its high latency is unacceptable during a conflict and therefore it must be automated. What is needed is an automatic, intelligent system that identifies terrestrial and airborne transmitters (and their locations/trajectories) that cause EM intrusions and interference with satellite downlinks.

2. DESIGN

2.1 Design Overview

The Phase II Terrestrial RFI-locating Automation with CasE based Reasoning (TRACER) system will consist of a set of automated and automatable tools. Using an enhanced ABNet, it will monitor the RTS and DF antenna signals to detect and classify EMI. After using RAPTOR [1] to confirm or exclude space-based sources of interference, TRACER would present to the operator an intuitive description and classification of the intrusion and its current impact on operations, if any. Based on details of the signal (its ABNet classification, its direction and strength, etc.), one or more cases of EMI investigation methodologies would be retrieved. Many of the actions in the associated BTNs simply involve looking up information from electronic sources, and since these operations are essentially "free," they would be executed immediately and the data used to update the probabilities of the various possible types of the source of the EMI. For example, one hypothesis might be that the source is an aircraft. Based on this hypothesis, the first bearing and estimated distance could be plotted on Google Earth and one of the real-time flight tracking sites could be accessed and the flights in the air at the time of the first EMI data point also plotted. When the DF antenna has made its second sweep, the amount of bearing change will tend to confirm or refute the hypothesis and, in any case, this second estimated location will also be plotted. If this sweeping-induced delay were considered too great, there could be a mode that immediately went into tracking mode when either an incursion or interference was detected. A fraction of the sweep period could be used to track the emitter for a small amount of time to quickly determine if it is airborne, stationary, or likely moving along the surface, based on the bearing rate of the emitter. In general, as new data arrives, the various hypotheses proposed by the various applicable cases will have their probabilities updated and only the most likely current hypotheses will be pursued. These hypotheses and their probabilities would be displayed to the TRACER operator both for his situational awareness and to allow him to adjust them based on the current global or local tactical situation.

The above process will quickly resolve the majority of the EMI cases because the majority will have been encountered before, and the same methodology used to find or confirm them will be applied in the current case. However, some situations will be harder to resolve, and in these cases TRACER will present additional tools to the RF Analyst. These include the following: presenting opportunities to triangulate using an antenna not involved in a support (and since TRACER will have access to the real-time schedule through our RAPTOR project, it will know when the next such opportunity is); displaying a historic timeline (using DataMontage) of when similar EMI signals have been detected in the past, along with plotting them in Google Earth; predicting the effects of the EMI on future scheduled supports; the eventual, classified version of TRACER displaying the type of satellite and what its current mission is to help with situational understanding; displaying two types of courses of actions: one to help mitigate the current, interfering situation and the other being suggested investigative actions; and providing overlay maps of infrastructure, buildings, businesses, and their business types along the plotted line of bearing of the EMI (and its approximate distance, if known).

The enhanced ABNet EMI classification is an important tool for the real-time TRACER user and the RF Analyst. For signals previously encountered, it will instantly provide emitter and platform type (e.g., video transmission / airborne), which will be displayed with the initial notification. And if the signal is similar to but somewhat different from some past signals, these past similar signal classifications will be displayed, which may provide some clues. And if it is completely different from any signal encountered before, this fact will also be displayed, which may be helpful from a situational awareness perspective. In an adversarial situation it may be the case that interference is a result of jamming and that the jamming has multiple, different sources. This may be resolvable through simple symbolic reasoning based on the DF antenna detection angles (i.e., different simultaneous bearings implies different sources), but an adversary may use multiple emitters that do not broadcast simultaneously, essentially hopping the source of jamming around. This would be difficult to track well with the current sweeping-only DF employment. Even attempting to dwell on the interference would only produce sporadic results, but at least occasionally the DF antenna would happen to hit the EMI during a sweep and while dwelling there, see it disappear. ABNet, if properly trained with simulated multiple jammer data, should be able to determine when simultaneous emitters are causing EMI, which, given its unusualness, would be important information for both the human operator and for a TRACER Case/BTN designed specifically to handle this kind of case.

