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CLOUDSAT AT 11—NOW WHAT?

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The CloudSat mission recently completed eleven years of on-orbit operations, providing unique radar profiles of the vertical structure of clouds. CloudSat is a member of the A-Train, an international constellation of Earth-science satellites at 705 km altitude with an ascending node at 1:30 PM local time. Five years into the mission, the CloudSat spacecraft survived a near-death experience when its battery developed a current-limiting impedance restriction. Dramatic changes were made to the operations of the spacecraft, allowing the mission to continue providing unique weather- and climate-related data on clouds. While several more years of operations are possible, a number of challenges still exist. We discuss the science, the history, and options for the future of CloudSat.

INTRODUCTION

The CloudSat spacecraft carries a single science-instrument payload: the Cloud Profiling Radar (CPR). The CPR is the first-ever spaceborne 94-GHz millimeter-wavelength radar. The CPR measures calibrated backscattered power from condensed water droplets and ice crystals in the atmosphere as a function of distance from the spacecraft, thus providing a vertical profile of the majority of clouds that significantly affect the Earth's radiation budget and detecting precipitation including snowfall, drizzle, and all but the heaviest rainfall (where the radar signal attenuates).

This year marked 11 years since CloudSat was launched, during which time (except during the 2011-2012 battery anomaly) the spacecraft has been part of the Afternoon Constellation, also called the A-Train, an international group of six Earth-observing spacecraft in polar, sun-synchronous, frozen orbits that differ only in their respective phasing (see Figure 1) and the mean local times of their ascending nodes (MLTANs). The coordinated observations of these satellites give important information about weather and climate. The CPR has a single footprint, not a swath, and makes measurements continually along the groundtrack of the spacecraft.

CLOUDSAT SCIENCE

CloudSat was originally proposed as a 2-year mission. The goal of CloudSat was to create the first global survey of the vertical structure of cloud systems and to provide profiles of the amount of liquid water and ice water in clouds. The high value and uniqueness of the data has been recognized, and NASA has approved extension of the mission several times; the most recent approved

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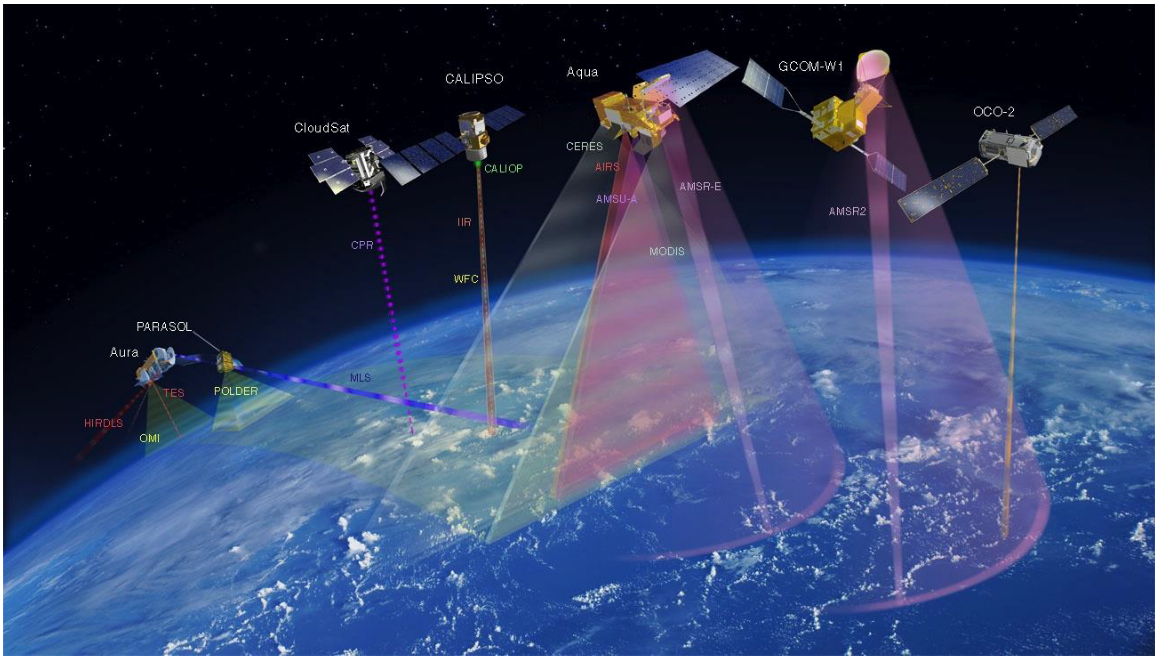

