

Non-traditional Sensor Tasking for SSA: A Case Study

Alex Herz, Ella Herz, Kenneth Center, Isabel Martinez, Nick Favero

Orbit Logic, Greenbelt, Maryland

Clinton Clark, William Therien, Mark W. Jeffries, Jr.

ExoAnalytic, Mission Viejo, California

ABSTRACT

Industry has recognized that maintaining SSA of the orbital environment going forward is too challenging for the government alone. Consequently there are a significant number of commercial activities in various stages of development standing-up novel sensors and sensor networks to assist in SSA gathering and dissemination. Use of these systems will allow government and military operators to focus on the most sensitive space control issues while allocating routine or lower priority data gathering responsibility to the commercial side.

The fact that there will be multiple (perhaps many) commercial sensor capabilities available in this new operational model begets a common access solution. Absent a central access point to assert data needs, optimized use of all commercial sensor resources is not possible and the opportunity for coordinated collections satisfying overarching SSA-elevating objectives is lost.

Orbit Logic is maturing its Heimdall Web system - an architecture facilitating “data requestor” perspectives (allowing government operations centers to assert SSA data gathering objectives) and “sensor operator” perspectives (through which multiple sensors of varying phenomenology and capability are integrated via machine-machine interfaces). When requestors submit their needs, Heimdall’s planning engine determines tasking schedules across all sensors, optimizing their use via an SSA-specific figure-of-merit.

ExoAnalytic was a key partner in refining the sensor operator interfaces, working with Orbit Logic through specific details of sensor tasking schedule delivery and the return of observation data. Scant preparation on both sides preceded several integration exercises (walk-then-run style), which culminated in successful demonstration of the ability to supply optimized schedules for routine public catalog data collection – then adapt sensor tasking schedules in real-time upon receipt of urgent data collection requests.

This paper will provide a narrative of the joint integration process - detailing decision points, compromises, and results obtained on the road toward a set of interoperability standards for commercial sensor accommodation.

1. BACKGROUND

With the emergence of commercial sensor systems like ExoAnalytic’s Global Telescope Network, there exists an opportunity to overlay such tasking and observational data enterprises with a globally-reachable web-based “front-end” to accept the desired SSA informational needs of multiple users, then determine overarching optimized tasking plans utilizing all participating sensor systems to perform the observations and deliver back the resulting data on highly responsive timelines.

Orbit Logic’s Heimdall Web solution was developed to enable access to existing COTS planning capabilities through web-based user interfaces. The ability to access enabling software solutions from web browsers at client sites anywhere in the world is an operational model that has become not just commonplace but necessary in the age of “cloud-based computing technology”.

Heimdall Web’s capabilities have been evolving incrementally. The initial prototype included the ability to administer the web server (by creating accounts and define permissions), configure sensors with flexible web entry forms, generate observation schedules for registered sensors, supply tasking requests to the operators of those sensors by auto-generated emails, then allow the sensor operators to accomplish the data collection activities using their native processes. Acceptance or rejection of the requests, status of the observation activity, and return of the data product were all accomplished using links embedded in the original tasking email. These links directly access

service endpoints of the Heimdall Web server, allowing the “reach-out” for use of the sensors to occur without any human intervention on the Orbit Logic side.

Implementing this initial solution had the advantages of facilitating generic integration with any sensor operator, regardless of the complexity of their systems, the details of their internal processes, or their data formats. The downside to this approach are the latencies introduced by the human operator (e.g. checking email, translating information between the email request and the operator’s system, etc.). Those temporal penalties amplify as the volume of tasking requests scales. At some point, human workload limitations significantly interfere with the ability of the Heimdall Web solution to utilize any given sensor operations process to its full capacity.

Heimdall Web, from its conception, was designed to enable completely automated interactions – including interactions with automation processes at sensor operations sites. Working with ExoAnalytic provided us with the opportunity to realize that paradigm, by first working out the details of those machine-to-machine interactions and then verifying the proper exchange of information between them.

Initial Heimdall Web focus was exclusively on the interaction between the core planning and scheduling engine and sensor operation sites. Missing was the ability to meet the needs of another user community – those interested in specifying the data gathering objectives for the Heimdall system... Preliminary capabilities had been put in place to specify the space objects to be considered for tasking, but that needed to be built-out and formalized as a completely new family of web-accessible user interfaces. Completing that work would result in a Heimdall “Requestor’s Perspective” allowing users interested only in the “end-results” of the SSA process chain to acquire that information without the need for any insight into the (potentially many) sensor systems usable to achieve it.

2. TECHNOLOGY OVERVIEW

Heimdall Web

Orbit Logic’s *Heimdall Web* solution architecture and ops concept provides a modern, centralized, and scalable solution to coordinate and optimize the use of sensor assets by configuring them for contribution at various levels, and by providing the tools to control the prioritization of observation opportunities when generating optimized tasking schedules [1]. With these characteristics Heimdall affords responsive, information-based tasking and scheduling of heterogeneous sensor networks (systems of systems in fact) that vary not only in sensor capabilities and location, but also by their participation and classification levels. By providing feedback interfaces from the sensor sites and a common platform, the authorized sharing of information between sites is enabled for better overall cooperation and for responsive reallocation and tasking by the central planning and tasking component.

Heimdall Web combines the Heimdall scheduling engine with web-based User Interfaces (UI) in a novel split architecture, as depicted in Figure 1 [2]. Traditional (classified) SSN sensors require their own schedule optimization. One classified instance of Heimdall can be applied to this problem. A parallel instance of Heimdall (indicated within the yellow-dashed box on the right side of the graphic) can manage the growing commercial (unclassified) sensor market. The commercial-side of this split architecture has received a significant level of development activity in the past year with a focus on integration strategies with various commercial sensor operators and the build-out of new features to support the specification of desired tasking. Note that in the diagram the two sides of the Heimdall split architecture converge at two points; 1) designating targets in the public catalog to be handled by the commercial side in order to “offload” the SSN for high-priority activities, and 2) supplying all commercial-side observation data to the classified side to “inform” the SSN. The original use case for the figure’s upper data flow (from the “traditional” side of the architecture to the “commercial” side) is to acquire the orbits of all operational unclassified satellites from the public catalog (Spacetrack.org), and use all of the commercial sensor systems integrated with the commercial instantiation of Heimdall to optimize a schedule over all of them (accounting for access, observability, sensor capabilities, sensor site status, weather, and other space-object-oriented characteristics related to maximizing SSA information gain). Because Heimdall Web provides sensor operators with a means pushing the data resulting from observation activities to its database, the complete set of data related to this “nominal” or “background” scheduling activity is available to the traditional side via the information delivery channel at the bottom of the diagram.

