THREE CORNER SAT CONSTELLATION: C&DH, STEREOSCOPIC IMAGING, AND END-TO-END DATA SYSTEM

Elaine Hansen,
Anthony Colaprete, and Dan Rodier

University of Colorado at Boulder
Campus Box 520
Boulder, Colorado 80309-0520
(303) 492-3141
Elaine.Hansen@Colorado.EDU
Anthony.Colaprete@Colorado.EDU
Daniel.Rodier@Colorado.EDU

Brian Underhill, Assi Friedman, Joyce Wong, and Helen Reed
Arizona State University

Stephen Horan and Bobby Anderson
New Mexico State University

Abstract. The Three Corner Sat Constellation (3ΔSat) consists of three nanosatellites, which will demonstrate stereo imaging, innovative command and data handling, and formation flying with RF communications and cellular phone communications. The creation of this constellation is a joint effort between Arizona State University (ASU), the University of Colorado at Boulder (CU), and New Mexico State University (NMSU). The 3ΔSat will provide accurate stereo images and range data of a variety of meteorological phenomena. With three independent nanosatellites observing a particular scene, triangulation will provide accurate range information that will be used to create three-dimensional depth maps. The cooperative communications and control of the satellites in the constellation will allow them to form a virtual formation to accomplish the mission objectives. In this paper, we will describe the science instrumentation and observing approaches, and will report on the distributed operations approach and intelligent End-to-End Mission Operations System, which enable this innovative mission.

Mission Objective

3ΔSat has two primary science objectives. The first is to image local atmospheric events in stereo with a spatial resolution of less than 250 meters. Stereo images of local events, such as cumulus towers, atmospheric waves, and aerosol plumes, will allow the assembly of three dimensional data sets including cloud shape and size. The second objective is to make a global survey of cloud types, thickness, and altitudes. These surveys will assist with climate modeling and prediction by allowing us to create statistical maps of cloud types and properties. Surveys will consist of stereo imaging of clouds with spatial resolutions of approximately 1000 meters and range resolution of 250 meters. There are several advantages in using stereo imaging from space over conventional imaging. The first is to derive range data which can be substantially more accurate than range data acquired by other more traditional means, and also to cover a much greater area. The three nanosatellites will allow stereo imaging and the use of triangulation to determine accurate range data and to create three-dimensional images and depth maps.

A "virtual formation" is proposed and will be demonstrated as part of our primary program. The virtual formation is a cooperative effort between satellites operating as a network to accomplish targeting and data acquisition. Satellite health, status, and science data are transmitted to the ground and to the other satellites via communications links without the need for strict physical proximity between the satellites. This allows the communication links to carry the command and control data necessary to accomplish the mission regardless of the physical location of the satellites. The locations of the satellites will need only to be "in range" and mutually known in order for each to support its portion of the mission, but exact physical separation is not a requirement for the formation network. For accurate stereo imaging, the satellites need a nominal spacing of tens of kilometers. With a controlled deployment to achieve this initial spacing, the satellites will remain in range for the lifetime of the mission, which is anticipated to be at least four months. Given this initial spacing and lifetime, propulsive capability is not needed.

In addition to the conventional RF communication links, 3ΔSat plans to use existing commercial telecommunications network assets in Low Earth Orbit (LEO) for communications and operational coordination as one of the primary experiments for the constellation. This is of considerable interest to the government and private-sector space communities, as it demonstrates how government and private sector users can transition space-to-ground communications away from closed, proprietary networks to generally available, commercial networks. The LEO communications network has the definite advantage of providing extended coverage relative to direct-to-ground broadcasts. With the LEO networks, the 3ΔSat Constellation members can be contacted regardless of their position relative to the university ground stations which have predictable visibility outages. The communications networking influences the design of the End-to-End Mission Operations System (EEMOS), which is a distributed space and ground system. The distributed arrangement includes a Satellite Processor Board on each satellite that serves as its local controller, data interface, on-board memory, and processor. By using the communications interfaces, 3ΔSat Constellation operations can be controlled and managed by a processor on one of the three satellites while the other two satellite processors are reserved for local control, target selection, data filtering, and imaging synchronization.

Stereo Imaging

Stereo imaging from space has several advantages over conventional imaging, the most obvious being the ability to derive range data. This range data can be more accurate than range data acquired by more traditional means and, at any instant, covers a much greater area. Stereo imaging involves correspondence matching between an image pair and calculation of the resulting disparity. From the disparity, triangulation can be used to produce range data, three-dimensional images, and depth maps. Accurate depth maps with range resolutions of about 250 meters enable the study of relatively small-scale, short-lived atmospheric events such as cumulus-cloud towers.

Zones of deep convection, in areas such as the Midwest, frequently create large cumulus towers that extend from the middle troposphere into the lower stratosphere. These zones of convection are highly unstable and frequently impassable to air traffic. Radar, while able to warn aircraft of large convection cells, is unable to give accurate data as to their extent in altitude. Thus, air traffic is frequently diverted hundreds of miles regardless of the altitude extent of the convection cells. With better measurements of cloud heights, some air traffic may be able to traverse these convective boundaries by flying over areas of shallow convection.

