Leverage your science data return by flying with the International Earth Science Constellation (ESC)

Michael J. Machado*[a], William J. Guit[a], Warren F. Case[b]
[a]NASA Goddard Space Flight Center (GSFC), Greenbelt, Maryland USA 20771; [b]Arctic Slope Technical Services, Inc., GSFC, Greenbelt, Maryland USA 20771

ABSTRACT

Constellations have proven to be an effective and efficient way to acquire earth science data. By flying together, sensors on all satellites in a constellation take measurements of the same air, water, or land mass at essentially the same time. The sensors form a single "virtual satellite". The key to making a constellation effective and efficient is keeping the operations as independent as possible in order to minimize the operational burden and costs. The Earth Science Constellation (ESC) has been successful on all counts and continues to welcome new missions to continue its 18+ year record of coincidental earth science observations. The ESC also serves as a model for future constellation designs. This paper describes the ESC and its evolution from its initial launches in 1999 through the present and how new missions might benefit from joining the ESC.

Keywords: Morning Constellation; Afternoon Constellation; Earth Science Constellation; A-Train

1. INTRODUCTION

A number of space missions have elected to operate in the same, or in nearly the same orbit for the purpose of making coordinated, co-registered, and near simultaneous science measurements. This is accomplished by matching the orbital parameters and by aligning the orbital positions of these satellites, one relative to another, in such a way that the fields of view of their instruments can overlap while maintaining adequate spacing between spacecraft to ensure mission safety for all constellation members. This allows two or more satellites to measure phenomena at the same geographic or atmospheric location within a few seconds or a few minutes of one another. Two such manifestations of this concept are the Afternoon Constellation (also known as the 'A-Train') and the Morning Constellation of Earth observing satellites. Together, they comprise the ESC of satellites in low earth orbit at 705 kilometer altitude (Fig. 1 and Tables 1 and 2).

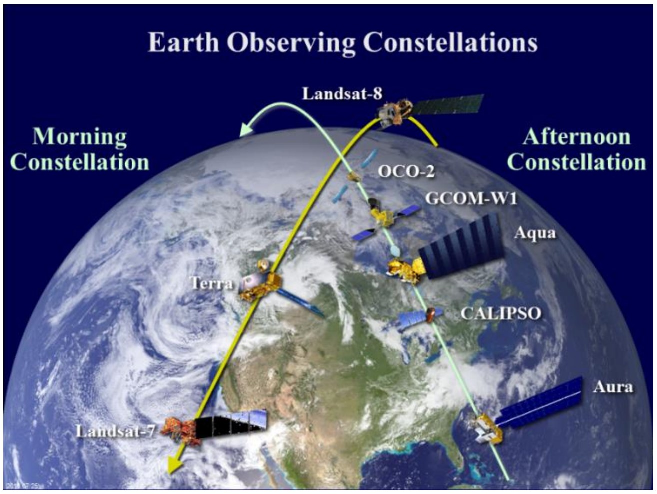

Figure 1. Earth Science Constellation (ESC)

*michael.j.machado@nasa.gov; phone 1 301 614-5677; nasa.gov

Table 1. Morning Constellation Missions

Satellite	Summary Of Mission	Instruments	Launch	Responsible Organization
Landsat-7	Provides global coverage, and spectral characteristics to allow comparisons for global and regional change detection and image data to various international users throughout the world during times of sudden global changes (e.g., earthquakes or floods).	ETM+	April 15, 1999	US Geological Survey (USGS)
Terra	Terra is a multi-national, multi-disciplinary mission that will help us to understand how the complex coupled Earth system of air, land, water and life is linked.	MISR CERES MOPITT ASTER MODIS	December 18, 1999	NASA/GSFC
Landsat 8	Provides moderate-resolution measurements of the Earth's terrestrial and polar regions in the visible, near-infrared, short wave infrared, and thermal infrared. Landsat 8 provides continuity with the 45+ year Landsat land imaging data set.	OLI TIRS	February 11, 2013	USGS

