# Collection Planning for the OrbView-3 High Resolution Imaging Satellite

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**ABSTRACT**

Commercial imaging satellites must respond to thousands of requests to image different areas of the earth within tight time constraints.  To effectively satisfy and manage these requests, geodynamic, camera, and spacecraft constraints must be reconciled within a matter of minutes to create a workable plan for capturing images during a particular spacecraft pass.  These constraints include customer-defined target viewing constraints, spacecraft power limitations, data storage attributes, pointing constraints, spacecraft agility limitations, high gain antenna blockages, cloud cover and more.  Orbit Logic developed and delivered a high fidelity spacecraft simulator that is tightly integrated with scheduling optimization algorithms to meet this challenge.  Dubbed the OrbView Tasking System (OTS), it is used today by GeoEye for OrbView-3 image collection planning.  OTS incorporates spacecraft slew, scan, and other models, reconciles all constraints and efficiently generates valid collection plans using multiple optimization algorithms and/or manual planning inputs. It also incorporates innovative visualization capabilities for intuitive assessment of collection plans. This system is being upgraded for use with GeoEye-1, in addition to OrbView-3, and will be incorporated into a new system called the Collection Planning System (CPS).  CPS includes a planning server that will manage multiple instances of OTS for increased computational performance and system scalability. This paper will describe the OTS and the overall approach to optimizing collection planning for OrbView-3 as well as the system's overall applicability for use with any imagery, radar, or remote sensing mission.

The OTS is designed to support rapid collection plan optimization over a user-defined timeframe (generally a specified portion of one satellite orbit).  In addition to the myriad of physical system and target constraints noted above, quality of previously planned images and priority of targets are critical factors in collection optimization for future passes. The system provides a user-configurable filter for choosing those constraints most important to the satellite operator or system user, with the result being a more qualified list of candidates for in-depth computation and planning.  Once this filtered group of target areas is ascertained, the OTS then competes multiple optimization algorithms against each other to determine the "best" collection plan. The quality of each candidate plan is judged using a common user-configurable figure-of-merit equation.  Each algorithm employs a different approach to solving the collection problem and, importantly, each algorithm will always return a plan consistent with spacecraft constraints and performance. Whether performed manually or in an automated fashion, the plan is output to the ground command and control system for uplink to the spacecraft. For a single orbit, an optimized collection plan can be computed in a matter of minutes with specific performance being dependent upon several factors including the number and density of targets within the field-of-regard during the planning window, spacecraft agility, and the number of constraints configured as "hard" constraints.

OTS uses an agile and flexible user interface to provide parameter specification and visual verification of the plan. The user has the ability to specify various parameters for each image collection included in the plan (including scan start time, imaging mode, scan direction, line rate,

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and more). OTS incorporates Satellite Tool Kit (STK) from Analytical Graphics, Inc. for user map displays and visualization of the optimized collection plan. STK provides a visual verification of the optimized imaging plan as well as assists the user in understanding system constraints and spacecraft behavior. This visual capability combined with OTS's adaptable architecture and extensive modeling results in a robust system that can be easily tailored for any spacecraft mission that must accommodate large target decks with numerous physical constraints and unique spacecraft capabilities.

## I. Introduction

On June 26, 2003, OrbView-3 was launched into orbit as the first high-resolution imagery satellite for ORBIMAGE, Inc. (recently renamed GeoEye). Its mission is to provide one-meter panchromatic and four-meter multispectral digital imagery on a global basis. The spacecraft has the agility to point its camera at any target within its field-of-view and image in any oblique direction, representing more capability than the more prevalent "push-broom" imaging satellites. The flipside of increased agility and oblique imaging capability is that choosing the target (and series of targets to image on any specific orbit) becomes a more significant challenge, since the solution space is greatly expanded compared to the simpler push-broom planning case.

Imagery collection planning for satellites such as OrbView-3 requires software that can manage large order decks, accurately model spacecraft systems, adhere to spacecraft and target constraints, provide for operator input and review of generated collection plans, and interface with external systems that need plan outputs, provide target deck updates, or provide feedback on planning results. In addition to these general requirements, collection planning must often be accomplished within aggressive time constraints to meet order response timelines and account for generally poor long term cloud forecasting