Cloud heights are critical to our understanding of the Earth's climate and our ability to better model it. Because of their dynamic nature, both spatially and temporally, incorporating clouds and their effects into Global Circulation Models has been difficult. One key piece of data that is missing is the height and thickness of clouds at a global level. Using stereo imaging, we plan to measure the heights of clouds with a precision of less than 250 meters and make a statistical study of their type, height, and thickness.

In the last decade, studies have indicated that just as important as clouds, other aerosols, including mineral aerosols such as dust or sand, play an important role in Earth's climate system. Recent experiments have been undertaken to understand the composition, structure, and distribution of mineral aerosols on both a local and global scale. Stereo imaging allows the statistical study of aerosol cloud structures, such as sand storms, and can provide information on the relationship between uplift efficiencies (the local ability to lift aerosols off the surface), boundary-layer thickness, and particle sizes with local environments.

As the time between traditional satellite imagines can be long (minutes), highly dynamic objects such as clouds and dust storms are currently stereo imaged in a way that makes the range data inaccurate. Stereo images from the GOES8 and GOES9 weather satellites have proven the effectiveness of using two satellites to view the same scene, however, these satellites can only view together for a few hours per day, and, since they have relatively low image resolution, the range data is poor. For highly dynamic objects, several satellites with relatively good resolution need to image the same location at the same time. By using a formation of satellites, stereo images of small, highly dynamic objects can be made, and from these stereo images, accurate range data can be calculated.

The 3ΔSat imaging system is designed to meet the requirements set forth by the mission objectives, including both high and low resolution stereo imaging of objects changing spatially on time scales of less than 1 minute, with a range resolution of <250 m. In addition to these mission requirements, several programmatic requirements also need to be met, such as low power, low mass, low volume and low cost. To meet all of the requirements, advanced imaging technologies and distributed operations are used.

Imaging Concept

To achieve the range resolution needed, a baseline between each image of at least 30 km downtrack is required. This baseline can be created virtually by flying a single imager over a target and imaging at the start and finish of the fly over. However, such a method requires the spacecraft to fly for several minutes at ~3000 km after the first image before it can make the second image. In this time the scene that is being viewed may change, thus leading to false disparity between image pairs, or "stereo blur." This is particularly a problem with atmospheric phenomena such as clouds and waves. To avoid stereo blurring, two spacecraft with an estimated 30 km between them will simultaneously view the same location. The 3ΔSat Constellation will also be able to simultaneously view the same location with three spacecraft, flying one after the other, each having its own imaging system. Two of the spacecraft have "passive" imaging systems, while the third has an "active" imaging system. The passive images consist of two sensor systems, each with two selectable fields of view, for a total of four image fields per spacecraft. The active imager consists of a single sensor system and a two-axis motor-driven pointing mechanism. The two passive spacecraft fly in front of and behind the active pointing spacecraft (see Figure 1).

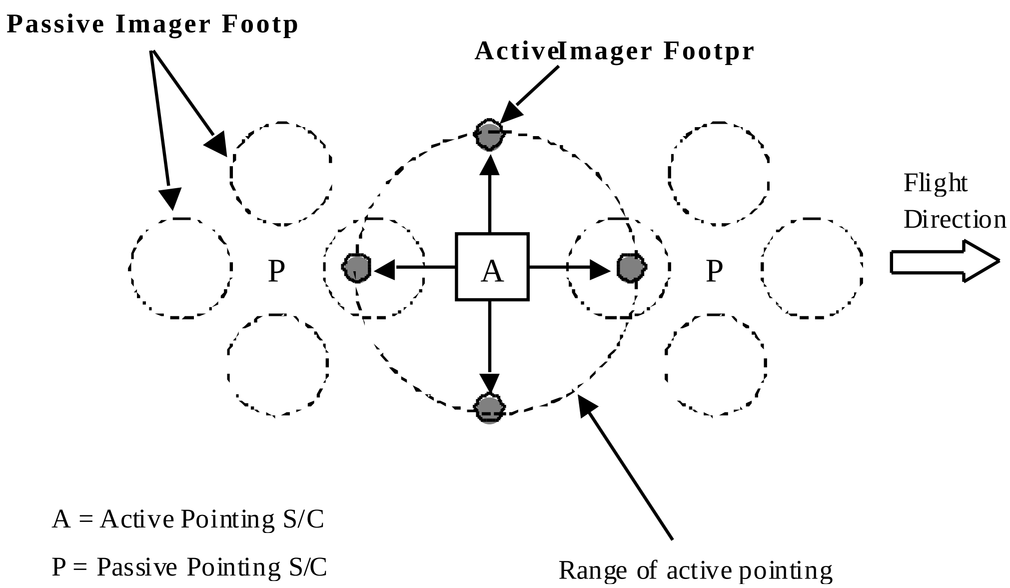

Figure 1. The mission concept includes three spacecraft flying in formation. Two of the satellites have passive imaging systems, while the third (center S/C) has an imaging system with active pointing control.