Table 2. Afternoon Constellation Missions

Satellite	Summary Of Mission	Instruments	Launch	Responsible Organization
Aqua	Aqua is named for the large amount of information that the mission is collecting about the Earth's water cycle, including evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice.	AIRS AMSU-A HSB AMSR-E CERES MODIS	May 4, 2002	NASA/GSFC
Aura	Aura (Latin for air) studies the Earth's ozone, air quality, and climate. It is designed exclusively to conduct research on the composition, chemistry, and dynamics of the Earth's atmosphere. Limb sounding and nadir imaging observations allow studies of the horizontal and vertical distribution of key atmospheric pollutants and greenhouse gases and how these distributions evolve and change with time.	HIRDLS MLS OMI TES	July 15, 2004	NASA/GSFC
CALIPSO	Observations from space-borne lidar, combined with passive imagery, lead to improved understanding of the role aerosols and clouds play in regulating the Earth's climate.	CALIOP IIR WFC	April 28, 2006	NASA/GSFC NASA/LaRC CNES
GCOM-W1	The GCOM-W1 observes integrated water vapor, integrated cloud liquid water, precipitation, sea surface wind speed, sea surface temperature, sea ice concentration, snow water equivalent, and soil moisture.	AMSR-2	May 18, 2012	JAXA
OCO-2	Three grating spectrometers will make global, space-based observations of the column-integrated concentration of carbon dioxide, a critical greenhouse gas.	Three grating spectrometers	July 2, 2014	NASA/JPL

The two constellation names are derived from the times of their equator crossings. All Morning Constellation satellites (currently Landsat-7, Terra, and Landsat-8) cross the equator at points where the local time on the ground is approximately 10:30 a.m. This makes these satellites ideal for observations of land processes. All Afternoon Constellation satellites, currently Aqua, Aura, Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), Global Change Observation Mission - Water 1 (GCOM-W1), and the Orbiting Carbon Observatory-2 (OCO-2) cross the equator at points where the local time on the ground is approximately 1:30 p.m., which makes these satellites ideal for observations of atmospheric and water processes. ESC orbits are also ‘sun-synchronous’ since orbital precession is used to maintain similar lighting conditions throughout the entire life of the missions.

The ESC is truly international in scope, involving space agencies from the United States (NASA, the United States Geological Survey [USGS], and the US Air Force), France, and Japan (Fig. 2). Each ESC mission is independently funded and independently responsible for its own mission operations.

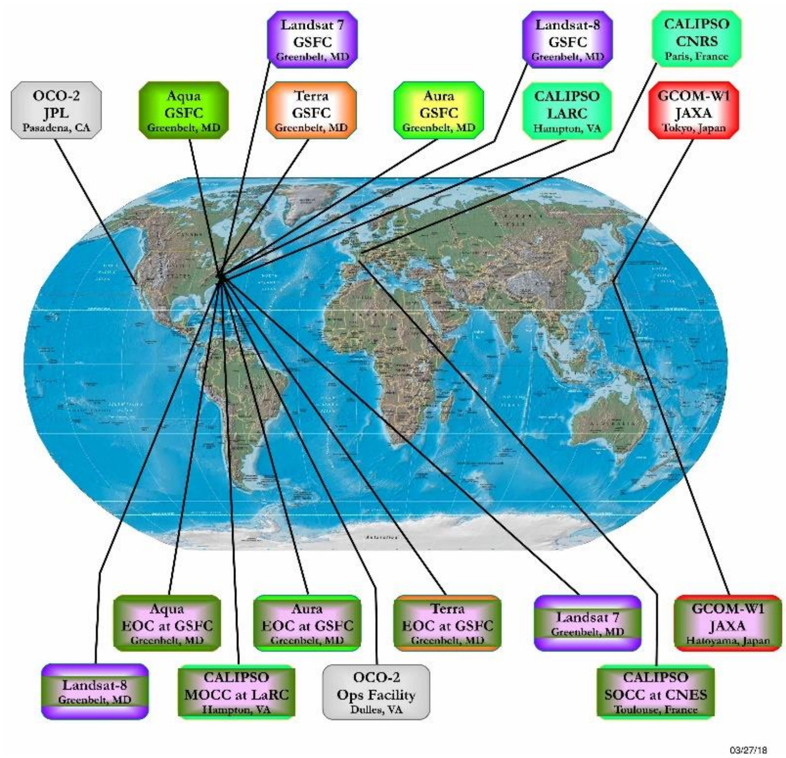

Figure 2. Project management and control centers

2. WHY FLY IN CONSTELLATIONS?

There are two types of satellite constellations of interest:

- A *homogenous constellation* is the better known of the two. It typically consists of dozens or hundreds of similarly built satellites spaced around earth orbit in a way to increase coverage and/or reduce latency. Two examples are the Global Positioning System (GPS) constellation and the Iridium commercial communications constellation.
- A *heterogeneous constellation* consists of a “train” of related (but distinct) satellites generally in the same or very similar orbital plane and altitude with similar objectives. The individual satellites may be built and operated by different organizations. Quite often, the individual spacecraft fly relatively close together. The Morning and Afternoon Constellations (which make up the ESC) are examples of heterogeneous constellation. This type of constellation is the subject of this paper.