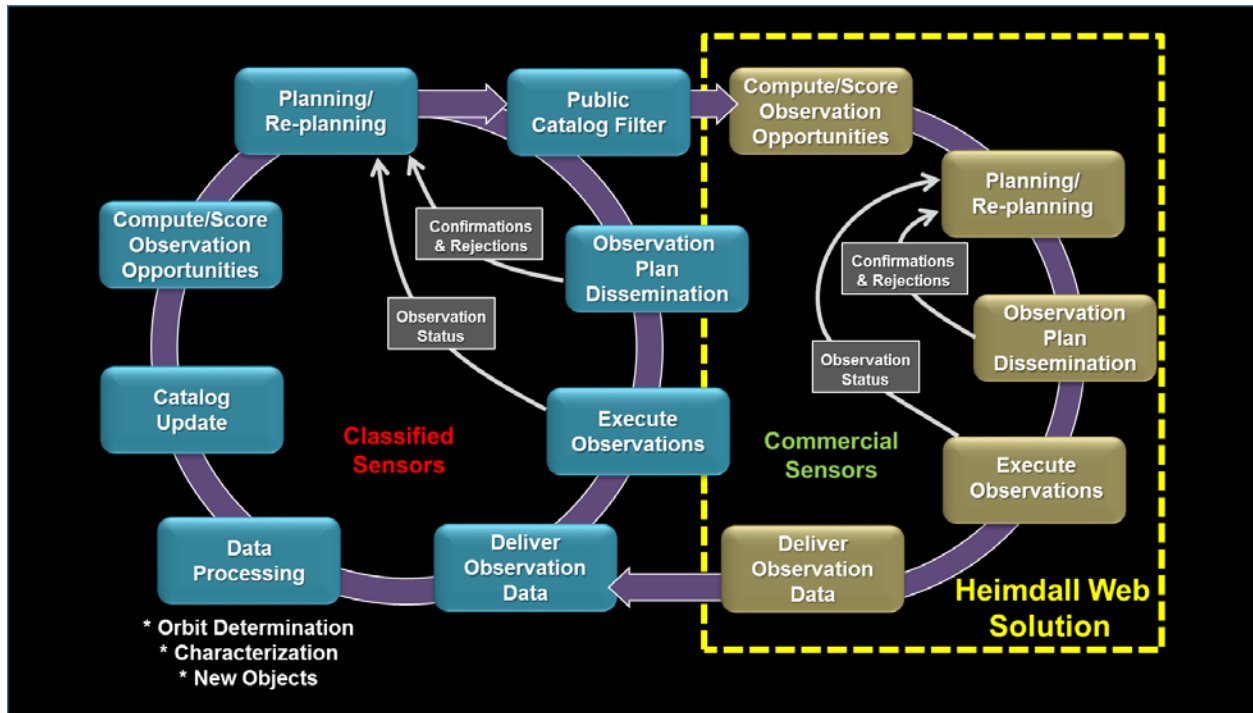


Fig. 1. Heimdall System Architecture Diagram

This nominal use case for interaction between the traditional and commercial sides of the Heimdall split architecture enables the traditional side to be more “aware” of the states of public catalog objects and adjust its observation activities accordingly, but it does not allow the traditional side to specify which objects may be more important to monitor and how they should be serviced. Meeting this new use case was the motivation for the development activities described in this paper, including a “Requestor’s Perspective” accessible by a new collection of web pages.

Verifying that a commercial sensor network could be used to realize these requestor-provided directives was accomplished by collaborating with ExoAnalytic, with whom we worked closely to arrive at the sensor tasking and observation data return associated with these new requestor-oriented features.

ExoAnalytic Global Telescope Network

ExoAnalytic Solutions operates a global commercial SSA telescope network producing a large quantity of high-quality, real-time correlated observations of man-made space objects in near-geosynchronous Earth (near-GEO), highly elliptical (HEO), and medium Earth (MEO) orbits. The current observatory footprint and the planned sites for 2017 are shown in Figure 2. The ExoAnalytic Global Telescope Network (EGTN) currently consists of 20+ automated observatories with 160+ sensors on five continents (Africa, Australia, Europe, North America, and South America) and Hawaii. By the end of 2017, we expect to have approximately 200 sensors in our network.



Figure 2: ExoAnalytic Global Sensor Network Footprint

The ExoAnalytic network is powered by the ExoAnalytic Space Operations Center (ESpOC) software suite. The ESpOC command center enables remote command and control of all EGTN sensors, automatically integrates and fuses data from multiple sensors in real-time, and overlays all collected data in real-time on a full-sky common operational picture. EGTN observatories have a variety of configurations ranging from 1 to 15 telescopes as well as the supporting computer systems. Image processing and data reduction are performed at the sensors in real-time by the local ESpOC operating system. All EGTN telescopes are owned, operated, and tasked by ExoAnalytic.