Figure 1. A-Train satellite operations are coordinated through semi-annual meetings of a mission operations working group (MOWG), led by the Earth Science Mission Operations (ESMO) Project at the NASA Goddard Space Flight Center (GSFC). PARASOL is a former A-Train member that operated in a lower orbit for the last few years of its mission. ***(Figure courtesy of NASA Earth Science Project.)***

extension is through FY20. The extended mission significantly enhances CloudSat's original science objectives by enabling the creation of a long-term data record for improved understanding of intraseasonal, interannual, and decadal variability. CloudSat observations have provided new perspectives on: the structure of the major storm systems of the Earth; the radiative heating of the atmosphere by clouds and the impact on the global circulation; how microphysical processes affect the production of precipitation; and the pathways by which aerosols affect clouds. CloudSat data are also widely used to evaluate other satellite cloud and precipitation products.[1]

Although the CPR measurements alone are of great intrinsic value, there is added benefit in combining CloudSat data with data sets from other satellite sources. This is the intrinsic value of the A-Train Constellation. Matching the vertical profile information of the CPR with other satellite data provides an opportunity to evaluate cloud products derived from other satellite sensor data and provides the opportunity to develop entirely new information about clouds and precipitation. In particular, there is strong synergy between CPR and the CALIPSO lidar observations, leading to the design of formation-flying between CloudSat and CALIPSO in the A-Train, with a goal to match CloudSat observations closely in time (and space) with the lidar observations of CALIPSO,[2] as well as other more conventional satellite observations. Measurements by the MODIS instrument (moderate-resolution imaging spectroradiometer) on the AQUA satellite provide context information for CloudSat measurements, and MODIS data are used as input in several of the algorithms in the CloudSat data processing system.

CloudSat data products are generated, archived, and distributed by the CloudSat Data Processing Center, run by CIRA, the Cooperative Institute for Research in the Atmosphere at Colorado State

University. CIRA also maintains a list of more than 1200 published science papers to date that used CloudSat data.

CLOUDSAT'S FIRST ELEVEN YEARS

CloudSat launched in April 2006 together with the French CALIPSO spacecraft on a Delta II launch vehicle out of Vandenberg Air Force Base. CloudSat and CALIPSO joined the A-Train shortly after launch. The A-Train is a six-member constellation of satellites that includes, in addition to the CloudSat and CALIPSO satellites, the EOS Aqua and EOS Aura satellites, OCO-2, and GCOM-W. The orbits of the constellation are sun-synchronous with a mean equatorial altitude of 705 km and an inclination of 98.2 degrees, thus keeping the mean local times of their ascending nodes fixed. The size and inclination of the orbit are maintained by propulsive maneuvers as needed to correct for atmospheric drag and the tidal torque of solar gravity. The eccentricity of the orbit is 0.00118, which causes it to be 'frozen,' i.e., there are no long-term eccentricity changes, resulting in an orbit of constant shape and orientation with respect to the Earth and Sun, thus reducing altitude variations over any spot on the Earth and improving the repeatability of scientific observations.

All spacecraft of the Constellation make their routine maneuvers with full knowledge of the operations of other spacecraft, a coordination which is managed by the Earth Science Missions Office (ESMO) at GSFC. This oversight ensures the overall health and safety of the constellation, ensuring that close approaches that would have an unacceptable probability of collision are avoided. The general approach to managing such risks is based on the concept of the 'control box'. This is a theoretical construct centered at a reference position on a satellite's nominal 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. It is this limitation in both the along-track and cross-track movements that creates the notion of a 'box.'