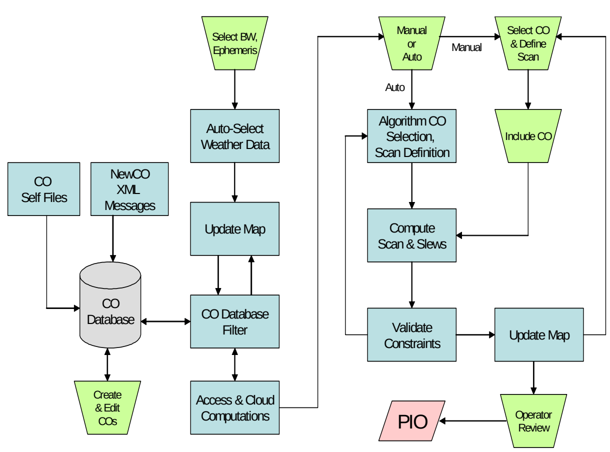
Orbit Logic responded to this collection planning challenge by developing the OrbView Tasking System (OTS) for GeoEye. Integrating a high-fidelity spacecraft simulator with multifaceted optimization algorithms, OTS routinely reconciles constraints and generates optimized OrbView-3 collection plans based on the current spacecraft ephemeris, cloud cover forecast, and a database of thousands of imagery orders (each of these imagery orders represents an area of interest this is called a "collection order" or "CO" by GeoEye. The reader will see this "CO" terminology used throughout the paper). This process is accomplished in a matter of minutes for each spacecraft orbit each day, and produces valid collection plans that optimize the return from limited imaging time and system resources.

This paper will first examine the planning process as implemented in OTS. This will be followed by a discussion of the system models as well as a look at the OTS approach to optimization. The paper will conclude with a summary of OTS and future capabilities in development.

## II. Planning Process

### A. Nominal Process

The planning process begins with the operator selecting the planning window and specifying order database filter criteria. Through the main planning GUI, the operator kicks off automated scheduling algorithms to generate the collection plan for the planning window. The operator may edit the collection plan and review a time-based visualization of the plan prior to transmitting it to the command generation system. *Without manual editing the process takes less than 5 minutes per planning window.*

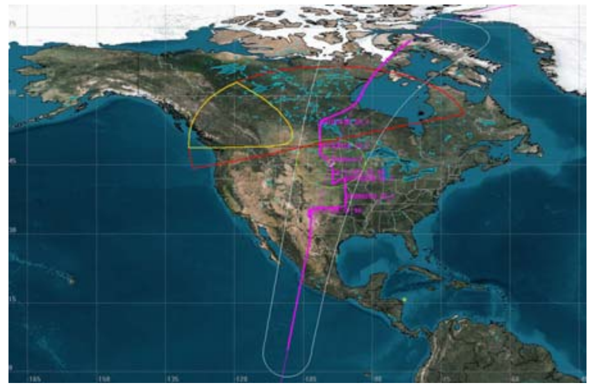



OTS workstation software also guides the operator through manual plan generation or editing by providing valid constrained access start and stop times for each order, a camera model that chooses default camera settings, computed scan parameters, and constraint validation checks for the collection plan.

To start a new planning session on the OTS Workstation, an operator selects the imaging window through the OTS Setup GUI. The appropriate (latest available prior to the start of the imaging window) ephemeris file and cloud data is automatically retrieved from configurable network target directories. As an additional convenience to the operator, these files are named and ordered to facilitate identification in case manual selection of alternate data is desired or required.

