WENESSA, Wide Eye-Narrow Eye Space Simulation for Situational Awareness

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Abstract

In an effort to achieve timelier indications of anomalous object behaviors in geosynchronous earth orbit, a Planning Capability Concept (PCC) for a "Wide Eye-Narrow Eye" (WE-NE) telescope network has been established. The PCC addresses the problem of providing continuous and operationally robust, layered and cost-effective, Space Situational Awareness (SSA) that is focused on monitoring deep space for anomalous behaviors. It does this by first detecting the anomalies with wide field of regard systems, and then providing reliable handovers for detailed observational follow-up by another optical asset. WENESSA will explore the added value of such a system to the existing Space Surveillance Network (SSN). The study will assess and quantify the degree to which the PCC completely fulfills, or improves or augments, these deep space knowledge deficiencies relative to current operational systems.

In order to improve organic simulation capabilities, we will explore options for the federation of diverse community simulation approaches, while evaluating the efficiencies offered by a network of small and larger aperture, ground-based telescopes. Existing Space Modeling and Simulation (M&S) tools designed for evaluating WENESSA-like problems will be taken into consideration as we proceed in defining and developing the tools needed to perform this study, leading to the creation of a unified Space M&S environment for the rapid assessment of new capabilities. The primary goal of this effort is to perform a utility assessment of the WE-NE concept. The assessment will explore the mission utility of various WE-NE concepts in discovering deep space anomalies in concert with the SSN. The secondary goal is to generate an enduring modeling and simulation environment to explore the utility of future proposed concepts and supporting technologies. Ultimately, our validated simulation framework would support the inclusion of other ground- and space-based SSA assets through integrated analysis. Options will be explored using at least two competing simulation capabilities, but emphasis will be placed on *reasoned analyses as supported by* the simulations.

1. Introduction

AFRL/RDS has reinitiated a Wide-Eye, Narrow-Eye (WeNe) SSA study in an effort to clarify the advantages of a cluster of collocated telescopes working together to both surveil very large regions of the sky and perform detailed follow-ups on objects whose behavior has been flagged anomalous. The astronomical community has several examples of related, sometimes non-collocated capabilities, including Gamma Ray Burster detection by space-based telescopes having only coarse positional information that is followed up with high resolution ground-based detection and characterization. Other transient astronomical events including new comet and asteroid sightings are followed up in a similar fashion. The collocation of WeNe telescopes is not a strict necessity for SSA but does ensure a simplified handover of objects without parallax corrections, and allows command and control over a local, secure network.

Surveillance (and the related notion of reconnaissance) of space has always been challenging – pixel fields of view on the sky are small[1], and angular extents of the surveilled regions are vast. Object number density (per solid angle) is a strongly increasing function of detection magnitude – with satellite, both active and dead, rocket body, and debris numbers per square degree growing as a power law of the limiting detectable brightness.

Examples of Physical and technological bounds

The purpose of the discussion below is to convey a sense of the problem rather than focus on any unique design constraints of WeNe, which is in the process of being formulated. The difficulty of a surveillance mission might be quantified by a combination of surveillance area coverage and its angular resolution, and the limiting magnitude for detections. If this surveillance volume could be monitored continuously, any event determined anomalous could be reported with negligible time latency. Because this is not possible given the physical and technological limitations described below, a key figure of merit for any WeNe embodiment is the maximum latency time corresponding to the worst-case delay between the onset of an anomaly and the time of its detection.

An upper bound of geosynchronous surveillance area derives from the latitude extremes of surveillance. Uncontrolled GEO satellites drift away from the equatorial plane by up to 15 degrees, over the timescale of decades. Although most all active GEO satellites are within several degrees of the equatorial plane, anomaly awareness over a latitude extreme of 20 degrees provides an interesting upper bound. Since fixed site telescopes can reliably cover 60 degrees or more on either side of the meridian, the angular area per site might exceed 7200 square degrees.