A heterogeneous constellation is sometimes referred to as a “virtual satellite” since all the instruments on the various constellation spacecraft are taking measurements of the same air or land mass at about the same time. It is as if the instruments were flying on a single spacecraft. There are several advantages to this constellation approach versus placing all the instruments on one spacecraft.

- **Constellations facilitate cost-sharing.** One spacecraft can be built, launched, and operated by one space agency such as NASA while another spacecraft is built, launched, and operated by another space agency, such as the Centre National D’Etudes Spatiales (CNES).

- **Constellations allow infusion of the latest technology and sensors.** In general, unmanned spacecraft are not able to benefit from technology advancements after launch to improve instruments and subsystems. The well-known exception is the highly successful Hubble Space Telescope which benefitted from servicing missions, however that ended with the retirement of the Space Shuttle. By launching satellites into constellations, users can benefit from the most recent technology advances.
- **Constellations reduce overall risk.** If a single, large free-flying satellite with multiple instruments fails prematurely due to a launch or early mission anomaly, then all scientific measurements are lost. However, if the instruments are spread among multiple satellites in a heterogeneous constellation, then the loss of a single satellite is less impactful. Case in point: the OCO mission failed during launch in 2009 and never reached orbit, but there was enough support in Congress so funds were allocated for a replacement satellite named OCO-2 which launched four years later.
- **Constellations allow more focused observations.** Scientists can use the results of the early missions to design new missions which take advantage of the findings.
- **Constellation satellites can be less complex.** A satellite with only one or two instruments can be much less complex and therefore less costly than one with 10 or more instruments.
- **Constellation satellites can have fewer constraints.** Satellites with fewer instruments typically have fewer constraints when it comes to sharing onboard resources such as power, communications, etc.

3. COORDINATION IMPERATIVE

The primary reason for constellation coordination is to ensure the integrity and safety of the constellation satellites. The Morning Constellation missions launched first and maintained relatively large inter-satellite orbital spacings, so little coordination between mission teams has been required. In contrast, the A-Train satellites have flown as close as only 10 seconds apart, so it became clear at the outset that the A-Train missions would need to coordinate their operations to some extent in order to ensure their missions' safety.

In order to perform these independent and coordinated measurements and thereby derive greater science value than the individual missions alone, each satellite in the Morning and Afternoon Constellations needs to know the trajectory and mission operations plans of the other missions. Each mission has a vested interest in the well-being of the other satellites and of the constellation as a whole by not allowing the orbital configuration to be disrupted or broken. Such a circumstance could allow the safety and/or integrity of another member satellite to be compromised or threatened by collision or close approach. For example, a satellite in a "safe-hold" mode and unable to perform the orbital maneuvers necessary to maintain its location could become an unwitting threat to other constellation members. Under a worst-case scenario, a prolonged anomaly on one or more satellites at the same time could create the need for other satellites to exercise "defensive" maneuvers to avoid a collision.

4. CONSTELLATION COORDINATION

To ensure the safety of all member spacecraft of the constellations, the A-Train mission and science teams created a Constellation Mission Operations Working Group (MOWG) in 2003. The MOWG team members created an *Operations Coordination Plan* which provides high-level agreements among the constellation members that outlined the means for addressing member-related anomalies. This document describes the coordination plans for the constellations, developed to ensure the health and safety of each constellation as a whole and to enable the coincident observations required for science. Note that constellation operations coordination does not extend into the detailed operations of each of the missions. Each mission has an operations plan to follow which is based on each mission's science plan and requirements.

The Earth Science Mission Operations (ESMO) Project at NASA GSFC leads the coordination of all Constellation mission teams, facilitates the exchange of information between missions, independently assesses anomalous situations that may arise, and provides recommendations for remedial actions in the event of anomalies. The mission teams operate their missions independently and maintain their satellites in their respective positions in the Constellation but all missions have a collective responsibility to ensure the safety of the Constellation.

ESC satellites generally follow the Worldwide Reference System-2 (WRS-2) which was originally established by the series of Landsat satellites (Fig. 3). However, the MOWG had to develop an orbital configuration that would determine the range of locations allowed for each mission. The challenge was to devise a configuration that did not place undue maintenance burdens on each mission team's operations.

