

ANALYSIS FOR MONITORING THE EARTH SCIENCE AFTERNOON CONSTELLATION

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The Earth Science Afternoon Constellation consists of Aqua, Aura, PARASOL, CALIPSO, CloudSat, and the Orbiting Carbon Observatory (OCO). The coordination of flight dynamics activities between these missions is critical to the safety and success of the Afternoon Constellation. This coordination is based on two main concepts, the control box and the zone-of-exclusion. This paper describes how these two concepts are implemented in the Constellation Coordination System (CCS). The CCS is a collection of tools that enables the collection and distribution of flight dynamics products among the missions, allows cross-mission analyses to be performed through a web-based interface, performs automated analyses to monitor the overall constellation, and notifies the missions of changes in the status of the other missions.

INTRODUCTION

The development of programs and missions involving constellations and formations of spacecraft represents an increasing trend within the scientific community. The ability of multiple spacecraft and the instruments they host to conduct coincident observations of targets results in a powerful investigative capability. However, with these new approaches and the benefits they offer come increased mission design challenges and heightened levels of responsibility to ensure proper coordination and safety among the spacecraft involved. Techniques to define, implement, and maintain the constellation/formation required must be developed. Management approaches and relationships to ensure collaboration and coordination among the mission management teams involved must be established and maintained. Fundamental to addressing these challenges and the responsibilities of mission management are access and sharing of information and constant monitoring of the health and safety of the constellation/formation. To implement these functions, new types of systems and tools must be developed to ensure on-demand access to the most up-to-date information and automation of routine analysis tasks to provide constant monitoring of the spacecraft comprising the constellation/formation. The implementation of these tools, specifically those associated with monitoring the status of the constellation/formation, is the focus of this paper.

To better explore the methods and types of systems and tools used to monitor the status of constellations and formations of spacecraft, the Earth Observing System (EOS) Afternoon Constellation is considered. Section 2 presents an overview of the EOS Afternoon Constellation. The spacecraft comprising the constellation are identified. The Flight Dynamics (FD) techniques used to define, implement, and maintain the constellation are reviewed. Section 3 describes the current approaches to managing and coordinating operation of the Afternoon Constellation. The methods employed by EOS management are summarized. The collection of tools used to support the management of the constellation, known as the Constellation Coordination System (CCS), is summarized. Section 4 focuses on the specific capabilities implemented within the CCS to automate and report on analysis tasks associated with monitoring the constellation.

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THE EOS AFTERNOON CONSTELLATION

EOS is a collection of missions, spacecraft and data systems, working together to study the Earth's land masses, oceans, and atmosphere over long periods of time. The spacecraft of the EOS program are varied, operating independently of one another and in groups as constellations and formations. Two primary constellations exist within EOS, the EOS Morning Constellation and the EOS Afternoon Constellation. Spacecraft comprising the Morning Constellation form a train, one essentially following the other, as they move from north to south through the descending nodes of their respective orbits. The spacecraft comprising the Afternoon Constellation form a train as they move from south to north through the ascending nodes of their respective orbits. The missions associated with each of these constellations work together to coordinate operations and perform coincident science observations of the Earth.

The remainder of this section identifies and describes the spacecraft comprising the EOS Afternoon Constellation, their orbital characteristics, and the manner in which the constellation is defined and maintained.

Members of the EOS Afternoon Constellation

The Earth Science Afternoon Constellation currently consists of three operational spacecraft: Aqua, Aura, and the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL). These three satellites will be joined by CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) later in 2005, and by the Orbiting Carbon Observatory (OCO) in 2008.

The spacecraft comprising the Afternoon Constellation are managed by a variety of organizations. Aqua and Aura are operated by the Earth Science Mission Operations (ESMO) Project from the EOS Operation Center (EOC) at the NASA Goddard Space Flight Center, Greenbelt, MD. PARASOL is operated by the French Centre National d'Etudes Spatiales (CNES) from the Spacecraft Operations Control Center (SOCC) in Toulouse, France. The CALIPSO spacecraft is operated by CNES from the SOCC in France, while the instrument activities are coordinated through the Mission Operations Control Center (MOCC) at NASA Langley Research Center (LaRC). CloudSat is managed by the NASA Jet Propulsion Laboratory (JPL) and will be operated from the Research, Development, Test and Evaluation Support Complex (RSC) control center at Kirtland Air Force Base in New Mexico. OCO is a JPL-managed project and will be operated by Orbital Sciences Corporation from a control center in northern Virginia.

Orbital Characteristics of the EOS Afternoon Constellation Spacecraft

The mission orbits of the satellites in the Afternoon Constellation are frozen, sun-synchronous, repeating ground track orbits with equatorial altitudes of approximately 705 km. The orbit plane is inclined approximately 98.2° to the equator with a mean semi-major axis of approximately 7077.7 km. This orbit results in a 16-day, 233-revolution repeat cycle. Because all of the spacecraft in the Afternoon Constellation are in similar orbits, simultaneous and near-simultaneous measurements of the Earth's land masses, oceans, and atmosphere can be made.

Any repeating ground track orbit can be referenced to a set of equally-spaced ground track nodes.³ These nodes correspond to an ideal orbit, one that is circular and unperturbed by atmospheric drag or the tesseral gravity field. The ideal satellite, by definition, will have a ground track that crosses the equator precisely at the referenced nodes. However, a true orbit will deviate from this ideal as perturbations act upon the orbit, causing the actual satellite to have a different equator crossing time, Figure 1. This difference in time results in the spacecraft being out of phase, $\Delta\Phi$, measured as the difference along track between the actual and ideal equator crossing. In addition, during this time between the actual and ideal crossings the Earth will have rotated an amount $\Delta\lambda$. The corresponding distance measured along the equator that the true ground track deviates from the ideal reference node is the ground track error.