Telescopes of aperture diameter greater than 10 cm typically have seeing-limited, rather than diffraction-limited, optical blurs for the 2 arcsec and larger atmospheric seeing conditions considered here; this consideration provides a crude estimate for a lower bound on the number of pixel IFOVs over the surveillance area. Specification of optics diameter is thus not required for this estimate. This level of angular resolution may seem small yet is needed to monitor deviations of object positions from nominal, as angles as small as 2 arcsec still connote distances at GEO in excess of 300 m.

Thus, the surveillance region for the single fixed site used above as an example exceeds 10^{10} pixel IFOVs; in the case of sensor arrays capable of 10 to 20 MPixel snapshots (a currently valid range for the scientific grade of sensor array needed for SSA), an excess of 500 to 1000 snapshots is required to provide coverage over the full surveillance region. Since a cluster of 500 to 1000 collocated telescopes (or even sensor- camera lens pairings) is viewed as impractical, step-scanning of the surveilled regions is required and thus implies a revisit time for returning to any patch of sky; this corresponds to a time an anomaly could arise before being detected.

The argument above suggests that there must be a minimal revisit time for any practical, affordable GEO surveillance system. The time delay must however meet user needs to provide information that is in accordance with timescales to respond appropriately to certain classes of anomalies. The command and control system that accommodates this time delay and follows up on reported indications of anomalies with characterization taskings is complex. The ConOps is not deterministic, the system behavior is not predictable, and its simulation is no easy feat.

The WeNeSSA effort therefore seeks to develop and validate a Modelling & Simulation capability that allows the performance of proposed WeNe systems to be evaluated on the basis of selectable limiting magnitude and maximum allowable warning times. The task would be nearly overwhelming, except for the experience gained with the Dynamical Optical Telescope System (DOTS; see Fig. 1) at the AFRL/RDSM AMOS site, and its modeling and simulation software system (TASMAN), to be described below.

[1] For the analysis below, we assume seeing-limited optical blurs of about two arcsec full widths, with pixels matched to the blur to emphasize radiometric signal over resolved imagery resolution.

Fig. 1. The Dynamic Optical Telescope System of the MSSS.

2. Other WeNe complexities

Complex backgrounds at fainter levels of GEO object detection

It must also be kept in mind that surveillance of the GEO belt is against a foreground of more rapidly moving LEO and MEO objects, and against a background of structured celestial radiation. The background includes streaking stars whose density grows as the brightness limits for GEO object detection are lowered but also increases with decreasing latitude relative to the *galactic plane*, tipped with respect to the GEO plane. Zodiacal radiation is strongest at smaller sun angles in the ecliptic plane, which is tipped by the obliquity of the ecliptic relative to the GEO belt. These remarks suggest a strong GEO longitude and seasonal dependence in the backgrounds which will be most evident at the higher sensitivities and fainter limiting brightness levels. Fainter limiting magnitudes serve to both increase the star densities and raise the contributions of extended (structured) zodiacal and galactic backgrounds. Intricacies and interactions with these foreground and background sources are such that the difficulty of the problem of faint anomaly detection in support of a given number of GEO objects (N_{geo}) grows faster than linearly with N_{geo}, as a greater number of fainter objects are observed against more complex backgrounds.

Control System Modeling

Many commercial and small telescopes, and even larger Air Force telescopes dedicated to SSA, are hosted on agile pointing platforms that are easily capable of following LEO objects. Handovers by one telescope to another may involve the slewing of the latter by large angles approaching 100 degrees, yet still result in worst case slewing times not exceeding several mins. Given this level of telescope slew rate, movements to commanded positions are relatively efficient. However, real-world issues of failed reacquisition (lost object), interruption of the handover tasking by the control system (handover “recalls”), cloud obscurations, and other forms of delayed reporting back to the to the WeNe client, do increase the complexity of the control system. We wish to emphasize that diverse issues of this type with real-world hardware and observing conditions make modeling of the control system non-trivial[2]. For this reason, a WeNe Modeling and Simulation capability with the fidelity to accurately model such control systems is viewed as essential for high confidence performance estimates.