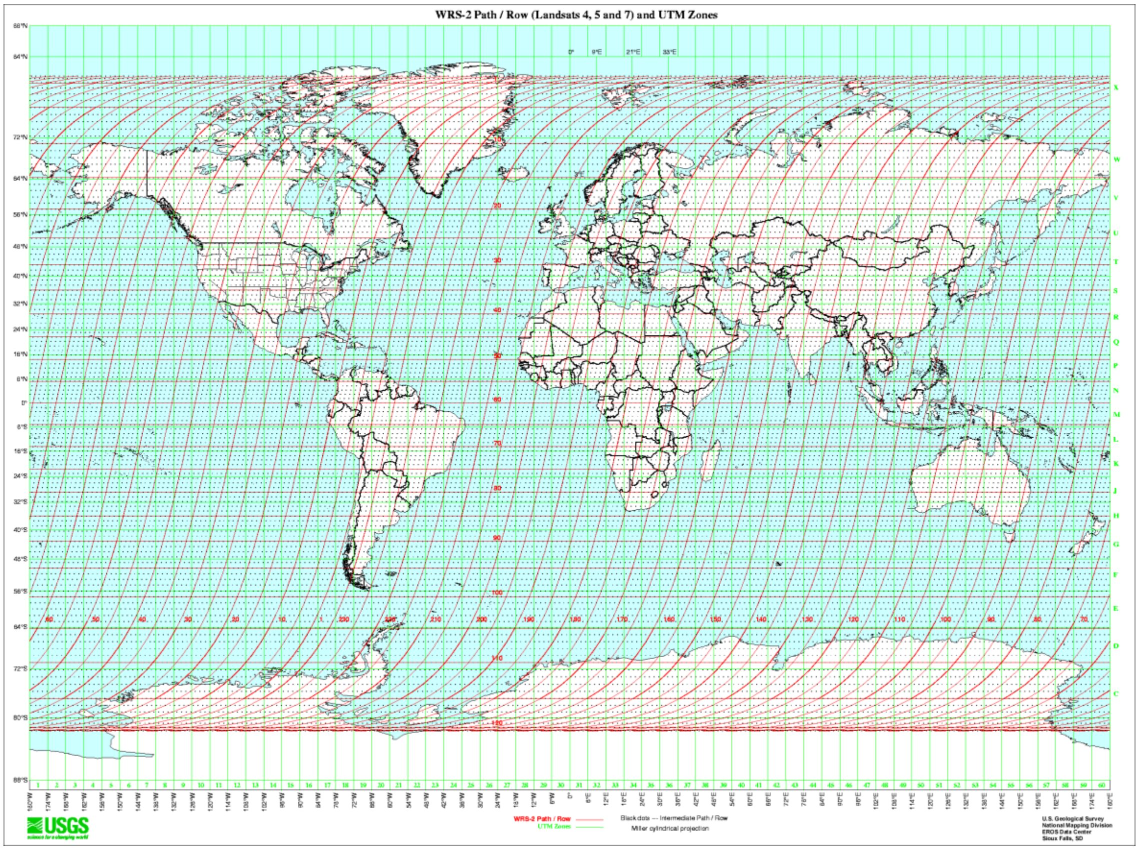

Figure 3. WRS-2 Global Path and Row
(Source: USGS image available at https://landsat.usgs.gov/sites/default/files/images/wrs2.gif)

The MOWG then established a framework whereby each mission was allocated constellation space for its operations; this space became known as its 'control box' (Fig. 4). A control box is a theoretical construct centered at some reference position on a satellite's drag-free orbit with dimensions defined by an allowable along-track movement relative to the box's center (the reference position). In practice, this along-track movement is coupled with an East-West movement of the satellite's ground-track relative to the idealized ground-track of the drag-free orbit in the Earth fixed frame. It is the fact that the limitations in either the along-track or ground track cross-track movements create the notion of a "box". The important point is that a constellation mission can maneuver and move around as much as it likes as long as it stays within the limits of its control box. Hence there is little need to coordinate with other teams on a daily basis, so the costs and complexities of constellation flying are minimized. There are two significant exceptions to this independent flying:

1. All Afternoon Constellation teams coordinate their annual inclination adjust maneuvers in the Spring in order to maintain their science ground track requirements.
2. To enhance their science return, some constellation missions have additionally performed "formation flying" by maintaining the inter-satellite distance within a specified tolerance. This level of coordination is above and beyond that required for constellation flying.