The control boxes of the different members of the constellation are illustrated in Figure 2 where the size of the box is also indicated. CloudSat conducts frequent maneuvers to keep the footprint of the CPR overlaying the smaller footprint of the CALIPSO lidar, with a goal of having the lidar spot within 4 km of the center of the CPR footprint 90% of the time.

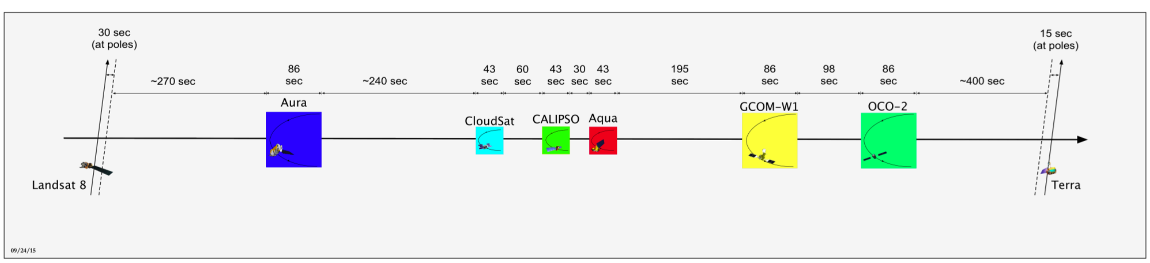

Figure 2. The current nominal configuration for the A-Train includes control boxes separated by generous margins to mitigate the risk of collision. Members of the A-Train have agreed to try to operate their spacecraft to stay within their respective control boxes. ***(Figure courtesy of NASA Earth Science Project.)***

A Near-Death Experience

In April 2011, CloudSat experienced a severe battery anomaly that placed the spacecraft into safe 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 705 km with a local time of 1:30 AM for the descending node, the spacecraft experiences $\approx$34 minutes of eclipse every orbit; 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 loads 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 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. After months of anomalous operation and repeated under-voltage conditions, the flight team was able to stabilize the spacecraft and successfully reduce loads on the battery. The story of the heroic efforts by the mission partners to recover the spacecraft has been told in detail elsewhere.[3]

The key to recovery was developing a plan to operate the spacecraft only when solar power is available. 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, pronounced 'doo-wop').

A Whole New Way to Operate

Due to the power limitations posed by the severe battery anomaly, CloudSat operations were restricted to Daylight Only Operations (DO-Op). This meant that all ground station contacts, science data collection and spacecraft maneuvering have to be performed during the sunlit portion of the orbit. This required a large number of command blocks be uploaded to the spacecraft to control sequencing each orbit. In DO-Op, on every science orbit the spacecraft collects Cloud Profiling Radar (CPR) data during the sunlit side of the orbit and then transitions from a nadir-pointed spacecraft to a spin-stabilized spacecraft just before entering eclipse (see Figure 3). Upon eclipse exit, the solar arrays acquire the sun to charge the battery, and Reaction Wheel Assemblies (RWAs) are powered up to stabilize the spacecraft and establish nadir pointing. Lastly, the CPR is powered on to begin science observations. This sequence is repeated orbit after orbit and day after day. It has proven to be a very robust mode of operating the spacecraft.

One of the key and essential features of DO-Op is that the spacecraft operates with a momentum bias while on the daylight segment of the orbit. This is a major change in momentum manage-