[2] We mention below, for example, the complexities of the extension of the DOTS Site Wide Scheduler to multiple DOTS sites.

Sensor array technology

Finally, sensor array technology is driven by a commercial market, and pixel count and sensitivity improve over time. The ability to accurately model overall sensitivity, as limited by both the sensor internal noise levels, and photon noise statistics associated with increased sky brightness through locational and lunar cycle dependencies, is also crucial to a high fidelity simulation and thus indispensable.

3. TASMAN, a simulation framework for WeNe

TASMAN, or Tasking of Autonomous Sensors in a Multiple Application Network, continues the Air Force Research Laboratory's (AFRL) efforts to develop a simulation environment (software and processors) that can test SSA tools (including real-time WeNe) in a closed-loop environment. The level of validation of TASMAN by the DOTS allows scripted and Monte-Carlo testing of WeNe tools and capabilities for rigorous testing of new tools and/or capabilities under various operating conditions and scenarios. This allows detailed concept evaluations to be performed prior to and without having to invest in hardware.

The goal of TASMAN is to develop a physics-based SSA network simulation environment that includes models of the Space Surveillance Telescope (SST), the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system, the Space Based Space Surveillance system (SBSS) and the MSSS telescopes, including DOTS. The sensor models are capable of producing accurate simulated observations of desired satellites including both astrometric and photometric measurements. The simulation environment must also be capable of injecting variable threat scenarios into the environment and changing parameters such as revisit rates and the number of objects of interest in the simulations.

TASMAN was developed by using a multi-threaded, parallel architecture which simulates the primary components of a sensor network in closed loop operation, including mission planning with network tasking and sensor scheduling, sensor observations from either a low fidelity statistical sensor model or high fidelity scene generation and image generation, processing, orbit determination and updates based on these sensor measurements, and feedback to mission planning for new scheduling and response to events.

As shown in Fig. 2, TASMAN includes the high level computer software components (CSCs) of TASMAN shown in blue rectangles including a Tasker, a Scheduler, a low and high fidelity Scene Simulator, and an Orbit Determination CSC. Key data, organized within four databases, was needed in support of these CSCs are shown in the grey "drums" which include a Star Catalog, Truth Ephemeris, Estimated Ephemeris, and Sensor Properties. The objectives of these CSCs and databases are now described.

The **Scheduler** will take information from the Tasker, check each individual Sensor for capabilities by reading the same properties as Sensor and then produce a schedule for each individual sensor. These collections will be based on each Sensor's position and capability in regard to the Tasker providing the mission goals. There will be a continuous feedback loop from Orbit Determination to the Tasker that provides a dynamic response capability in the Scheduler. The schedule is produced by generating a start time for each individual object and then providing the number of frames and the exposure time of each frame.

The **Sensor** software package will create the Sensor object that is used by the scene simulator, scheduler and orbit determination. This reads from the "Sensor Property" file. These properties include the dark and read noises, pixel sizes of images, telescope input aperture, position vectors/trajectories and the instantaneous field of view (IFOV). The Scheduler will use this object to determine if the expected collection can be performed. The Sensor will also retrieve information from the Truth Ephemeris to provide initial checks for positions of targets and other objects in proximity of the expected line of sight (LOS).

The **Scene Simulator** will receive information from the Sensor and Scheduler and then interface with the Star Catalog to produce either simulated imagery or simulated observations. This specific software will use the sensor LOS, object Truth Ephemeris and the Star Catalog to create individual star positions and target positions based on the properties defined in the Sensor Property file. This image will also contain star-streaks for a rate track image, or object streaks for a sidereal track image. There are other combinations such as rate-track with offset or a LOS tracking with velocities, which are through open loop schedule formats. The Scene Simulator will apply certain detection threshold checks for each Sensor to create the correct image based on the Minimum Detectable Target (MDT) magnitude for that Sensor.