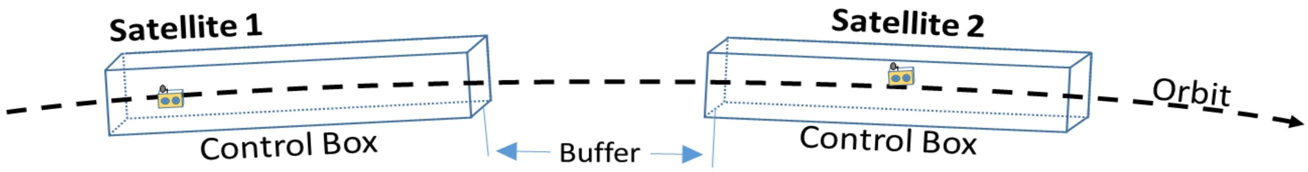

Figure 4. Control boxes for orbital spacing

The MOWG also established guidelines and procedures to follow in the event of spacecraft anomalies. When a satellite anomaly occurs that potentially affects another satellite, members coordinate their efforts to avoid the threat of one satellite drifting dangerously close to another, possibly creating a risk of collision. In some cases, risk mitigation maneuvers may be necessary to avoid collision. These procedures have successfully been followed on more than one occasion.

Another important reason for coordination is to enhance the overall science return. Most satellite instruments operate continuously and produce a steady stream of science data. Some of these data will be made available and shared with other member missions for correlation with their science data. This is the scientific benefit of flying together in the constellation. However, maneuvers come at a cost since they can temporarily interrupt the continuity of the science data stream. Also, if a maneuver occurs at a particularly critical observation time for another satellite, the opportunity for coincident science observations and data correlation will be temporarily lost. Coordination can help mitigate those occurrences.

5. EARTH SCIENCE CONSTELLATION DEVELOPMENT

5.1 Morning Constellation Development

The Morning Constellation currently consists of three on-orbit missions (Fig. 5). Two are USGS missions and one is a NASA mission. Landsat-7 (launched on April 15, 1999) and Landsat 8 (launched on February 14, 2013) continue the 40-year Landsat project of collecting information about Earth from space. Terra was launched on December 18, 1999. Two earlier satellites, NASA's Earth Observing-1 (EO-1) and Argentina's Satelite de Aplicaciones Cientificas-C (SAC-C) satellites were launched together on November 21, 2000. SAC-C was declared lost in August 2013 after 13 years of successful operations. EO-1 was decommissioned in March 2017 after 16+ years of successful operations.

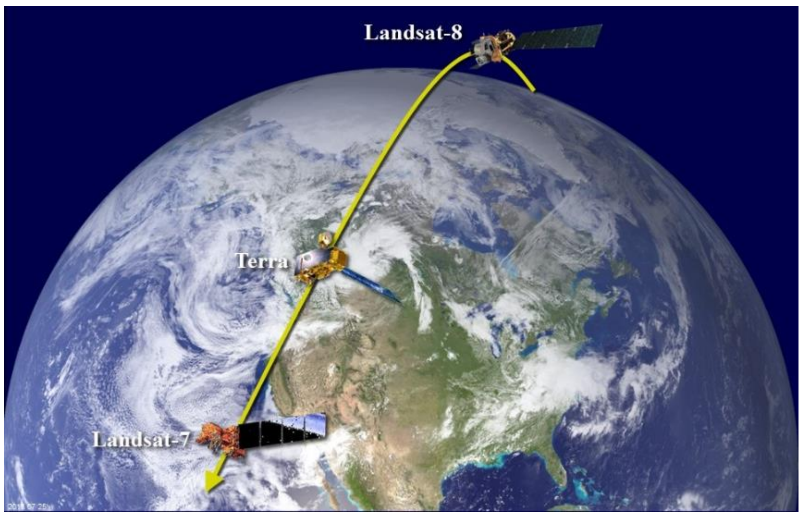

Figure 5. Morning Constellation

These satellites are designated the Morning Constellation because they cross the Equator at between 9:45 and 10:30 mean local time (MLT) at the descending node. This time was chosen because the daily cloud cover is typically at a minimum over land so that surface features can more easily be observed. During their operational periods, the satellite tracks on the Earth's surface, their orbital heights (705 km), and their inclinations (98.2 degrees) are the same.