The passive imaging spacecraft fields of view are pointed off nadir by 30°, and are rotated from one another by 90°, as illustrated in Figure 1. Each field of view is approximately 30°, allowing a very large area to be viewed at any instant with low spatial resolution. As described above, using the forward flight of these passive spacecraft alone will enable us to create stereo images. This quality, coupled with the large fields of view, will provide near global coverage with low spatial resolution, thus allowing us to make the statistical surveys required by the mission. To study specific clouds or rapidly changing scenes, the active imaging spacecraft will be utilized.

Since the spacecraft are passively gravity gradient stabilized, the inherent error in their pointing stability will cause the passive imaging footprints of the two spacecraft to meander to within 30° of the active imaging spacecraft. The active pointing imager can then acquire images within the field of view of either of the two passive spacecraft. Even though these two images have differing spatial resolutions, accurate range data can be determined with the use of inter-pixel interpolation. A star map taken from onboard the active imaging spacecraft will give the attitude of the active imager to within a milliradian. Sun and horizon sensors on the passive imaging spacecraft will give the attitude of the passive imagers to within a degree. Image recognition software on the ground will align the selected image pairs to within a pixel.

Imaging Systems

Both the passive and active imaging systems use similar, if not identical, parts. At the heart of each imaging system is a CMOS active pixel array (APA). These arrays represent the next generation of imaging sensors, providing many features that make them more attractive for space-based imaging than traditional CCD's. An APA does not require the peripheral electronics typically needed by CCD cameras for transferring pixel information across the chip. This reduces the total size and power consumption significantly. For example, a typical CCD may require 25 cm^3 of volume and 3 Watts of power, while a comparable APA is no larger than a processor chip and requires less than 1 Watt. Furthermore, the output of a CCD camera would require the addition of an analog-to-digital converter (ADC), thus consuming more volume and power, while an APA can have an ADC built into the chip.

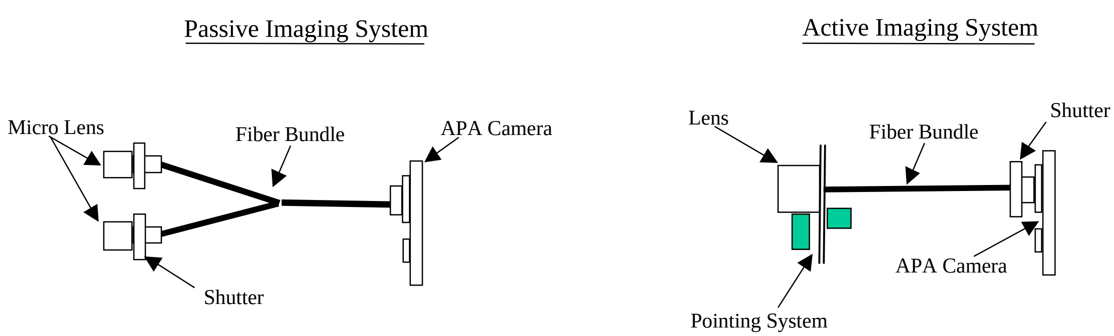

Figure 2. The passive pointing system consists of two micro lenses coupled to the APA (active pixel array) camera via a bifurcated fiber bundle. Each passive imaging spacecraft contains two of the systems shown above (left). The active imaging system consists of a single video lens incorporated in the pointing driver. This lens is coupled to an APA camera by a fiber bundle.

The APA is fitted with a standard C-mount adapter that is coupled to an image fiber bundle. This fiber bundle, comprised of 30,000 individual light guides, receives light from a remote fixed focal length lens. In the case of the passive imaging system, each fiber bundle branches off from the APA camera into two separate f/1.8 micro lenses. Each of these lenses provides a field of view of about 45°, while weighing only a few grams, to meet the small space and weight requirements of this mission. The active imaging system utilizes an f/16 fixed video lens. This lens will provide the smaller field of view (about 7°) needed for the required higher spatial resolution. All shuttering will be done using switchable FLC (ferrous liquid crystal) half-wave plate shutters. These shutters are entirely electrical and have no moving parts, making them reliable and low-power. Shuttering of the active imaging system will be done at the sensor, while shuttering of each passive imager is done at the lens itself. The shutter is closed until power is applied. The layout of the passive and active imaging systems is shown in Figure 2.