An important component of TRACER is accessing legacy databases and websites and being able to easily add new ones. A separate module for handing external data sources will facilitate these capabilities while also gracefully handling the situation when the needed access is unavailable.

Relating to the concept of new data sources is adding new methodologies. For EMI situations not encountered before and for which the actions and processes already in the case base and automatically executed could not resolve the case, the RF Analyst would use the toolset provided by TRACER to resolve the problem, while TRACER tracked and recorded his actions. Thus, when the analyst was able to finally track down the source of emissions, TRACER would have already recorded the process (and the results of each step) that the analyst went through. This process can be displayed to him in graphical form for final editing before being inserted as a new case in the case base. In the future, when a similarly classified signal is encountered with similar other circumstances (e.g., similar timing and directional characteristics), the newly input process will be automatically executed by TRACER to try to similarly identify the emitter. Once new emitters are identified and localized, their actual distance from the antenna (and therefore their actual emitter power) will be known. This data is used to update the estimate of emitter power (or ranges of power) for different types of emitters.

2.2 System Description

TRACER's overall architecture is shown in Fig. 1. As described in the Solution Overview, based on ABNet's classification and other data immediately available relating to the EMI event (i.e., direction, signal strength, channels affected, etc.), the most similar stored cases are retrieved. Each case includes the investigative methodology to be applied to the case's type of situation, in the form of a BTN. The retrieved cases' BTNs are sent to the SimBionic Runtime engine, which executes them in parallel. These BTNs will have been earlier entered with the SimBionic Graphical editor either by the RF Analyst SMEs themselves, or based on a description from them of the methodology appropriate for that specific type of EMI event. That engine is designed to run multiple BTNs in parallel, so multiple applicable cases, each with its own process, all running at the same time and creating a stream of actions at the same time, is not a problem. As each of these actions is generated, how it is handled depends on what type it is. Data Retrieval, since it involves no operator time, will likely be executed immediately. If for some reason the source of data is not available, that will be reported to the user. Sources of data include websites, legacy databases, and the real-time schedule and major equipment statuses for the satellite control network (available from our RAPTOR system). Data resulting from data retrieval or any other actions is sent to the BTN that requested it to determine the effect on the BTN's flow chart/decision tree, specifically which new task that BTN should transition to. The data is also sent to the data object associated with the current EMI being investigated.