Both Landsat 7 and Landsat 8 are collaborative efforts between NASA and the USGS to provide moderate-resolution (15 meters – 30 meters, depending on spectral frequency) measurements of the Earth's terrestrial and polar regions in the visible, near-infrared, short wave infrared, and thermal infrared. USGS manages the Landsat 8 mission. The Landsat 8 operations center is at NASA GSFC.

NASA's Terra mission provides global and seasonal measurements of the Earth system, including such critical functions as biological productivity of the land and oceans, snow and ice, surface temperature, clouds, water vapor, and land cover while improving our ability to detect human impacts on the Earth system and climate, and helping develop technologies for disaster prediction, characterization, and risk reduction from wildfires, volcanoes, floods, and droughts.. NASA GSFC manages the Terra mission.

For additional descriptions of the missions and instruments, visit the following websites:

- Landsat 7 – http://landsat.usgs.gov
- Landsat 8 - http://landsat.usgs.gov
- Terra – http://terra.nasa.gov

5.2 Afternoon Constellation (A-Train) Development

The Afternoon Constellation currently consists of five on-orbit missions (Fig. 6). Aqua and Aura are NASA missions. CALIPSO is a multi-national U.S. and France mission with NASA jointly cooperating with CNES. GCOM-W1 is operated by the Japan Aerospace Exploration Agency (JAXA). OCO-2 is a NASA mission. This grouping of satellites provides scientists with the opportunity to perform coincident observations using data from two or more instruments on various satellites with measurements taken at approximately the same time.

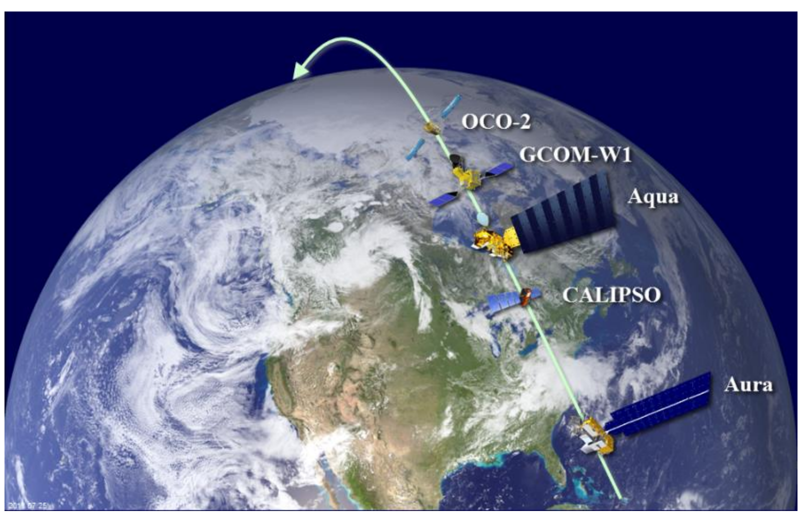

Figure 6. Afternoon Constellation (A-Train)

NASA launched the Aqua satellite on May 4, 2002. On July 15, 2004, NASA launched the Aura satellite and phased it with Aqua such that one of the Aura instruments, the Microwave Limb Sounder (MLS), is able to view the same air mass that Aqua observed eight minutes earlier. In 2008, Aura was moved forward to eliminate this eight-minute delay. CALIPSO was launched with another Earth observing mission (CloudSat) on April 28, 2006 on a single expendable launch vehicle. CALIPSO flies from 30 to 116 seconds behind Aqua. GCOM-W1 was launched on May 18, 2012 and maintains an MLT at the ascending node (MLTAN) that is 259.5 seconds earlier than Aqua's MLT. OCO-2 was launched on July 2, 2014 and maintains its MLTAN to be 25 seconds later than the MLT of the ascending node of Aqua.

In addition, four other missions were once associated with the Afternoon Constellation:

- The PARASOL mission, operated by CNES, was launched on December 18, 2004 and flew between 15 and 58 seconds behind the CALIPSO control box until it left the constellation orbit in December 2009 and subsequently decommissioned in December 2013.
- The CloudSat mission, a joint NASA and Canadian Space Agency mission operated by the USAF, was jointly launched with CALIPSO in April 2006 and was placed in front of CALIPSO by 12.5 ± 2.5 seconds (then later by 17.5 ± 2.5 seconds). CloudSat experienced problems in 2011 that caused it to drop below the A-Train while the CloudSat team corrected the problems. It rejoined the constellation in June 2012 at 60 seconds (minimum) behind CALIPSO. This tight configuration enabled synergistic measurements with Aqua, which is a key science benefit of the Afternoon Constellation. CloudSat finally left the A-Train orbit in February 2018 due to hardware issues. CALIPSO is expected to follow in September 2018 to extend the coordinated scientific observations with CloudSat.
- NASA Orbiting Carbon Observatory (OCO) was launched in 2009 but never made it to orbit due to a due to a fairing separation failure during launch.
- In 2011, NASA's Glory mission suffered the same fairing separation failure and did not reach orbit.

