Utilizing novel non-traditional sensor tasking approaches to enhance the space situational awareness picture maintained by the Space Surveillance Network

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ABSTRACT

The Space Surveillance Network (SSN) is tasked with the increasingly difficult mission of detecting, tracking, cataloging and identifying artificial objects orbiting the Earth, including active and inactive satellites, spent rocket bodies, and fragmented debris. Much of the architecture and operations of the SSN are limited and outdated. Efforts are underway to modernize some elements of the systems. Even so, the ability to maintain the best current Space Situational Awareness (SSA) picture and identify emerging events in a timely fashion could be significantly improved by leveraging non-traditional sensor sites.

Orbit Logic, the University of Colorado and the University of Texas at Austin are developing an innovative architecture and operations concept to coordinate the tasking and observation information processing of non-traditional assets based on information-theoretic approaches. These confirmed tasking schedules and the resulting data can then be used to "inform" the SSN tasking process. The 'Heimdall Web' system is comprised of core tasking optimization components and accompanying Web interfaces within a secure, split architecture that will for the first time allow non-traditional sensors to support SSA and improve SSN tasking.

Heimdall Web application components appropriately score/prioritize space catalog objects based on covariance, priority, observability, expected information gain, and probability of detect - then coordinate an efficient sensor observation schedule for non-SSN sensors contributing to the overall SSA picture maintained by the Joint Space Operations Center (JSpOC). The Heimdall Web Ops concept supports sensor participation levels of "Scheduled", "Tasked" and "Contributing". Scheduled and Tasked sensors are provided optimized observation schedules or object tracking lists from central algorithms, while Contributing sensors review and select from a list of "desired track objects". All sensors are "Web Enabled" for tasking and feedback, supplying observation schedules, confirmed observations and related data back to Heimdall Web to complete the feedback loop for the next scheduling iteration.

1. BACKGROUND

Since the launch of Sputnik I, the U.S. Air Force has been interested in monitoring Earth orbiting objects. With this interest, a worldwide network of (primarily) radar and optical sensors was piecewise developed, transitioned, and integrated into a system that is now known as the Space Surveillance Network (SSN) and a global tasking center, the Joint Space Operations Center (JSpOC). The SSN has the mission of detecting, tracking, cataloging and identifying artificial objects orbiting the Earth, including active and inactive satellites, spent rocket bodies, and fragmentation debris. However, much of the architecture and operations behind this critical system are limited and outdated, including: 1) a 24-hour tasking cycle typically conducted via email or stove-pipe mechanism, 2) ad-hoc reactionary tasking via phone, 3) minimal feedback to the JSpOC on missed tasking or abnormal detections, 4) little to no information sharing between sensor sites, 5) tasking typically based on set return rate, not information gain expected, and 6) sensor sites do not always return possibly beneficial information such as covariance, observation time, observation quality, or sensor specific feature data, such as radar cross-section and visual magnitude.

With modern software approaches and data interoperability standards, the opportunity exists to engineer a modern, secure, scalable, centrally-hosted application and associated interfaces with appropriate information-based optimization schemes to coordinate SSN sensor tasking for improved catalog maintenance and efficiency. To further address the existing shortcomings, the recently proposed OrbitOutlook program is considering the use of non-traditional and non-government operated sensors to aid in improving space domain awareness [1].

The Orbit Logic team initially developed the capability to incorporate expected information gain to increase the value of planned observations [2]. More recent work is described in this paper, where we have extended the software to enable the tasking and return of observation data from non-traditional sensors - a capability that will significantly aid the JSpOC in its ability to gain and maintain its Space Situational Awareness picture.

2. TECHNOLOGY OVERVIEW

Orbit Logic, the University of Colorado, and the University of Texas at Austin have designed and prototyped a new system that integrates SSA scoring and scheduling components in an innovative multi-user architecture with an operations concept to coordinate tasking and observations for SSN and non-SSN assets to better maintain the space catalog for improved space situational awareness. This web-based system, termed *Heimdall Web*, facilitates the interactions between the traditional and non-traditional systems in a scalable and highly configurable manner that provides significant benefit to both.

A **public** prioritized object catalog will be generated based on the SSN catalog using a new Service Oriented Architecture (SOA) -enabled component within the JSpOC, and it is this catalog that the *Heimdall Web* algorithms will access to set observation schedules for Scheduled sensors and tasking lists for non-SSN Tasked sensors. Those objects that the central Heimdall systems cannot fit into an observation schedule or observation task list for available Scheduled or Tasked sensors at the desired frequency, will be posted for consideration by 'Contributing' sensors. The Heimdall design will support the ability of authorized contributing sensor organizations to browse, filter and search this list of desired observations so they can determine their own contribution to the overall SSA effort. The design even includes the ability for these Contributing sensors to use tools offered through the web application to define and configure their sensors and generate de-conflicted and optimized observation schedules for selected desired objects and events of interest for their own use. Contributing sites will post their observation results to the central application for tracking and fulfillment, which will dynamically update the desired observations list. A feedback mechanism allows sensor sites to provide observation results back to the central system, which can react by fulfilling an observation requirement or by re-tasking it to another sensor, as appropriate.

The design includes integration of an SSA-specific FISST-based component for computing observation opportunity Information Gain and Probability of Detection. This University of Colorado provided Task Prioritization component was refined and extended in a parallel effort and has been integrated and tested with Orbit Logic's scheduling algorithm component. SSA task prioritization ensures that limited sensor resources are applied where needed to maintain the object catalog.

The scheduling and tasking algorithm component includes configurable high fidelity sensor models that generate optimized and de-conflicted observation schedules for multiple sensors based on computed observation opportunities, sensor availability schedules, task prioritization inputs, and a configurable SSA-specific Figure-of-Merit (FOM). This scheduling and tasking component continues to be enhanced and refined. Its role is the generation of observation schedules and tasking lists. The performance and scalability of these algorithms has been proven in an early demonstration to the JSpOC and in other controlled tests with non-SSN sensors. Schedules can be very quickly generated (in seconds or minutes) and re-generated as needed based on dynamic factors such as SSN/sensor status updates, new object detection, and object activity detection. This kind of algorithm performance enables revolutionary operations concepts that are far more responsive than the current JSpOC sensor tasking processes. The configurable SSA FOM ensures the proper balance between maintaining the object catalog, detecting new objects, and gathering data on anomalous object activity.