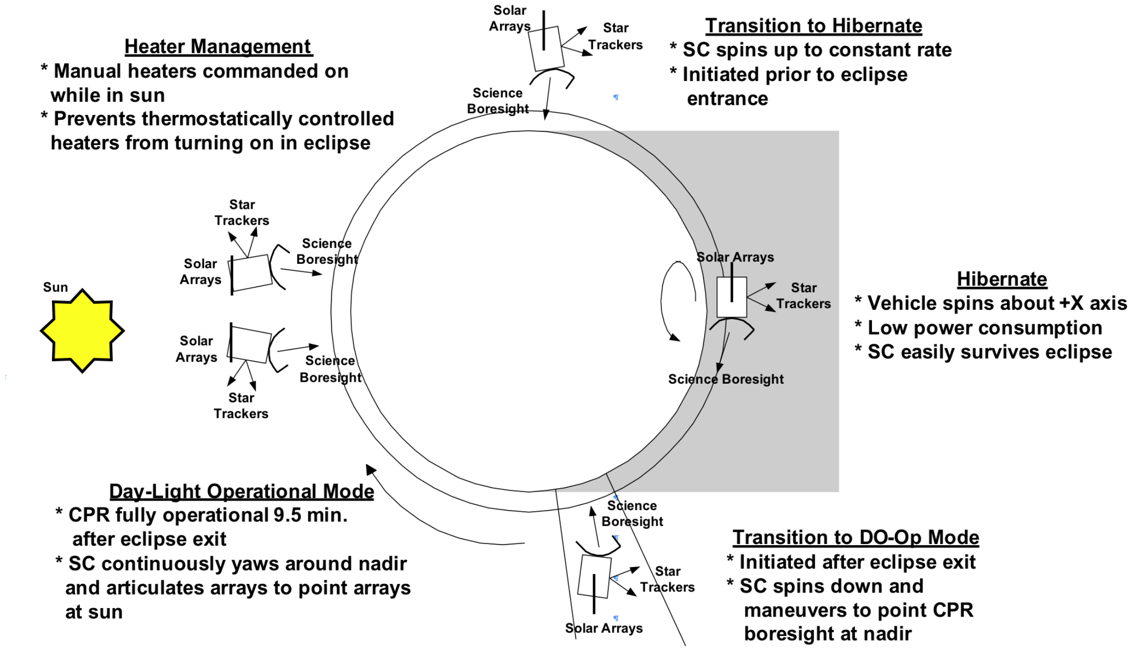

Figure 3. CloudSat's DO-Op mode for daylight-only operations.

ment 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.

Return to the A-Train

After a few months of successful operations below the A-Train, the spacecraft was given permission to rejoin the constellation. CloudSat was successfully maneuvered back into the A-Train Constellation in May 2012. The process followed to design the maneuver campaign for the return to the A-Train has been described[4] in detail. We give an overview here.

The return to the A-Train presented a significant orbital mechanic challenge to the CloudSat orbit analysts, Don Keenan and Barbara Braun of the Aerospace Corporation. Not only was the CloudSat orbit below the A-Train's, it was also no longer frozen, nor was it sun-synchronous, and its MLTAN had drifted away from the desired value. All of those conditions needed to be corrected, and the 60-day synodic period with the other A-Train satellites meant that opportunities to get back in line only occurred at discreet times every other month. The challenge was exacerbated by CloudSat's specific constraints, namely that maneuvers could only occur on the sunlit side of its orbit, which effectively eliminated half of the discreet opportunities for return, and additionally that propellant was a consumable that needed to be conserved. Of course, conjunctions with other A-Train satellites were to be avoided throughout the maneuver campaign for the return. Finally, there was time pressure to get CloudSat out of its lower orbit and back to the A-Train before the GCOM-W launch in May 2012.

When faced with this challenge in the fall of 2011, the CloudSat analysts chose the following strategy. They decoupled the inclination and MLTAN corrections from the orbit size and frozen-orbit corrections by choosing to use only cross track and tangential maneuvers respectively, the first at sunlit equator crossings to control inclination and consequently MLTAN drift rate and the second to control orbit size and the eccentricity vector (the vector for which eccentricity and argument of periapse are polar coordinates). During the campaign, circumstances led them first to lower the orbit further in order to reduce the synodic period of CloudSat's orbit with the A-Train's, which then allowed two rendezvous opportunities by their May deadline. Finally, the analysts adopted the use of eccentricity space to see how maneuvers changed the eccentricity vector and how it evolved between maneuvers. (An unrelated analysis[5] shows how every maneuver that is not purely cross track changes the eccentricity vector.) By viewing the situation in eccentricity space, the CloudSat analysts were able to choose the timing and positions of their tangential maneuvers so that when the final orbit raise was done the eccentricity vector ended up in the frozen-orbit position.

