CLOUDSAT ANOMALY AND RETURN TO THE A-TRAIN: LESSONS LEARNED FOR SATELLITE CONSTELLATIONS©

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In April 2011, CloudSat suffered a severe battery anomaly, leaving the spacecraft in emergency mode without the ability to command or maneuver the spacecraft. Before the team was able to recover spacecraft operability, CloudSat passed close to the Aqua satellite in the A-Train and then exited the A-Train. A new mode of operations, termed Daylight Only Operations (DO-Op) mode was developed to enable CloudSat to resume science operations in an orbit under the A-Train by November 2011, and in July 2012 CloudSat re-entered the A-Train. This paper describes challenges and lessons-learned during the anomaly, the exit from the A-Train and the return to the A-Train. These lessons-learned may apply to other current and future satellite constellations in Earth orbit.

INTRODUCTION

The CloudSat spacecraft was launched with the CALIPSO spacecraft on 28 April 2006 as part of the NASA Earth System Science Pathfinder (ESSP) program. The only instrument payload on the CloudSat spacecraft is a millimeter-wavelength radar that provides scientists unique data on the vertical profiles of water and ice within clouds. Following orbit insertion, both CloudSat and CALIPSO were maneuvered into the A-Train Constellation, into locations defined by 'control boxes'.

The control box construct was established originally to address science requirements, i.e. to maintain optimal spacing of satellites to maximize science return without requiring a great deal of active coordination between spacecraft teams. If a satellite stays within its own control box, it should never create a collision risk to any other satellite. The control box boundary provides an early warning if a satellite leaves its designated area and potentially threatens another satellite.

CloudSat originally flew in a small control box *mainly inside* of CALIPSO's control box (~15 seconds from CALIPSO) and between 15-120 seconds behind Aqua (Figure 1). CloudSat performed frequent propulsive maneuvers to maintain the CloudSat radar-footprint overlap with CALIPSO's lidar (CALIOP) instrument.

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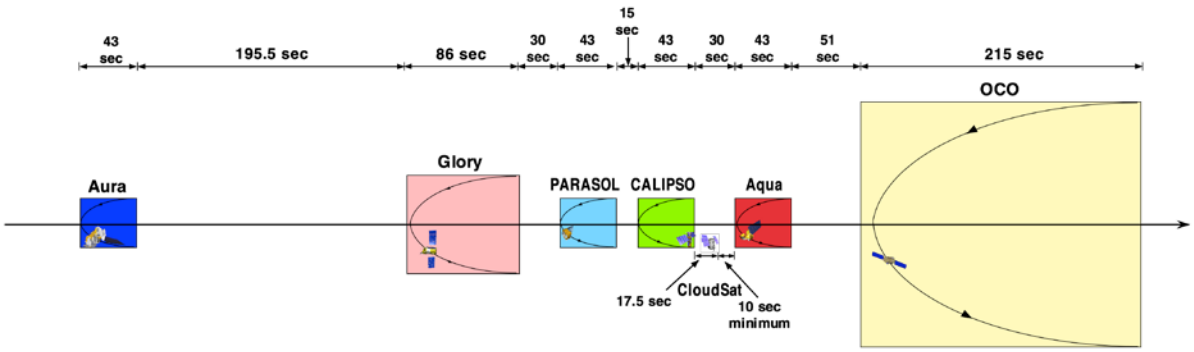

Figure 1. The control box architecture of the A-Train Constellation prior to April 2011. CloudSat was located between CALIPSO and Aqua.