Configurable permissions will allow Heimdall Web app administrators at the JSpOC to control the level of information sharing with non-SSN users and sites based on user login. Some users may be permitted to see what all sensors are doing, while others may be limited to only seeing their own sensor's tasking. On the JSpOC Mission Services (JMS) side, user access will be controlled using existing JMS services and protocols.

3. HEIMDALL SYSTEM ARCHITECTURE

The major components of the Public and JMS Heimdall Web Applications and their major interfaces are shown in the diagram below in Fig. 1 and described in the following sections. Unless specifically identified otherwise, components and architecture and capabilities are the same on both the Public and JMS versions of Heimdall.

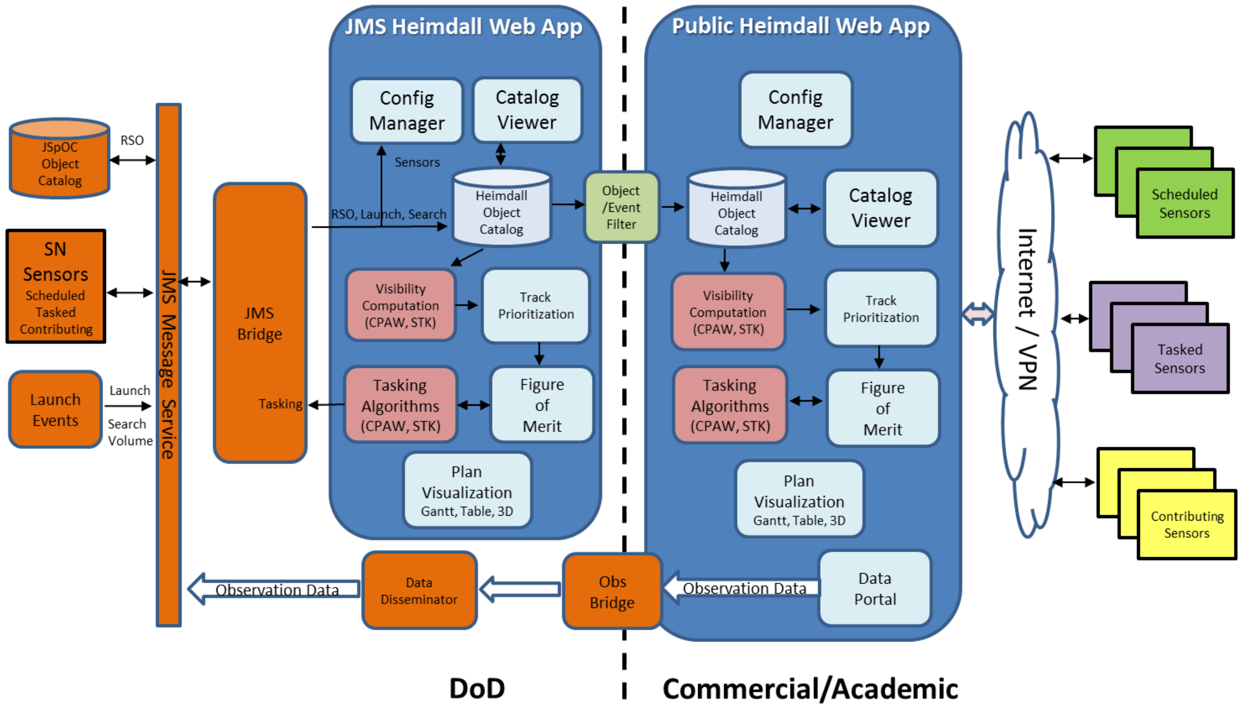

Fig. 1. Heimdall System Architecture Diagram

Heimdall Web User Interfaces

Providing an SSA-beneficial software automation framework for a sensor network as distributed as the SSN and other worldwide non-traditional sites necessitated a web-enabled solution – one with the ability to monitor the state of space environment from many coordinated consoles and manage data flows in a highly configurable manner. As such, the web-based Graphical User Interfaces (GUIs) comprising the Heimdall solution are key to the overall operations concept.

Our Heimdall Web software prototyping effort initially focused on upgrading and integrating several existing Orbit Logic software components associated with SSA sensor tasking. The resulting capability facilitated automation of the process flow for sensor scheduling and interactions with the sensor operators through a central web application reachable through and authorized client web browser.

One of the primary user features exposed through the web interface is visualization of the sensor tasking plans. The Heimdall Web App provides multiple ways for an operator to view, explore, and understand planned SSA tasking for ground and space sensors.

A configurable dashboard table view dynamically presents upcoming observations in time order, highlighting observations in progress and moving through the list of observations as time progresses. The presented list of observations can be filtered based on user preferences. The same Dashboard page provides a more global perspective in a 3D visualization pane. Driven by Cesium, this view is normally configured to run in real-time as a companion to the table view on the Dashboard, showing observations in an accurate graphical view as they occur throughout the collection of available sensors. The user may also select specific observations in the table view, and the Dashboard page Cesium 3D view automatically zooms in on the associated sensor resource and forwards to the time of the selected observation to display a static view of the specific observation geometry.

Heimdall Web App table and 3D views are driven by the latest object catalog database and associated planned observations saved within the object data there. The screenshot of Fig. 2 shows the table view and associated configurable filter, along with the embedded 3D Cesium view and associated metrics.