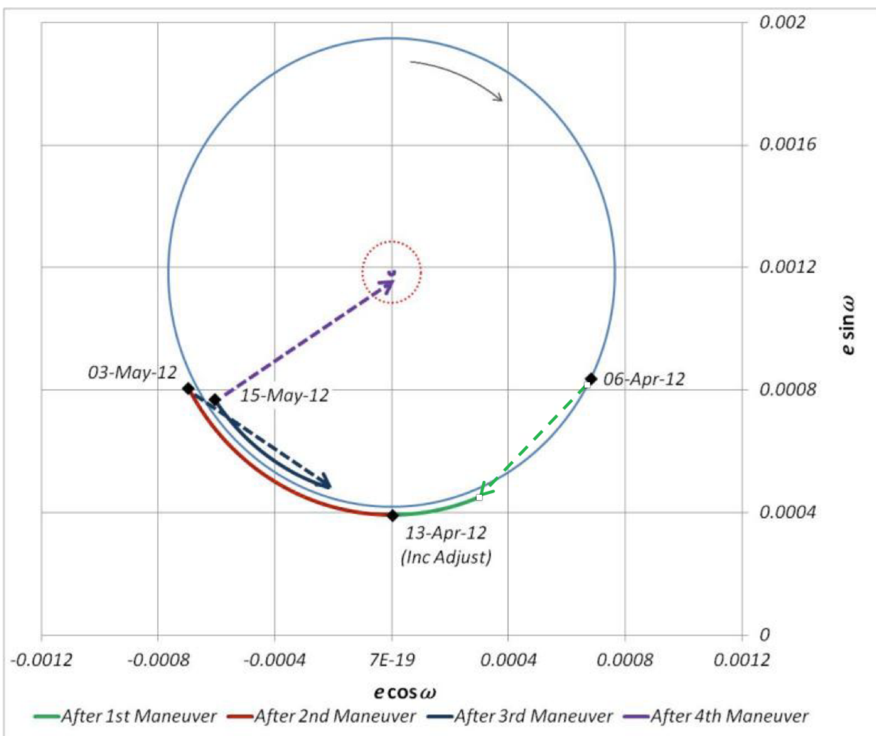

Figure 4. The effect of maneuvers on the eccentricity vector and its natural clockwise evolution during the maneuver campaign for the return to the A-Train. ***(Drawing derived from original courtesy of Barbara Braun.)***

The resulting maneuver campaign began with an orbit-lower maneuver on 2012-04-06 and a pair of inclination adjust maneuvers on 2012-04-13 to begin drifting the MLTAN back to the desired time. The first orbit-raise maneuver was on 2012-05-03; the second and final orbit-raise maneuver on 2012-05-15 both put CloudSat back in the A-Train with the right phasing and achieved a frozen orbit, as shown in Figure 4. The MLTAN drifted to the desired value and the drift was halted by a second inclination adjust maneuver on 2012-07-18.

BACK IN BUSINESS

A-Train formation flying

Formation flying in the A-Train Constellation requires that CloudSat maneuver to maintain its position in a specified control box. CloudSat also follows CALIPSO and overlays the CPR footprint with CALIPSO's LIDAR instrument to provide a synergistic measurement enabling the production of joint data products. The A-Train configuration is illustrated in Figure 2.