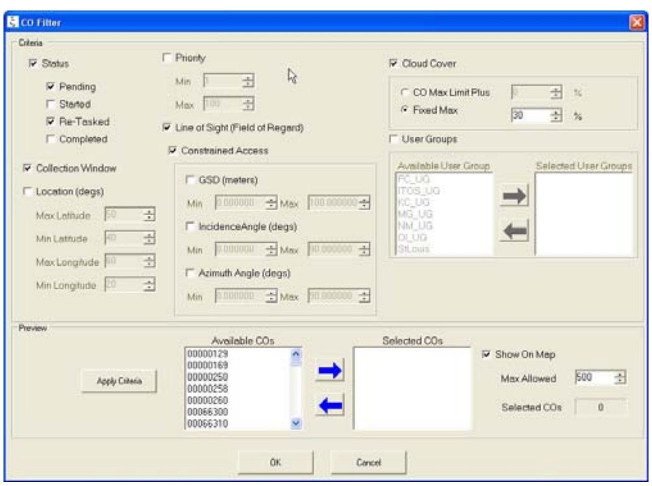
### B. STK Map Display

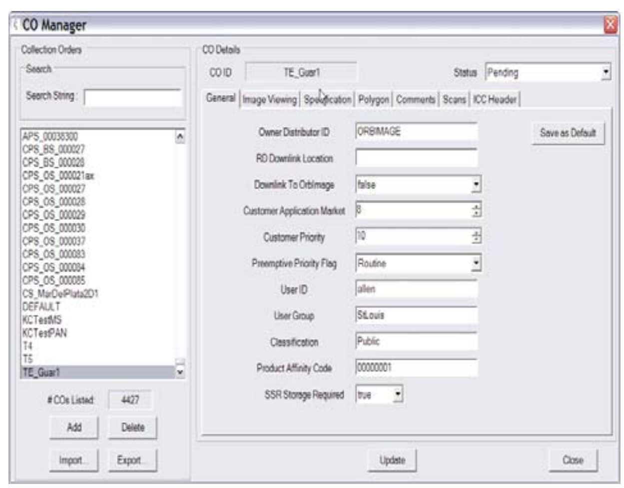
OTS utilizes Satellite Tool Kit (STK) from Analytical Graphics for its 2D view of the spacecraft ground track, satellite field of regard, overhead sun and moon positions, sun glint point, collection order (CO) ground targets, cloud cover, and sensor swaths. The map display is a key feature that assists the operator in the manual collection planning process. Inputs from Setup are used to show the imaging window extent on the map, including satellite field-of-regard swath on the ground. COs that pass filtering may be displayed on the map upon operator request. Color-coding of COs based on status is an additional aid to the operator. The operator may also use the mouse and click on the map to request specific orders be included in the plan.



### C. Collection Order Filtering

The CO database stores the active COs that have been requested for OrbView-3. Filter criteria are used by OTS to generate the list of COs to be considered for collection planning for a specific window. The default criteria include CO status, constrained CO access during the window, and the CO-defined collection window. Other criteria such as CO priority range and cloud cover percentage are available. A CO must meet all filter criteria or be manually selected to pass the filter. An operator may also browse through the list of COs in the database, review CO parameters, edit CO parameters, delete COs from the database, and create new COs manually using the CO Manager GUI. The CO Filter window and CO Manager are shown below.




As noted, the CO filter can utilize constrained access and weather data as criteria that all COs must satisfy. As important parameters to the imagery capture process, these parameters and related calculations are explored further below.

*1. Access Computations*

CO access may be computed as part of the CO Database Filter process, or post-filter (or both). CO access refers to the time during the imaging window when a CO satisfies all configurable access constraints, satellite and system access constraints, and CO-defined access constraints. Such constraints may include GSD, incidence angle, sun angle, azimuth angle, satellite imaging mode off-nadir angle constraints, and more. The CO Database Filter process allows the application of some or all of these access constraints (user configurable). OTS uses internal custom code for filtering access computations which provides exceptional performance.

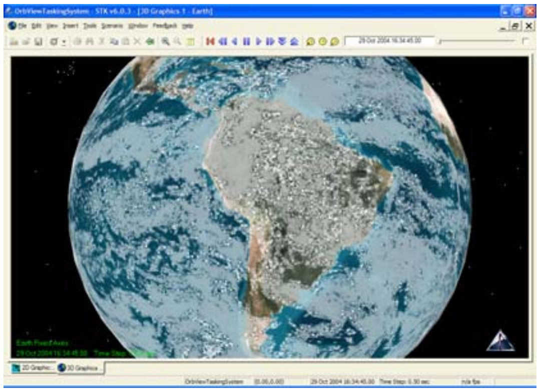
Post-filter, higher-fidelity access constraints are computed to provide valid scan start and stop times for each CO that passes the filter. In some cases the higher fidelity access computations disqualify a CO post-filter, or provide qualified access duration shorter than that required to image the area. In these cases the algorithms will not include that particular scan in the plan, and the software will not allow an operator to include the CO manually in a plan.

*2. Forecast Weather Data*

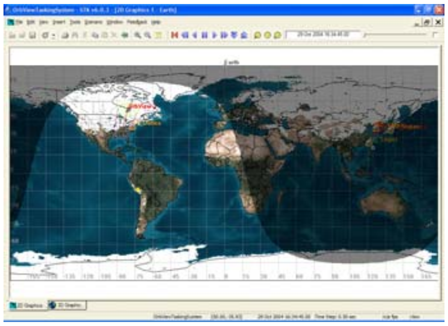
Forecast weather data is used to support collection planning activities. OTS receives weather data hourly from the Air Force Weather Agency (AFWA) in the form of GRIB-format data files. The files include the current actual cloud cover plus forecasted cloud cover for the globe for each of the next 10 one-hour periods, plus current snow cover for the globe. OTS uses the raw files to generate the following binary Portable Gray Map (PGM) files using the AFWA native weather grid resolution:

1. Current snow map
2. True Cloud map for each forecast period
3. Display Cloud map for each forecast period

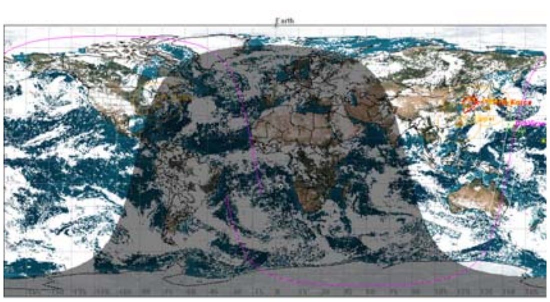
The True Cloud map is also used for average CO cloud cover computations in the CO filter and is the actual AFWA forecast cloud cover represented in PGM format. The Display Cloud map is used for operator display (overlaid on the STK map) and may be the same as the True Cloud map or altered for ease of use (the operator may configure the Display map to not show cloud cover less than 30%, for instance, and select either an all-white or grayscale display option). Samples of the OTS map display with overlaid weather data are shown below:



3D Globe with Grayscale True Cloud Cover

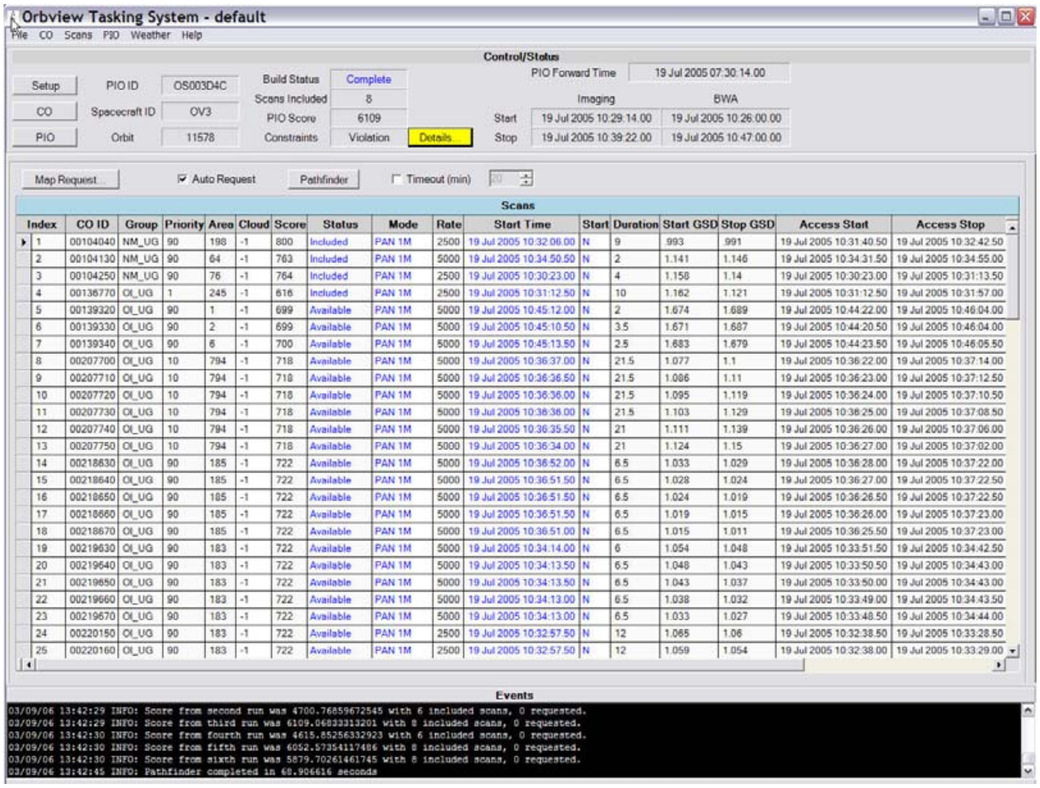


2D Map with Snow Cover



2D Map with 40% Minimum Cloud Cover

After the completion of the CO filtering process the candidate COs are displayed in the main planning window depicted below. The operator may continue with manual planning or manually kick off the automated planning algorithms.




## D. Manual Collection Planning Process

The manual planning process allows the operator to select individual COs to be included in the Collection Plan, and allows the operator to set all attributes of the CO scan (scan direction, imaging mode and related parameters, and scan start time). The software uses CO-defined parameter values, if available, or sets default values based on configurable parameters and models. Invalid options are rejected by the software with an operator message. Valid CO scan settings that cause a constraint violation (such as not enough time for the slew from the previous scan) cause messages and color-coded flags to assist the operator in correcting the problem. Problems are flagged as the operator builds the plan incrementally (including one CO at a time) so violations do not pile up and become difficult to resolve.