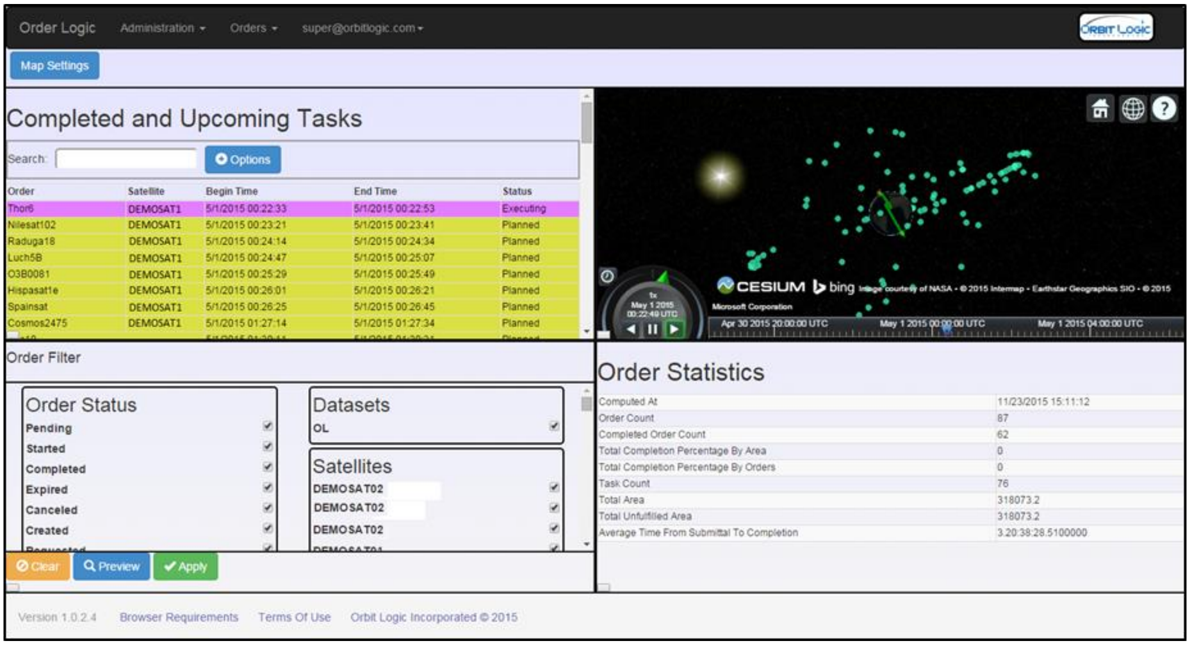

Fig. 2. Heimdall Web Application Dashboard Page

A Gantt View provides a familiar way for operators to explore the schedule of planned observations in a time format. Like the table view, the Gantt view (shown in Fig. 3) is configurable by the operator to show or hide certain details.

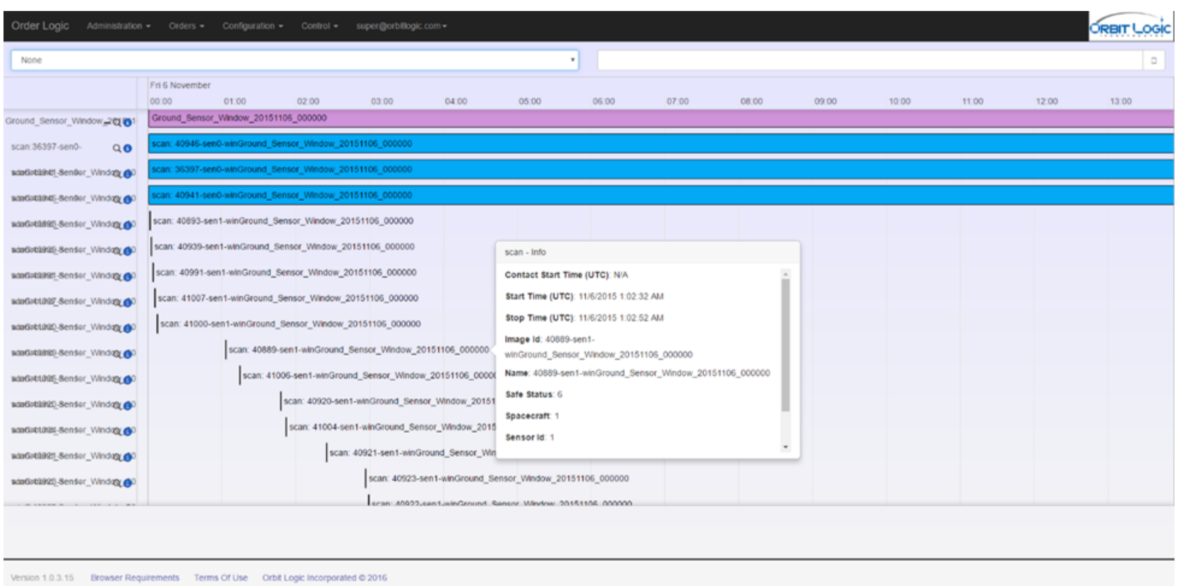

Fig. 3. Heimdall Web Application Gantt View

Configuration Manager

The Configuration Manager component of the Heimdall Web application provides the ability for authorized users (administrators) to define and configure permissions for users, add and configure new SSA sensors, specify sensor downtime, specify optimization goals, review performance metrics, and perform other related setup and configuration functions. The Heimdall Web App is a configured instance of Orbit Logic's Order Logic web application. As shown in the architecture figure above, two separate instances of the Heimdall Web App will be deployed to support both JMS operations and external non-traditional sensor tasking.

Changes made within the Heimdall Web App configuration pages are stored to the associated Heimdall database for use internally and/or used to send Application Programming Interface (API) configuration commands to some of the Heimdall Web App solution component applications – which include Systems Tool Kit (STK), STK Scheduler, and the Collection Planning and Analysis Workstation (CPAW). The web app sends commands to STK Scheduler and STK using STK Scheduler's TCP (Transmission Control Protocol) interface, and to CPAW through the separate CPAW TCP interface.