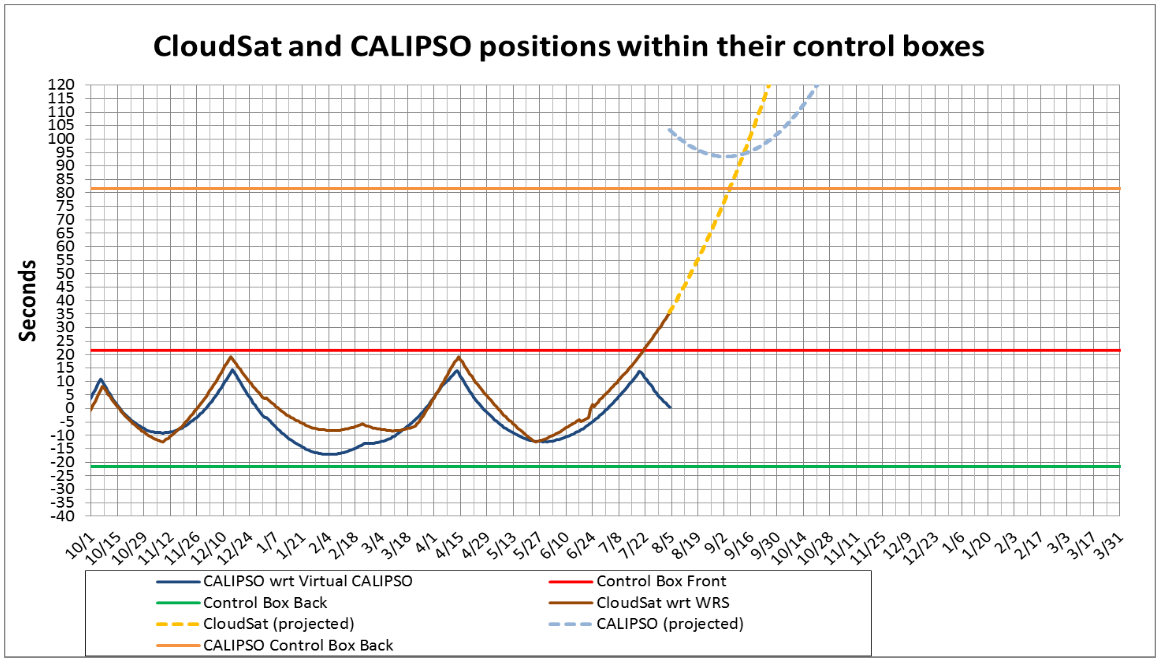

Figure 5. CloudSat and CALIPSO use tangential accelerations to control thier positions in their control boxes and CloudSat uses tangential decelerations to control its position with respect to CALIPSO. Orbit raises set the drift of the spacecraft position in its control box toward the back of the box and orbit lowers set the drift forward. *(Plot courtesy of Barbara Braun.)*

Orbit Raise / Orbit Lower Maneuvers CloudSat conducts Orbit Raises to manage the spacecraft's position in the constellation control box as shown in Figure 5. This ensures that CloudSat remains at a safe distance from the CALIPSO spacecraft. Maneuvers are coordinated, such that each mission maneuvers within a few days of each other, to maintain optimal positions in their respective constellation control boxes. Orbit Lowers are then conducted to maintain a 4 km ground track overlap with CALIPSO's LIDAR observations.

Inclination Adjust Maneuvers The A-Train Constellation is anchored by the Aqua spacecraft. All other missions align their MLTAN relative to that of Aqua. In order to maintain a consistent MLTAN, an annual inclination adjust maneuver (IAM) campaign is performed each spring. Aqua plans the IAM campaign, and CloudSat conducts inclination adjust maneuvers in concert with the other A-Train member missions.

Collision Avoidance Maneuvers Flying at an altitude of 705 km also presents challenges with respect to orbital debris. Conjunction assessments are performed several times per day to assess the risk of collision with any debris or other orbiting satellites (active and inactive). CloudSat criteria requires a Collision Avoidance Maneuver be executed if the probability of collision rises above 1 in 10,000. Because CloudSat is restricted to daylight-only maneuvers, the decision to maneuver is required at least 24 hours in advance of the conjunction. As conjunctions can also arise quickly and unpredictably, pre-built collision avoidance maneuver sequences are stored on the spacecraft for rapid execution.

CHALLENGES TO FUTURE OPERATIONS

CloudSat was launched with ample propellant for its proposed mission and the spacecraft was designed with redundancy in all major subsystems. Over the years, though, the battery, the radio receiver, and the reaction wheels have experienced failures which make them single fault vulnerable. And of course, the CPR instrument is necessary. Propellant, battery, reaction wheels, receiver or CPR failure: Which one will end the mission?

Propellant

There's another certainty besides death and taxes, and that is that eventually CloudSat would run out of propellant. The biggest lien on ΔV capability is to perform maneuvers to finally retire the spacecraft in a lower orbit that will cause it to reenter the Earth's atmosphere within 35 years of launch, which CloudSat currently intends to do. In the meantime, an annual inclination campaign is the biggest ongoing draw on propellant. Over all, enough propellant remains even with those liens to allow regular operations for at least four more years; it is unlikely that fuel will be the lifetime-limiting component.