The **Astrometric and Photometric Image Processing** software will perform image processing operations on the image received from Scene Simulator to detect stars and objects in the field of view (FOV). The star detection process produces the true sensor LOS and IFOV which are then used to produce metric observations for any detected objects in the FOV. Since the previous components have already defined all the properties for the Sensor, these properties are already available to Astrometric and Photometric Image Processing. During the star detection process, the individual star photometry is compared to the "cataloged magnitude" available in the Star Catalog to determine the photometric fit for the individual frames. This information is used to produce a calibrated photometric estimate of each of the detected objects in the frame. Once all the frames have been processed, Astrometric and Photometric Image Processing produces a track estimate for each combination of the detected objects across all the frames.

The **Orbit Determination** software will receive the tracks from the Astrometric and Photometric Image Processing component and starts comparing the information with the Truth Ephemeris to determine if the detected object is really the expected object. The observations that match will then be used to provide updated orbit information into the Estimated Ephemeris, or the catalog. Since the entire scenario must know truth, the Sensor and Scene Simulator can only use the Truth Ephemeris for executing the simulation. The orbit update process uses a batch least-squares approach to fit the new observations into the existing Estimated Ephemeris information for each detected track. During simulation initialization, the Truth Ephemeris is propagated for each object to initialize the Estimated Ephemeris for all available catalog objects.

The **Tasker** receives information from Orbit Determination, such as uncorrelated track (UCT) observations, to determine new courses of action for the simulation. The Tasker can then request new object observations from the Scheduler under the constraint of known information. Using the UCT as an example, the Scheduler would need to know items such as last detection time and last known brightness as well as an estimated orbit regime. This component provides the closed-loop feedback mechanism for the simulation that ensures self-containment. Other information that the Tasker might produce would be an indication of a Missing Tasked Object which may trigger a Missing Object Search. This information is available from the Astrometric and Photometric Image Processing in the absence of a track for an object that was expected by Scheduler. This can only be known once the Orbit Determination process has completed and all detected objects' orbit updates are completed.

The **Star Catalog** is an extensive database which provides astrometric information (Right Ascension/Declination) and brightness in various filter bands for each observed star. This catalog is over 25 gigabytes in size as compressed binary information, and includes nearly 1 billion stars. This component is used by the Scene Simulator for placing the stars in the correct position with the correct brightness for the observed filter. This component is also used by Astrometric and Photometric Image Processing for comparing the detected stars to the expected stars for determining the true sensor pointing LOS. In addition, the Astrometric and Photometric Image Processing also uses the expected brightness to help compute a photometric fit (accuracy) estimate to use in creating the estimated brightness for each detected object.

The **Sensor Properties** file creates the Sensor object used in each of the individual software components. In addition to the properties mentioned above, it also includes sensor position/trajectory, expected read/dark noises, selected integration times, number of frames per collection, the default estimated zero-points, the calibration files such as darks and flats, the spectral filter selection, the ensquared energy, the full width half maximum (FWHM), the sensor size in pixels, any specified level of pixel binning, and the initial alignment rotation matrix known as the cdMatrix for the Astrometric and Photometric Image Processing.

The **Truth Ephemeris** is a file lookup for truth ephemeris information that comes in the form of the Open Loop Ephemeris Types. It includes, in addition to orbital ephemeris data, an object model with sizes and shapes, an attitude profile, an initial state vector and any articulating solar arrays as well as any possible maneuvers for the simulation to use. The Truth Ephemeris is used to create the initial catalog, or the Estimated Ephemeris, by propagating the initial state vector using the detailed propagation special perturbation (SP) model in Orbit Determination. The Truth Ephemeris is also capable of making objects maneuver in the simulation, which is why the Sensor object must use the Truth Ephemeris for producing information that is used for Scene Simulation. Without the Truth Ephemeris, all objects would follow the Estimated Ephemeris, which does not have the ability to produce manipulated orbits.

The **Estimated Ephemeris** file will contain the current state of the catalog at any given time. At initialization, the Truth Ephemeris will be propagated to create an Estimated Ephemeris for each object available. Observations received from Astrometric and Photometric Image Processing will then be used by Orbit Determination to update the Estimated Ephemeris for the object in each track. The Estimated Ephemeris will also be used to create updated pointing locations for each tasked object in the next Scene Simulation, or to aid in the initial starting location of any Missing Object Search or the trajectory of a UCT.

