Combined SSA Sensor Tasking for Space-to-Space and Ground-to-Space

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ABSTRACT

Comprehensive and persistent Space Situational Awareness is best achieved when the sensors employed for observations and searches are coordinated to eliminate duplication of effort and to maximize the utility of the information that can be extracted from the resulting data products. The desired results of sensor tasking optimization are; 1) to better maintain custody of objects of interest, 2) to detect object changes as quickly as possible, 3) to respond to events as quickly as possible, and 4) to maximize the discovery and tracking of new uncorrelated objects. All objectives must be balanced for overall SSA efficacy.

Effective approaches toward achieving the objectives summarized above frequently involve both ground-based and space-based sensor assets. Each of these sensor categories has inherent strengths and weaknesses (and each is subject to its own operational constraints), but a well-planned utilization of both can result in a highly effective overall capability.

Orbit Logic has developed a unique system that solves the difficult problem of optimizing the tasking schedules of ground-to-space and space-to-space SSA sensors in a coordinated fashion. The framework is highly configurable using web-based interfaces, allowing models of ground- or space-resident sensors to be parameterized, orbital objects to be specified, search areas to be defined, and an SSA-specific figure of merit (FOM) to be dynamically tuned to mission operational needs. The latter allows the generated sensor tasking schedules to best meet current operational priorities.

The system has recently received enhancements to its advanced planning algorithms to optimize the distribution of tasks over all assets of a specific sensor class (space or ground), resulting in significant improvement of the FOM results, especially for large numbers of custody objects and search cells. The validated schedules honor not just access constraints, but factor in ground site weather, object observability relative to the selected sensor, sensor performance limitations, and (when possible) serendipitous collections of multiple objects.

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). In addition, new space-based assets, both commercial and government-operated, are available to image and search for other space objects, providing a totally new set of data from assets that operate with an entirely different set of capabilities and constraints.

Even before the addition of space-based tracking assets like SBSS, coordination of various ground assets was almost non-existent. Each asset operated independently with minimal coordination or direction from the JSpOC, and almost no coordination with other observation assets. With modern software and network 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 SSA sensor tasking for improved catalog maintenance and efficiency. Adding further complexity to the situation is the emergence of non-government operated sensors (commercial, academic, and amateur sensor networks), which can provide significant additional observation capabilities and data.

The Orbit Logic team initially developed the capability to incorporate expected information gain to increase the value of planned observations [2]. Additional previous work by Orbit Logic provided an architecture, software tools, and an operational concept to incorporate non-traditional sensor capabilities and data into the SSN mission [10].

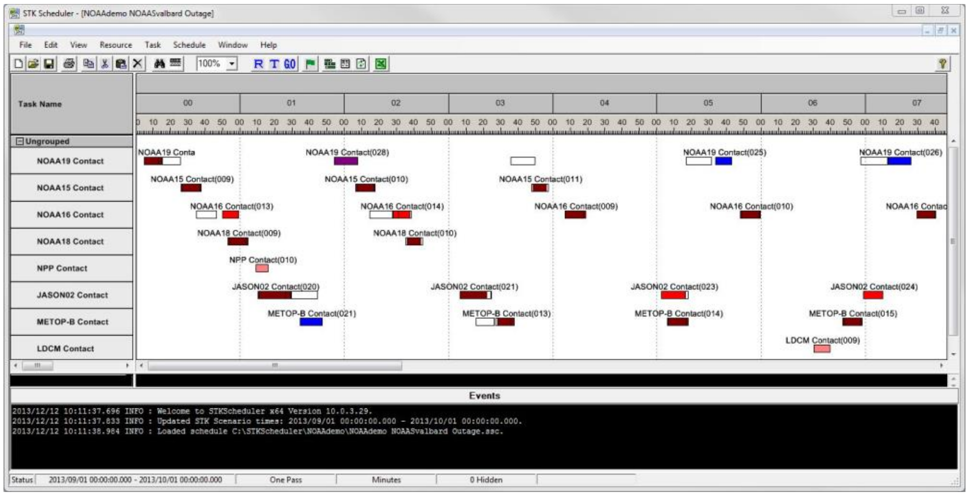
This paper the continuation of previous work for ground assets (SSN and non-traditional) and combines it with capabilities for space-based SSA sensor assets using commercial imaging satellite collection planning software as well as a COTS web-based tool for imaging order management. The web server was modified to interface with the STK Scheduler COTS product for ground sensor tasking for SSA and with the separate COTS software product CPAW for imaging satellite collection planning, configured for SSA. The resulting system provides for coordinated SSA observation tasking for a diverse set of space and ground sensors.