Each EGTN observatory ExoAnalytic collects angles-only astrometric measurements (RA and DEC) and photometric measurements (visual magnitude). The EGTN collects, processes, and disseminates real-time observations with data Quality of Service (QoS) that meets the following performance metrics:

- 100% global coverage of GEO, HEO, MEO orbits
- Provide detections with astrometric error between 0.1-0.5 arcseconds
- Provide detections of objects as dim as 18.5 visual magnitude (Vmag)
- Provide detections with timing precision less than 10 milliseconds
- Performance of routine calibration, reporting of sensor and noise bias

3. ENHANCING HEIMDALL TO SUPPORT SSA DATA REQUESTORS

Previous verification of Heimdall Web’s capabilities has been conducted with the US Air Force Academy and with Analytical Graphics, Inc. using the Falcon Telescope Network (FTN) and AGI’s COMSPOC sensors, respectively [1]. These activities utilized Heimdall Web’s default email-based tasking notification capability and links embedded in these emails to push status and data back to the Heimdall server. Multiple successful rehearsals and “live fire” exercises demonstrated the ability to create optimized tasking schedules utilizing both FTN and COMSPOC sensors and push the resulting data to Heimdall’s database. These interactions are indicated in the upper-right of Figure 3.

When these activities were conducted, the engine behind the “Heimdall Web App” (grey box in the figure) facilitated the selection of the objects of interest (from the public catalog), and then the initiation of the scheduling activity (utilizing visibility computations, track prioritization techniques and application of an SSA-specific figure of merit). The resulting schedule was broken into sub-schedules (by sensor operator), and separate transactions with the two participants were orchestrated by Heimdall Web’s automation processes. While those sensor tasking-related jobs were being handled, full visibility into their progress could be monitored via administrative web pages. While insight into these activities was invaluable to the Heimdall system administrators, the views provided were very much focused on system verification.

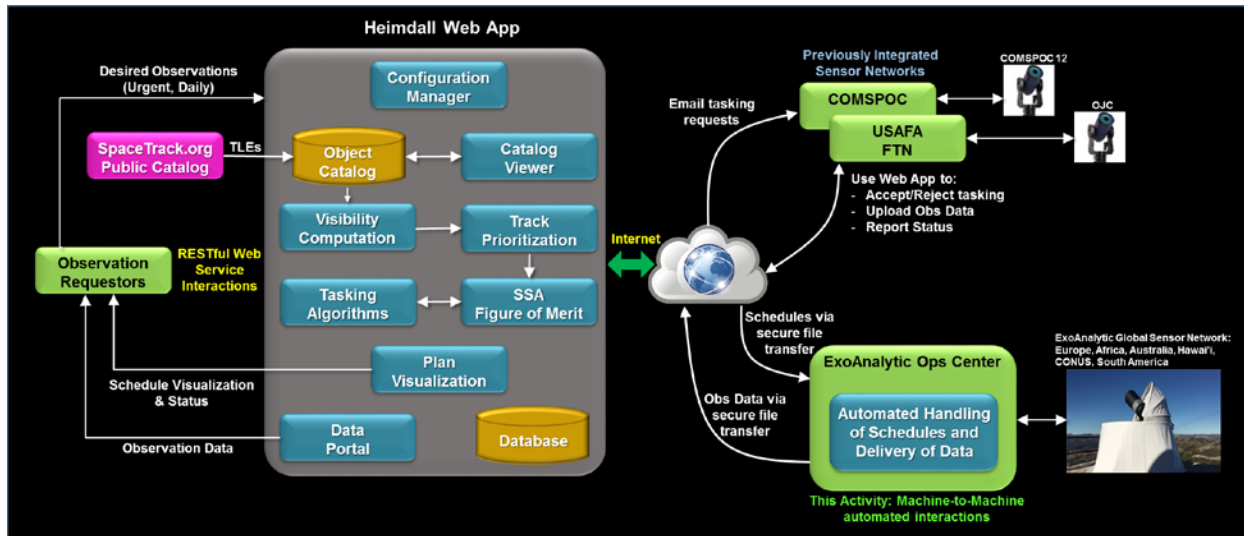


Fig. 3. Heimdall Web App and External Functional Interconnects

What the Heimdall Web system used for initial system verification exercises lacked were features that would allow an external user (not a Heimdall administrator) to assert SSA objects of interest, manage their status, and gain access to the data resulting from their servicing. This user group is distinct from the users that constitute the sensor operators (who accept tasking schedule and return observation data), and from the administrators (who maintain the integrity of the system-level enterprise solution). This category of users are “Requestors”, and they are the true end users of the Heimdall solution.

Focusing on providing enabling capabilities for requestors meant addressing several areas. Most importantly, requestors need a means of indicating their SSA monitoring priorities – “what objects am I particularly interested in” (more so than the average public catalog object), and “which objects are of significant interest” (information needed as soon as it can be acquired). Offering the ability to have a requestor specify these monitoring desires resulted in the realization that three categories of objects should be maintained in the Heimdall Object Catalog:

Daily Objects – Objects of regular interest to a given requestor, maintained in a list that is guaranteed to be satisfied by observations in every regular Heimdall planning window (nominally 24 hours).

Background Objects – All active unclassified satellites included in the public catalog (as available from SpaceTrack.org). These objects are considered by the Heimdall scheduling engine at the lowest priority – best effort is made to accommodate them within the sensors available and within current constraints.

Urgent Objects – Objects of high interest, especially in need of immediate servicing. Accommodation of urgent objects is given priority over both daily and background objects.

Providing the requestor with the ability to specify daily and urgent objects (and the desired tasking characteristics associated with those objects) necessitated both accommodating the notion of tasking categories into the Heimdall architecture and developing web pages to specify and manage them. The left side of Figure 3 indicates these areas of new development, including the specification by the requestor of desired observation activity, visualization of the planned satisfaction of those observations, tracking of the status of their tasks, and the view/retrieval of the resulting data once it has been delivered to the Heimdall databases.

If a requestor desires the servicing of objects they deem to be urgent in nature, the implication is that the data resulting from those requests needs to be acquired and delivered back in extremely short timeframes. Discussions with potential users of the Heimdall “Requestor Perspective” indicated the desire for these timelines to be “as quickly as the inherent system pacing temporal items will permit.” This objective seems hopelessly underdefined, but in fact targeting enhancement of one very specific aspect of Heimdall’s architecture would be critical in reducing

the time between a urgent request and the delivery of the resulting data – transitioning to a completely machine-to-machine exchange between Heimdall and the sensor systems handling the tasking and image processing.