Catalog Viewer and Object Catalog

The Catalog Viewer allows Heimdall web app users the ability to view and search the Object Catalog and see the current state of each object and history of observations (along with associated observation data, if available). The user's access to functionality, data access, and fields displayed is limited by their configured access permissions. The Catalog Viewer is also used by Contributing Sensors to see and search the current Observation Priority for each catalog object, to allow them to select a set of objects for which to plan observations.

The catalog of objects and key object attributes are stored in the Heimdall Object Catalog PostgreSQL database. Heimdall-planned tasking and observation statuses are stored in the database and associated with applicable objects in the catalog.

On the JMS side, the Heimdall Object Catalog will be provided by JMS services. Heimdall will access these data service sources directly or through a software abstraction layer (or JMS translation module). Regardless of the choice made for the future deployed system, the data abstraction module (indicated as "JMS Bridge" in the figure) retrieves RSO data and event characterizations (launch and missing objects as examples) from JMS and passes that data through to Heimdall, which populates and updates its Object Catalog.

Visibility Computations

At the start of the planning process, constrained access computations are performed for each valid sensor/object combination. Computations consider line-of-site visibility, lighting constraints (when applicable), sensor capabilities, sensor field-of-regard, object attributes, and any applicable object/sensor assignments and preferences and constraints. Because access computations for each object are independent of the access computations for other objects, these computations can be performed in parallel on many cores in order to speed computation time for large object catalogs (as is performed by AGI's SSA Software Suite). The initial Heimdall architecture uses two separate constrained access computation engines; STK (for ground sensor RSO visibilities) and Orbit Logic's CPAW for space sensor RSO visibilities.

Systems Tool Kit (STK) from Analytical Graphics provides a comprehensive toolset and associated API for computing valid observation opportunities (visibilities/accesses) including a wide range of constraints such as object position/orientation, lighting, radar cross section, sensor field of regard, and more. STK Connect commands are sent via a TCP-based API interface, and resulting computation results are returned via a text file that is subsequently parsed to extract the key data. The Heimdall Web App leverages the Order Logic STK interface for making computation requests and receiving resulting observation opportunity windows for each object. Note that "objects" may include launch trajectories and search areas/volumes in addition to the typical orbital space objects.

Track Prioritization

Heimdall employs a Track Prioritization module to enhance the effectiveness of sensor observations by considering expected information gain in the planning loop. The University of Colorado and the University of Texas at Austin have contributed algorithms that have proven highly effective in allowing Heimdall to produce plans that result in significantly enhanced SSA.

Methods based on Finite Set Statistics (FISST) provide a means for solving multi-object, multi-sensor information fusion problem using techniques derived from Bayesian inference. The common goal of a multi-object filter is to provide an estimate of (1) the number of objects in the state space and (2) a state vector describing the trajectory and/or characteristics for each one. The Bayes multi-object filter provides a multi-object analogue to the Bayes single-object filter. However, the development of the Bayes multi-object filter has traditionally proven difficult, leading to the development of approximation methods such as multiple hypothesis trackers (MHT) that associate measurements with a given object track (or tracks) and catalog viable hypotheses that satisfy gating criteria [3]. Unfortunately, the number of hypotheses can grow in a combinatorial fashion, and pruning and other methods must be employed to maintain tractability. Alternatively, FISST-based methods leverage the concept of random finite sets (RFS) to represent and estimate the multi-object state space in a more mathematically rigorous fashion [4]. In the context of space-object tracking, the FISST-based filters provide a tractable means for estimating a multi-object state [5, 6].

An RFS provides an alternate representation of the multi-object state that allows for its approximation within the setting of the FISST filter. In the context of SSA, the RFS has a random but finite number of observed objects (i.e., cardinality), and each element of the RFS is described by a state vector probability density function (PDF). Higher moments of these quantities, e.g., variance on the cardinality, provide information on solution confidence. The observations generated from a single optical image (possibly of more than one object) are treated as a measurement set, and the FISST-based methods use this to approximate the state space RFS. In its most general form, the FISST multi-object filter provides a Bayes optimal solution to this problem, but raises issues of tractability. Hence, approximations of the FISST filter have been developed.

One simplification for the sake of tractability is the cardinalized probability hypothesis density (CPHD) filter, which approximates the density of objects. From this, the state vector of single objects may be extracted. The Gaussian Mixture CPHD (GM-CPHD) filter provides an analytic solution (for linear Gaussian models) to the CPHD equations and describes the density of the object space as a weighted sum of Gaussian distributions [4, 6]. For the space-object tracking problem, Fig. 4 conceptually illustrates the object density function generated by the GM-CPHD to describe the object space. In the figure, each Gaussian component (mean and covariance) represents a possible object, and the CPHD weight (not depicted) describes the likelihood of its existence. A weight of unity identifies a confirmed object, while a weight of nearly zero indicates it is likely a false detection (possibly resulting from sensor clutter). Although this illustration of the GM-CPHD depicts a Gaussian distribution for each object's state, non-Gaussian states may be considered [6, 7].