2. TECHNOLOGY OVERVIEW

Multiple COTS software products that have been previously configured and deployed for SSA sensor tasking and/or imaging satellite collection planning were integrated and enhanced for the new combined space and ground asset SSA observation tasking system described here. The individual COTS software components are summarized below, including high level descriptions of new configuration capabilities and enhancements to support the this paper's SSA mission focus.

STK Scheduler

STK Scheduler is a broad-based schedule optimization solution for space system operations. Highly configurable for a wide range of domains and missions, licenses have been deployed supporting NASA, DoD, national intelligence, and international space programs. Within STK Scheduler, tasks and resources model real-world systems and constraints. Multiple scheduling algorithms generate optimized schedule solutions that deconflict resources and adheres to defined constraints. A configurable Figure-of-Merit (FOM) allows users to adjust the goals of the algorithms. STK Scheduler has a comprehensive API supporting full integration with other ground system elements. Figure 1 shows a Gantt view of an optimized task schedule.



```
2013/12/12 10:11:37.696 INFO : Welcome to STKScheduler x64 Version 10.0.3.29.
2013/12/12 10:11:37.833 INFO : Updated STK Scenario times: 2013/09/01 00:00:00.000 - 2013/10/01 00:00:00.000.
2013/12/12 10:11:38.984 INFO : Loaded schedule C:\STKScheduler\NOAAdemo\NOAAdemo NOAASvalbard Outage.ssc.
```

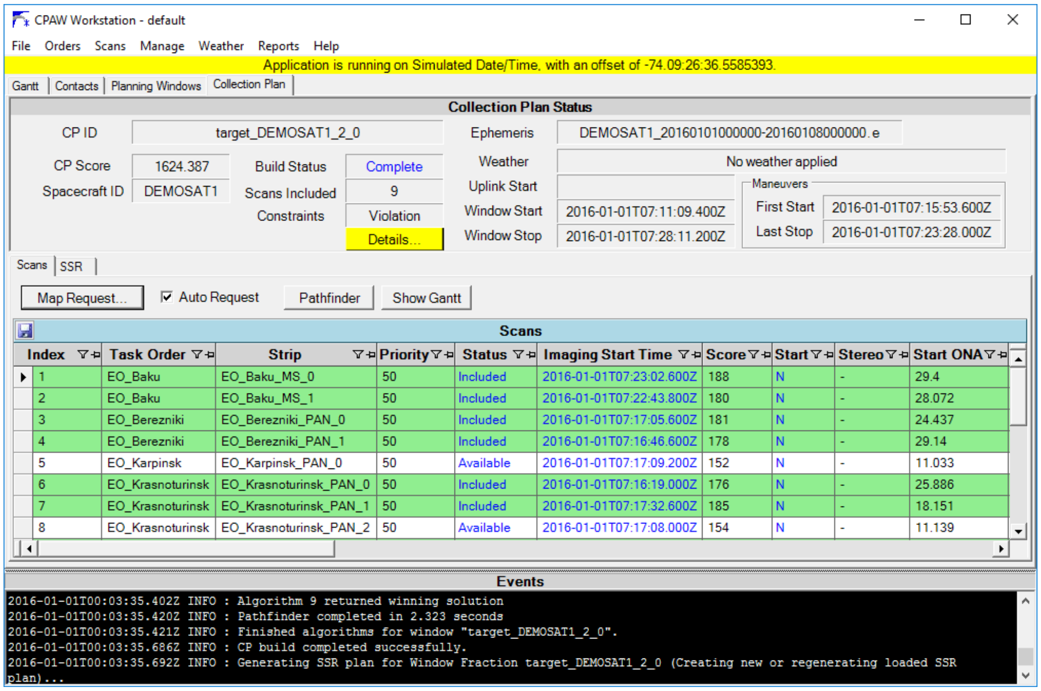
Fig. 1. STK Scheduler Screenshot

STK Scheduler is the primary scheduling engine behind Orbit Logic's Heimdall solutions for SSA [2] [10]. For SSA sensor tasking deployments, an SSA Enhancement plug-in is added that provides an SSA-specific FOM, SSA-specific target attributes, and the Track Prioritization Component from the University of Colorado for observation opportunity information gain computations [2] [10].