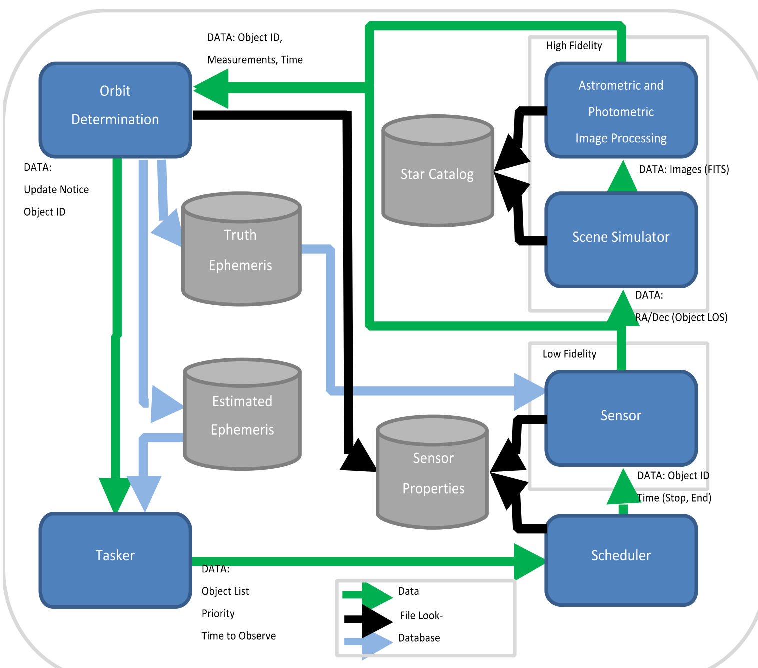

Fig. 2. TASMAN Top Level Architecture

TASMAN is capable of generating requirements for the DOTS program including revisit rates, number of objects, timeliness and system capacity. TASMAN was initially tested against scenarios including simple maneuvers and rendezvous between satellites.

The TASMAN effort has developed a suite of integrated algorithms and software to provide easily configurable simulations of optical space surveillance networks with sensors on the ground and in space. TASMAN is used to simulate the entire closed-loop cycle for space situational awareness which includes tasking sensors and scheduling observations, detecting targets and producing observations, correlating observations to a catalog, producing orbit estimates, and re-tasking the sensors based on dynamic events. TASMAN components and services were designed to be parallelizable across multiple computing nodes and are run in real time operations for DOTS as well as being run in synchronization with a clock service so that simulations execute at much faster than real time. TASMAN also simulates observations of space objects simultaneously from multiple optical sensors and produces simulated metric and photometric measurements. Fig. 3 is an overview of the TASMAN architecture illustrated by its high level functions.