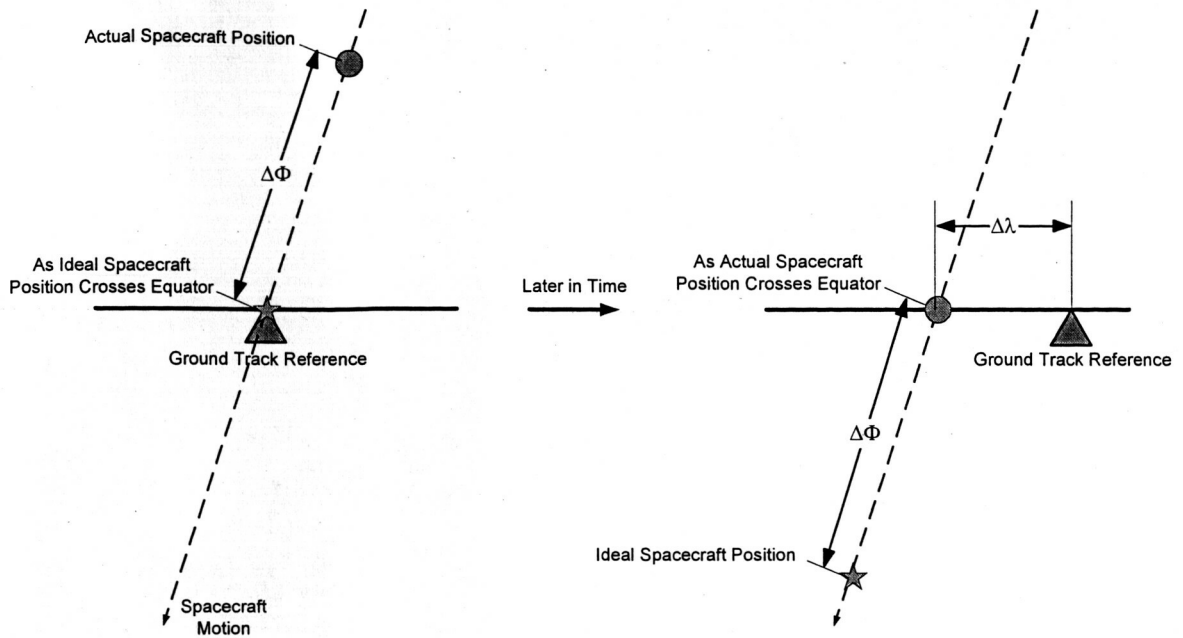


Figure 1. Relationship between Ground Track Error and Phase of a Spacecraft Relative to a Ground Track Reference Point

The dominant perturbation that causes a ground track error is atmospheric drag. As drag causes the orbit to decay, the true satellite will cross the equator sooner than the ideal satellite. If it is desired to maintain the ground track within a set distance of the reference nodes, orbit-raising maneuvers are required. These maneuvers will raise the true semi-major axis above the semi-major axis of the ideal orbit and reverse the drift of the ground track error. The maneuver strategy based on maintaining the ground track error within a desired band around the reference orbit is referred to as longitude targeting.^{6,7}

The same 16-day, 233-revolution repeat cycle being used by the Afternoon Constellation has been used by Landsat-4, Landsat-5, and the EOS Morning Constellation satellites: Landsat-7, Terra and the Satellite de Aplicaciones Cientificas-C (SAC-C). Each of these spacecraft has a requirement to maintain its ground track at the descending node within a specified distance of the reference path of the Worldwide Reference System 2 (WRS-2), a standard reference ground track developed by the Landsat project. Locations along the WRS-2 are often designated by one of the 233 Paths, numbered sequentially from 295.4° East longitude, and as one of the 248 Rows, numbered north and south of the equator. A given Path starts at Row 1, which is at 80.78° North latitude. The Path heads south and crosses the equator (Row 60), then proceeds to 81.85° South latitude (Row 122). It then proceeds northward to the equator (Row 184) and on to 81.85° North latitude (Row 246). The ground track path heads South a short distance until it reaches Row 1 again. At this point the path number is incremented by 16. After 233 orbits (16 days), every path has been traced and the cycle repeats.

Definition and Maintenance of the EOS Afternoon Constellation

A number of fundamental concepts are utilized to define and maintain the EOS Afternoon Constellation. Most important of these are the control box and the Zone-of-Exclusion (ZOE). The characteristics of the Afternoon Constellation and the use of these concepts to manage the constellation are discussed below.

Though the six missions in the Afternoon Constellation have overlapping and complementary science goals, they are operated as independent missions. The spacecraft are said to be flying in "constellation" since they are all in similar orbits and fly in relatively close proximity to each other. The location of each spacecraft in the Afternoon Constellation has been selected to meet the mission's individual science goals and to allow the orbit maintenance strategies of each mission to be independent of the others but "coordinated" when necessary. The CloudSat science goals require that, in addition to flying in

constellation with Aqua, it will fly in formation with CALIPSO. Formation flying implies that the maneuvers of two (or more) spacecraft are coupled so that a desired geometry is maintained. This means that CloudSat's position is not independent and is determined relative to the actual position of CALIPSO. Because of differing ballistic coefficients, CloudSat will have to periodically lower its orbit so that it can catch up to CALIPSO. Formation flying also requires that CloudSat match all orbit-raising maneuvers performed by CALIPSO.

Figure 2 shows the relative position of each spacecraft as they fly in their respective orbits. If the spacecraft were unaffected by atmospheric drag and had perfectly matched inclinations, the relative positions of each of the spacecraft within the constellation would remain constant.

Since the orbits are not perfectly matched and are affected by atmospheric drag, the spacecraft drifts. Therefore each mission is expected to maintain its spacecraft within a specified region or "control box" around its ideal position in the Afternoon Constellation, Figure 2. The stars in Figure 2 mark the ideal reference location of each spacecraft within the Afternoon Constellation. Aqua is the lead satellite in the Afternoon Constellation; its ideal equator crossing time marks the start of the constellation. The location of each of the other satellites, both ideal location and actual location (indicated with a circle), is measured from this ideal point, with the exception of CloudSat, which measures its location relative to CALIPSO. Each spacecraft can maneuver independently within its control box without affecting the other missions. The parabolic motion within the control box of each spacecraft as its orbit evolves over time is known as the circulation orbit. Thus a fundamental concept related to the definition and maintenance of the Afternoon Constellation is the control box.