CPAW

The Collection Planning and Analysis Workstation (CPAW) provides high fidelity spacecraft, sensor, environment, and target modeling to support imaging satellite collection planning. Multiple CPAW planning algorithms compete to generate optimized collection plans for one or more imaging satellites against a database of collection orders. Originally developed for commercial imaging satellite operators collecting against a target deck of point and area targets on the ground, CPAW was recently enhanced to also support the definition and collection of space-based targets. In addition to collection planning, CPAW also provides features for contact scheduling, recorder management and downlink planning. For SSA-related CPAW deployments, the SSA FOM and Track Prioritization

Component [2], [10] are integrated. Figure 2 shows a screenshot of a CPAW user interface page presenting a table view of tasks comprising an optimized plan.



Application is running on Simulated Date/Time, with an offset of -74.09:26:36.5585393.

Collection Plan Status

CP ID: target_DEMOSAT1_2_0
CP Score: 1624.387
Spacecraft ID: DEMOSAT1
Build Status: Complete
Scans Included: 9
Constraints: Violation
Ephemeris: DEMOSAT1_20160101000000-20160108000000.e
Weather: No weather applied
Uplink Start:
Window Start: 2016-01-01T07:11:09.400Z
Window Stop: 2016-01-01T07:28:11.200Z
Maneuvers
First Start: 2016-01-01T07:15:53.600Z
Last Stop: 2016-01-01T07:23:28.000Z

☑ Auto Request

Scans

Index	Task Order	Strip	Priority	Status	Imaging Start Time	Score	Start	Stereo	Start ONA
1	EO_Baku	EO_Baku_MS_0	50	Included	2016-01-01T07:23:02.600Z	188	N	-	29.4
2	EO_Baku	EO_Baku_MS_1	50	Included	2016-01-01T07:22:43.800Z	180	N	-	28.072
3	EO_Berezniki	EO_Berezniki_PAN_0	50	Included	2016-01-01T07:17:05.600Z	181	N	-	24.437
4	EO_Berezniki	EO_Berezniki_PAN_1	50	Included	2016-01-01T07:16:46.600Z	178	N	-	29.14
5	EO_Karpinsk	EO_Karpinsk_PAN_0	50	Available	2016-01-01T07:17:09.200Z	152	N	-	11.033
6	EO_Krasnoturinsk	EO_Krasnoturinsk_PAN_0	50	Included	2016-01-01T07:16:19.000Z	176	N	-	25.886
7	EO_Krasnoturinsk	EO_Krasnoturinsk_PAN_1	50	Included	2016-01-01T07:17:32.600Z	185	N	-	18.151
8	EO_Krasnoturinsk	EO_Krasnoturinsk_PAN_2	50	Available	2016-01-01T07:17:08.000Z	154	N	-	11.139