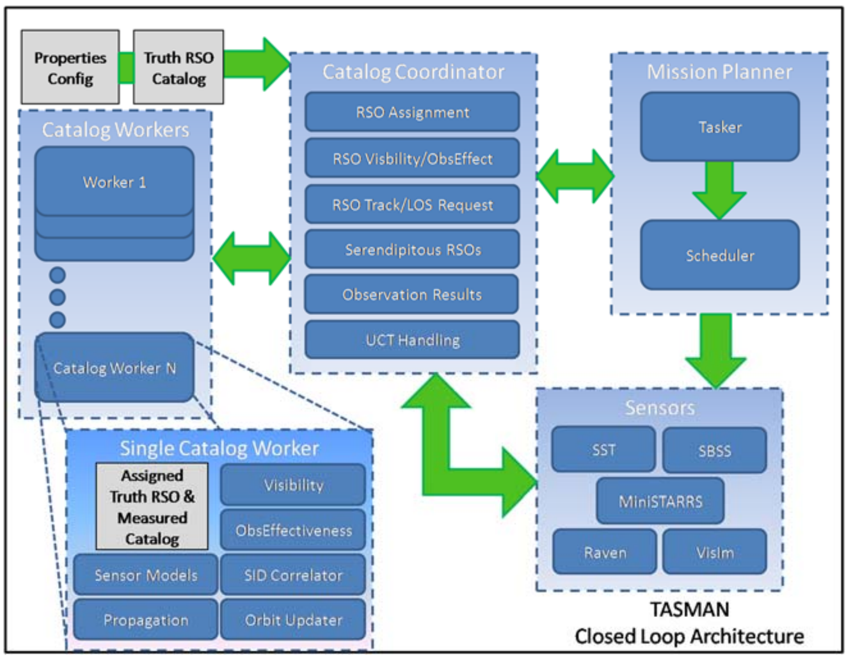

Fig. 3. TASMAN High Level Functions

TASMAN was developed using asynchronous message-passing, as a multi-threaded service-oriented architecture. With this architecture in place, studies were performed on observation effectiveness, error growth constrained scheduling, and tasking versus the more traditional search scheduling of sensors including AMOS Raven, SBSS and SST. Several feature enhancements were made to TASMAN in support of the DOTS mission analysis and requirements verification:

- Enabled Site Wide Scheduler (SWS) to dynamically generate scheduling supporting all DOTS missions for MSSS sensors through AMOS Mission-Planning and Scheduling with mount automation and all Ravens through AstroGraph,
- Refined closed loop messaging for Catalog Coordinator,
- Added orbit analysis service for maneuver and conjunction estimation,
- Added Tactical Persistent Monitoring (TPM) service, maintaining custody of UCTs and graduating their orbits,

- Added Task Reconciler And Information Disseminator (TRAID) executive service to initiate missing object searches in SWS, ASR tool processing for SSA missions, and DOTS dashboard publishing, and,
- Enhanced AstroGraph for medium fidelity image and track simulation, all sky and differential photometry, and multi-frame processing/chunking for SVK hierarchical data format data.

The TASMAN architecture allowed developers to combine all DOTS services under a single application called with TASMAN, and the DOTS Closed-Loop Astrograph and SWS (CLAS) applications[3] were also used to support modeling and simulation effort and analysis for an Advanced Technology Demonstration (ATD) to optimize and characterize performance of DOTS technologies deployed across the GEODSS sensor network. Complex indications and warnings analysis was included in the ATD analysis and utilized physics-based results from the high fidelity simulations produced by the CLAS.

In summary, the TASMAN mission-planning framework supports a centralized network tasker, centralized or distributed sensor schedulers, sensors operating as independent remote agents, and an integrated network scheduler with coordinated sensor observations. This framework allows analysis of the current AF Space Command SSN. Under this framework, a variety of mission planning algorithms were evaluated including covariance-based scheduling using observation effectiveness and kinematic state error growth minimization. TASMAN sensor components execute schedules created from mission planning inputs and generate simulated observations using either low or high fidelity methods. In low fidelity mode, a sensor model computes the detection probability and creates simulated observations with errors for all detected objects in the sensor field of view using the resident space object (RSO) truth ephemeris, observation geometry, sensor properties, and simulated environmental state. In high fidelity mode, high resolution simulated scenes are created using super-sampled Point Spread Functions. The high fidelity mode uses comprehensive star catalogs complete to 20th visual magnitude and RSO truth ephemeris from Special Perturbation (SP) orbits as input to image processing algorithms to generate observations for selected sensors. These sensors include the SBSS, MSSS sensors and Ravens. TASMAN orbit determination services merge sensor observations to initialize and update RSO orbits and leverage a C++ astrodynamics library called Turboprop. New and updated RSO orbits and states then feed back into the TASMAN mission planning services for further tasking and scheduling. Performance is assessed between the estimated and truth catalogs. The entire TASMAN simulation is unified via a simple messaging interface with point to point, publish and subscribe, and service auto-discovery capabilities that can be adapted to a variety of networking protocols and services.