# III. System Models

Collection planning is enabled by a set of models that simulate and predict the physical environment, spacecraft subsystems, targets, and ground stations. With accurate models, OTS generates effective collection plans that maximize the quality and quantity of imagery collected. The deployed operational systems and the quality of collected OV3 imagery confirm the accuracy and effectiveness of the software system modeling.

## A. Physical Environment

OTS uses STK to model the spacecraft's orbit and the positions of the sun, moon, stars and planets as well as ground facilities and specific targets and areas of interest. OTS generally uses a predicted ephemeris file provided by a mission flight dynamics system that provides position data at 1 minute increments. STK software within CPS interpolates between these data points.

## B. Weather Processing

Weather is a critical factor in the quality of an optical image. Generally, if there is significant cloud cover over a target of interest, the image will be of marginal quality. OTS uses the latest available global cloud cover forecast to compute the average cloud cover over each target area. Computed cloud cover is a factor in determining the FOM score for an individual candidate CO, and affects whether or not a CO is included by the algorithms in a plan. See Section IIC2 for sample weather maps.

## C. Spacecraft Power

CPS models power consumption and battery charging for the duration of each planning window. A power allocation associated with each planning window is used to ensure spacecraft power constraints are not violated. In cases where a manually-planned collection plan has a net power consumption (sum battery charge minus net imaging consumption) that is greater than the allocation, the user is notified that there is a violation in the plan.

Satellite-specific power consumption computations are based on configurable background bus power consumption and computed total imaging power consumption (based on the current set of included images and configurable imaging-mode-specific power consumption rates). The battery charging formula is based on a baseline charging rate (a configurable parameter), days since launch (accounts for solar array degradation over time) and the angle profile between solar array normal and the sun vector over the duration of the planning window. The attitude profile for a planning window is of course driven by the selection of included scans and the required slews to maneuver between the scans. The result is the sum battery charge for the planning window.

## D. Spacecraft Data Storage

OTS models data generation rates during imaging. Each scan generates an amount of data equal to the data generation rate for the specific imaging mode (using configurable parameters) multiplied by the duration of the scan. The total data generated during a planning window equals the sum of data generated by all scans included in the collection plan for that window.

Data storage modeling results are valid as long as the total data generated is less than the data storage allocation for the planning window, In cases where a user-defined collection plan generates more data than the allocation for the window, a violation is generated to warn the user.

## E. High-Gain Antenna and Ground Terminal Access

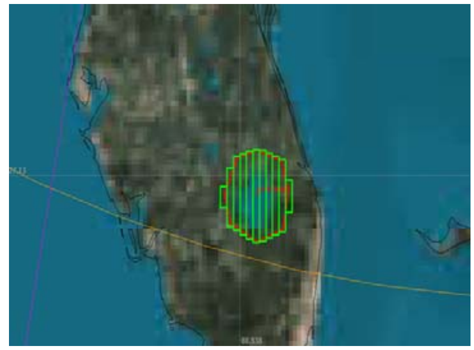
This model only applies to collection plans for "real-time" planning windows (those plans generated for planning windows during ground station contacts with simultaneous real-time or near-real-time downlink of collected images during the same contact).

Ground terminal locations (LAT/LON/HEIGHT) and horizon masks (minimum elevation angle) are modeled in STK and internally by the OTS engine. OTS 's computations are used to verify ground terminal constrained access for the duration of any planning window that is flagged as a "real-time" planning window.

The High-gain antenna Az/El pointing profile is also checked against a blockage table to ensure no structural blockage (antenna pointing through spacecraft structure while tracking the ground terminal) occurs during data downlink for the planning window. High-gain antenna slewing rates and accelerations are also computed to verify that maximum rate and acceleration limits (both configurable) are not exceeded during the planning window. For manually-planned collection plans, the user is notified if any of these access, blockage, or slew limits are exceeded. Automated planning avoids building plans with these constraint violations.

## F. Target Access

Target areas that are non-rectangular or larger than can be imaged with a single scan can be split into 4-corner rectangular strips with a configurable width using an OTS-provided utility. This tool allows large order areas to be split into manageable strips for access computations and planning purposes.



Access start equals the time when both start side corner points of a CO strip are within the satellite Field of Regard and satisfy all target-defined constraints (including min/max incidence angle, min/max azimuth angle, and max GSD). Access stop equals the time when both end side corner points leave the satellite Field of Regard or fail to satisfy all target-defined constraints (including min/max incidence angle, min/max azimuth angle, and max GSD). OTS does not allow a CO scan to extend outside of the computed constrained access window for the CO.