Each imaging system will be operated by a low-power micro-controller (e.g., a BASIC Stamp). The total power for the system can be maintained under about 3.5 Watts, with peak draws never exceeding 7 Watts for the passive system and 9 Watts for the active system. Identification of targets, targeting and data processing will be handled by the main flight processor on each spacecraft. Position knowledge from the two passive spacecraft will be relayed to the targeting processor, which in turn will relay commands to the active pointing spacecraft to acquire the target. Data from the two spacecraft with overlapping fields of view will then be processed by the third main flight processor. In the case that any of the three spacecraft fail, raw instrument data from any one of the spacecraft can be downlinked directly.

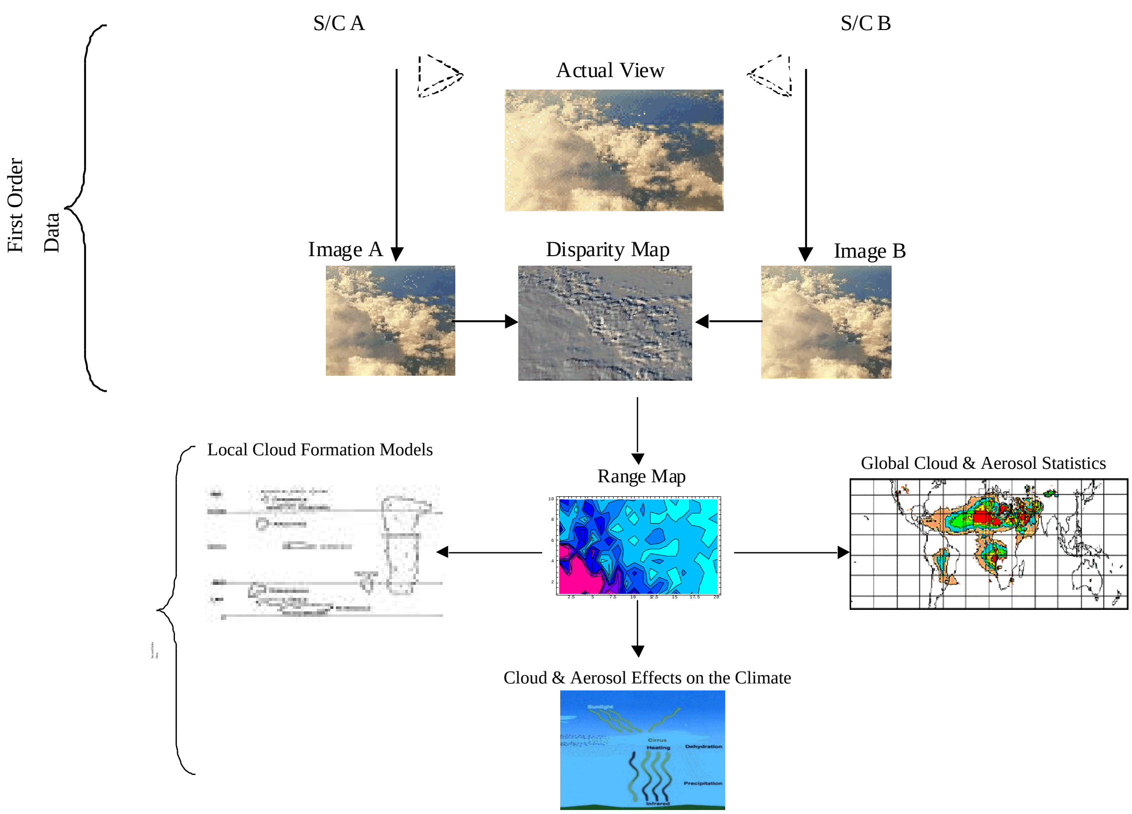

Figure 3. The mission data flow starts with a selection of coincident images from at least two of the three spacecraft. The difference, or disparity, between these two images is then calculated. From this disparity, map range data can be derived, and data products, including 3-D cloud structure and cloud top heights, generated.

Figure 3 shows the general data flow scheme and end data products. Once any two coincident image data sets are downlinked, they are correlated and their disparity is measured. The disparity in the images is the measure of the inter-pixel difference between the two images. From this disparity, maps of the range from the spacecraft to any pixel in either image can be calculated. The altitude of the spacecraft minus this distance will give the heights of the cloud tops. The spacecraft altitude can be derived in a similar way when surface features are visible in an image pair. Multiple range maps can then be compared to derive other data products, such as 3-D cloud structure and global statistics on cloud top heights.

Distributed Constellation Operations

Operations of the 3ΔSat Constellation will be distributed across the three satellites and three University Ground Systems as illustrated in Figure 4. As part of this distributed arrangement, each satellite uses a satellite processor that serves as its local controller, command/data interface, on-board memory and processor.