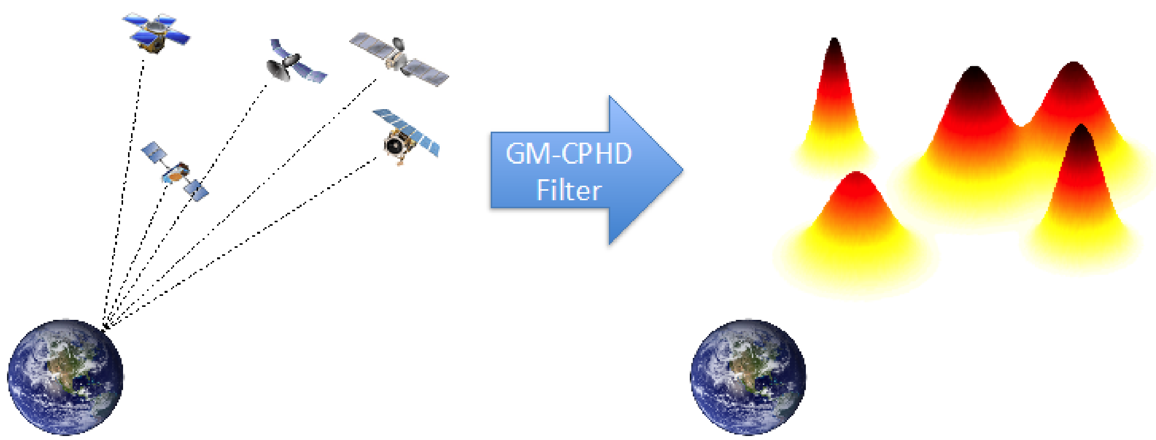

Fig. 4. GM-CPHD filter estimates a multi-target density function

In a synergistic research effort, CU and Orbit Logic demonstrated the use of the CPHD solution for computing the information gain for a proposed measurement scan. This included the quantification of the effect of a sensor scan on both the multi-object and single-object states, which allows for ranking candidate observation opportunities. In the case of multi-object information gain, the metric provides information on both serendipitous collects (multiple objects in the field of view), elimination of unlikely components in the object density function, and can account for probability of detection. The original Track Prioritization Tools (TPT) code was implemented in the Python scripting language [8].

CU and Orbit Logic ported the original Python-based Track Prioritization Tools (TPT) to C/C++. Where possible, a modular software design approach was employed to allow for future parallelization. For example, propagation of the Gaussian mixture components in the multi-object state can be performed in parallel. Other enhancements have been completed as well, including an implementation of the information gain (IG) calculation using the multi-object state. This new version improves accuracy and computational efficiency when multiple objects are in the field of view

The Track Prioritization Component is called by STK Scheduler and CPAW after observation opportunities have been computed for space objects and search areas in order to generate Information Gain and Probability of Detection values (for space objects) and Predicted Object Density values (for search areas) for each observation opportunity. These computed values are some of the parameters used in the SSA-specific Figure-of-Merit (described in the next section) to score observation opportunities for algorithm optimization in the generation of observation schedules.

SSA-specific Figure-Of-Merit

Heimdall Web makes use of an SSA-specific Figure-of-Merit (FOM). The SSA FOM scores each observation opportunity based on inputs (such as predicted Information Gain) from the Task Prioritization component and other factors (such as computed object visual magnitude), time since last observation, orbit covariance, anomalous behavior rating, and more.

Each factor has an associated configurable weighting attribute to specify the importance of the FOM factor relative to other FOM factors. Weighting attributes may be set to any value, including 0 (ignored) and negative (penalty) values, allowing for virtually unlimited tuning of the scoring FOM.

Additionally, the FOM is split into object factors and search area factors (as well as common factors that apply to both), and the scores for objects and searches are normalized against each other. Lastly, configurable weighting factors allow for the importance of object observations vs. searches for new objects to be defined.

The SSA FOM is tightly coupled within the SSA versions of STK Scheduler and CPAW. All observation opportunities are automatically scored using the configured SSA FOM as part of the standard processing flow in both software tools. The FOM for CPAW (space sensors) and STK Scheduler (ground sensors) are separate, allowing for different configuration/factor weighting values for each.

In a future version of the architecture the SSA-specific FOM will also be made available via web interface for optional use by Tasked and Contributing sensors for their own local schedule optimization.

Scheduling/Tasking Algorithm

One of the core features of the Heimdall solution is the ability to generate coordinated, optimized observation schedules for the full set of available ground and space-based sensors for SSA observations. Ground sensor observation scheduling is performed by STK Scheduler scheduling algorithms, while space-based sensor observations are scheduled by CPAW scheduling algorithms. Coordination between ground and space sensor planning is performed through process flow control by the Heimdall Web App, and the availability of observation fulfillment status through the shared Object Catalog database.

STK Scheduler provides multiple scheduling algorithms as well as an algorithm builder tool to define refined algorithms for specific needs. Algorithm options include Greedy, Neural, Random, Squeaky Wheel, Genetic, and others. In the SSA configuration, algorithms are fed the list of SSA FOM-scored observation opportunities and use that list as the basis for generating a high value, valid, deconflicted, coordinated observation schedule for all available ground sensors. The Heimdall Web App calls the STK Scheduler algorithms using an available STK Scheduler STK Connect command via its TCP/IP API with string keyword-value pairs. The specific algorithm may be configured within the Heimdall Web App, but an option also exists to call an algorithm-builder-defined custom combination algorithm that computes solutions using multiple algorithms and returns the highest FOM-scoring solution. Earlier versions of the STK Scheduler algorithms were successfully demonstrated to JSpOC personnel as part of the SSA Software Suite from Analytical Graphics for a large scale SSN sensor tasking problem (10,000 objects, 24 hour schedule, 30 sensors), with optimized observation schedule solution time under 2 minutes.

CPAW, the component responsible for space sensor planning, has a similar set of algorithms for tasking schedule generation. Multiple algorithms are fed the SSA FOM-scored observation opportunities and iterated with high fidelity space sensor models to generate a high value, valid, deconflicted, coordinated observation schedule for all available space-based sensors. The nine available CPAW algorithms may be configured on or off via the Heimdall Web API, with the algorithm solution from the highest SSA FOM-scoring plan returned. CPAW scheduling algorithms are called via the available CPAW API using command strings delivered via TCP/IP interface. Scheduling results are saved directly to the Heimdall Object Catalog database, associated with applicable objects.

The Heimdall Web App controls the order of calls to CPAW and STK Scheduler for ground sensor and space sensor observation schedule generation, respectively, in order to create a coordinated observation plan across all available space and ground sensors. Fulfillment status based on planned observations is stored in the Heimdall Object Catalog database to support this coordination.

In a future version of the architecture the CPAW and STK observation schedule generation algorithms will also be made available for optional use by Tasked and Contributing sensors for their own local sensor scheduling via web interface.