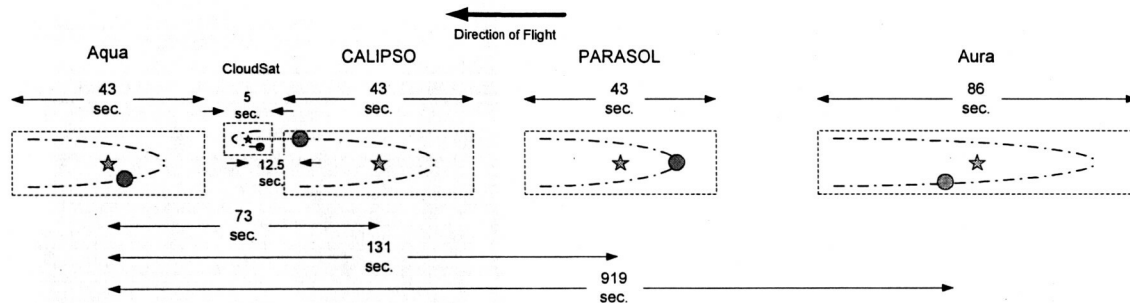


Figure 2. Definition of Control Boxes for the EOS Afternoon Constellation

(The ideal position of each spacecraft within its control box is identified with a star. The actual position of each spacecraft and its movement within the control box as its orbit evolves is illustrated with a circle and dashed line respectively. Note that the OCO spacecraft, which precedes Aqua by 9 minutes and 51 seconds, is not included in this figure)

A control box is a representation of the goals that the orbit maintenance strategy must achieve. A control box may be defined to meet the science requirements of the mission or to help ensure the health and safety of the spacecraft. The Afternoon Constellation uses two interrelated definitions of control box. The first, the ground track control box, is the distance from an ideal reference ground track that the satellite actively maintains within a desired band by performing maneuvers. The second, the phasing control box, is the difference in equator crossing time between an ideal satellite and the actual satellite. The latter is used in the Afternoon Constellation to determine whether a member satellite is in its expected position within the constellation.

While the ground track control box is measured in terms of distance from the WRS-2 ideal reference nodes, the phasing control box is defined in terms of the "relative phase" of each satellite with respect to the lead satellite. The relative phase is used to describe the position of the spacecraft within the Afternoon Constellation with respect to Aqua, the lead satellite.¹⁰ The relative phase of any satellite in the constellation, $\Delta\Phi$, is the difference between that satellite's equator crossing time t_n , and the ideal equator crossing time of the lead satellite, Aqua, t_{ni} :

$$\Delta\Phi = t_n - t_{ni} \quad (1)$$

The separation of equator crossing times ensures that two spacecraft in the constellation will never arrive at the intersection point of their orbit planes at the same time. Phasing the spacecraft also reduces conflicts at the polar ground stations used by many of the missions.⁹ This separation in equator crossing time helps to eliminate radio frequency interference between the satellites and allows the ground antennas to slew back from tracking one spacecraft in order to track the next spacecraft. If the lead satellite crosses the equator precisely at one of its reference nodes, its phase is zero (refer to Figure 3). If it deviates from the reference ground track, the ground track error $\Delta\lambda$ can be used to calculate the lead spacecraft's phase $\Delta\Phi$ as:

$$\Delta\Phi = \frac{\Delta\lambda}{\omega_E R_E} \quad (2)$$

where ω_E is the Earth's rotation rate and R_E is the radius of the Earth.

For the other satellites in the constellation, the relative phase $\Delta\Phi_2$ can be calculated by measuring the equator crossing time difference between the lead and following spacecraft. The phase of the lead satellite, $\Delta\Phi_1$, is then added to this difference to give the phase between the following spacecraft and the ideal location of the lead spacecraft, as shown in Figure 3.

$$\Delta\Phi_2 = (t_2 - t_1) + \Delta\Phi_1 \quad (3)$$

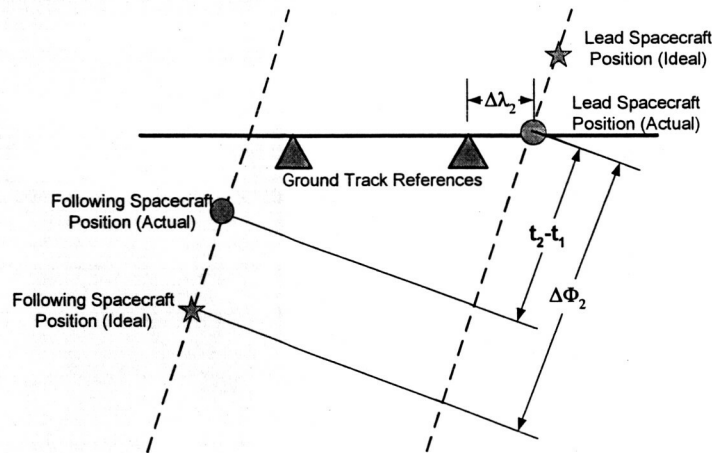


Figure 3. Relative Phase of a Following Satellite

The location of a control box can be described either as an absolute control box, measured from the front of the constellation or from a reference ground track, or as a relative control box, measured relative to the location of another satellite or the actual ground track of another satellite. Aqua uses an absolute control box measured to the WRS-2 reference ground track, while all other missions in the Afternoon Constellation use absolute control boxes measured from Aqua's ideal location. The exception is CloudSat, which uses a relative control box, measured with respect to CALIPSO's location.