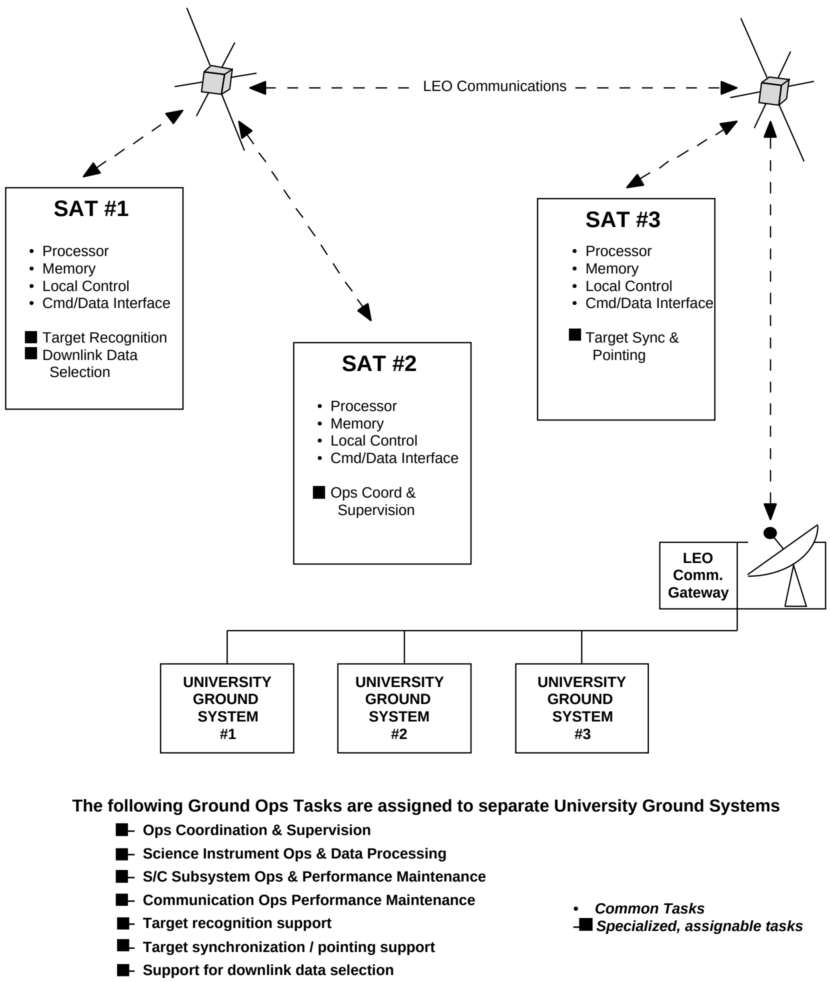

Figure 4. Operation of the 3ΔSat Constellation will use distributed capabilities on the three satellites and three University Ground Systems.

Each satellite processor will be responsible for important constellation-wide activities, in addition to its local functions. The full three-satellite constellation will be controlled and coordinated by a processor on one of the three satellites using the intra-constellation links. This operations coordination function will include supervising the operations of the three spacecraft, managing their resources, detecting and responding to any constellation problems, and coordinating constellation operations.

Additional constellation activities will be accomplished by the other two satellite processors. These activities include recognizing targets such as clouds, selecting science data for downlink, synchronizing science observations, and controlling the pointing of the active science instrument.

The three University Ground Systems are also part of the distributed operations system. Each ground system will be capable of handling any of the ground operations tasks. But instead of performing all of the tasks at each of the sites, processing will be divided among the three universities, and the results shared. The tasks performed by the trio of University Ground Systems include:

- Ground coordination and supervision of Constellation Operations
- Science instrument control, monitoring, calibration, and performance maintenance
- Spacecraft subsystem operations and performance maintenance
- Communication operations and performance maintenance
- Support of target recognition
- Support of target observing synchronization
- Support of active-instrument pointing
- Support of downlink data selection.

Any university team can remotely access and utilize the ground system hardware and software at the other university sites. By working together, the distributed constellation nodes can collectively accomplish the mission without overburdening any one satellite or ground team. The distributed arrangement instead provides for numerous, graceful responses to equipment failures or personnel schedules. If one satellite fails, all tasks can be accomplished and all mission objectives met with the two remaining satellites. If one University Ground System is out of service, all activities can be supported by the other two ground systems. And if a university team wants to break for final exams or a holiday, the other teams can step in and continue constellation operations.

Operations Automation

Operations of the 3ΔSat Constellation will be progressively automated. The 3ΔSat Constellation is designed to be operated by both humans and machines working in a complementary manner. This design enables autonomous operations by both the satellite and ground-based computers, along with manual operations by individuals interactively controlling flight and ground systems from the University Ground Systems.

The distributed arrangement of operations capabilities both in space and on the ground enables the operations style to evolve as experience is gained and as users become more confident in automatic responses to events. At the start of the flight mission, operations will be done manually. Once confidence is obtained in manual operations, they will be automated and accomplished with operator supervision. When confidence is gained in these supervised operations, they will be migrated to the on-board system and accomplished autonomously.

