

Options for the Continuing Evolution of the Earth Science Constellation

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The International Earth Science Constellation (ESC) comprises the Morning Constellation and the Afternoon Constellation of earth observing satellites orbiting at 705 kilometers in sun-synchronous, 16-day repeating orbits. The Afternoon Constellation is often referred to as the 'A-Train'. The Morning Constellation satellites cross the equator at a mean local time (MLT) of around 10:30 a.m. every orbit. Afternoon Constellation satellites similarly cross the equator at an MLT of around 1:30 p.m. every orbit. The primary ESC goal is to provide a comprehensive, long-term set of Earth observations to the Earth science research community. In that regard, the missions have done an outstanding job. The ESC is truly an international asset, with control centers in the United States, France, Japan, and Argentina.

Morning Constellation operations began with the launches of Landsat-7 and Terra in 1999. The Afternoon Constellation operations began with Aqua in 2002, Aura in 2004, Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL) in 2004, CloudSat in 2006, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) in 2006. However, as missions aged, parts failed, and new missions were launched, the ESC has had to be flexible enough to absorb all of the changes. The Morning Constellation added Earth Observing One (EO-1) and Scientific Application Satellite-C (Satellite de Aplicaciones Científico-C or SAC-C) in 2000 and Landsat-8 in 2013, but lost SAC-C and EO-1 in 2013 and 2017, respectively. The Afternoon Constellation added Global Change Observation Mission – Water (GCOM-W1) in 2012 and Orbiting Carbon Observatory-2 (OCO-2) in 2014, but lost PARASOL in 2013. Sadly two missions destined for the Afternoon Constellation, OCO and Glory, experienced launch failures in 2008 and 2011 and did not reach orbit.

There have been many ESC success stories and challenges for both Morning and Afternoon Constellation operations. The ESC teams established orbital control boxes and Zones of Exclusion (ZOE) to ensure mission safety and developed a Constellation Coordination System (CCS) to provide a means to exchange ephemerides and to notify missions of unsafe conditions. Inter-constellation orbit crossing guidelines and a managed crossing approach were developed in 2010 to improve safety of crossings at the poles. Although missions have experienced anomalies over the years, many returned to normal operations without any impact to neighboring missions and without having to leave their control box or constellation. On one occasion, a mission had to exit the constellation due to an anomaly, but successfully developed a safe mode of operations and later rejoined the constellation.

Several questions must be addressed in order to continue the successful ESC operations and science. These are particularly important now since most ESC missions are well past their design lifetimes and there are few new missions planned (Landsat-9 and GCOM-W2 being the only ones currently identified). For example, what happens when a major spacecraft subsystem fails? Does this trigger the spacecraft to exit the constellation so as not to threaten the other ESC satellites? Even if the parts are working, what happens when the fuel runs out? What is the best way to maximize science return while still meeting the international requirement to re-enter within 25 years after operations? Is it better to maintain tight science requirements or relax these in order to focus on a longer life and new scientific opportunities?

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This last question is a complicated one. Stated another way, should a mission relax its altitude and MLT science viewing requirements in order to get the maximum number of years of science or should it dedicate its remaining fuel to maintain the climate record at the existing altitude and tight MLT, even though this will result in a shorter mission overall? Terra was confronted with this very issue. If its MLT was allowed to drift or its altitude lowered, instruments which were designed to operate within a specific operational window would be affected. The long climate record that began in 2000 would not be directly comparable to successive observations without corrections or adjustments. After numerous discussions among operations personnel and scientists over a 3 year span, it became clear that maintaining the altitude and tight MLT requirements was most important even if it meant a shorter overall lifetime.

Many of the ESC evolution options available to particular missions must be considered carefully since they have impacts to the other constellation members. The Aqua mission is considered the cornerstone of the Afternoon Constellation and significant scientific collaboration relies on Aqua's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument data. If Aqua were to change requirements and drift to another MLT, this would certainly affect many multi-mission collaborations. NASA Headquarters gathered the ESC mission scientists and mission operators in 2016 to discuss some of these options. When looking at the options for extending the Aqua mission by relaxing the science requirements, the Aqua (and Earth Science) community decided it best to continue with normal operations and maintain the tight science requirements thereby also maintaining the long term climate record at the present orbit. This means that Aqua will run out of the necessary fuel required to stay in the constellation in early 2022, at which point it will need to exit for the safety of member missions. Aqua will continue to operate at an orbit outside the A-Train operational envelope where it will then drift until the mission is terminated.