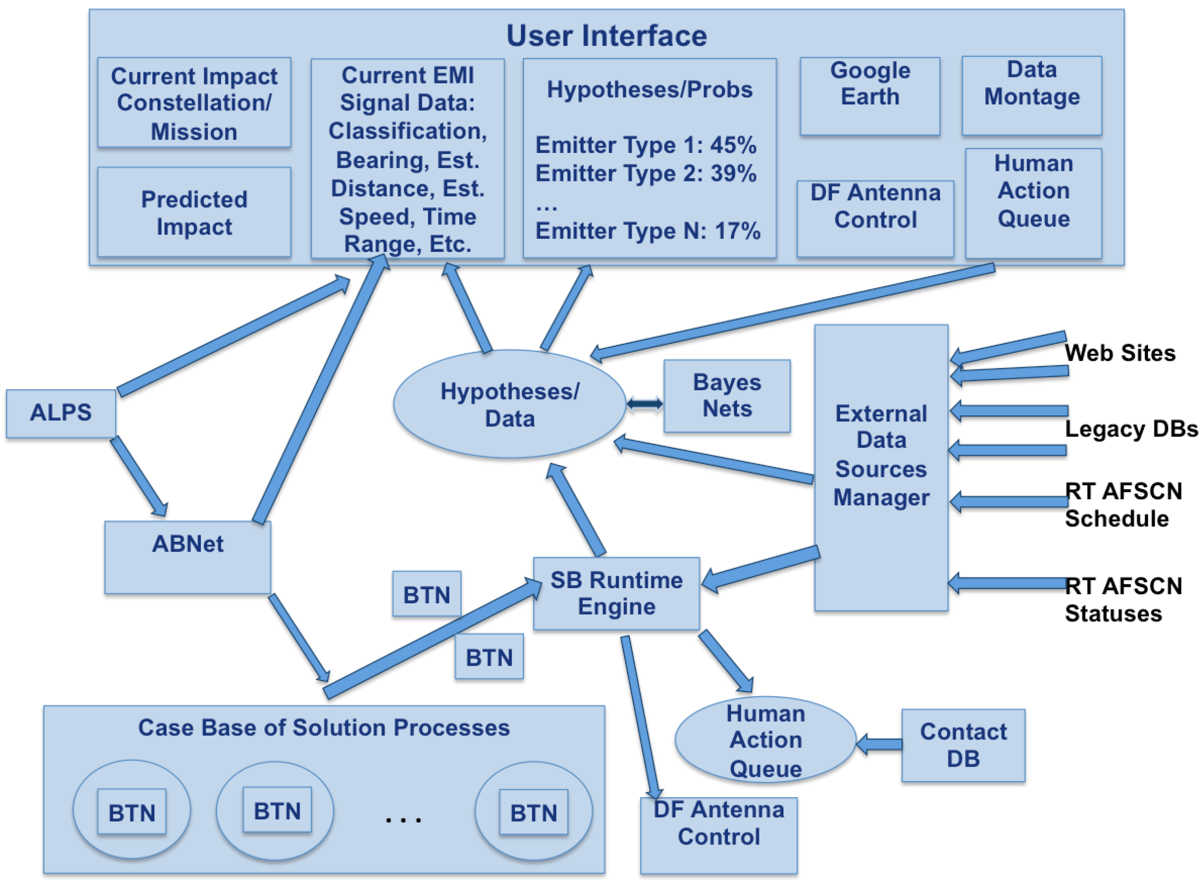

Fig. 1. Overall TRACER Architecture

Some of the BTN actions may create a new hypothesis to be pursued as to the type and/or location of the emitter and/or remove a hypothesis previously created by this BTN. Meanwhile, as additional data is received relating to the current EMI, Bayesian Networks are updating the probabilities that various hypotheses (that have been created by the BTNs) correctly identify the source of the EMI. These are kept sorted and displayed to the user along with the current probability estimate. (In addition to several hypotheses being pursued in parallel for a single EMI event, several different EMI incidents (normally from different times but also possibly happening to occur at the same time) can be investigated simultaneously.)

BTN actions that require human execution (such as phone calls) are placed on the Human Action Queue and displayed to the user in decreasing order of importance (where the top action is the one that most likely confirms or refutes the most important (i.e., most critical (e.g. adversary-related) and most probable) hypothesis. The BTN action might involve other user interface actions such as plotting possible emitter locations as well as candidate aircraft flight paths in Google Earth and/or the associated time event data in DataMontage. The human action might involve the suggested use of the DF or a currently (or soon to be) unused satellite-support antenna. The user interface would include widgets for instructing the DF antenna to dwell on or track the EMI source as well as to directionally steer it more manually. If allowed, a TRACER BTN action might be to recommend these same things with the RTS antenna (but obviously not the satellite-support antenna) directly.

The horizontal beam width of the DF antenna is wide enough that EM signals are detected across several degrees of azimuth. Thus an automatic dwelling/tracking algorithm would swing back and forth to continually find, in a noise tolerant sense, the DF antenna azimuths that bracket the signal as well as the maximum magnitude. For moving sources, these azimuth angles would move over time. We will develop an automatic dwelling and tracking capability as well as providing a remote control capability to be used by TRACER's BTNs or the human user. These capabilities would be developed to ensure that only a fraction of the time is spent with these activities so that the majority of the time continues to be dedicated to 360-degree sweeps.

The External Data Sources Manager provides a layer of abstraction between the rest of TRACER and various external sources of data so that new sources can be easily added and when old sources change, the needed changes in TRACER are well isolated. Various technologies exist for extracting data from legacy databases and websites and these will be leveraged for development efficiency. Another role of the External Data Sources manager is to cache retrieved data so if the same data is requested twice (perhaps from different BTNs), the retrieval is only performed the first time and all subsequent requests for the same data are simply fulfilled from the cache.