To work the details of minimizing the urgent tasking timelines, Orbit Logic performed close technical work with ExoAnalytic. The result, shown in the lower right of Figure 3, was the implementation and demonstration of an interconnect strategy between the Heimdall server’s automation framework and ExoAnalytics automated tasking and data retrieval process.

Following sections will discuss the work accomplished to integrate the Heimdall solution with ExoAnalytic’s global telescope network, then exercising the resulting capability using new front-end web pages supporting the SSA Requestor’s interface.

4. INTEGRATING WITH THE EXOANALYTIC GLOBAL TELESCOPE NETWORK

A portion of integrating with ExoAnalytic’s global telescope network was straightforward, owing to Heimdall Web’s sensor configuration user interface pages. Orbit Logic worked with ExoAnalytic to identify a subset of their telescopes that would be made available for testing and demonstration activities. The set consisted of telescopes located in California, South America, and Australia. After adding ExoAnalytic as a sensor operator using the Heimdall administration pages, specific telescopes were input for use in the activity – each with its own ExoAnalytic internal designation. In addition to the locations of each telescope, their characteristics were also configured, including their slewing capabilities, field-of-view, and any site-related observing constraints. Once this data entry was complete it was possible to generate tasking schedules that made use of the ExoAnalytic sensor resources.

Next to consider was how to jointly achieve the objective of minimizing the timelines for urgent tasking requests. Heimdall Web server supports native RESTful web service interfaces that will allow a client to populate or retrieve information from the framework. In actuality this is the mechanism that is used by a web browser to interact with pages hosted by the server. One possibility was to utilize these existing interface definitions to exchange schedules, status and observation data with ExoAnalytic’s control center.

ExoAnalytic, however, already had a well-defined and highly utilized (and thus highly-trusted) process in place at their control center allowing tasking instructions to be specified for individual telescopes and the image data to be retrieved from remote telescope sites and processed (to arrive at a sequence of correlated Right-Ascension/Declination observations associated with public catalog objects).

The trade to be made spanned the dimensions of resource effort, implementation time, and risk. After brief consideration, the decision was made to work to ExoAnalytic’s native data formats. This choice was easy to make, because the Heimdall framework supports a plug-in module capability that could be leveraged to create data format translators to convert bi-directionally between formats that Exo’s process natively understood and Heimdall’s REST services. Taking this approach also relieved ExoAnalytic of any significant process modifications on their end, allowing the Orbit Logic / ExoAnalytic team to concentrate primarily on the system-level functional behaviors.

With the translation strategy agreed-to, mechanisms for data exchange between Heimdall and Exo’s control center needed to be worked. ExoAnalytic’s control center process already had the ability to receive telescope tasking files via secure file transfer protocol (SFTP). Additionally the capability existed to copy the observation data files resulting from telescope tasking into a designated location in the control center file system that was also accessible to an SFTP remote client (in this case a client hosted on Orbit Logic’s Heimdall Web server).

Given the existing capability on the ExoAnalytic side, Orbit Logic implemented automation mechanisms on the Heimdall server that could insert and retrieve the key files from their system, as shown in Figure 4. This included the delivery of tasking files for individual telescopes, and the retrieval of integrated observation data that could be related back to the original tasking.

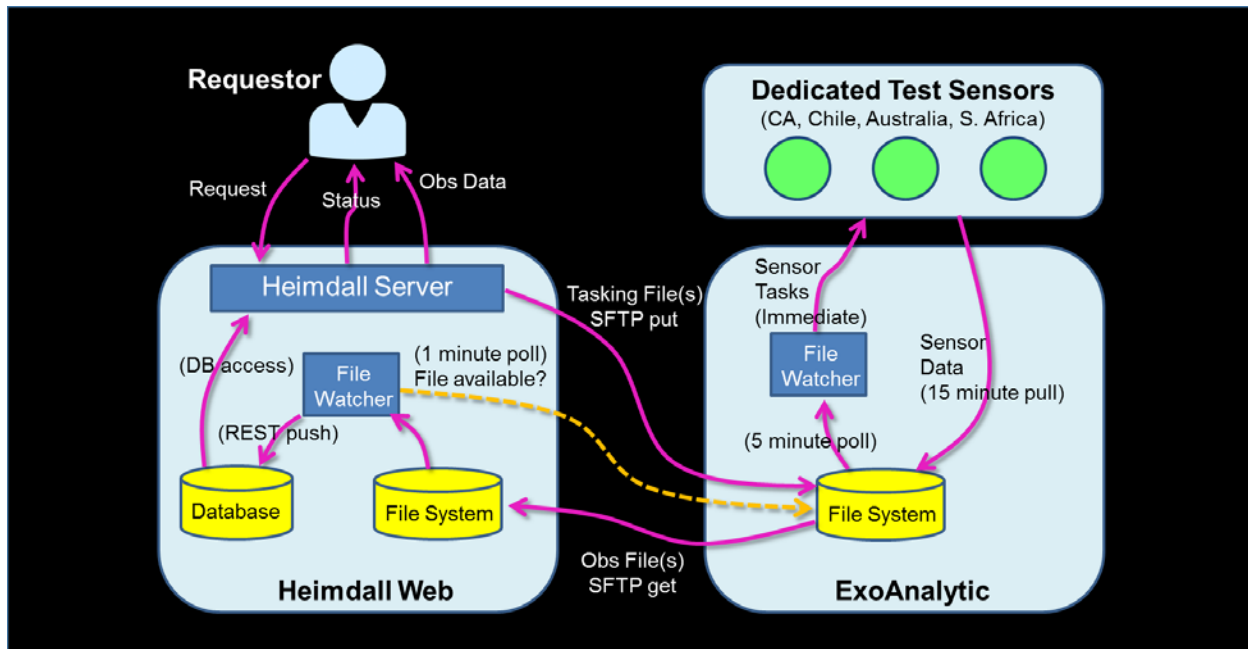


Fig. 4. Machine-to-machine automation approach

Walking through the machine-to-machine data flows of Figure 4:

- Urgent SSA requests input via web pages by the requestor result in dynamic re-planning activities by the Heimdall Scheduling engine, which may result in utilizing one or more ExoAnalytic telescopes to provide immediate observations. Telescopes already engaged in active tasking that are effected by the urgent request will require updated tasking instructions as soon as the coordinated schedule has been determined (typically in a matter of seconds). Each file must be in ExoAnalytic’s native telescope tasking format, so a Heimdall translation plug-in is utilized to create each file.
- These files are pushed to the ExoAnalytic server by SFTP transfer.
- On the ExoAnalytic side, a file watcher utility checks the incoming schedule folder every 5 minutes for new instructions. New files are processed to determine the telescope that is effected, and the file (already in the format understood by the remote telescope controller software) is immediately pushed to the telescope site, where it replaces any in-progress instructions.
- Data from remote telescopes is continuously streamed to the ExoAnalytic control center, where the raw images are processed to arrive at textual metric observation reports with association to public catalog objects. These observations are accumulated in files pushed to a “pick-up” folder area in 15 minute increments.
- A file watcher utility on the Heimdall server is also employed – to watch for available observation data files. When a new file is detected, that file is immediately retrieved with an SFTP get, then processed with a Heimdall translation plug-in to process each observation contained within the file and associate it with the original schedule task (via use of a globally unique identifier string).
- The net result of translation is to push every observation into the Heimdall database using a Heimdall-native RESTful service call, where it can subsequently be accessed by Heimdall server-hosted features (status browsing, results review, requestor download).

5. REQUESTOR PERSPECTIVE WEB VIEWS

As mentioned in section 3, one of the major undertakings of this activity was to create new capability within the Heimdall framework to support the “Requestor Perspective” – that is to enable users of Heimdall with “pure consumer” interests in SSA data end artifacts to interact with the architecture using a special collection of web pages.

The primary enhancement to the Heimdall architecture to facilitate this need was to add support for distinguishing between the categories mentioned in section 3 (*Background*, *Daily*, and *Urgent*). This merely necessitated adding

the ability to identify tasking requests as belonging to one of the three categories and including the logic in the scheduling engine to accommodate each category appropriately in periodic and ad-hoc planning cycles (e.g. adding a new daily tasking request might not significantly interrupt telescope schedules for the remainder of the periodic planning interval, but an urgent task, if it can be satisfied, most assuredly will do so immediately...).

If the following subsections, the new “Requestor Perspective” Web-based User Interface pages (WebUIs) are introduced and their roles discussed. The Requestor “role” is granted to specific Heimdall system users via access rights in the administration controls. Only users with the requestor role have access to these pages, and visibility to requestor-perspective data is protected within user groups (e.g. requestors in group A cannot see the tasking, status or data of requestors in group B).

WebUIs for Expression of SSA Data “Desirements”

A family of new WebUIs now exist in Heimdall Web to allow requestors to assert space objects that are of particular interest to them. The means by which these objects (and other influencing parameters) are expressed using the web pages is identical whether the object is requested with *Urgent* or *Daily* compartmenting. The difference is in the handling and prioritization of the request by the Heimdall orchestration logic. Consequently, the input pages for *Urgent* tasking are described here with the assurance that the input and management of *Daily* desired tasking is accomplished in a remarkably similar manner.

Access to any of the new “Requestor Perspective” pages is gained from the Heimdall Web main dashboard by top-bar menu items. A click on the “Urgent Tasking” items will take the user to a page where a new object of interest can be specified. This is accomplished in one of several supported ways:

- 1) Entering a satellite common name will search SpaceTrack.org for matches in real-time. As possible matching results are returned and displayed, the user may select the one that they recognize as their object of interest.
- 2) Entering a satellite number (NoradId)
- 3) Entering a custom object using Right Ascension and Declination (presumes knowledge of a specific object’s location at a specific time)
- 4) Entering a Latitude/Longitude-formatted location specification (same caveat as for method 3)
- 5) A Two Line Element set (TLE) specification may be input (by copying strings into a type-in field, or by using a file widget to locate and load a file from the file system of the workstation running the requestor’s web browser).

In Figure 4, the WebUI in the background is the page that allows addition of new urgent objects. The user interface design has several categories that can be expanded or collapsed to manage the level of detail being presented to the user (this helps to keep the most important details in the foreground so that a user can add information as quickly as possible in an effort to streamline the “urgent” process interactions). The first of these “categories” is the identification of the object (as mentioned in the bulleted list above).

The second category is “Observation Life Cycle”, which defines the temporal parameters of desired object access. This includes the duration over which the object will be of interest, the frequency with which observation data is desired, and the number of times (if specified) that observation data is needed.

If the requestor has detailed information on characteristics associated with the object (albedo, size, etc.), the “Observation Properties” category may be selectively populated. User-provided values will override the default values and may improve the success of observations conducted according to the planning engine’s observability computations.

An ‘Add’ of a new object results in that object being ‘staged’. This allows the WebUI user to specify several new objects, if desired. As they do this, the objects will accumulate in the staging view. When satisfied with the list, all new objects may be submitted to Heimdall’s dynamic scheduling engine simultaneously.

Once new *Urgent* objects have been submitted to the scheduling engine, they will appear in a managed list, visible as the screenshot in the foreground of Figure 5. This page provides a real-time view of each ‘order’ associated with a requestor-specified urgent activity (noting that a single activity may generate multiple orders, where each order may result in multiple object observations). With each ‘order’ entry is an indication of the sensor performing the

acquisition, the begin and end times of the observation, and the status of the order (which may be ‘Unsatisfied’, ‘Requested’, ‘In Progress’ or ‘Completed’).