In addition to the control box, a second concept fundamental to the management of the Afternoon Constellation is the ZOE. The ZOE is used to ensure the health and safety of the individual spacecrafts in the constellation. The ZOE is represented by an ellipsoidal region around each satellite, much smaller than the control box, which is considered a 'no-fly zone' for all other satellites. Currently each Afternoon Constellation satellite uses the same size ZOE, a 2 km x 25 km x 25 km region (radial, along-track, and cross-track respectively). In general, entry of a satellite into another's ZOE triggers evaluation of whether an evasive maneuver by either satellite is required. Each mission has agreed to plan their entrance and exit from the Afternoon Constellation such that they do not enter the ZOE of any of the other missions. Thereafter, entry into a ZOE is expected rarely, such as in the event that a spacecraft becomes disabled and unable to maintain its position within the constellation. Procedures related to ZOE violations are

documented in the Afternoon Constellation Operation Coordination Plan¹³ and the Afternoon Constellation Contingency Procedures document.¹⁴

COORDINATION OF THE EOS AFTERNOON CONSTELLATION

The spacecraft comprising the Afternoon Constellation are varied. The spacecraft are operated independently of one another while at the same time their operations are coordinated with the other members of the constellation. In addition, the spacecraft are managed by a variety of organizations. The result is a diverse set of requirements and a complicated system of spacecraft, organizations, and personnel. To address these requirements, new management approaches and relationships must be established and new tools must be developed to support the overall coordination of the constellation.

Management Approaches and Relationships

To ensure the safety and success of these missions, coordination during mission planning and mission operations is critical. The ESMO Project at GSFC has helped to facilitate the coordination of activities between these missions by establishing a Mission Operations Working Group (MOWG). The MOWG provides a forum for technical exchange among the mission teams involved in the Afternoon Constellation. The MOWG develops the Operations Concept and Contingency Procedures for the Afternoon Constellation. In addition, the MOWG sponsors the development of the systems and tools necessary to support the management of the system. This has resulted in the development of the Constellation Coordination System.

Constellation Coordination System

The CCS is a collection of tools that have been assembled to facilitate data exchange and communication and supports the management and coordination of the Afternoon Constellation through user-initiated and automated analysis tasks that monitor the health and safety of the constellation. Much of the functionality of the CCS is accessible through a web-based interface though some functionality is fully autonomous. The main capabilities of the CCS include acquisition and delivery of mission data products, access to tools for on-line flight dynamics analysis, performing automatic analyses for constellation monitoring, and notification of constellation status changes. Figure 4 shows the components of the CCS and its interfaces to the CCS user community.

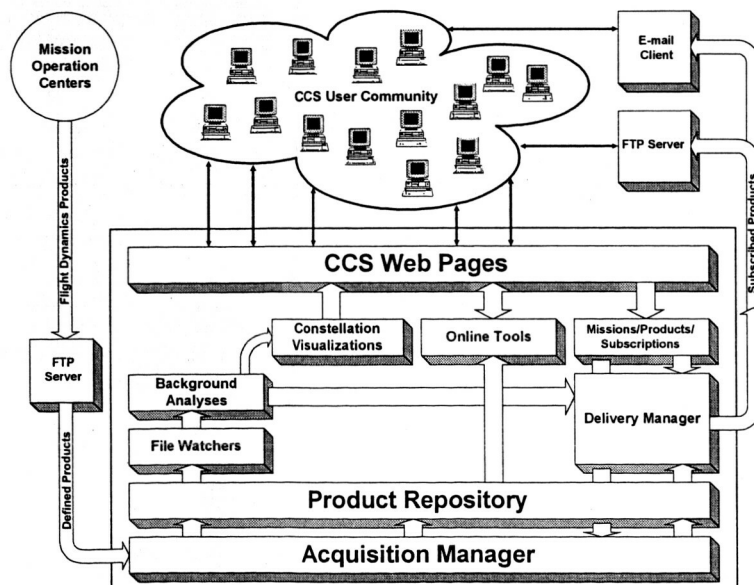


Figure 4. The Constellation Coordination System Overview

The CCS is accessed through the CCS web site. Through the website a user can register for an account and request access (on a mission-by-mission basis) to data products associated with the Afternoon Constellation. Access to the site is limited until the user has been authorized by the mission's point of contact to use one or more mission's data products. Once authorized, the user is able to access the key functionality of the system including the configurable Portal Page, the Product Center, and the On-Line Analysis Tools.

The configurable Portal Page is the first page a user sees after logging onto the site. The Portal Page always displays the status of the Constellation using Status Bars but the user can set up this page to include other frequently-accessed functionality and displays associated with the constellation. Included in the types of information available on the portal page are real-time 2-D and 3-D displays of the Afternoon Constellation, lists of available mission data products, and constellation status visualizations and reports. Figure 5 shows one user's CCS Portal Page. In addition to the Status Bars displayed at the top of the page are the 2-D Current Satellite Location display, the Product Center list, the "MLT View PM", and the WRS Visualization of the Afternoon Constellation.