Spacecraft reliability sometimes plays a paramount role. CloudSat experienced a battery anomaly in 2011 which complicated its ability to operate nominally. As this presented a safety risk to other constellation satellites, CloudSat lowered its orbit and left the Afternoon Constellation in October 2011. After much research and testing, a new more limited mode of CloudSat operations was devised that provided enough confidence for CloudSat to raise its orbit and return to the constellation in June 2012. Six years later, this scenario played out again when CloudSat experienced a reaction wheel failure which required it to leave the Afternoon Constellation orbit again (this time likely for good) in February 2018.

Fuel reserves are key. Mission planners are sometimes forced to examine ways to continue science collaboration despite dwindling fuel reserves. CALIPSO performed its final orbit inclination adjust maneuvers in spring 2018 to maintain its relative location within the Afternoon Constellation, but has insufficient fuel to do so in spring 2019. CALIPSO is faced with deciding whether to maintain its altitude while letting its MLT drift, or lowering its orbit to ensure it will not present a safety concern to other ESC satellites. CALIPSO may even decide to match CloudSat's lowered orbit since the two spacecraft perform related science.

Coincidental science observations may continue even at a lower orbit. Periodically, a lower satellite and a higher satellite will pass each other or pass over the same location. In CloudSat's case for example, it currently passes under the A-Train every few weeks. Researchers can correlate CloudSat science observations with other spacecraft during these periods since they are taking measurements of the same air mass or land features at about the same time.

Coincidental science observations are not limited to current and past members of the ESC. China launched the TanSat mission in late 2016 into an orbit with a very similar altitude and MLT. TanSat was invited to join the A-Train, but declined, however the hopes are that its science data can be correlated closely with ESC science data and perhaps TanSat will decide to join the A-Train at a later time. In a similar fashion, coordinated science can also be pursued with other constellations such as the National Oceanic and Atmospheric Administration (NOAA) and European Space Agency (ESA) constellation flying at an altitude of 824 kilometers on a 20-day repeat ground track. This constellation features the Suomi National Polar-orbiting Partnership (SNPP), Sentinel- 5 Precursor (S5P), and the Joint Polar Satellite System missions (JPSS-1, and eventually JPSS- 2, JPSS-3, and JPSS-4).

External help may be employed to extend the life of a constellation mission. Landsat-7 performed their last inclination adjust maneuver in February 2017 and no longer has sufficient fuel to prevent its MLT from drifting to earlier and earlier times. As time goes on, the MLT will occur earlier in the morning, causing the lighting conditions to deteriorate and adversely affecting the quality and usefulness of its observations. To address this, the Restore-L technology demonstration mission plans to dock with Landsat-7, grapple it securely and then raise (or lower) its orbit. Restore-L

will also transfer propellant to the Landsat-7 spacecraft for independent orbital movements. This has never been tried on an earth science satellite, so the process is unproven.

If the Restore-L servicing mission is successful, the same refueling option could be applied to other ESC missions like Terra, Aqua, and Aura. The servicing costs, risks, and long lead times (from approval to execution) are perhaps the biggest obstacles. Eventually, spacecraft may be designed with refueling and robotic maintenance in mind by allowing modules (such as instruments or sensors) to be swapped out via a robotic servicing mission similar to the way the Hubble Space Telescope was serviced by Space Shuttle astronauts. The potential cost savings of re-fueling multiple spacecraft with one launch of a servicing satellite present an interesting opportunity, i.e., perhaps both Aqua and Aura could be refueled for the price of a single launch.

As ESC missions exit the constellation, perhaps they could join together at a lower altitude which, although not ideal, would allow coincidental science to continue, albeit at a different altitude and MLT. It has been lightly suggested that these missions past their prime might be regarded as a so-called ‘geriatric’ constellation! As missions allow their MLT to drift, science teams would need to modify their algorithms in order to make sense of the data at these alternate locations. This can require significant time and money to get the results to match or make sense compared to historical climate records.