4. OPERATIONS CONCEPT

In this section, we describe how the Heimdall Web architecture is applied to the target operational system, consisting of the JSpOC's traditional SSN sensors and a growing collection of non-traditional sensor sites.

Planning Cycles

The regular (nominal) planning cycle will be initiated on the public side of the Heimdall Web architecture by computing observation opportunities for all objects in the public catalog for all participating non-traditional sensors (commercial, academic, amateur). The public catalog is drawn from space-track.org and may be supplemented with additional objects and events from the JMS side. These opportunities will drive the generation of candidate observation tasks and the scoring of each observation opportunity by the Task Prioritization component (which computes predicted Information Gain and other attributes) and the overall SSA Figure of Merit.

After scoring, the scheduling and tasking algorithm component generates deconflicted score-driven optimized observation schedules (for Scheduled Sensors) and task lists (for Tasked Sensors). A desired observation list is then generated for non-traditional Contributing Sensors. This desired observation list is based on the current public catalog and planned observations.

On the government side of the system, observation schedules, tasking lists, and desired observation lists are generated by the JMS-side Heimdall app and made available to SSN sensors via the existing service flow. Feedback and observation data from the non-traditional sensors on the public side of the system are fed into the processing function within the JSpOC as it becomes available, and is used for object detection, characterization, and orbit maintenance.

Non-traditional data and observation schedules will help inform the planning process, allowing SSN sensors to focus on necessary observations for critical objects and events when non-traditional sensors have not provided sufficient data. The repeat cycle for planning may be configured to any desired frequency. Fig. 5 shows the planning cycle for SSN and non-SSN sensors and how they interact.

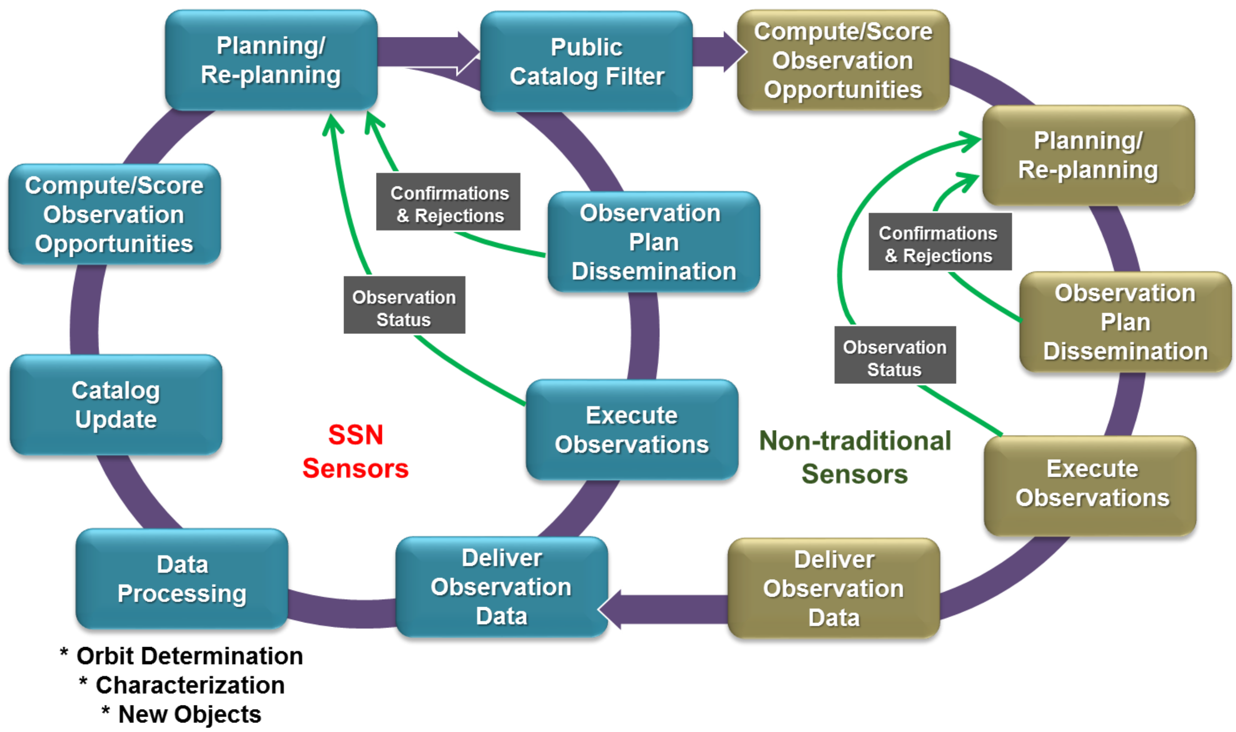

Fig. 5. Heimdall SSA Planning Cycle Diagram

Contributing and Tasked sensors will be offered access to the Heimdall scheduling algorithms and configurable SSA FOM (via SOA implementation on the JMS side and via web interface on the commercial side) to assist them in generating their own independent sensor observation schedules, as shown in the planning cycle above.

Ad-hoc Planning

In addition to the nominal regular planning cycle, the performance of the algorithms included in the Heimdall Web system allows for responsive off-nominal rescheduling and re-tasking based on ad-hoc (unanticipated) events (new object detection, detected object activity changes, etc.), unexpected sensor downtime, scheduled observation failures, and more, as indicated in the planning cycle diagram above. Configurable thresholds will be available to the JSpOC operators to define when rescheduling and re-tasking should be automatically kicked off by the system. Of course the JSpOC will always have the option to manually reschedule/re-task SSN and/or non-SSN sensors at any time.

It should be noted that manual intervention or participation is **not** required in this Concept of Operations (CONOPS). Insight for operators is provided by the various software components, as are GUI controls for manual intervention or guidance and reconfiguration, but after initial setup, the system can (and likely should, to gain the advantage of fast response times) run in a "lights-out" mode in most situations.