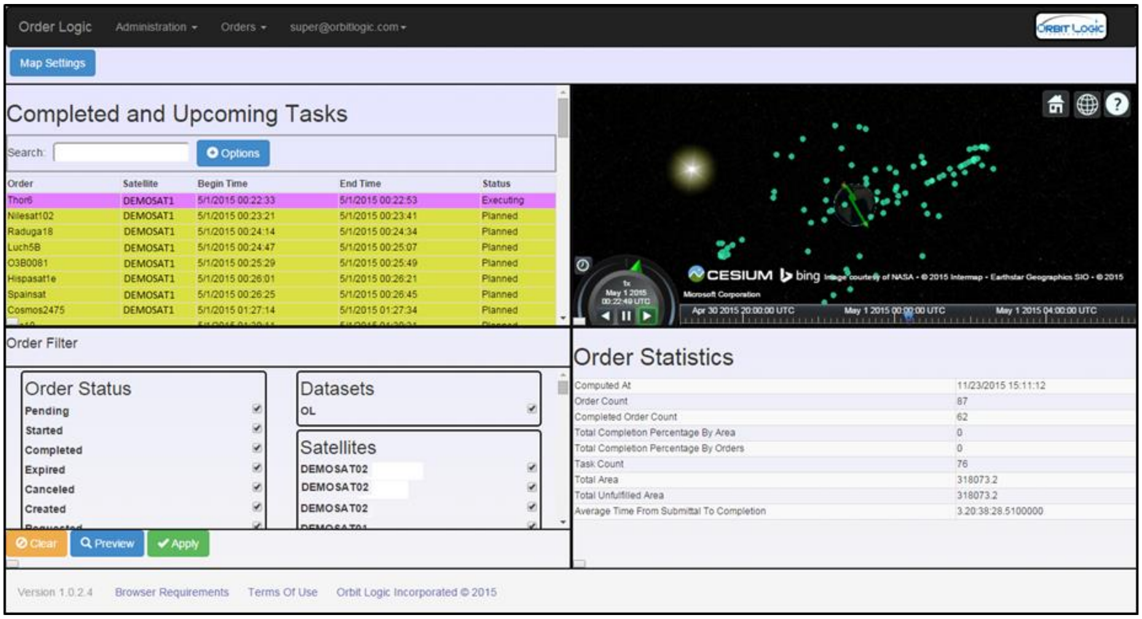
Events

```
2016-01-01T00:03:35.402Z INFO : Algorithm 9 returned winning solution
2016-01-01T00:03:35.420Z INFO : Pathfinder completed in 2.323 seconds
2016-01-01T00:03:35.421Z INFO : Finished algorithms for window "target_DEMOSAT1_2_0".
2016-01-01T00:03:35.686Z INFO : CP build completed successfully.
2016-01-01T00:03:35.692Z INFO : Generating SSR plan for Window Fraction target_DEMOSAT1_2_0 (Creating new or regenerating loaded SSR
plan)...
```

Fig. 2. CPAW Screenshot

Order Logic

Order Logic was developed as a user-facing interface for Orbit Logic's planning software application. The web application has previously been configured as the program-specific front end for both STK Scheduler and CPAW planning applications (for ground and space-based assets, respectively). In the solution described in this paper, Order Logic is configured to interface with both the STK Scheduler <u>and</u> CPAW planning engines, and has additionally been enhanced to provide overall workflow and automation control. Figure 3 shows the Order Logic "Dashboard" presenting the top-level view of task status and visualizing current sensor collection activities.



Completed and Upcoming Tasks

Search:

Order	Satellite	Begin Time	End Time	Status
Thor6	DEMOSAT1	5/1/2015 00:22:33	5/1/2015 00:22:53	Executing
Nilesat102	DEMOSAT1	5/1/2015 00:23:21	5/1/2015 00:23:41	Planned
Raduga18	DEMOSAT1	5/1/2015 00:24:14	5/1/2015 00:24:34	Planned
Luch5B	DEMOSAT1	5/1/2015 00:24:47	5/1/2015 00:25:07	Planned
O3B0081	DEMOSAT1	5/1/2015 00:25:29	5/1/2015 00:25:49	Planned
Hispasat1e	DEMOSAT1	5/1/2015 00:26:01	5/1/2015 00:26:21	Planned
Spainsat	DEMOSAT1	5/1/2015 00:26:25	5/1/2015 00:26:45	Planned
Cosmos2475	DEMOSAT1	5/1/2015 01:27:14	5/1/2015 01:27:34	Planned

Order Filter

Order Status
Pending ☑
Started ☑
Completed ☑
Expired ☑
Canceled ☑
Created ☑

Datasets
OL ☑

Satellites
DEMOSAT02 ☑
DEMOSAT02 ☑
DEMOSAT02 ☑

Order Statistics

Computed At	11/23/2015 15:11:12
Order Count	87
Completed Order Count	62
Total Completion Percentage By Area	0
Total Completion Percentage By Orders	0
Task Count	76
Total Area	318073.2
Total Unfulfilled Area	318073.2
Average Time From Submittal To Completion	3.20:38:28.5100000

Fig. 3. Order Logic Web App Screenshot

3. SYSTEM ARCHITECTURE

The major components of the combined space and ground sensor tasking system for SSA, and their major interfaces, are shown in the diagram below in Fig. 4 and described in the following sections.