As mentioned previously, the case base is organized such that it has a hierarchy from the most general to the most specific, as shown in Fig. 2.

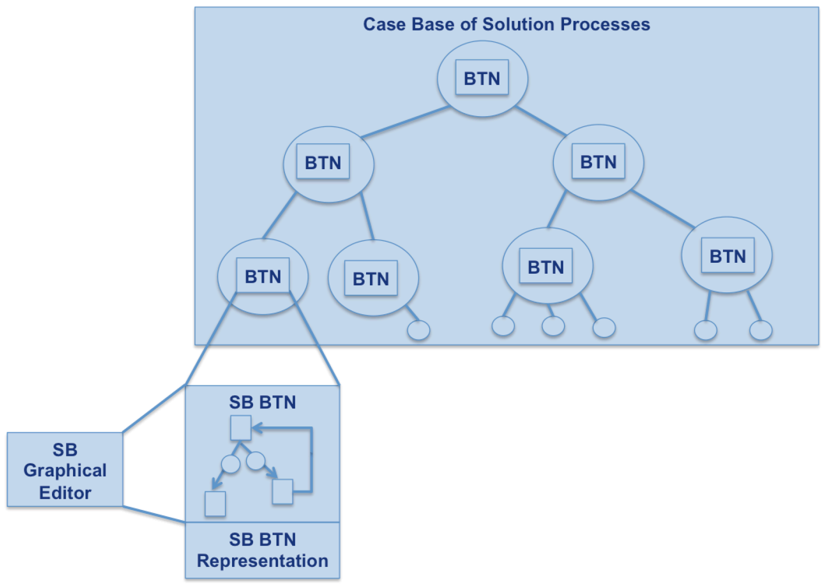

Fig. 2. Case Base Hierarchy

Normally the most specific applicable cases, based on the current information, are retrieved and used. Not previously mentioned is that BTNs can call each other. This is useful to prevent duplicating commonly used steps. For example, it may be that one process common to all cases is to first check on known space-based sources of EMI. This first step (borrowed from the RAPTOR project) might be in the BTN for the highest case in the hierarchy. Another step that might be similarly general is determining the change of bearing rate (to determine if the emitter is likely airborne). More specific cases (lower in the hierarchy) could reference this BTN in case they were initiated immediately, perhaps as a result of a very refined ABNet classification. The BTNs will have been created in the SimBionic Graphical Editor by the RF Analysts themselves or based on their descriptions of the methodology they followed in the various different cases. Below the most specific cases with BTN methodologies are the specific episodes of EMI that they were applied to and all the data associated with those investigations, including the ultimate resolution.

TRACER includes an intuitive user interface (UI) which quickly presents the operator with all the information he needs to instantly understand the current situation, based on the current set of data for the particular incident as well as corrective and investigative courses of action. The UI includes several sections, all of which will be displayed on the main screen to avoid navigation through deep menus as well as the possibility of important information being hidden behind alternative tabs. One section describes the current EMI event, with a graphical depiction (showing, in compressed form, the signal magnitudes across all channels and their subfrequencies), ABNet refined classification, DF Antenna bearing (plus additional bearings if available from triangulation), distance estimate (if known), bearing rate, estimated speed (if known), time period EMI was active for, etc. Next to this section would be the current set of Hypotheses that attempt to explain and identify the EMI along with calculated probabilities that each is correct, sorted in decreasing probability order. For any selected set of hypotheses, the associated bearings (and estimated distances, if available) would be plotted on Google Earth. This data would also be tied to synchronized DataMontage time-event graphs of the points and other important events for EMI (e.g., start/end of EMI at each antenna that picked it up, start/end of relevant supports, events associated with different hypotheses (e.g., if aerial, takeoff or landing, radio communications, etc.)). Also displayable overlaid on the Google Earth plots would be infrastructure, buildings, business names and types, etc.