Sensor Participation Levels

One of the key elements of the Heimdall Web approach is the ability to work with sensors at varying levels of participation. Three levels of participation are defined in the operations concept:

- ***"Scheduled"*** - sensors accept full tasking control and follow detailed observation schedules provided by the JSpOC. These are also known as "Dedicated" sensors.
- ***"Tasked"*** - sensors accept prioritized tasking lists from the JSpOC, but perform their own observation opportunity computations and local scheduling. These are also known as "Collateral" sensors.
- ***"Contributing"*** - sensors are authorized to review a "prioritized observation list" on the Heimdall website, and choose which observations they are willing to contribute.

It is important to note that all three sensor participation levels may be present on the SSN and non-SSN side of the system. The configured participation level for a sensor will determine if they receive an optimized, deconflicted observation schedule, list of objects to track, or simply online access to the desired observations list from the central scheduling component. Note that Contributing and Tasked sensors will have online access to Heimdall scheduling tools to assist them in generating observation schedules for their sensors, if desired. The participation level of any sensor may be modified at any time by an authorized user.

Scheduled and Tasked sensors are more committed assets (through organizational commitments or contractual mechanisms), and can include government, amateur, academic, or commercial sensors and sensor networks. Examples of sensor networks include the SSN (government), Falcon Telescope Network (Academic), and the ComSpOC® (commercial). Individual sensors (amateur or otherwise) could also be authorized to make contributions, and it is likely that this kind of "crowd sourcing" of SSA observations could be a powerful new data source. The scalability of the Heimdal Web architecture easily supports this business model.

Feedback from Scheduled and Tasked sensors (acceptance/rejection of tasking and observation success/failure), and notifications of observations made by Contributing sensors provides inputs for the next regular planning cycle and/or the automated initiation of re-planning based on configurable thresholds.

Catalog Maintenance

The JSpOC maintains the master space object catalog within the JMS architecture. The Heimdall Web system will pull selected information from that catalog to use for the purposes of tasking and scheduling through the JMS translation component, and will refresh its data from the catalog for every nominal and off-nominal scheduling/tasking run and to maintain its "desired observations list".

It is anticipated that the public Heimdall Web application will not update its own catalog based on observation data, but rather pass that data back to the JMS side of the system for processing and catalog updates. All catalog inputs to the public Heimdall Web application will come from the JMS/JSpOC catalog via the Filter component.

Sensor Feedback

Regardless of the level of participation of the specific sensor, the Heimdall Web architecture provides the interfaces for sensors to provide information back to the central system. Sensor-provided information can include downtime (for maintenance or other reasons), the status of scheduled or tasked observations, a list of contributed observations, as well as observation data (via the Data Portal component). These interfaces are designed to directly address several of the performance factors impacting efficient operation of the SSN today, enabling sensor feedback and allowing the overall system to respond immediately to new information as needed.

Sensor-contributed data may be shared or protected as configured by the sensor and/or JSpOC personnel, allowing for any desired level of openness and collaboration or data protection. Any relevant sensor-provided information (like expected downtime and observation status) will be used to help optimize the tasking and scheduling of available sensors.

Access Management

Access management consists of layers of configurable privileges that are used in parallel to control each user's abilities in the system as follows: Permission Sets – control functionality available to a user at a high level. Data Sets – specify which data the user can access. View Modes – define which fields and buttons the user can access. User management combines basic user profile information with security and access management for each user. Each user is registered with an e-mail address, password, View Mode, Permission Set, and one or more Data Sets. User accounts can either be registered by an administrator or requested by a user. Within the Heimdall web application JSpOC users with administrative-level permissions will define and configure the permissions for users.

Configuration and Maintenance

The Heimdall web application will be hosted and maintained at the JSpOC and will be configurable (by authorized admin-level users) to add, edit, and delete SSN and non-SSN sensors as they become available for scheduling and/or tasking. Details of the sensor's location, horizon mask, field of view, slew rate, phenomenology, and observation capabilities will be configured via GUI forms. JSpOC administrators may also authorize external organizations to log in, add, configure, and maintain their own sensors within the Heimdall web application, if desired. In addition to the definition and configuration of available sensors within the application, authorized personnel may define and configure new users, configure Figure-of-Merit weighting values, adjust performance goals, and specify other software settings such as the nominal planning schedule, event thresholds for re-planning, and filters for object catalog lists for different sensor participation levels.

5. DEMONSTRATION OF CAPABILITIES AND RESULTS

Performance Goals

This Heimdall Web tool research and development effort has resulted in a Tasking and scheduling capability to enable truly responsive and automated sensor re-tasking at the cadences required to respond to dynamic object catalog events, sensor status, or changing mission goals and priorities. The software architecture being developed, when integrated, is intended to allow the network of SSN and non-SSN sensors to perform well against a set of Key Performance Parameters (KPPs) quantifying the performance goals of the desired future system. These include:

a) Time from central tasking to acknowledgment of receipt (Goal: <1 hour)
b) Percent of accepted taskings successfully performed (Goal: >95 percent)
c) Time from collect to data delivery (Goal: <1 hour)
d) Time from missed collect to report (Goal: <1 hour)
e) Time from site outage or tasking conflict to central alert (Goal: <30 minutes)
f) Time from alert of site outage to redistribution of tasking to remaining sites (Goal <30 minutes)
g) Given a set number of sites and a number of Earth orbiting objects, average max axes of position error (Goal: <15 km) while maintaining a specified revisit rate on a subset of objects

Our initial demonstration of capability (described in the next section) was crafted to verify interoperability between key components of the architecture in a relevant network setting, as well as beginning to establish a baseline within which the previously listed KPPs could be measured and tracked. As we progress in our development and ultimately integrate with the operational system, we expect to exceed these metrics.

Heimdall Web Non-Traditional Sensor Tasking Demonstration

A demonstration using the prototype Heimdall Web App software for non-traditional sensor tasking was performed to validate software operation, computations, component interfaces, external interfaces, and the ops concept workflow.