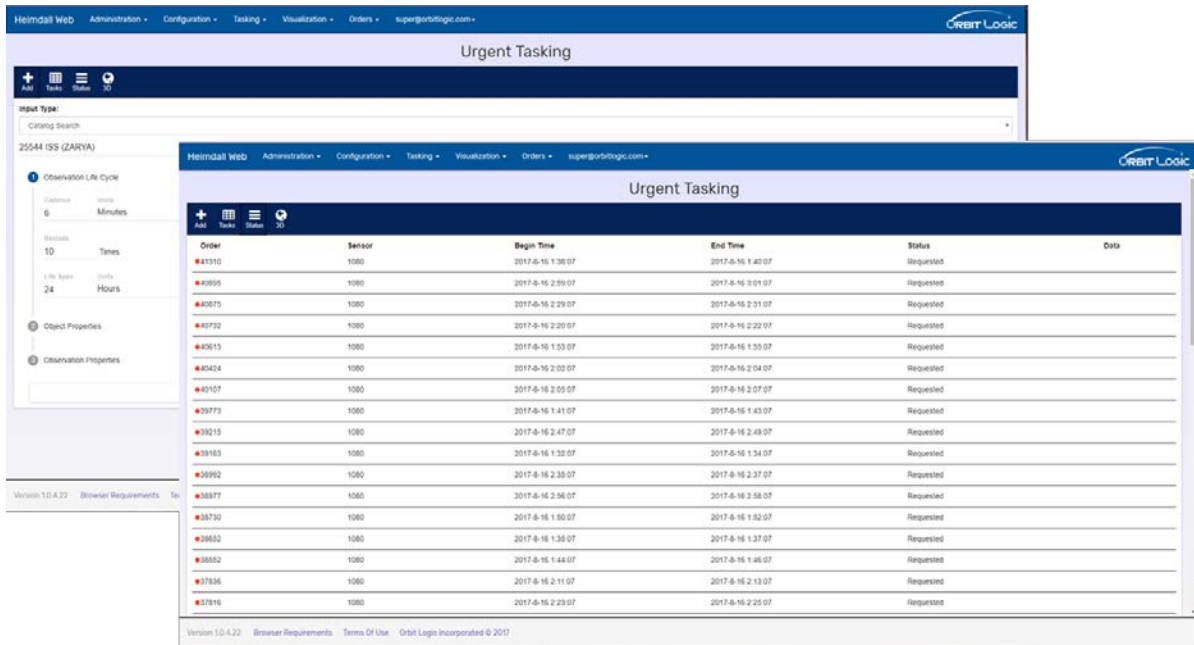


Fig. 5. Pages for Urgent Tasking Request Entry and Management

At any point, a requestor may use Heimdall Web’s Cesium™ based visualization capabilities to understand the schedules being generated and dispatched for execution. Figure 6 shows the “Tasking Status Page”, which can provide either a current or future view of task fulfillment status. Use of the controls in the 3D visualization widget allow the use to inspect the geometric relationships between tasked sensors and space objects relative to the generated tasking plan. Overall fulfillment statistics quantify the success of the plan in meeting the specified orders. Details of any specific order are available by clicking on an entry in the table on the left side. Although not shown, a Gantt view of the current sensor tasking schedule is also available in a companion page.

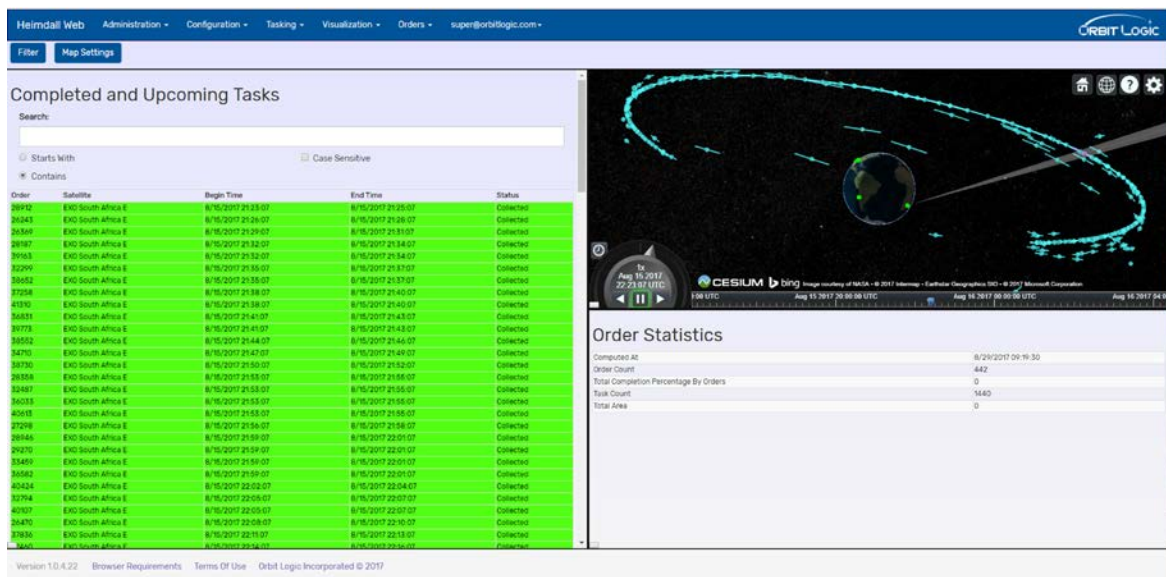


Fig. 6. Sensor Tasking Status Page

Once observation data is provided to the Heimdall by ExoAnalytic’s control center, it is parsed and pushed to the Heimdall database. On a per-order basis, this results in the status being advanced to ‘Complete’, which is visible in the summary status pages. Orders indicated as ‘Complete’ can be right-clicked and an option selected to go to the Observational Data browser page (shown in Figure 7). In this view, all of the observations associated with an Urgent request action may be browsed in a table. Download of this data to a file on the requestor’s workstation is easily accomplished by using a prominent one-click button.