4. Relation of TASMAN to an ultimate WeNeSSA Simulation Framework

TASMAN is unique in its simulation of an actual multi-telescope WeNe (i.e., DOTS) conducting a surveillance, indication, and warning mission from a high-altitude site. It offers an iterated simulation that has been fine-tuned to accurately represent performance of the actual WeNe system. This connotes a high level of verification for Modelling and Simulation software that serves to inform future WeNe simulations.

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[3] CLAS includes truth and catalog objects simulated via event-based messaging and a simulation clock. CLAS can simulate all DOTS missions and all DOTS use cases are run with CLAS as part of Bamboo Continuous Integration. CLAS simulations use software services identical to those used for operations at the MSSS. Any of the services can be deployed as separate virtual machines (VMs). These CLAS/MSSS services include Site Wide Scheduler (SWS), Catalog Coordinator, Orbit Analysis, Executive, ASR Tools, Astrograph, and Tactical Persistence Monitor (TPM). Astrograph, the sensor image processing service, was configured for use with CLAS in simulation mode to output statistically correct results including probability of collect (Pc) and metric accuracy instead of producing these values from the pixel data.

The flip side of this coin is that TASMAN is not as easily reconfigured to simulate other optical system embodiments as a modular, open source code environment would be. The prospects for accurate WeNe assessments with TASMAN, by a non-expert government entity as an example, are not promising. The true utility of TASMAN will persist as a controlled simulation providing high fidelity simulations conducted by its subject matter experts, in response to well-defined customer scenarios. For these reasons, we are investigating ways to define a TASMAN baseline that captures salient features of its simulation of DOTS performance in the form of an output parameter set. The breadth and depth of this baseline simulation "capture" would allow for its faithful reproduction by a future TASMAN run. It would also be the basis of an instantiation of an alternative, open source simulation that would thereby encompass a measure of verification for the DOTS embodiment to anchor suggested excursions from DOTS, including the simulation of multiple DOTS sites around the globe. The output parameter set is still in definition[4].

5. Comments on Code Federation; A potential role for AFSIM

The recent AFSIM Vers. 2.1 release includes interesting space-related capabilities. In addition to orbit generation via elements sets, object maneuvering is also provided in the form of element set parameter changes induced by delta-V burn amplitudes and directions. Additional work is underway, in support of future AFSIM releases, for slower maneuver representations (those taking place over a significant fraction of the orbital period), and in the out-of-plane direction (i.e., changes in inclination). More common coordinated maneuver types including Hohmann, orbit circularization, and other transfers are supported. Orbit intersection strategies in the new AFSIM release are simulated under the constraints of meeting a time goal, or on the basis of conserving delta-V, or specifying a maximum delta-V. Planning scripts are included to accomplish maneuver simulation in a transparent way, and at user-specified times or specified positional way points. The scripted maneuvers are checked against delta-V and any other levied constraints. Finally, an initial orbit determination reporting capability on the basis of the AFSIM sensor module is included, and additional capabilities for multi-sensor fusion are under study for future releases.

6. Conclusions

The core WeNeSSA activities make heavy use of TASMAN and will investigate in particular the extension of its modeling of the single-site DOTS to multiple sites. "WeNeSSA Evolved" will simulate an objective system for WeNe, with lower fidelity simulations explored first for quick turn studies on newly proposed WeNe concepts. The ultimate desire is for the WENESSA simulation to embody a modular, open source code environment, allowing quicker-look WeNe concept assessments without specialized knowledge of code intricacies. This approach would allow use by non-expert government entities, possibly in conjunction with AFSIM. TASMAN will continue to be employed for high fidelity evaluation of refined WeNe concepts, perhaps after a cursory exploration with a lower fidelity simulation.

[4] The simulation baseline might capture, for example, a distribution of the indication times, and of the warning times, from Monte Carlo trials for which the starting position of the anomaly is varied. Example cases might include maneuvers of objects of progressively fainter magnitudes, occurring (1) in daylight, (2) in Full Moon night sky, and (3) against stressing galactic or zodiacal background levels.