## G. Restricted Access

Restricted areas are defined in STK and displayed on the map display with a bold red outline. OTS verifies that the sensor footprint does not impinge on any defined restricted area during imaging times defined in the collection plan. If any incursions are found, a violation is generated to warn the operator.

## H. Camera

A CPS camera model is provided to help determine the appropriate camera settings for images. Parameters and setting vary by imaging mode and can include line rates, TDI settings, and other camera parameter types generally driven by sun angle and other similar computable values. The camera model is an option that may be disabled in lieu of a configurable default settings or target-defined settings. The operator may override automatically-selected camera settings at any time (although the software will always warn the operator if the selection is contrary to the camera model).

## I. Scan

Based on operator, model, or algorithm-defined target scan start point, scan start time, and imaging mode parameters, OTS computes the attitude profile of the spacecraft necessary to scan the target area. Orbit Logic algorithms automatically adjust for squint angle effects to ensure that no portion of the target area is excluded from the scan. Orbit Logic developed a baseline configurable and mode-specific scan model for OV3 for initial testing and operations, and later integrated a spacecraft-vendor-provided scan model for higher modeling fidelity. Scan attitude profiles are the boundaries for slews within the planning window, so scan attitude profiles are computed first, with slew profiles computed to string the scan profiles together (see Section J, below).

## J. Attitude Slews

Attitude slews are computed from the planning window starting attitude to the start of the first scan, between scans, and from the end of the last scan back to the default safe spacecraft attitude (generally a sun-pointing attitude). OTS integrates a spacecraft-vendor-supplied black-box slew function to compute spacecraft slews.

Every time a scan is modified or a new scan added during the OTS collection plan definition process, two new slews (slew to scan start and slew from scan end) must be verified and computed. Inputs and outputs from the slew functions generally include:

Inputs:

- o t = delta time from start of slew in seconds (double)
- o q1 = start quaternion (offset from ECI frame)
- o w1 = start rate in spacecraft body frame
- o a1 = start acceleration in spacecraft body frame
- o q2 = stop quaternion (offset from ECI frame)
- o w2 = stop rate in spacecraft frame
- o a2 = stop acceleration in spacecraft frame

Outputs:

- o t = delta time from start of slew in seconds (double)
- o q = quaternion at time t (offset from ECI frame)
- o w = body rate at time t (in spacecraft body frame)
- o a = body acceleration at time t (in spacecraft body frame)
- o Enumerated message ( 0 = no message, 1 = general fault)

OTS uses the computed slew attitude profiles, along with the scan attitude profiles, to build the overall planning window attitude profile. The boundary window attitude profile is used to compute any attitude-related violations.

When a slew cannot be completed in the time requested, or the Slew Function cannot converge on a solution, OTS provides information to allow the operator and/or algorithm to adjust scans (direction, imaging parameters, or start time) so that spacecraft slew/agility limits are not exceeded. Algorithms make these adjustments automatically.

Several configurable parameters used by the Slew Function are available for review and editing by the OTS operator. Slew Function parameters are generally adjusted only after infrequent spacecraft calibration activities.

### K. Sensor Exclusion

Spacecraft star trackers and cameras generally have bright object pointing constraints defined by spacecraft and camera vendors. Some of these constraints are "hard" and must be avoided in any collection plan, and some are "soft" in that they are allowed but may degrade image quality or geolocation accuracy. OTS predicts bright object incursions based on sensor models, spacecraft position data, bright object (sun and moon and sun glint point on the Earth) position propagation computations, defined minimum off-boresight angle, and the slew/scan attitude profile over the duration of planning windows.

OTS makes these predictions AFTER each scan is "included" in the collection plan (only then is a partial or complete planning window attitude profile known). There are no pre-computed violations since these would be target-specific and start time specific and it would be inefficient to pre-compute violation-free scan start windows for thousands of targets within the satellite field-of-regard during a planning window. Violations are resolved by changing the scan start time or removing that target from the plan (either manually or via automated scheduling algorithm).

## IV. Optimization Algorithms

OTS utilizes a competition between multiple optimization algorithms to create the best collection plan. Each algorithm (Orbit Logic currently provides eight proprietary optimizing algorithms) attack the collection planning problem in different ways. Each algorithm attempts to maximize its scoring of a common (and configurable) Figure-of-Merit (FOM). The collection plan solution with the highest FOM score is chosen.