The benefits of this progressive style of automation are many. It enables autonomous operations management, control, and operations responses to be developed and checked out on the ground before migrating autonomy to the on-board system. It enables autonomous capabilities to be balanced — between systems on the ground and in space and between humans and computers — to best meet the needs of the program. It enables autonomous operations and interactive operations to be utilized cooperatively to optimize space experiments and to accomplish this at a lower cost. It enables users to get the most payoff from space missions without expensive pre-launch development of automation and without large development teams.

The 3ΔSat demonstrates methods to automate tasks that are difficult to define in advance (such as health and status monitoring), but are easier to automate as operations experience is gained. The distributed 3ΔSat approach enables autonomy migration through a distributed arrangement of software tools which supports "shared control" of space systems by on-board autonomy, ground autonomy, and ground operations personnel, as illustrated in Figure 5.

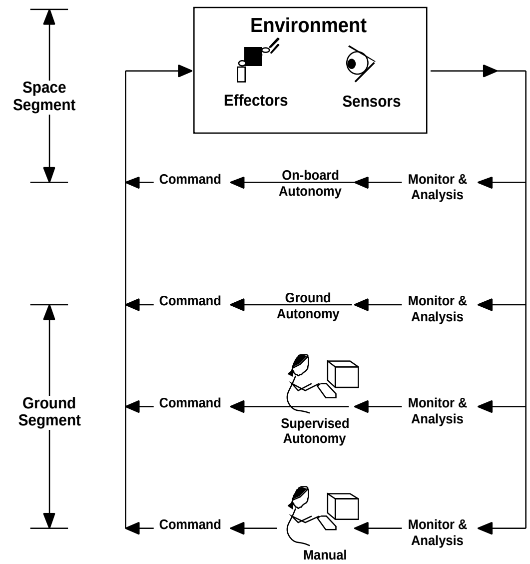

Figure 5. The distributed 3ΔSat Shared Control Architecture provides for a mix of manual and autonomous operations.

End-to-End Mission Operations System

The End-to-End Mission Operations System, or "EEMOS," is a proven, distributed system designed to utilize existing COTS tools and integrated prototypes, to enable interested students to access constellation data products, and to help students analyze science measurements. The proposed operations system is based on the functions, staffing plans, documentation, training techniques, organization, distributed user capabilities, and operational concepts that have been demonstrated on a Hitchhiker payload, manifested on the Shuttle in 1997, and the Citizen Explorer Satellite Mission to be launched in December 1999. Based on the approach demonstrated on these missions, 3ΔSat will use the EEMOS to support all three spacecraft and three university ground systems from early development, through calibration, satellite integration and test, flight operations, and long-term analysis. This approach allows us to produce one low-cost, reliable operations system for use throughout the program. The key elements of this approach are as follows:

- A thorough system-level test and verification of all EEMOS hardware, software, automated procedures, algorithms, and displays are accomplished well before launch, while the EEMOS is being used to support test, integration, and calibration.

- Project engineers, scientists, and operations personnel become familiar with the EEMOS and its user interfaces well before launch. Any enhancements or refinements to the EEMOS are incorporated and tested throughout prelaunch test and calibration activities when impacts to cost and schedule are minimal.

- Operations personnel supporting test activities alongside scientists and engineers acquire extensive on-the-job training and gain an in-depth understanding of the satellite.

- The EEMOS has capabilities both on the ground and on-board. A subset of the capabilities of the ground operations system are duplicated in the on-board satellite processors. This enables important health and safety monitoring to be accomplished autonomously on-board, and enables critical faults to be recognized on-board and responded to without delay.

The EEMOS will support the functions needed to operate the three spacecraft, as illustrated in Figure 6. Planning and scheduling functions are needed to schedule data-taking periods, to prepare command sequences for on-board execution, and to access timelines and orbit prediction data from the local operations database. Coordination, command and control functions are required to control and monitor realtime operations. Data services are needed to receive, process, and disseminate data to scientists, engineers, and the public and to provide formatted satellite data for the other operations functions. Formatted orbit data, along with relevant spacecraft parameters, are analyzed to determine spacecraft orbit and attitude. Formatted and processed science and engineering data, along with definitive orbit and attitude data, are forwarded to the mission database, where they can be accessed and analyzed by team members, schools, and the general public.