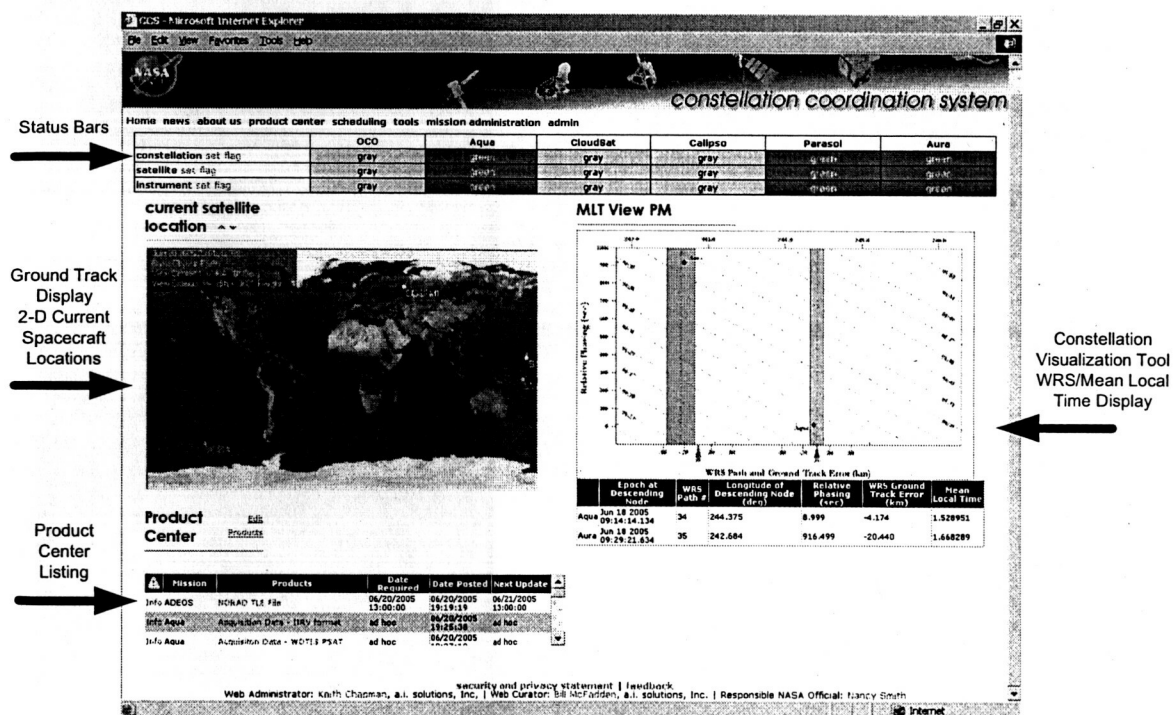


Figure 5. CCS Portal Page

The CCS Status Bars are a mechanism agreed to by the member missions to exchange messages about the health and safety of the individual satellites.¹³ Status Bars display each Afternoon Constellation mission's status with regard to the constellation as a whole, the ability of the spacecraft to maneuver, and the condition of its instruments. The three Status Bars, the Constellation Status, Satellite Status, and Instrument Status, are displayed across the top of all pages in the CCS web site. It is the responsibility of the Constellation Mission Operators (CMOs) from each mission to set/change the status flags for their mission; the CCS does not automatically change any of the status flags based on the Background Analyses it performs. When changing a Status Flag, a short message is entered that will display when a user holds the cursor above the status flag. A longer message can be entered which will be included in the email that is sent once the flag is changed. Changes to the Constellation Status flag always result in an email being sent to the CMOs of all the Afternoon Constellation missions. Changes to the Satellite and Instrument Status Flags can optionally have an email sent. In addition to the mission CMOs, emails can also be sent to the Constellation Mission Administrators or all Authorized Users of the missions.

A major component of the CCS web site is the Product Center. Access to the Product Center is through a product list. The Product Center is a repository of all flight dynamics data products provided by the missions to the CCS. Products that have been acquired by the CCS are available to authorized users through the website for viewing or can be downloaded to the user's workstation. Additionally, a user can subscribe to receive an email when a product arrives on the system or to have the product automatically transferred using file transfer protocol (ftp) to a location of their choosing.

Two displays related to the satellites' ground tracks and locations are available for the user's Portal Page. The 2-D Current Satellite Location is a snapshot of the location of each of the Afternoon Constellation satellites on a Mercator-type plot; the satellite location is computed using the latest delivered predicted ephemeris for each mission. The 3-D display (not shown) depicts the satellite ground tracks over the spherical Earth.

Though the web site is the most visible portion of the CCS, many interactions occur without direct user intervention. This is particularly true of the product acquisition and delivery functionality. The flight dynamics data products used by the CCS are generated by each mission in their respective Mission Operation Centers. Once the data set is generated and vetted by the mission it is posted to a ftp server. The CCS periodically polls the ftp server looking for products that have been defined for it to acquire. Each mission has a CCS Mission Administrator who is responsible for defining that mission's products using the CCS web site. Products found on the ftp server are brought into the CCS and made available through the Product Center. Once acquired by the CCS, subscribers of a product will receive email notification of its arrival and/or the product will be ftp'd to their chosen location. File watchers within the CCS wait for designated products to arrive and trigger the CCS Background Analyses or update the Constellation Visualizations.

The On-Line Tools are analysis modules that allow a user to perform flight dynamics analysis using state data provided by the missions. These data, which may be in the form of state files, ephemeris files, or two-line elements, can be used to produce reports and plots of orbital parameters and events. Displays including multiple satellites can be generated. In addition to the member missions of the Morning and Afternoon Constellations, two-line element data set is available for over 60 satellites, allowing a wide range of analyses to be performed.

IMPLEMENTATION AND AUTOMATION OF CONSTELLATION MANAGEMENT FUNCTIONS WITHIN THE CONSTELLATION COORDINATION SYSTEM

In addition to providing general access to information and supporting the overall management of the Afternoon Constellation, the CCS provides a number of functions designed specifically to automate routine analysis tasks and report on the status of the constellation. Through these functions continuous monitoring of constellation parameters, control boxes and ZOE's of each spacecraft, is performed. The elements of the CCS responsible for performing these functions are identified and described below.

Constellation Status Bar

The Constellation Status Bar is used to indicate whether a spacecraft is within its control box (mission flag is set to green), predicted to leave its control box (mission flag is set to yellow), or is predicted to enter the ZOE of another spacecraft (mission flag is set to red). As discussed in the previous section, it is the responsibility of the CMO(s) from each mission to set/change the status flags for their mission. The CCS does not automatically change any of the status flags based on the analysis tasks performed but does notify the CMO of a spacecraft of possible constraint violations based on the analysis performed (discussed below). When changing the Status Flag, the CMO can enter a message that will be sent to the CMOs of the other Afternoon Constellation Missions. The CMO can also choose to have the status change message sent by the CCS to a wider distribution.

Visualization Tools

Two visualizations of the Afternoon Constellation are available to be placed on the CCS Portal Page to support management of the constellation: the Control Box Visualization and the WRS Visualization. Both can provide at-a-glance indications of the current configuration of the Afternoon Constellation, either with respect to each mission's control boxes or with respect to the WRS-2.

The Control Box Visualization, Figure 6, shows two side-by-side x-y plots. On the left hand side is a plot of mean semi-major axis versus ground track error. This ground track error is relative to the control box that each spacecraft is maintaining with respect to the WRS-2. The colored bands represent the ground track control boxes of each spacecraft; since the size of the PARASOL, CALIPSO and Aqua ground track control boxes are the same (± 10 km), only one band (in this case, the blue Aqua band) is visible for those satellites. The largest (orange) band depicts the Aura control box limits of ± 20 km while the very small band (red) shows the CloudSat ground track control box of ± 1 km of the CALIPSO ground track. In this example, all 5 satellites shown are at the center of their ground track control boxes and thus are exactly on the WRS-2 path (or path offset) they expect to follow.