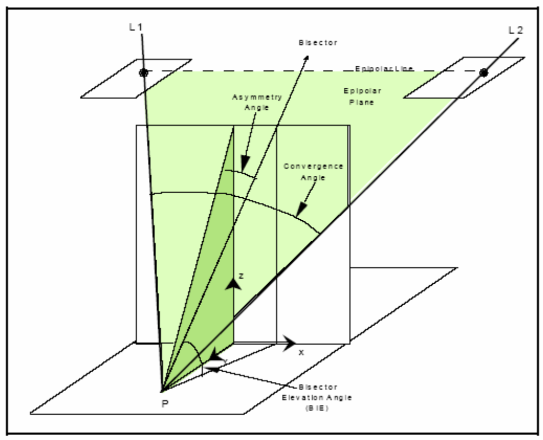
Some algorithms provide better solutions when the targets are close together while others excel when the targets are spread apart. All algorithms are designed to always return a valid collection plan even if manually interrupted or timed-out. The algorithms generally complete their processing in a matter of seconds or minutes (depending on target deck size, scan and slew profile, planning window length, etc.)

The FOM is composed of a term evaluating the efficiency of the overall plan and a summation of the scores for each included scan. The score contribution of each scan is based on several factors including order priority, cloud cover prediction, order area, days remaining until the order expires, imaging resolution, and more. The weighting for each of the terms can be changed by adjusting configurable constants. Because the FOM is only loosely coupled to the scheduling algorithms, even an entirely new FOM is relatively easy to integrate, if needed.

## V. Other Planning Considerations

### A. Stereo Planning

Stereo collections are supported in both manual and automated plan generation processes. By default, both stereo scans must be completed within the same imaging window. Stereo geometric constraints (convergence angle, bi-sector elevation angle, and asymmetry constraints) are supported by the software and are configurable within the target specification. Violation of any stereo-related constraint in a collection plan is highlighted to the operator in the manual planning process. Automated planning adheres to all specified constraints.




### B. Reasons Not Collected

Inevitably questions will arise about why a specific order was not included in an automatically-generated collection plan. The planning algorithms can potentially make millions of decisions to generate a single collection plan for even a relatively short planning window. An operator could not possibly read through a log of algorithm decisions... it is just too much data.

OTS, however, provides (in response to a user query related to a specific unscheduled target) a list of any targets included in the plan during the queried target's access window and within a configurable time window before and after its access period. This may allow the user to lock in the desired target in place of the originally included target.

### C. Plan Statistics

The OTS planning GUI provides summary statistics for the current collection plan (whether in process or one that has been retrieved for review). These statistics include total area collected, number of included scans, power and data storage information, and total scan time.

Whenever the current value is outside a configurable or hard-coded range, the field text is highlighted in red. For instance, whenever the remaining power is negative, it is shown in red. These statistics and highlighting assist the operator in identifying and resolving problems and helps guide manual planning.

### D. Validation and Verification

OTS uses models to verify that generated collection plans respect resource, attitude, and imaging constraints. Target access constraints cannot be violated since OTS does not allow scans to occur outside of computed constrained access windows. Other constraints can be violated in manually-generated plans, but the user is notified of any violations with messages and color-coded display indications.

Each violation is operator-configurable to be "BLOCKING" or "ALLOWED". OTS precludes the transmission of any collection plan that includes one or more BLOCKING violations. CPS requires user-confirmation prior to the transmission of a collection plan with one or more ALLOWED violations. The Figure-of-Merit (FOM), which is used to score algorithmically and manually-generated collection plans, penalizes plans for constraint violations.