Another section would describe the Current Impact of the current EMI event, including whether the event is interfering with a current support or not, whether it is on the same channels as the current support or not, and (for the classified version of TRACER) constellation and general and specific mission of the IRON being supported by the antenna that is experiencing incursion or interference. Next to this would be a section for the Predicted Impact on future supports. These would be supports scheduled to use the affected antennas and channels. To the degree that the timing of the future EMI is predictable (e.g., it is continuous, the emitter is in a known orbit or a known flight pattern, or the EMI seems to adhere to a known temporal pattern (even if the source has not been identified)), then only information describing which specific future supports will be affected will be listed, along with the information analogous to the Current Impact Section.

The UI also includes a section for operator actions that includes the Human Action Queue, which would include specific investigative steps such as looking at automatically created plots, making calls (to contacts with phone numbers in the Contact DB), requesting triangulation from a support antenna, etc., and mitigation steps such as slaving the antenna to the orbit of the supported satellite. It also includes a section for DF Antenna Control to monitor what it is currently doing (e.g., where it is currently dwelling/tracking, % of time dwelling/tracking versus sweeping), whether dwell on EMI detect is currently set, steering input commands, etc.

Some examples of procedures that TRACER would follow in different circumstances and the kind of data it would retrieve and check are described below. The first step, from RAPTOR, is to check for space-based emitters. If a space-based emitter is detected during a satellite support, RAPTOR will process it. Otherwise it falls under TRACER's SCOPE.

In parallel with the RAPTOR space-based emitter check, TRACER will determine the bearing rate (either by dwelling checking immediately or waiting until another bearing is determined during the next sweep). High azimuth bearing rates indicate that the signal is most likely aerial. Smaller variances would most likely be terrestrial, like, for example, grounds maintenance using a riding lawnmower or tractor putting out noise spikes near an antenna.

For likely aerial emitters, TRACER will acquire the time frame, azimuth, and amplitude of the signal and use open source websites such as FlightAware, FlightRadar24, and other open sources. If TRACER still cannot determine ownership of the aerial emitter, TRACER will place an action on the Human Action Queue to coordinate with Federal Aviation Authority (FAA) radar approach control, which services the affected station to obtain a tail number if possible. Regardless of whether the aerial emitter is known or unknown, DF bearings and signal strength and the Friis equation will be used to determine estimated locations and these will be plotted on Google Earth to show the estimated flight path(s) of the emitter. For non-aerial sources if an emitter owner is not revealed, then the software will use Google Earth Professional to look along the azimuth bearing(s) to identify possible source candidates.

3. ABNET PROTOTYPE

ABNet is based on Neural Network (NN) technology to learn, from previously recorded, historic data, normal and previously encountered abnormal signals in order to detect known and unknown abnormal signals in real-time. ABNet provides detections of unknown unexpected abnormal EMI in the antennae output signals and 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 are output to the user. ABNet has already been used to independently find abnormal antenna signals (ABSigs) and use these along with the space catalog (manually) to compile a list of 150 known non-adversarial threats.

The RAPTOR effort is providing an additional layer of reasoning and logic to process ABNet outputs to provide automatic determination of new space object culprits and predictions of future EMI resulting from these and previously known culprits. Additional information will be incorporated into ABNet and in the automatic post processing that occurs when ABSigs are detected, including the list of known non-adversarial threats, 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. ABNet and its post-processor will automatically identify new candidate known non-adversarial threats from the live space catalog. Additional processing will automatically use the orbital parameters of the known non-adversarial threats to predict future EMIs based on the current satellite support schedule. The normal ABNet outputs will be highly processed and reasoned over to generate these predictions and detections for display in a clear, concise, and easily understood manner.

3.1 DF&NN ABNet Study Results

TRACER ABNet Results summary:

- 97% Detection accuracy
- Needed to lower threshold from -119 to -121
- Categorized into 7 Major, 22 Minor Categories
- Correct categorization ~90%
- Results produced in real-time (Actually about 10x real-time for three antennas).