APRIL 2011 BATTERY ANOMALY

In April 2011, CloudSat experienced a severe battery anomaly that placed it into emergency mode and rendered normal operations impossible. Over weeks, attempts to recover the spacecraft failed as the battery was unable to support the spacecraft loads through eclipse even in its lowest power mode. Investigation revealed that CloudSat's effective battery capacity had dropped from nearly 50 Amp-hours before launch to approximately 2.5 Amp-hours. Given CloudSat's polar, sun-synchronous orbit at 705km, the spacecraft experiences ~34 minutes of eclipse every orbit year around; this means approximately one-third of every orbit period is spent in shadow. And given that the spacecraft requires far in excess of 2.5 amp-hours in order to support normal operations during eclipse, the spacecraft after the battery anomaly was incapable of providing the payload and most subsystem loads during eclipse.

Examination of CloudSat's orbit indicated that the spacecraft was drifting out of its control box and toward Aqua, albeit very slowly, with closest approach predicted for early-to-mid June. The CloudSat and Aqua teams followed the previously-established A-Train Contingency Procedures for managing and reporting contingencies affecting A-Train safety. The A-Train Contingency Procedures require that a coordinated action plan be established; specific actions were defined and agreed to by both affected satellites. Therefore, the CloudSat and Aqua navigation teams began preparing a plan for Aqua to perform an evasive maneuver should CloudSat remain unable to maneuver. In early June 2011, the CloudSat team was able to execute a sequence of complex operations that recovered control, conducted an orbit lower maneuver and returned the satellite to safe mode, within one sunlit period. Aqua was ready to maneuver, but no longer needed to. CloudSat was still a crippled spacecraft, but now was orbiting under the A-Train and no longer posing a threat.

For several more weeks, the CloudSat team continued to deal with the battery anomaly. The vehicle could not perform science or normal bus operations during eclipse because it had to remain in a very low power, passive state. Eventually, the talented engineers at Ball Aerospace & Technologies Corporation (BATC) – those who designed and built the spacecraft bus – developed the radically new mode of "Daylight Only Operations" (DO-OP), described below.

DAYLIGHT-ONLY OPERATIONS (DO-OP) MODE

Essentially, the spacecraft transitions on every orbit from a nadir-pointed spacecraft in the sun to a spin-stabilized spacecraft in eclipse (Figure 2). One of the key and essential features of DO-Op is that the spacecraft in the DO-Op mode operates with a momentum bias while on the day-light segment of the orbit. This is a major change in momentum management from before the anomaly when the spacecraft was a "zero-momentum-bias" bus. Just prior to eclipse entrance, nearly all the components on the bus and instrument are powered off, except for the spacecraft control computer, the data recorder for science data and the GPS receiver. As the reaction wheels spin down in eclipse, momentum is gradually transferred from the reaction wheels to the bus thereby spinning the spacecraft, and when eclipse exit occurs all of the system momentum has been transferred to the bus and the vehicle is rotating about its maximum inertia axis. Immediately after eclipse exit the reaction wheels, star trackers, and solar array drives are turned back on, and the attitude control subsystem regains control of the vehicle, orienting the vehicle so that solar arrays are pointed at the Sun and the science payload can be powered back on. Yawing the vehicle continuously through daylight insures that the star trackers avoid the sun. An additional note is that, due to power limitations in eclipse, CloudSat is no longer able to support ground contacts nor conduct maneuvers during eclipse.