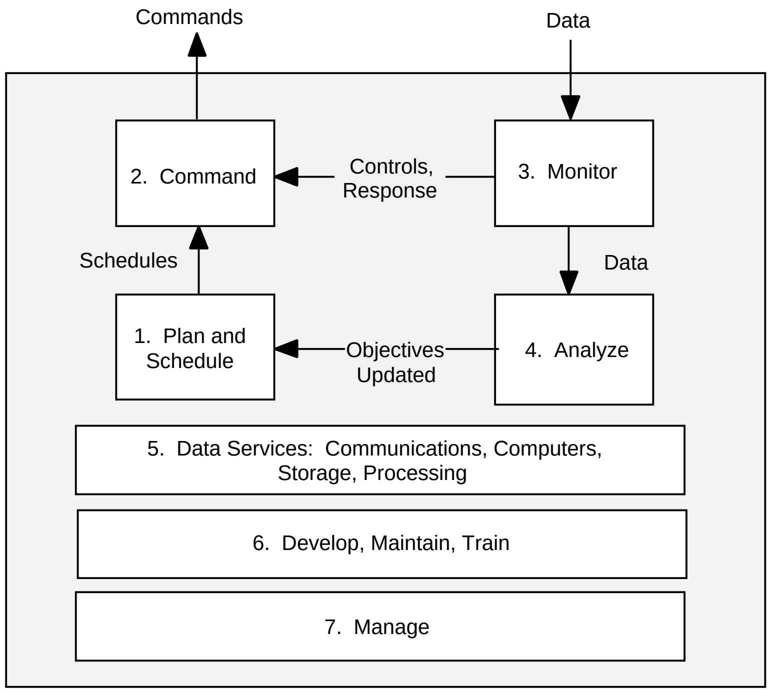

Figure 6. The EEMOS architecture supports the seven basic mission operations functions.

In the EEMOS architecture, these seven functional capabilities are replicated in each of the three University Ground Systems and on at least one of the satellites as illustrated in Figure 7. The functions performed at the three University Ground Systems are concerned with the operation of specific mission subsystems. One Ground System is concerned with Communications System operations; one Ground System is concerned with the operation of the science instruments; and the third Ground System is concerned with the operation of the entire spacecraft and its subsystems. One of these university Ground Systems will also serve as the Ground Coordinator and Supervisor responsible for: coordinating the plans and schedules of the science payload, communications system, and the spacecraft; commanding and monitoring these system segments; receiving, handling, storing, and distributing data; and analyzing the performance of the overall constellation.

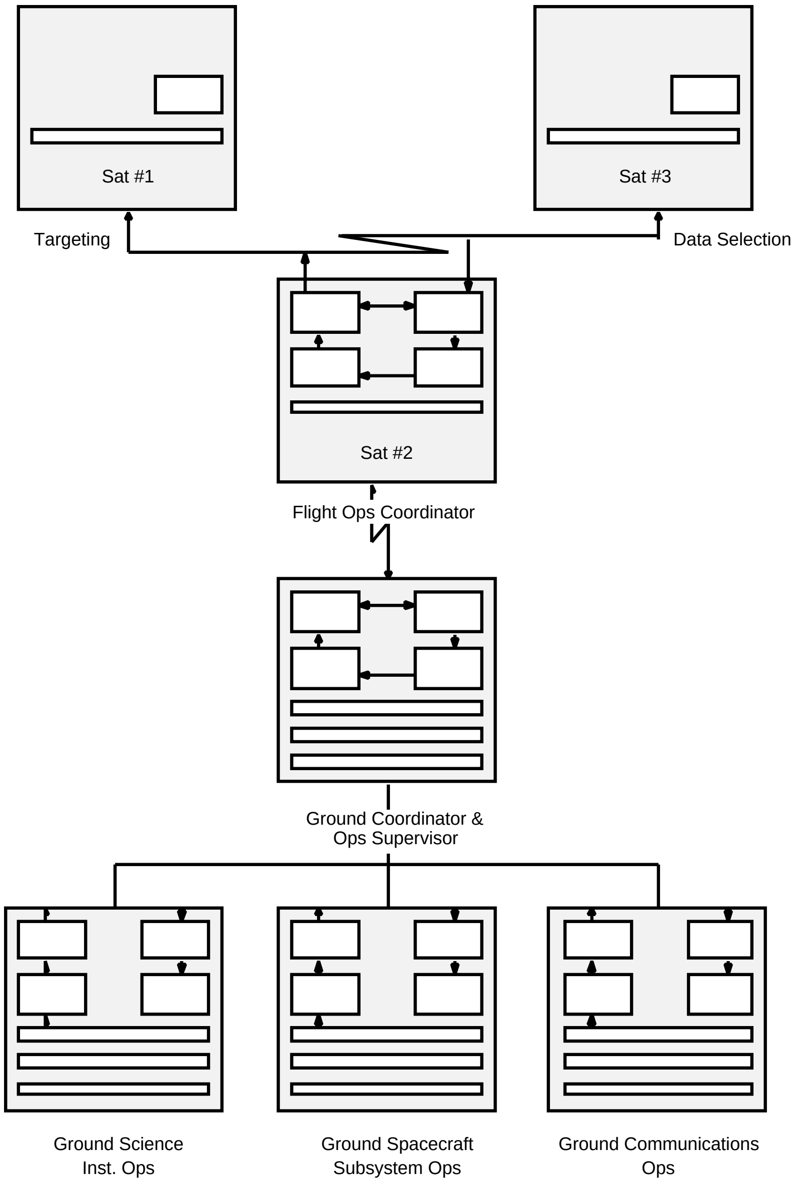

Figure 7. The same seven functions are performed at each location in the distributed arrangement of flight and ground sites.