Perhaps the most obvious option to continue the current climate record would be to launch new missions with new and improved instruments into the ESC orbit. Indeed, the United States Geological Survey (USGS) has been doing this since 1972 for the Landsat series of satellites up to and including Landsat-8 in 2013. To this end, the primary USGS goal is for Landsat-7 to continue taking observations through the launch and commissioning of the Landsat-9 mission which is currently under development. Whether Landsat-7 meets this goal depends on its continuing health, its MLT drift, a possible Restore-L intervention, and the actual Landsat-9 launch date. Alternatively, smaller CubeSat’s or instruments could be developed to replace costly large-scale observatories. These could be flown on the International Space Station (ISS) or as free-flying satellites at various altitudes, but optics and nanotechnology limitations prevent the duplication of a MODIS type instrument. In either case, the risk of losing the long-term climate record at the ESC’s 705 kilometer altitude and tight MLT bands will be high.

Unfortunately for most of the ESC missions, there are no planned missions to continue many of the same measurements that would seamlessly extend the climate record developed by ESC instruments since 2000. Some missions that have recently launched (or in the planning stages) do offer similar observations, but these are at different altitudes and MLTs, so they are similar but not exact replacements. The NASA Decadal Survey notes the importance of the Earth Science Constellation missions, but it has not triggered the development of any follow on missions. In response to the 2007 Decadal Survey, NASA’s Earth Science Division (ESD) published *NASA’s Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (Architecture Plan). The Office of Inspector General (OIG) conducted an audit on *NASA’s Earth Science Mission Portfolio* in November 2016. The audit report (IG-17-003) *Results In Brief* found that “although the Architecture Plan envisioned launching 17 missions by 2020, including 11 by the end of 2016, as of September 2016 the Agency had launched only 7 missions, and it is unlikely the others will launch on the schedule outlined in the Plan.”⁴ The *Results In Brief* went on to say that “While the delays have not prevented NASA from substantially meeting stakeholder needs for Earth observation data, more than half the Agency’s 16 operating missions have surpassed their designed lifespan and are increasingly prone to failures that could result in critical data loss and gaps in long-term observation records.”⁵ The most recent Decadal Survey draft report did recommend many new satellites and instruments, but none are destined to join the ESC. The Japan Aerospace Exploration Agency (JAXA) has plans for a follow-on mission to GCOM-W1 (appropriately named GCOM-W2), but its launch date is uncertain. NOAA, ESA, and other space agencies have numerous missions with similar observation capabilities, but none that matches the current ESC compliment. If no new missions are developed and the current missions continue adhering to strict science requirements (and assuming no on-orbit failures), then the older missions will begin to run out of fuel and will have to exit the ESC. CALIPSO will slowly drift out of the ESC but will remain in the MODIS instrument observation swath until December 2020. Terra will have to exit around January 2022, Aqua in March 2022, and Aura in February 2023 (possibly sooner). It is conceivable that by 2022, the

[4] NASA Office of Inspector General, “NASA’s Earth Science Mission Portfolio Results In Brief,” Report No. IG-17-003, November 2, 2016

[5] NASA Office of Inspector General, “NASA’s Earth Science Mission Portfolio Results In Brief,” Report No. IG-17-003, November 2, 2016

only missions remaining will be Landsat-8 and Landsat-9 in the Morning Constellation and OCO-2 and GCOM-W1 in the Afternoon Constellation.

In closing, the perfect solution to extend the ESC-developed climate record indefinitely would be to maintain the existing ESC missions and/or replenish them with exact or improved copies. This paper has attempted to present real world options that can be employed to maximize the future science return. While most of these options are not ideal, they show some of the ESC's flexibility and capability. The earth science community must provide feedback as to the best scenarios based on benefit to the overall science. Although many of the older ESC missions can operate outside the constellation beyond 2022, the coordinated science will be reduced if no further missions are developed and if re-fueling is not exercised.