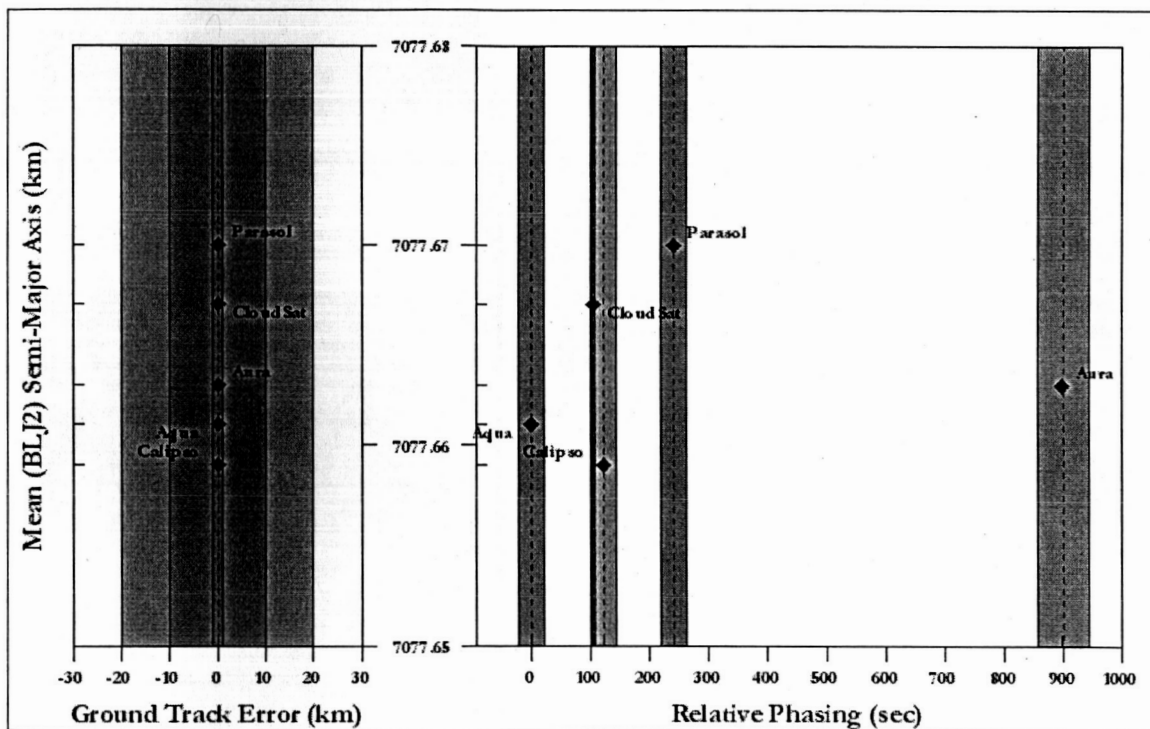


Figure 6. Control Box Visualization

On the right hand side of Figure 6 is a plot of the mean semi-major axis versus the relative phase of each spacecraft. This shows the spacing and alignment of each spacecraft within the constellation relative to the ideal Aqua location. The user can think of this as looking at the constellation from the side, with the direction of motion as towards the left, since Aqua is the lead satellite. In this example, all 5 satellites are in the center of their phasing control boxes. As the satellites drift through their circulation orbits, their positions within their depicted representative colored bands will change. It is obvious from this visualization as well as the WRS visualization, the Afternoon Constellation is not configured like a string of pearls, as one might expect. This plot also illustrates the close proximity of Aqua, CALIPSO, CloudSat and PARASOL, while Aura is quite far behind in terms of phasing. The OCO is expected to fly ahead of Aqua by approximately 12 minutes.

The WRS Visualization, Figure 7, is a single x-y plot that shows relative phase versus longitude of the descending node. The WRS-2 paths in the vicinity of the spacecraft are marked as red triangles along the bottom of the graph, along with axis label markers showing the distance in kilometers from the WRS. The ground track control box for each spacecraft is shown as a colored band. The dashed lines represent the mean local time (MLT) at the ascending node. This plot is designed to show the relationships between the equator crossing difference, or phase, the ground track error, and the mean local time.