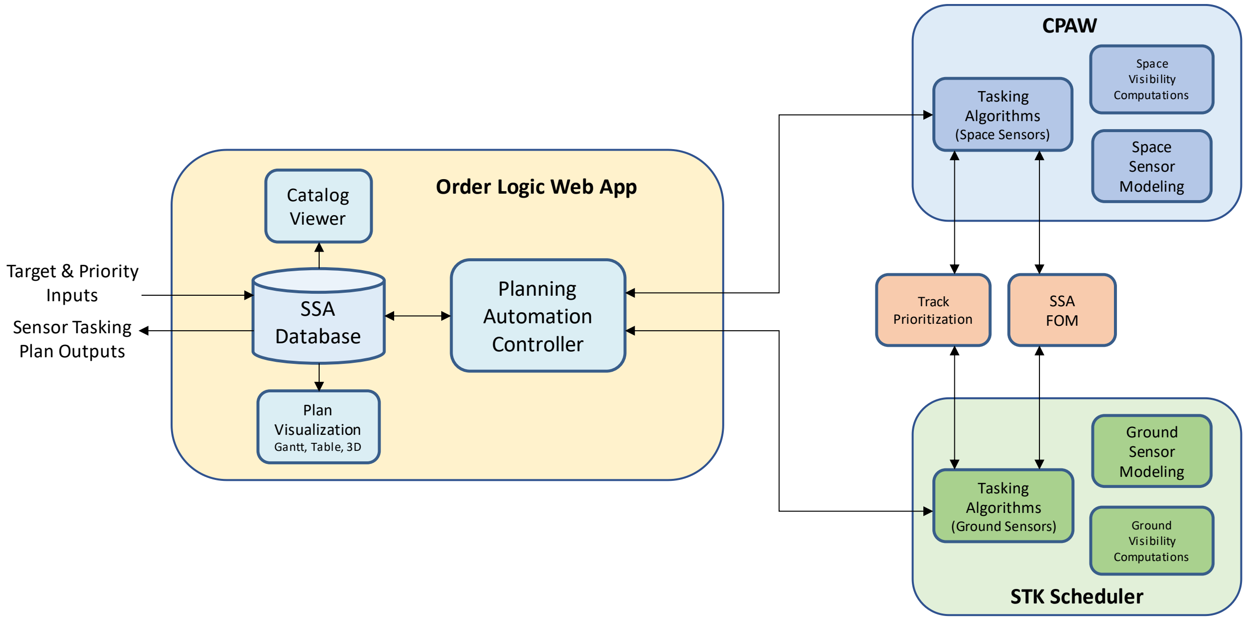


Fig. 4. System Architecture Diagram

Order Logic Web App

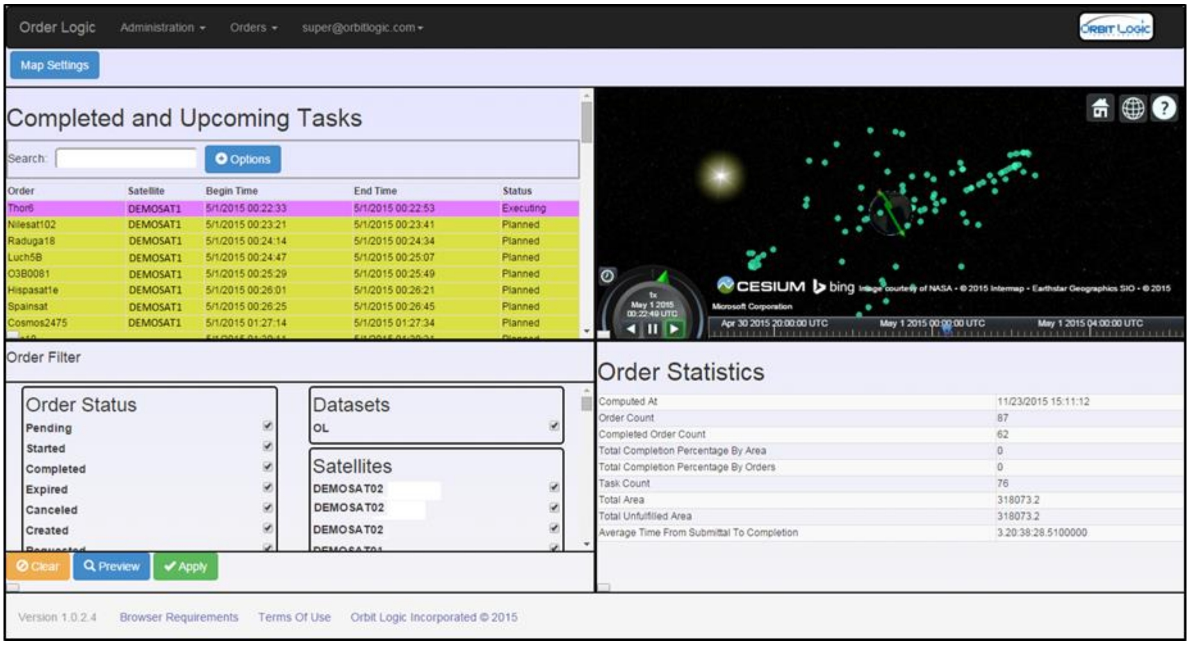
Core to the overall system architecture is the use of a single database for SSA objects and sensor observation plans. The use of a centralized database allows for coordinated observation planning and related fulfillment tracking. The scalable PostgreSQL database supports thousands of space objects, including space search area definitions and their status (both past and future scheduled observations). An API allows external applications specify objects and search areas for observation, or edit the attributes of existing objects. With this API, externally-tasked sensor can also be provided for fulfillment tracking purposes.

Order Logic's Planning Automation Controller provides configurable planning automation control for event-based or time-based planning for each sensor asset, whether in space or on the ground. The controller allows for sensors to be planned as a group, or to be planned individually based on their operational schedule. The automation controller uses the CPAW and STK Scheduler APIs to request space sensor and ground sensor observation plans, respectively. Returned plans are stored in the database and are available for review by operators through Order Logic UIs. The automation controller may also be configured to distribute sensor tasking plans for execution by external systems.

Order Logic user interfaces (UIs) provide tabular, Gantt, and 3D views into the object attributes and observation plans. 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 advances to the time of the selected observation to display a static view of the observation geometry of interest.