The ComSpOC® (a commercial SSA sensor network set up by Analytical Graphics, Inc.) and the Falcon Telescope Network (an academic sensor network led by the U.S. Force Academy) each agreed to offer a sensor for limited use in the demonstration. Sensor data (including location, minimum elevation angle for observations, minimum orbit altitude for observations, maximum object visual magnitude, sensor setup time, and day/night observing capabilities) was provided to allow Orbit Logic engineers to define and configure their sensors via the Heimdall Web App UI.

- ComSpOC® sensor: 1093
- FTN sensor: Falcon OJC

Two observation objects were selected and defined in the Heimdall Web App object catalog manually by Orbit Logic engineers, with the latest orbit data pulled from spacetrack.org:

- "NAVSTAR 70" GPS navigation satellite (MEO (Medium Earth Orbiting), NORAD (North American Aerospace Defense Command) ID 39741)
- "INTELSAT 16" commercial communications satellite (GEO (Geostationary), NORAD ID 36397)

A date (January 7, 2016) was selected and agreed upon by Orbit Logic and representatives of the ComSpOC® and Falcon Telescope Network. Prior to January 7th, 2 dry-runs were conducted to verify software functionality and interfaces to the ComSpOC® and FTN sensor operators. Note that all interactions are via email notification and Heimdall Web App user interface, so no special software was required on the sensor operator side to connect to the Heimdall Web tasking system (just an internet connection, email application, and web browser). The following is a summary of the live-fire test that included actual observation attempts by ComSpOC® and FTN sensors on the evening of January 7th, 2016:

- Inspection of sensor definition via Heimdall Web App user interface (manual)
- Definition and inspection of demo tasking object catalog (manual)
- Initiation of sensor tasking process via Heimdall Web App user interface (manual)
- Computation of sensor observation opportunities (auto)
- Track prioritization of sample object catalog observation opportunities (auto)
- Sensor observation scheduling for optical sensors (auto)
- Inspection of scheduled and tasked sensors and desired observation list (manual)
- Transmission of an observation schedule to the ComSpOC® and FTN (auto)
- Confirmation of sensor tasking acceptance by ComSpOC® and FTN (manual)
- Observation attempts by ComSpOC® commercial sensor and FTN academic sensor
- Confirmation of observations via Heimdall Web App (manual)
- Delivery of observation data to a secure fileshare via Heimdall Web App (manual)
- Process monitoring by an operator logged into Heimdall web app (manual)

Due to adverse weather conditions at both sites on the night of the test, no meaningful supportive observation data was collected by the sensors. Nonetheless the testing was completely successful in its intent, which was the verification of all data pathways between the key modular elements of the Heimdall Web architecture.

6. CONCLUSIONS

The research and development of the Heimdall Web architecture, currently progressing in maturity via ongoing contracts, has already validated several premises derived from the original concept.

The first is that the concept of a web application to integrate multiple computation engines for the generation of valid tasking schedules for SSA sensors has been proven to be technically feasible. We have, through trials involving configurations representative of the SSN sensors and the JSpOC catalog, shown that our scheduling engine is capable of rapidly producing verifiably correct tasking that should dramatically enhance SSA.

The second is confirmation that an appropriately-designed web application can be used to coordinate the tasking of geographically and organizationally diverse non-traditional sensors. This was proved-out in our dry-fire field test, which showed unequivocally that the web-based Heimdall components could effectively orchestrate the tasking and status monitoring of two sites.

Finally, we confirmed that an appropriately-designed web application can be used as a portal for sensor operators to obtain tasking data, provide feedback on tasking requests, and deliver observation data. This is a key and necessary feature of the final Heimdall Web solution – one that allows system operators to maintain an effective real-time view of the dynamic space environment as it becomes more congested and contested.

7. REFERENCES

1. Blake, Travis, Michael Sanchez and Mark Bolden, “OrbitOutlook: Data-centric Competition Based Space Domain Awareness (SDA)”, 30th Space Symposium, Colorado Springs, CO, 2016.
2. Alex Herz, Brandon Jones, Ella Herz, Dough George, Penina Axelrad, Steve Gehly, *“Heimdall System for MSSS Sensor Tasking,”* Proceedings of the 2014 Advanced Maui Optical and Space Surveillance Technologies Conference, Naui, Hawaii, 2015.
3. Donald B. Reid, “An Algorithm for Tracking Multiple Targets,” *IEEE Transactions on Automatic Control*, AC-24(6):843-854, 1979.
4. Ronald P.S. Mahler, **Statistical Multisource-Multitarget Information Fusion**, Artech House, Boston, Massachusetts, 2007.

5. Brandon A. Jones, Steven Gehly, and Penina Axelrad, "Measurement-based birth model for a space object cardinalized probability hypothesis density filter," *AIAA/AAS Astrodynamics Specialist Conference*, San Diego, CA, August 2014.
6. Brandon A. Jones and Ba-Ngu Vo, "A Labeled Multi-Bernoulli Filter for Space Object Tracking," AAS 15-413, *AAS/AIAA Spaceflight Mechanics Meeting*, Williamsburg, VA, 2015.
7. Ba-Tuong Vo, Ba-Ngu Vo, and Antonio Cantoni, "Analytic implementations of the cardinalized probability hypothesis density filter," 55(7):3553-3567, *IEEE Transactions on Signal Processing*, 2007.
8. Steven Gehly, Brandon A. Jones, and Penina Axelrad, "An AEGIS-CPHD Filter to Maintain Custody of GEO Space Objects with Limited Tracking Data", *Proceedings of the 2014 Advanced Maui Optical and Space Surveillance Technologies Conference*, Maui, Hawaii, 2014.
9. Gehly, S., B. Jones, and P. Axelrad, "A Sensor Allocation Scheme for Tracking Geosynchronous Space Objects," Accepted to *AIAA Journal of Guidance, Control, and Dynamics,* May 2016.