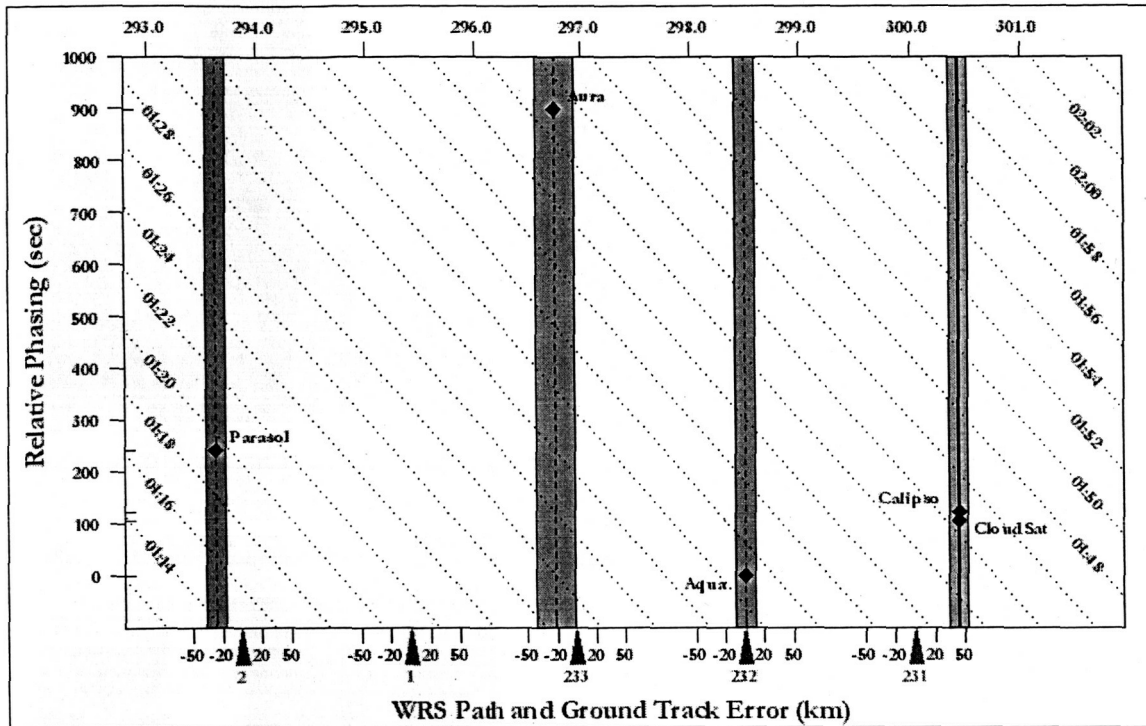


Figure 7. WRS/Mean Local Time Visualization

Automated Analysis Tasks

The Background Analysis component of the CCS performs two analyses specifically targeted to the Afternoon Constellation. Triggered upon receipt of predicted ephemeris data from the missions, these analyses use the concepts of the control box and the ZOE to monitor the status of the Afternoon Constellation. The first of these analyses is performed to check that the satellites in the Afternoon Constellation are predicted to stay within their respective control boxes. The second analysis is triggered if a satellite is predicted to leave its control box. This analysis examines whether the satellite that has left its control box is predicted to enter the ZOE of any of the other missions.

The first Background Analysis, referred to as the Control Box Analysis, is triggered each time a predicted ephemeris from one of the member missions is posted to the CCS. When triggered, the Control Box Analysis will confirm that CCS has ephemerides with overlapping time spans from all the missions currently in orbit. The lead spacecraft is propagated to the first descending node in the overlapping span. Each of the remaining spacecraft are propagated to that epoch and then to their next descending node, where their relative phase is calculated. The spacecraft are stepped forward one orbit at a time through the rest of the overlapping timespan. Three reports are generated by the Control Box Analysis for each spacecraft. A ground track error report, shown in Figure 8, lists the WRS ground track error at each descending node as well as the upper and lower bounds of the ground track control box. A phasing report, shown in Figure 9, lists the relative phase and bounds of the phasing control box.

Epoch	WRS Error (km)	Lower Bound	Upper Bound	EpochText
23999.564690949	-8.163742774	-10.000000000	10.000000000	Sep 21 2006 01:32:36.298
23999.633359606	-8.122320101	-10.000000000	10.000000000	Sep 21 2006 03:11:29.270
23999.702029074	-8.088047120	-10.000000000	10.000000000	Sep 21 2006 04:50:22.312
23999.770699931	-8.159009582	-10.000000000	10.000000000	Sep 21 2006 06:29:15.474
23999.839371053	-8.265585869	-10.000000000	10.000000000	Sep 21 2006 08:08:08.659
23999.908040833	-8.301507130	-10.000000000	10.000000000	Sep 21 2006 09:47:01.728
23999.976709884	-8.267180296	-10.000000000	10.000000000	Sep 21 2006 11:25:54.734
24000.045378414	-8.163610764	-10.000000000	10.000000000	Sep 21 2006 13:04:47.695
24000.114047014	-8.180270428	-10.000000000	10.000000000	Sep 21 2006 14:43:40.662
24000.182717002	-8.205765093	-10.000000000	10.000000000	Sep 21 2006 16:22:33.749
24000.251386701	-8.078875624	-10.000000000	10.000000000	Sep 21 2006 18:01:26.811
24000.320056817	-7.986502352	-10.000000000	10.000000000	Sep 21 2006 19:40:19.909

Figure 8. Ground Track Error Report

Epoch	Phase (sec)	Lower Bound	Upper Bound	EpochText
23999.564690949	17.600721761	-21.500000000	21.500000000	Sep 21 2006 01:32:36.298
23999.633359606	17.511416038	-21.500000000	21.500000000	Sep 21 2006 03:11:29.270
23999.702029074	17.437524783	-21.500000000	21.500000000	Sep 21 2006 04:50:22.312
23999.770699931	17.590517177	-21.500000000	21.500000000	Sep 21 2006 06:29:15.474
23999.839371053	17.820291636	-21.500000000	21.500000000	Sep 21 2006 08:08:08.659
23999.908040833	17.897736520	-21.500000000	21.500000000	Sep 21 2006 09:47:01.728
23999.976709884	17.823729160	-21.500000000	21.500000000	Sep 21 2006 11:25:54.734
24000.045378414	17.600437152	-21.500000000	21.500000000	Sep 21 2006 13:04:47.695
24000.114047014	17.636354759	-21.500000000	21.500000000	Sep 21 2006 14:43:40.662
24000.182717002	17.691320296	-21.500000000	21.500000000	Sep 21 2006 16:22:33.749
24000.251386701	17.417751384	-21.500000000	21.500000000	Sep 21 2006 18:01:26.811
24000.320056817	17.218598089	-21.500000000	21.500000000	Sep 21 2006 19:40:19.909

Figure 9. Phase Report

The third report is only generated in the case for which the spacecraft is predicted to be outside of its phasing control box. This report, shown in Figure 10, is emailed to the person or persons who are designated as CMO for the mission that is predicted to violate its control box. Included in the header of a control box violation report is information about the ephemeris files used in the analysis and the span for which the analysis was run.