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. 5 shows the table view and associated configurable filter, along with the embedded 3D Cesium view and associated metrics.

Order Logic 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.



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O3B0081	DEMOSAT1	5/1/2015 00:25:29	5/1/2015 00:25:49	Planned
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Spainsat	DEMOSAT1	5/1/2015 00:26:25	5/1/2015 00:26:45	Planned
Cosmos2475	DEMOSAT1	5/1/2015 01:27:14	5/1/2015 01:27:34	Planned

Order Status

Pending ☑
Started ☑
Completed ☑
Expired ☑
Canceled ☑
Created ☑

Datasets

OL ☑

Satellites

DEMOSAT02 ☑
DEMOSAT02 ☑
DEMOSAT02 ☑

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Total Completion Percentage By Orders	0
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Average Time From Submittal To Completion	3.20:38:28.5100000

Fig. 5. Heimdall Web Application Dashboard Page

CPAW

The Collection Planning & Analysis Workstation (CPAW) provides a high fidelity spacecraft and sensor modeling environment for collection planning. Spacecraft and sensors in CPAW have physical attributes (agility, etc.) and constraints (sensor sun keepout, etc.). SSA tasks in CPAW include observations of space objects as well as search areas. SSA tasks in CPAW have standard scheduling attributes such as priority and recurrence, as well as physical properties (size, reflectivity, orbit, etc.) and observation constraints.

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 are performed in parallel on many cores in order to reduce solution time for large object catalogs. Multiple collection planning algorithms available in CPAW can also be run in parallel to arrive at solutions much more rapidly. The deconflicted and optimized plans generated by the algorithms are compared using the SSA-specific FOM (see subsequent description in this paper).