Observational Data

40946-sen1150-winGround_Sensor_Window_1150_20170112_000000 eod
 30487-sen1178-winGround_Sensor_Window_1178_20170112_000000 eod
 URGENT_TASKING-38551(05)-sen1176-winGround_Sensor_Window_1176_20170120_205308 eod
 URGENT_TASKING-40141(073)-sen1178-winGround_Sensor_Window_1178_20170125_183507 eod
 41882-sen1178-winGround_Sensor_Window_1178_20170127_184500 eod
 25049-sen1178-winGround_Sensor_Window_1178_20170131_170500 eod
 25462-sen1178-winGround_Sensor_Window_1178_20170131_170500 eod
 URGENT_TASKING-40141(2)-sen1178-winGround_Sensor_Window_1178_20170131_172656 eod

DOWNLOAD

Sensor ID	Target ID	JD	Site Lat	Site Lon	Site Alt	LOS RA	LOS DEC	LOS UNC	MAG	MAG UNC	SPA
1178	21821	2457785.23446...	-34.2694590000	140.3426290000	36.000000	146.4935466626	16.4738698742	3.984639	URGENT_TAS...		
1178	40141	2457785.23479...	-34.2694590000	140.3426290000	36.000000	152.5959817010	5.5573476288	5.345995	URGENT_TAS...		
1178	28786	2457785.23479...	-34.2694590000	140.3426290000	36.000000	152.0304843792	5.5830190323	5.345995	URGENT_TAS...		
1178	40141	2457785.23486...	-34.2694590000	140.3426290000	36.000000	152.5312025107	5.5575215613	5.664845	URGENT_TAS...		
1178	28786	2457785.23486...	-34.2694590000	140.3426290000	36.000000	152.0548566779	5.5833022871	5.664845	URGENT_TAS...		

Version 1.0.4.22 Browser Requirements Terms Of Use Orbit Logic Incorporated © 2017

Fig. 7. Review page for observation data

Once these new WebUI pages were implemented and hooked into Heimdall Web’s sever functions, Orbit Logic was ready to support initial integration exercises with ExoAnalytic.

6. VALIDATION ACTIVITIES (INCLUDING CHALLENGES AND RESOLUTIONS)

Orbit Logic and ExoAnalytic agreed to a walk-then-run progressive integration and test campaign to verify the features implemented for this activity.

The initial test involved a simple check to ensure that the translation plug-in developed for ExoAnalytic’s sensor tasking file format could produce a file that was properly interpreted by their control center processes. A specific sensor was selected for the activity, one that had a guaranteed view of a negotiated space target and favorable seeing conditions. *Background* objects in Heimdall’s orchestration process are nominally determined by accessing SpaceTrack.org with an Application Programming Interface (API) to retrieve a list of candidate objects. This process was overridden for the first test and a single object was specified manually by an Orbit Logic system engineer. The scheduling engine generated a plan for this single object to be observed by the single enabled ExoAnalytic telescope. The resulting file was automatically transferred to Exo’s control center using the previously described transfer mechanism. On the ExoAnalytic side, the file was manually inspected, determined to be valid, and was then released for execution by the selected telescope. This initial test was a success. ExoAnalytic was able to immediately confirm (using their real-time telescope status interfaces) that the scheduled observations were conducted as expected. After a short period of time, it was also confirmed that the observations had resulted in the return of imagery that after processing contained associated observation data for the space object that had been specified in the initial request.

Encouraged by the success of this initial continuity check, the team conducted the next test, which involved the scheduling of the observation of multiple space objects by the same sensor. The test case was initiated and the

tasking file for the sensor was generated and received by ExoAnalytic. The first observation in the series was successful, but several of the successive were not conducted as expected. Real-time troubleshooting by ExoAnalytic revealed that the observations in the tasking file were in conflict with the telescope's controller software. One field in the tasking file indicates the number of successive observations that should be made of an object. The time required by the telescope to complete the number of observations specified in the Heimdall-created file could not be accomplished before the start time of the next object in the schedule. This was a misinterpretation of the file format by Orbit Logic that needed to be rectified. The team concluded the test session for the day to make fixes.

During the next test session, the generated tasking schedule (again for a series of objects to be serviced by a single ExoAnalytic sensor) was properly handled by the telescope controller. In this round of testing observations of at least one object were not made. Again, real-time analysis by ExoAnalytic revealed that this particular object was close to the horizon and was not being observed because of the maximum sun angle constraints on the telescope controller. This particular constraint had not been captured when the ExoAnalytic sensors were originally configured, in fact this constraint was not included in the sensor configuration page. Orbit Logic made the required framework updates, which were verified during the next test with a similar set of targets. In that test, all tasked observations were successfully completed.

In this same session, the delivery of the observation data files was verified. Recall that a file watcher utility was implemented within the Heimdall server environment to check for observation data files as they were made available by the ExoAnalytic processing stage. While it would take more development time on the Orbit Logic side to fully integrate the observation data with the Heimdall database and displays, the test verified that the files themselves were being properly generated on the ExoAnalytic side and transferred to the Orbit Logic side by the automated machine-to-machine processes.

The next challenge in the progressive test plan was to verify that the urgent tasking feature of Heimdall worked as designed. A typical scenario would be that sensors are engaged in satisfying plans provided at the last 24-hour tasking cycle (consisting of *Background* and *Daily* tasks). If a requestor desires *Urgent* observations, the requests that they enter (using the WebUIs) will result in an ad-hoc scheduling activity by the Heimdall Engine. The end result would be (if the object is accessible to sensors supporting the activity) updated schedules to replace the go-forward tasking already in progress on sensors needed to service the urgent request. This series of interactions was exercised in the test plan by first generating the *Background* tasking schedule and providing it to ExoAnalytic's system (as in previous tests), verifying that observations were being received on the Heimdall side, and then using the new Requestor's Perspective WebUIs to define and submit an *Urgent* request (an object different than the ones that were being observed according to the original tasking schedule for the test sensor). This test was completely successful, verifying that the transition to a dynamically-created ad-hoc schedule accommodating the urgent request was accomplished smoothly and without unanticipated side-effects. Observational results associated with the *Urgent* object were received, archived and visible as 'Complete' (and thus downloadable) in the Requestor's WebUI pages – constituting a complete end-to-end demonstration of the goal capabilities. Furthermore, as a stretch case, the team tested the condition in which the *Urgent* task "expires" based upon its defined life cycle parameterization. That case also worked as expected, with the tasking schedule properly reverting back to the exclusive servicing of *Background* tasks without incident.