CCS Calipso Violation Report
 Analysis Start Epoch: Sep 21 2006 01:07:30.000
 Analysis Duration (days): 6.869791666666670
 Cloudsat Ephemeris: cloudsat_preephan_20060921_01.stk
 Calipso Ephemeris: cal_merephem_20060921123657.stk
 AQUA Ephemeris: aqua_predephstk_2006264_01.stk
 Control Box Values - Phasecenter: 73 sec
 Phasewidth: 21.5 sec

Constellation Epoch	Phase	Phase Requirement
Sep 21 2006 01:32:36.298	96.112999910	94.500000000
Sep 21 2006 03:11:29.270	96.816721954	94.500000000
Sep 21 2006 04:50:22.312	96.856416236	94.500000000
Sep 21 2006 06:29:15.474	96.906524761	94.500000000
Sep 21 2006 08:08:08.659	97.143517340	94.500000000
Sep 21 2006 09:47:01.728	97.462291580	94.500000000
Sep 21 2006 11:25:54.734	97.633736470	94.500000000
Sep 21 2006 13:04:47.695	97.660729367	94.500000000
Sep 21 2006 14:43:40.662	97.549436978	94.500000000

Figure 10. Control Box Violation Report

The second Background Analysis, referred to as the ZOE Analysis, is triggered each time a Control Box Violation is detected during the Control Box Analysis. The ZOE analysis takes the spacecraft that is outside of its control box, the reference satellite, and compares its location to the other constellation members. The

range between the reference spacecraft and the other spacecraft is calculated at each step in the ephemerides. Figure 11 shows the report that is generated from this calculation, including the total miss distance and the components of the miss vector centered on the reference spacecraft in the U-V-W frame. The CCS uses the Alfano/Negron Close Approach Scheme (ANCAS)¹² algorithm to calculate the time of closest approach between two satellites and to determine if the separation distance is within a satellite's Zone-of-Exclusion at that time. While CCS uses the same ZOE size for each Afternoon Constellation satellite, different ZOE sizes can be set by the user for each satellite.

Epoch Days	Range Km	RadialSeparation Km	AlongTrackSeparation Km	CrossTrackSeparation Km	EpochText
23999.547604167	3903.469705559	5.418567661	-3751.209030726	-56.015048801	Sep 21 2006 01:08:00.000
23999.548298611	3927.534237614	5.956083344	-3767.809691436	-193.794687564	Sep 21 2006 01:09:00.000
23999.548993056	3955.102672410	6.455833654	-3782.558784883	-330.790685828	Sep 21 2006 01:10:00.000
23999.549687500	3985.656070930	6.913083654	-3795.212692380	-466.449733595	Sep 21 2006 01:11:00.000
23999.550381944	4018.632714519	7.324224101	-3805.563406372	-600.223824243	Sep 21 2006 01:12:00.000
23999.551076389	4053.440878472	7.686130010	-3813.433716348	-731.572242348	Sep 21 2006 01:13:00.000
23999.551770833	4089.472200097	7.995743622	-3818.693349971	-859.963914301	Sep 21 2006 01:14:00.000
23999.552465278	4126.114135155	8.252176390	-3821.254239450	-984.879567233	Sep 21 2006 01:15:00.000

Figure 11. Range Report

If the components of the calculated close approach distance fall within the ZOE, email notification is sent to the CMOs of both missions involved. The report sent with that notification contains the information shown in Figure 12. Included in this Close Approach Report is the time of closest approach, the components of the miss vector, and the total miss distance. Detailed information about the ephemeris files used is provided so that the analysis may be recreated using the On-Line Tools before further action is taken.

Epoch of Close Approach	Alongtrack (km)	Crosstrack (km)	Radial (km)	Range (km)
Feb 05 2005 03:35:15.547	-18.907064554	0.154383431	-3.345206340	19.201031495
Feb 05 2005 04:24:40.778	-2.416100951	0.132800683	-2.906720822	3.782179099
Feb 05 2005 05:14:06.048	10.377578360	-0.429701907	-3.314828895	10.902836771

Figure 12. Close Approach Report

Upon receiving a Control Box Violation Notice or a Close Approach Report from the CCS, it is expected that the CMO will assess whether the data accurately reflects the status of their spacecraft. On-Line Tools versions of the Control Box or ZOE Analysis can be used to repeat the analysis using the same input data as used for the Background Analysis. The set-up of the On-Line analysis can be saved and shared with other CCS users, allowing personnel at separate locations to run the same analysis and discuss the results. If the information is determined to be accurate, the CMO will set the appropriate Constellation Status Flag for their mission and take the appropriate actions in response to the situation on-orbit.

CONCLUSION

As constellations and formations of spacecraft become more prevalent, the challenges associated with the coordination and management of missions become increasingly complicated. As a direct result, the need for tools to provide access and sharing of information and constant monitoring of the health and safety of spacecraft within the constellation/formation becomes greater, and the requirements placed on these tools become more demanding.

The EOS Afternoon Constellation consists of 6 independently operated and managed spacecraft. Each member of the constellation maintains its position and coordinates its operations tasks within the constellation based on negotiated definitions of a control box and ZOE for that spacecraft. These regions determine the area in which the spacecraft operates and assures no risks to the health and safety of the spacecraft resulting from the close proximity to other members of the constellation.

The CCS is a collection of tools which supports the coordination and management of the Afternoon Constellation by the EOS MOWG and mission teams for the individual spacecraft. The CCS provides access and distribution, visualizations, and on-line tools supporting the analysis and monitoring of spacecraft data. In particular, the CCS supports the coordination of the Afternoon Constellation through a variety of visualizations, reports, and automated analysis tasks developed specifically to routinely monitor the status, health, and safety of the constellation. The CCS is currently operational and supporting the three on-orbit members of the Afternoon Constellation: Aqua, Aura, and PARASOL. As the remaining members of the constellation are launched, the capability to support them within the CCS will be implemented.

In addition to supporting the Afternoon Constellation, the CCS provides similar levels of support to the EOS Morning Constellation of spacecraft. Further, while the EOS constellations are formed from a specific group of spacecraft, interest also exists across the broader science community in determining coincident science collection opportunities with non-member satellites. Missions such as the Ocean Topography Experiment (TOPEX) and the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) have expressed interest in coordinating their observations with Aqua's observations. The CCS has the centralized access, data for the member satellites as well as other missions, and the infrastructure that will allow it to easily expand to provide this service. The enhancement would not only provide analyses to determine coincident science opportunities with non-member satellites, but would also allow the science community to determine when a particular region on the Earth will be observed by the constellation or a specific satellite, e.g. the location of a volcanic eruption.

The CCS has proven itself to be a useful tool for the distribution, analysis, and monitoring of spacecraft data within the EOS Afternoon Constellation. Perhaps more importantly is the ability of the tool to facilitate and enable discussion, cooperation, and coordination among the constellation members and across a broad range of missions extending beyond the constellation.

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