### E. Plan Management

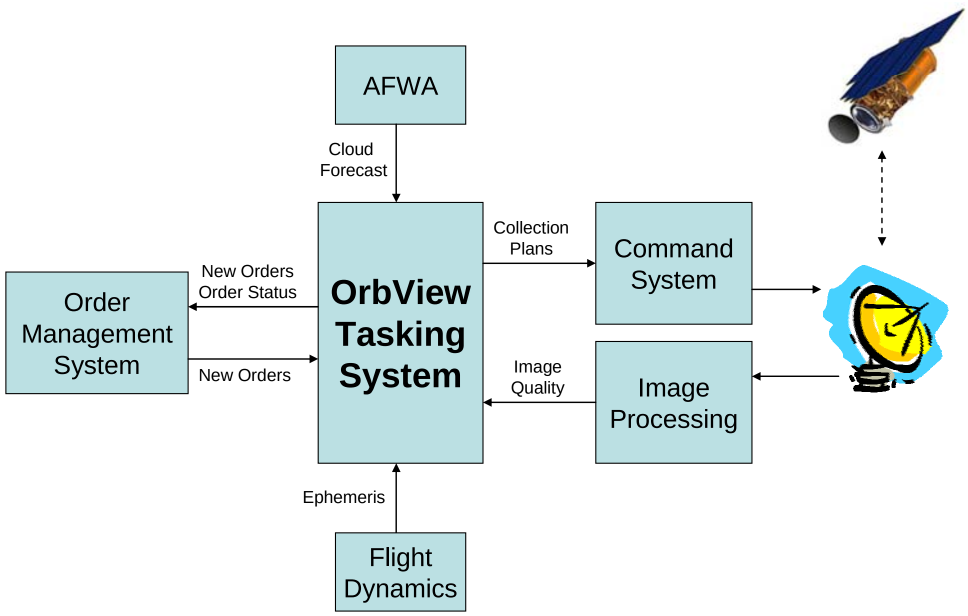
Collection Plans generated manually or by using the algorithms may be saved for later recall, editing, and transmission. OTS supports the creation and saving of multiple collection plans for the same imaging window, although once a plan is committed (sent to the command system (see Interfaces, below)), the software precludes another plan from being sent.

Order management software in OTS tracks order status. Orders included in a committed plan have their status modified to preclude these orders from being re-collected on another pass. See Closing The Loop, below, for additional order status management information.

### F. Closing the Loop (Interfaces)

OTS is just one component of a larger ground system used for the operation of an imaging satellite. OTS provides interfaces to accept new collection orders from an Order Management System, to receive ephemeris files and cloud cover forecasts from external systems, and to send collection plans to the command system for execution.

OTS also receives image quality feedback from the image processing component. This feedback allows OTS to manage CO status, and change an order to “completed” status for successful image quality reports, or to modify an order’s status to ensure its re-collection if the image quality was unacceptable for some reason (usually cloud cover).



## VI. Day-In-The-Life Operations with the OrbView Tasking System

OTS is used for collection planning before every opportunity to uplink new plans to the satellite. An operator uses the CO filter process one or more times to determine what's available. Several factors are considered with each run through the filter such as constrained access, weather forecast, and priority. However, priority does not always reflect the absolute priority of one CO to another so manual filtering on user group is performed first. For example, Group A and Group B both might submit an order with the highest possible priority. But the priority is relative to themselves, not to the total set of collection orders. The OTS operators know that Group B in general may have a higher group priority over Group A. So the operators look for Group B first. Certain user groups are of a higher priority to the business than others, so the operators attempt to make sure we've included all possible orders from those groups. If none are available, the OTS operators will filter through again looking for other available collections.

After the CO filtering process is complete and candidate COs are found, the operator manually kick's off the automated planning algorithms. Business directives sometimes require that an operator manually select an individual CO to be included in the Collection Plan. The operator will include and lock such CO's, and then kick off the automated planning algorithms.

If the collection window was under-populated with possible COs for collection and the plan can still accommodate more imagery, then the operator will manually create one or more COs on the spot to include in that plan.

The last step before handing off the plan to the command system is for the operator to play the plan on the STK Map Display, getting a visual feel for how the S/C will perform the planned imaging activities.

## VII. Summary and Future Development

The OrbView Tasking System (OTS) used for OrbView-3 planning by GeoEye uses a variety of system models and constraint computations before, during, and (in the case of manual planning) after planning operations to provide an efficient means of generating valid collection plans. By competing multiple planning algorithms and scoring their solutions using a common Figure-of Merit, a level of optimization is achieved. To address changing business goals and other operational issues, a high level of configurability is provided. And to support manual planning as well as manual review and editing of auto-generated plans, an animated STK map GUI provides situational awareness for the operator. These capabilities combined with the interfaces implemented with other ground system components provide an operationally-proven, efficient, and seamless closed-loop planning function for OrbView-3.

While OrbView-3 is an extremely capable imaging satellite, the next generation of commercial imaging satellites (GeoEye-1 from GeoEye and WorldView-1 from DigitalGlobe) will provide even better resolution and a significant increase in agility and onboard storage space. With these enhancements in capability come greater planning software challenges. Orbit Logic is addressing these challenges with a scalable architecture that includes lights-out automation for multiple planning workstations operating in parallel while still retaining an operator interface for manual planning. Orbit Logic is delivering the enhanced architecture solution to GeoEye and DigitalGlobe before the end of 2006 to support the upcoming launches of the GeoEye-1 and WorldView-1 spacecraft, respectively. The new systems will also support planning for the vendors' existing spacecraft (OrbView-3 or QuickBird-2, respectively) on the same enhanced architecture system.