CPAW algorithms support not only individual satellite collection planning, but also constellation planning when multiple space-based sensors are available. Testing has shown significant FOM score improvements for constellation planning as compared to sequential planning of space sensors individually, even when coordinated through database fulfillment tracking. The best observation opportunities across all sensors for each task are selected, subject to deconfliction with other tasking.

STK Scheduler

STK Scheduler using the associated SSA plug-in provides a high fidelity ground sensor modeling environment for SSA observation planning. Ground sensors in STK Scheduler have physical attributes (agility, etc.) and constraints (location, elevation mask, sensor sun keepout, etc.). SSA tasks in STK Scheduler include observations of space objects as well as search areas. SSA tasks in STK Scheduler have standard scheduling attributes such as priority and recurrence, as well as physical properties (size, reflectivity, orbit, etc.) and observation constraints.

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 are performed in parallel on many cores in order to speed computation time for large object catalogs. Multiple collection planning algorithms available in STK Scheduler are run in parallel to speed solution time. The deconflicted and optimized plans generated by the algorithms are compared using the SSA-specific FOM (see subsequent description in this paper). Unlike CPAW access computations for space sensors, ground sensor observation opportunity computations also include NOAA cloud cover forecasts!

STK Scheduler algorithms support not only individual ground sensor SSA observation planning, but also constellation planning when multiple ground sensors are available. Testing has shown significant FOM score improvements for constellation planning as compared to sequential planning of space sensors individually, even when coordinated through database fulfillment tracking. The best observation opportunities across all sensors for each task are selected, subject to deconfliction with other tasking.

STK Scheduler provides multiple scheduling algorithms as well as an algorithm builder tool to define refined (custom) algorithms for specific user 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 Order Logic Web App calls the STK Scheduler algorithms using STK Scheduler's STK Connect command API (TCP/IP interactions using string keyword-value pairs). The specific algorithm may be configured within the Order Logic 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.

Track Prioritization

Our combined SSA sensor tasking solution employs a Track Prioritization component 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 produce plans with significantly improved object catalog quality compared to plans that do not consider information gain.

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. 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 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

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, and more. Each factor has an associated configurable weighting attribute to specify the importance of one FOM factor relative to others. 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. The SSA FOM is used by both STK Scheduler and CPAW to score all observation opportunities BEFORE the scheduling algorithm runs, as part of the standard processing flow in both software tools.

4. OPERATIONS CONCEPT

The system described in this paper is designed for lights-out operation, but will provide insight and control to operator personnel through its Order Logic web app. Operators can review generated plans, change configuration parameters (such as FOM weightings), and pause automated planning. It should be noted that operator input is not required for nominal operations once the system is configured and running.

5. DEMONSTRATION OF CAPABILITIES AND RESULTS

Multiple runs with test data have shown good results for coordinated planning across a set of space and ground sensor assets for large (public) catalogs of space objects and defined search areas. The Order Logic web app is able to successfully maintain the object/search catalog, request optimized plans from CPAW for space assets and from STK Scheduler for ground sensors. Further, Order Logic UIs have successfully been used to review catalog object status and visualize tasked collection plans for both space and ground sensors combined.

6. CONCLUSIONS

The final conclusion from our work to date is that it is technically possible to perform coordinated and optimized SSA observation planning across a number of space and ground sensors with diverse capabilities for improved catalog maintenance. In the end, it may be more of a programmatic challenge than a technical challenge to coordinate multiple sensor assets across multiple organizations and locations.

7. FUTURE WORK

The current system requires a software update to add new sensors, but the eventual goal is to support the addition of sensors on the fly through configuration UIs and configuration file import.

The current system plans ground sensors and space sensors sequentially, albeit in either order. STK Scheduler is applied to all ground sensors. CPAW is applied to all space sensors, performing constellation optimization to ensure a deconflicted and optimized schedule across all available sensors in that group. Consequently, optimization across the full constellation of space and ground sensors is not currently performed. Eventually we will combine the planning into a single set of common algorithms that optimize observation planning across ALL sensors (space and ground).

8. REFERENCES

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