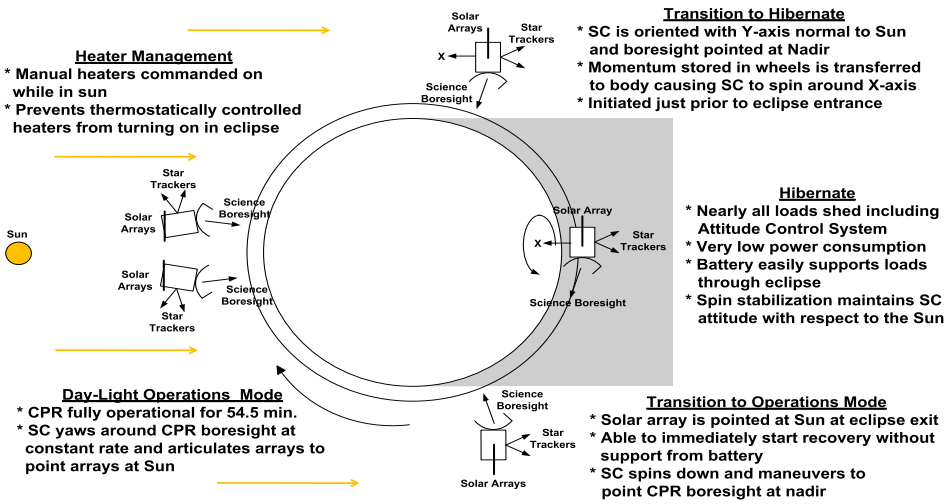

Figure 2. DO-Op mode allows CloudSat to continue science operations during the sunlit portion of every orbit.

RETURN TO THE A-TRAIN

In November 2011, the CloudSat team successfully restored the vehicle to consistent DO-Op operations. A request was made to the A-Train Mission Operations Working Group (MOWG) that CloudSat be allowed to re-enter the A-Train. By this time, CloudSat had demonstrated robust operations in DO-Op mode and had demonstrated the capability of performing both orbit-lowering and orbit-raising maneuvers. Risk assessments were conducted at JPL, and NASA approved the return to the A-Train contingent on A-Train MOWG agreement. The MOWG approved, but asked CloudSat to change its control box location to behind CALIPSO and in front of Aura. This new A-Train architecture (Figure 3) created more buffer-zone space in the event of a future CloudSat anomaly.

The return to the A-Train posed several complex astrodynamical problems, including avoiding the orbit entry and ascent to the A-Train of the GCOM-W spacecraft, launched in May 2012. CloudSat successfully returned to the A-Train in July 2012.

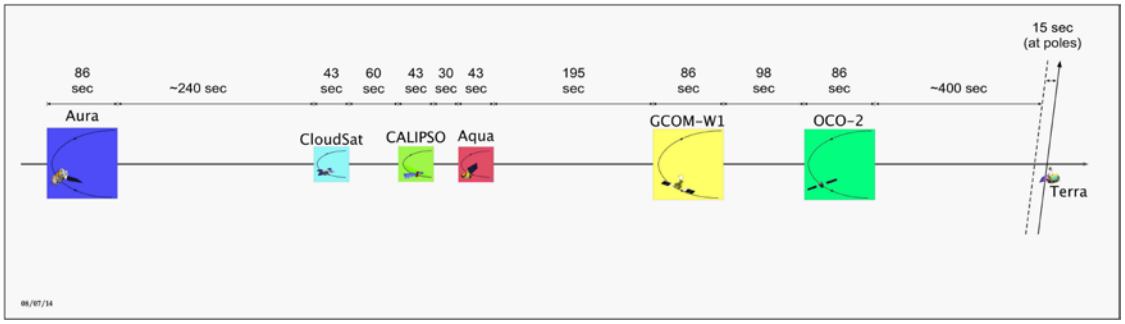

Figure 3. CloudSat re-entered the A-Train in May 2012 in a location between CALIPSO and Aura.

Should CloudSat experience a new anomaly that results in the spacecraft becoming unable to maneuver, it would cause the spacecraft to slowly drift forward in the A-Train, eventually passing all satellites in front of it (of course, this applies equally to all the spacecraft in the A-Train). As a consequence, the CloudSat operations team has established closely watched criteria (e.g. minimum battery voltage, reaction wheel friction, etc) that, when triggered, would cause the team to execute exit maneuvers to drop CloudSat out of and below the A-Train to a "safe-exit-orbit".