A key feature of the EEMOS is that it includes the on-board flight system as well as the Ground System. Most of the functions from the ground system are also included on-board. Thus, the flight system has the ability to command and monitor current activities, to halt the ongoing schedule, to process and store data, to evaluate these data, and to access results from the other space processors.

The EEMOS plays a key role in the project beginning at the start of the mission design phase and continuing through the flight mission and beyond. Throughout these phases, the EEMOS evolves to support the project's needs. The flight version of the

EEMOS is the same as that used and evolved throughout the project. This evolution will not end after launch, but continues as improvements are needed and as new tools are available.

Summary

In the past two decades, the importance of clouds and aerosols to understanding the Earth's climate system has been realized throughout the science community. Cloud heights are critical to our understanding of the Earth's climate and our ability to better model it. Because of their dynamic nature, both spatially and temporally, incorporating clouds and their effects into Global Circulation Models has been difficult. One key piece of data that is missing is the height and thickness of clouds at a global level. Using stereo imaging, 3ΔSat will be able to make global statistical surveys of cloud top heights. These surveys will assist with climate modeling and prediction by allowing us to create statistical maps of cloud types and properties.

Higher resolution stereo maps of local events, such as cumulus towers, atmospheric waves, and aerosol plumes, will also be made by 3^Sat. These maps will assist in the understanding of localized cloud and aerosol events. The statistical study of cloud and aerosol structures can provide information on the relationship between uplift efficiencies, boundary-layer thickness, and particle sizes with local environments.

The two science objectives of 3ΔSat include the statistical study of cloud top heights and the study of localized atmospheric cloud and aerosol structures. The imaging system and concept of 3ΔSat is designed to meet these objectives. By utilizing a virtual constellation of spacecraft with a combination of passive and active imaging systems, the required baseline and total number of images needed for this study is achieved. Utilizing the latest in imaging technology, each imaging system meets the programmatic requirements of a nanosatellite mission. Further more, the distributed use of active and passive imaging systems maximizes the science product by allowing flexible, low cost operations.

The 3ΔSat Constellation will conduct stereo imaging of localized atmospheric phenomena and will conduct a nearly global survey of cloud types and cloud top heights. The stereo imaging will be accomplished through the use of CMOS active pixel array imagers. Two of the satellites will utilize a fixed field-of-view orientation while the third satellite will incorporate an active imager pointing mechanism. This approach allows the 3ΔSat Constellation to reach its mission objectives while maintaining simplicity, low cost, and operational flexibility.

The Distributed Operations approach and the EEMOS, with their support of progressive automation, will enable significant cost savings in the development phase, the prelaunch test phase, and the flight operations phase [1]. At the same time, the EEMOS will enable these users to work from their distributed home institutions. The EEMOS is:

Automated to react quickly to events or anomalies to react deliberately to longer-term situations and to migrate operational experience to automated functionality.

Progressive to enable shared control by both on-board autonomous agents and by ground operators — and to enable hard-to-model functions to be automated by migrating sequences to the on-board system which have been proven through operational experience on the ground.

Responsive to unforeseen situations through the incorporation of autonomy.

Self-Monitoring and Reporting to enable the flight system performance to be observed, detected, and classified, and for resultant actions to be selected, executed, and reported.

Easy-to-Use through the inclusion of Graphical User Interfaces which can be evaluated and improved throughout the multi-year design, development, test, integration, and operations phases of the project.

Robust due to the extended opportunity to use, evaluate, and debug the EEMOS prior to launch, and to the architecture which reduces the total software by replicating a common set of software tools and applications for each of the operations teams.

Distributed to involve a distributed set of users at their home sites — including university student controllers and analysts — by incorporating a distributed organization, and communications capability.

Evolvable. The EEMOS evolves throughout the entire pre-launch phase to ensure that it can be evolved during the flight phase as well. This evolution is largely enabled by the use of common tools and applications on the ground and on-board which enable activities to migrate from a ground user, to ground automation, to on-board automation.

Interactive and Cooperative by enabling a mix of manual and autonomous operations while giving the supervisor priority over automated operations, and giving the ground Mission Controllers priority over all functions.

Integrated Space-Ground Architecture by replicating software tools and applications for common functions on-board and at distributed ground sites.

Consistent by enabling one EEMOS to be used throughout all phases of the mission from early design, through development, test, integration, launch, mission operations, and post-mission analysis.

Generic to enable one EEMOS architecture with one set of tools and applications software to support a range of space missions including Earth-orbiting satellites, solar probes, communications satellites, missions to the outer planets, and beyond.

Sponsors

AFOSR/DARPA/NASA Goddard, NASA Space Grant College and Fellowship Program, Lockheed-Martin, Honeywell, Motorola, Kinesix, AFRL, Cogitec, Space Quest, Microchip, Ball Aerospace, Interface and Control Systems, and Spectrolab.

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