All Afternoon Constellation satellites cross the equator within a few minutes of one another at approximately 1:30 p.m. MLTAN, hence it is referred to as the Afternoon Constellation. Each individual mission has its own science objectives, but all improve our understanding of aspects of the Earth's climate. The synergism that is gained by flying in close proximity to each other enables the overall science results of the Afternoon Constellation to be greater than the sum of the science returns of each individual mission.

The Afternoon Constellation satellites are spread out along-track in the orbit in order to provide room for each satellite's control box and safe spacing between them so that they don't overlap (Figure 7). This relative placement is intended to remain fixed over the lifetime of the constellation, but has been modified with the approval of the MOWG. And, with the placement and spacing fixed, each satellite can conduct its operations essentially independent of the other satellites.

For additional descriptions of the missions and instruments, visit the following websites:

- Aqua – http://aqua.gsfc.nasa.gov/
- Aura – http://aura.gsfc.nasa.gov/
- CALIPSO – https://calipso.cnes.fr/en/CALIPSO/ and http://www-calipso.larc.nasa.gov
- GCOM-W1 - http://global.jaxa.jp/projects/sat/gcom_w/
- OCO-2 - http://oco.jpl.nasa.gov/

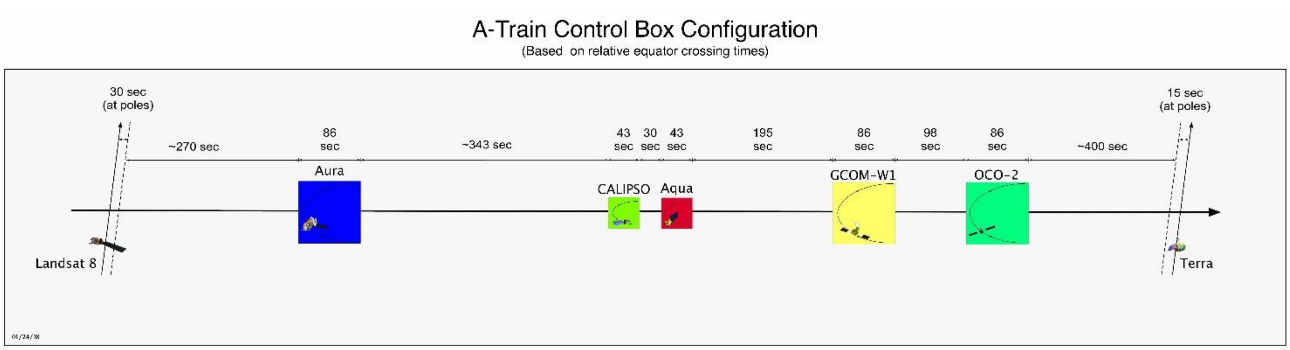

Figure 7. Afternoon Constellation control box configuration

6. CONSTELLATION TOOLS

To ensure safe constellation operations, ESMO developed the Constellation Coordination System (CCS), which is a web-based system to be used by all constellation members to monitor the constellation health and safety. CCS is used to share mission products and other critical spacecraft status information including constellation, satellite, and instrument health. Interface Control Documents (ICDs) between constellation members and ESMO detail items such as product definitions and formats. In addition, CCS has tools that provide explicit flight dynamics analysis and visualizations configurable by the users. CCS will also notify mission teams via e-mail if a constellation satellite is predicted to leave its control box or closely approach any other constellation satellites.

7. CONSTELLATION EVOLUTION

The ESC has evolved by adding new missions and retiring old ones (Table 3).

The new missions infused new technologies and improved sensors. Most recently, GCOM-W1 and OCO-2 joined the Afternoon Constellation in 2012 and 2014, respectively and Landsat-8 joined the Morning Constellation in 2013. Their new sensors benefit both from the multitude of other existing on-orbit sensors as well as from the long-term cross-calibrated climate observations from sensors that preceded them. This evolution will continue.