One issue that did interfere with the testing campaign was weather. Tests needed to be rescheduled on multiple occasions due to uncooperative weather conditions at the sites designated for test support. Heimdall does utilize weather forecast data as a constraint in its scheduling activity. If this feature was employed (it was not for the human-coordinated tests of this activity) schedules using those sensors would not be generated, however, observation activities (and especially those associated with *Urgent* requests) would also be unsatisfied. The resolution to weather-related pre-emption lies in redundancy. The true power of the Heimdall solution is its ability to scale up to use of a large number of highly distributed sensors. We have discussed with ExoAnalytic the use of dedicated sensors at multiple geographic sites (some in the same longitude regime) such that there is built-in redundancy to improve the probability of success in servicing a given space region. In a Heimdall/Exo solution specifically configured for a given customer's needs, the architecture would naturally adjust to weather-related service interruptions.

7. CONTINUOUS TESTING

Once Orbit Logic successfully completed the integrated (but limited) system testing campaign with ExoAnalytic, the team was assured that the external system interfaces were sufficiently functional. Since Heimdall is specifically intended to scale to large numbers of heterogeneous sensors hosted by multiple commercial operators, it was important to Orbit Logic that the Heimdall side of that system-of-systems paradigm be exercised continuously to seek out and fix and issues resulting from high-load enterprise use.

To accomplish this testing, Orbit Logic created a test server capability to stand in for instances of the machine-to-machine interface “receptors” that were used on the ExoAnalytic side of the solution described in this paper. This “Exo-like emulator” allowed us to configure multiple “virtual sensors instances” that could be given tasks and return sample observation data files. Earlier in this paper it was mentioned that *Background* objects were acquired by using the SpaceTrack.org API to retrieve public catalog objects on a 24-hour cycle. A filtered list of these objects (only active operational and unclassified satellites) is used by the Heimdall orchestration process to create a daily optimized schedule involving a globally distributed collection of emulated sensors. Those schedules are delivered to each emulated sensor in the same manner that they are delivered to ExoAnalytic’s telescope control center and proxy observation data files are similarly returned and processed in an operational-like manner. Consequently the continuous testing system is subjecting the Heimdall architecture to the load conditions that would be experienced in a deployed operational configuration on a day-to-day basis. Within days of deploying this continuous testing solution issues started to be identified and resolved. To date, the continuous testing has been executing for over six months and the framework is completely stable.

8. RESULTS

One of the major objectives of this activity was to determine the timelines that could be realized for the return of observation data associated with *Urgent* requests entered by an end-user. Of course the response time for an arbitrarily-specified object is subject to the capabilities of the assembled system (number of sensors, their locations, local conditions, and other competing tasks – some of which may also be urgent in nature), but we did collect data to measure the ideal response time (predominated by the execution time associated with dynamic rescheduling, the transfer of the schedule to the sensor operations center, the delays in recognizing the availability of data products at certain stages of the process, and the data processing delays). With all of these contributors in play, the maximum time to receive observation data back for an *Urgent* object (where the object is viewable by a sensor at the time the request is submitted) is 30 minutes. This maximum time would occur in a cases where the delivery of an urgent schedule sent to the ExoAnalytic server just misses the 15 minute periodic execution cycle of their file watcher utility. With process tweaks, this part of the latency could be considerably reduced.

Using the continuous testing framework described in the previous section, it has been possible to collect several performance metrics. Our standard test case consists a set of emulators representing 5 globally distributed sensors (located in Colorado, California, Chile, South Africa, and Australia) with capabilities matching those of ExoAnalytic’s existing systems. For the “background” object set, we obtain all active operational unclassified satellites in GEO orbits from the public catalog (numbering 450). When the periodic background scheduling cycle is conducted by Heimdall’s orchestrator, retrieving/filtering the orbits, creating the optimized tasking schedules for the 5 telescopes, and transmitting those schedules to the emulators takes place in approximately 3 minutes. Assuming no weather interruptions, the emulated telescopes accomplish all of their background tasks in just under 24 hours. Orbit Logic regularly inserts ad-hoc urgent tasks into the continuous testing framework to verify proper system transitions. Automation of those (currently manual) urgent request insertions is in development.

9. CONCLUSIONS

This paper has described the first implementation of true machine-to-machine processes for the automated scheduling and retrieval of observation data from commercial sensors using the Heimdall Web architecture. The activity was a complete success, with significant credit attributable to ExoAnalytic Solutions personnel whose support efforts allowed two key capabilities (Heimdall’s Web-enabled Sensor Schedule optimization process and

ExoAnalytic's Global Telescope Network and operations center) to be integrated together for a compelling capabilities demonstration.

This team sought to path-find the process of accommodating an existing commercial sensor network's operational capabilities into the Heimdall Web paradigm. This goal was achieved with relative ease through the use of plug-in format translation modules on the Heimdall side – an integration model that will be typical, as most mature sensor operations models will likely employ their own bespoke approaches for exposing process capabilities to external actors.

Orbit Logic developed extensions to the Heimdall framework to support end-users of SSA-related observation data. This "Requestor's Perspective" consists of Web-based User Interface pages that allow the entry of objects of particular interest and then facilitate insight into the status of sensor tasking that is satisfying that user's requests – including the ability to retrieve the resulting observation data as soon as it is received from the sensor operator. Behind the scenes, the Heimdall scheduling engine performs ad-hoc re-plans in response to the submission of these urgent requests, amending previously generated schedules in near real-time and providing them to active sensors as live updates.

Upon completion of the new Heimdall features and the Exo-specific format translators, the team conducted a series of successful integrations to verify that the objectives of the activity were met. These activities ultimately proved (via live demonstration) that desired observation data requested using web-based user interfaces can be dynamically inserted into the schedules of networked commercial telescopes without significant disruption to routine background tasks, and delivered back to the requestor in timeframes of less than 30 minutes.

10. REFERENCES

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