CloudSat determined that two sunlit exit maneuvers, separated by as much angular arc between them as practical and executed on the same orbit, would achieve a "safe-exit-orbit" from which it could begin its final end of mission preparation, including orbit lowering and spacecraft decommissioning. The CloudSat team would have liked the initial maneuver to be as long in duration as possible within the spacecraft's constrained maneuvering capability. This would result in the post-maneuver perigee and apogee being as far below the A-Train orbit as possible with a single maneuver. Then, if CloudSat should become incapable of maneuvering after this first maneuver, there would still be a margin of safety for the remaining constellation satellites in front of CloudSat (Sweetser and Vincent, 2014). But, unfortunately, it was discovered that a large initial maneuver would result in a larger than desired orbit-period change; period changes greater than about 12 sec create a potential command and control problem for the spacecraft in DO-Op mode. Thus, CloudSat settled on two exit maneuvers, each being just 2 m/s. Even so, there is still an adequate margin of safety relative to the remaining constellation satellites with CloudSat orbiting safely below them.

CloudSat has successfully operated in the A-Train in DO-Op mode since May 2012. Minimal component degradation and ample remaining consumable resources indicate a mission life expectancy through and possibly beyond FY19.

CONCLUSIONS AND LESSONS-LEARNED

1. Constellations are good for science. Although not discussed in this paper, the benefits of a constellation outweigh the complexities of operations in a constellation. A single observing system cannot capture all the processes and couplings involved in feedbacks in the climate system, because a single observing system is designed to make use of the basic properties of electromagnetic radiation in a range determined by the technology chosen, and it provides information only about a subset of all climate parameters (e.g.

clouds). Only a combination of sensors that provide nearly simultaneous observations of a range of climate parameters (e.g., clouds, rainfall, water vapor, radiation, aerosols, etc.) can help us improve our understanding of complex climate feedback processes. Major advances in understanding aspects of key climate feedbacks have resulted from the combination of observing systems in the A-Train. One essential element not mentioned but necessary for "good science" from a constellation of satellites is the free and timely exchange of collected science data among members. There must be willingness among the constellation member to share their science data and, for that matter, their operational data (i.e., ephemerides) to allow "good science" to result.

2. A coordination group such as the A-Train MOWG is essential. The primary goal of constellation management is overall mission safety. NASA formed the A-Train MOWG in 2003 to establish (through negotiation) a set of guidelines and agreements among all the mission teams. Through the MOWG, constellation management is accomplished cooperatively. The members of the A-Train agreed to a set of guidelines, processes, and procedures for flying together. A process was established to facilitate coordination among the mission teams to ensure orbital safety, while allowing the teams to maintain autonomy over their missions.

3. Pre-agreed-to contingency procedures developed by the MOWG provide an extra measure of safety when things go wrong. These procedures define each mission team's response or action plan to mitigate an on-orbit anomaly. Contingency procedures prepared Aqua to perform an evasive maneuver when CloudSat was drifting toward Aqua's control box.

4. Control boxes have proved their value in constellation architecture. Constellation management through control boxes does not place an undue operational burden on the day-to-day operations of the mission teams. Generally speaking, as long as a mission team keeps its satellite within its assigned space, coordination with the other teams is minimal, unless the satellites are formation flying together for the purpose of overlaying measurement footprints. Then it becomes necessary for the lead, or master, satellite to provide timely ephemerides and details about plans for future maneuvers to the 'slaved' satellite's operations team. Hence, there is a relatively small amount of extra coordination required over and above the effort of "control box flying". The CloudSat/CALIPSO experience has shown that this is workable and presents a minimum of extra effort for the lead satellite, which in the CloudSat/CALIPSO case is CALIPSO. The key is regularly scheduled communications for coordinating actions. A centralized coordination system confirms and monitors each satellite's position within its control box using each mission's daily predicted ephemeris, which is shared among all members. When a spacecraft leaves its control box, other constellation members are immediately notified.

5. Leaving a constellation deserves as much thought and planning as entering a constellation and usually isn't considered until long after the constellation is created. As spacecraft age, the exit plan may need to change and should be reviewed annually. Mission teams should consider what conditions would cause an urgent exit from a constellation.

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