4. PROTOTYPE DESCRIPTION

4.1 Main Flow of the Prototype

1. Data is always coming in from the signal data storage server, being evaluated by ABNet-Raptor and ABNet-Tracer.
2. The EventManager creates a new Event when either ABNet version detects a new intrusion. Additionally, if a new intrusion is detected at a site with a currently active Event, an Action will be kicked off to determine if the two incursions result from the same source. If so, the two Events will be merged into one.
3. A new Event has some actions kicked off immediately, regardless of hypothesized Classifications, such as recording the signal and tracking its location. In some cases the prototype might alert the user to the new Event immediately, but in others it will wait some time for these automatic actions to gather some info before creating hypotheses.
4. Initial Classifications are generated with respect to different properties of the event. E.g., type of transmission, platform, military/non-military. Each hypothesized Classification has an associated list of Actions that could help to confirm the Classification and/or move onto more specific classifications (e.g., an initial hypothesis might be that the Event has a Classification of aircraft, which might be refined to helicopter after following its movements).
5. Actions generate types of Evidence, which is submitted to the EvidenceManager, which acts as a publisher for NodeManagers connected to nodes in the Bayes net. Each NodeManager can subscribe for whatever sorts of evidence affect its node in the net. E.g., a NodeManager for the "platform" node might be interested in Evidence with type speed or location.
6. A NodeManager will update its node based on the evidence, which in turn affects other nodes in the net. When a node that acts as a classifier has its state updated, the corresponding Classifications for the event are updated. Return to step 4.

4.2 Prototype/Demonstration Summary Description

- Uses real Satellite Signal Data
- Includes adjustable real-time clock
- Investigates incursion in near real-time with tools
- Automatic ABNet Detection/Classification
- All antennas – automatically merged if EMI events are on same frequencies and same classifications
- Automatic Google Earth Plotting
    - Automatic plotting of local DF Maxima (Friis)
    - Automatic FlightAware Retrieval
    - Changeable parameters (Friis equation, error bounds)
- DataMontage event plotting
- Satellite Signal Data Viewer

5. FUTURE WORK

In full-scale TRACER would be developed in 3 incremental major versions (and several minor releases for each major version) to facilitate feedback. The first version would concentrate on delivering an immediately useful set of tools, the second version would focus on automated reasoning by the software, and the third would focus on enhancements suggested by feedback from the earlier two versions. More specific descriptions are given below.

The first version would include the following immediately useful tools:

- Automatically Graphing Latitude, Longitude, and time from the DF antenna data in Google Earth
- Automatically Graphing Flight Data in Google Earth
- Automatically Graphing Triangulation from all Antenna in Google Earth
- DF Antenna User Control & Automatically Dwelling/Tracking while scanning
- Mission Impact Reports (MIRs) Trending
- DataMontage for graphing time and event data
- Contact DBs for contacting various entities involved in resolving EMIs
- Mitigation Steps – actions to take to minimize the effects of the interference on the current support
- External Data Sources Manager: Interface to Websites, DBs, and other networks for needed data
- Interfaces to IFDS; FlightAware/PlaneFinder/FlightRadar24; RAPIDS; MARS/MIDAS; etc.
- ABNet Detection/Classification
- Predicting EMI effects against future supports
- Intuitive User Interface that includes:
    - Current EMI Data (Classification, Bearing, Range Est., Speed Est.)
    - Hypotheses (Place holder for second version)
    - Impacts
    - DF Antenna Control
    - Human Action Queue (For Mitigation actions, and, in the second version investigative steps)
    - DataMontage (Time Event Data Analysis User Interface)

The second version would add automated reasoning and include:

- Case Base Of Investigation Processes
- Each case represented as a Behavior Transition Network (BTN)
    - Similar to a flowchart and/or Finite State Machine
- Bayesian Networks for Probabilities of various Hypotheses
- Reasoning about future EMI Impacts
- Retrieving Similar Past EMI episodes
    - ABNet Classification
    - Site/Side
    - Channels
    - Static & dynamic signal characteristics
    - Time of Day and other context

The third version would implement requested enhancements based on the use of the first two versions.

Work on the full-scale system is just beginning.

6. References

[1] Stottler, R., Bowman, C., "Satellite-Based EMI Detection, Identification, and Mitigation" AMOS 2016.