Table 3. Earth Science Constellation Evolution

Year	Morning Constellation	Afternoon Constellation
1999	Landsat-7 and Terra launch	
2000	EO-1 and SAC-C launches	
2002		Aqua launches
2004		Aura and PARASOL launch
2006		CloudSat and CALIPSO launch
2009		OCO fails to reach orbit PARASOL lowers orbit
2011		Glory fails to reach orbit CloudSat lowers orbit
2012		GCOM-W1 launches CloudSat returns to original orbit
2013	Landsat-8 launches SAC-C declared lost	PARASOL decommissioned
2014		OCO-2 launches
2015		
2016		
2017	EO-1 decommissioned	
2018		CloudSat lowers orbit CALIPSO lowers orbit (planned) Both missions continue science observations
2020	Landsat-9 launch (planned)	

The retiring missions left the constellation due either to low fuel reserves or aging spacecraft subsystems (or in the case of SAC-C, a major on-orbit failure). Most recently, in February 2018, CloudSat left the Afternoon Constellation orbit for the second (and final) time over concerns of its aging attitude control system. At the same time, CALIPSO is currently letting its orbit MLT drift due to low fuel reserves, but has since decided to follow CloudSat to its lower orbit (this will tentatively take place in September 2018). Both CloudSat and CALIPSO plan to continue their 24x7 radar and lidar observations of cloud structures – they will just do so below the ESC orbit altitude so as not to endanger the remaining ESC missions.

Landsat-9 is planning to augment the Morning Constellation after launch in 2019. If all goes well, Landsat-7 will retire once Landsat-9 is safely in orbit, however it will then be dedicated to a technology demonstration project. After Landsat-7 has changed to a lowered orbit, NASA and USGS have agreed that a satellite servicing mission called Restore-L will attempt to grapple onto Landsat-7, refill its fuel tank, raise its orbit, and demonstrate other satellite service capabilities. If successful, these efforts can prove extremely valuable for extending the life of other existing missions.

Lastly, the ESC has also demonstrated its flexibility and robustness by its ability to adapt to changing mission requirements. Several examples are available.

- Aura was able to capitalize on the availability of additional ground station resources by moving several minutes closer to Aqua. This move eliminated the delay between Aqua and Aura's measurements of the same air mass, thereby improving the science return.
- CALIPSO realized that its science measurements could be improved by changing the pitch of its sensor, but this required a CloudSat agreement to reposition itself in order to maintain their coincidental observations.
- CloudSat's initial orbit lowering was handled very expeditiously by all teams due to concerns at the time over CloudSat's ability to control its attitude and power.
- CloudSat's return a year later was after a long and deliberate examination of the risks and rewards involving all the teams.

In all of these and other instances, the configuration management procedures and the approval processes that were established early in the ESC's life proved invaluable.

8. FUTURE OF THE CONSTELLATION

NASA, USGS, and the National Oceanic and Atmospheric Administration (NOAA) sponsors a Decadal Survey for Earth Science and Applications from Space to help shape science priorities and guide agency investments into the next decade. The survey is driven by input from the scientific community and policy experts. The most recent Decadal Survey placed high value on continuing constellation science, however aside from Landsat-9, there are no new missions planned for the ESC. Some of this may be tied to specific science requirements for the planned new missions that do not want or need to be in an ESC orbit at 705 km in either the morning or afternoon crossing orbit. But perhaps some of this is due simply because mission designers are not aware of the value of extending the current long-term record and taking advantage of coincidental observations from a number of on-orbit and long-calibrated science instruments. As is often said, when it comes to constellation science, the "whole is greater than the sum of its parts".

Some mission designers may have concerns about the added overhead and maintenance costs they would incur by flying in a constellation. To that, the ESC has convincingly demonstrated that the added value (established procedures, experienced years-long operations, constellation coordination tools, existing data exchange infrastructure, etc.) far outweighs any impacts to the operational and science teams. The rewards are enhanced science at minimal costs.

So, consider a constellation for your future missions. It doesn't even have to be with the ESC. Constellation-flying in general is very beneficial.

9. SUMMARY

This paper has attempted to show that constellations have proven to be an effective and efficient way to acquire earth science data. But the key to making a constellation effective and efficient is keeping the operations as independent as possible in order to minimize the operational burden and costs. The ESC is a prime example of the benefits gained by constellation flying with minimal impacts. The ESC continues to welcome new missions to continue its 18+ year record of coincidental earth science observations. New mission planners need only talk to the authors of this paper to begin the process of leveraging their science data return by flying with the Earth Science Constellation!