Cloud profiling radar instrument

The CPR has redundant High Power Amplifiers (HPAs); the HPA currently in use has operated for eleven years with small detectable signs of aging. The HPA will be considered as aged beyond requirement when the RF output power has dropped enough to deteriorate the radar minimum detectable sensitivity (MDS) to $\leq$-26dBZ (currently, the MDS is estimated at better than -27dBZ). Based on current trends, a switch from the primary HPA to the backup HPA is not expected sooner than 2018. Once the switch to the backup HPA occurs, a lifetime comparable to that demonstrated by the primary extended interaction klystron (currently $\approx$11 years) would not be surprising. It is unlikely that the CPR will be the life-limiting element of the mission.

Battery

The spacecraft battery remains stable. Spacecraft loads in eclipse are carefully managed and minimum voltages in DO-Op remain above 29V. A-Train exit criteria would be triggered for the battery if minimum voltages in DO-Op fall below 28V. All indications are that the battery will continue to perform well and support nominal operations for the next few years.

Battery performance in DO-Op remains challenging, but no further degradation has been seen. Charging methods have been changed to reduce internal battery heating in order to decrease the chance of an increase in the battery impedance. CloudSat can continue science operations under some scenarios even if an additional battery cell weakness or failure occurs. If further battery degradation occurs, the benefits of bringing in the spare battery cells, which remain healthy, will be re-examined, as well as evaluating options for further reduction in eclipse loads. CloudSat will exit the A-Train should the battery degrade to established critical levels and might be able to continue science operations in a lower orbit. There is a moderate chance that the battery could be the lifetime-limiting component.

Receiver

The loss of the current receiver would be mission-ending, but no degradation is seen in the receiver telemetry. The original receiver was locked up on an unusable frequency during a very-low-voltage event during the 2011 battery anomaly, and there is some speculation that it may be recoverable during a similar low-voltage event. This situation is not a situation that we would intentionally attempt to reproduce! Other recovery efforts to date have been unsuccessful, however. Meanwhile, the backup receiver has been working well.

Reaction Wheels

The mission operated flawlessly in DO-Op from October 2011 through mid-2017. In June 2017, reaction wheel assembly #1 (RWA-1) began showing signs of stiction. Attitude errors tripped yellow limits when the wheel rolled through zero crossings. Science operations were temporarily suspended, while the team investigated the anomalous behavior. An attempt to recondition the wheel, by spinning it up to high revolutions per minute (RPM), was made in late June, which originally looked promising. Upon returning to nominal operations, the stiction re-appeared immediately and operations were again suspended. With the effective failure of RWA-1, the team revised the onboard sequences to operate on three RWAs, instead of the normal four wheel control. Science observations, in DO-Op, were successfully resumed on 26 July 2017.

CloudSat's response

In response to these challenges, the CloudSat project has established exit criteria for safe operations that dictate departure from the A-Train under circumstances that threaten CloudSat's maneuverability. An exit procedure has been worked out, and the operations team has been trained to execute this exit, which uses two maneuvers to lower CloudSat's orbit so that it is 4 km below the nominal A-Train orbit all the way around the Earth (see Figure 6). Analysis[6] has shown that this orbit will stay at least 4 km below the A-Train even though it is not frozen.

After A-Train exit, the project will consider the new situation to decide among future options, including whether to maneuver to a safe disposal orbit and decommission the spacecraft to end the mission or to continue doing science measurements in an orbit below the A-Train. For example, in the face of a reaction wheel failure CloudSat might continue science operations on 3 wheels at a lower orbit or until a 2nd wheel shows signs of failure.

OPTIONS FOR CONTINUED SCIENCE

We look forward to continuing to take cloud profile data for years to come, but recent developments have greatly constrained our options for doing so. The CloudSat spacecraft has effectively lost one reaction wheel, and since one of the exit criteria is loss of a reaction wheel CloudSat will exit the A-Train. Very soon, CloudSat will be leaving the A-Train for a lower orbit. When we operate under the A-Train, we will lose the important synergy with CALIPSO, and we will have

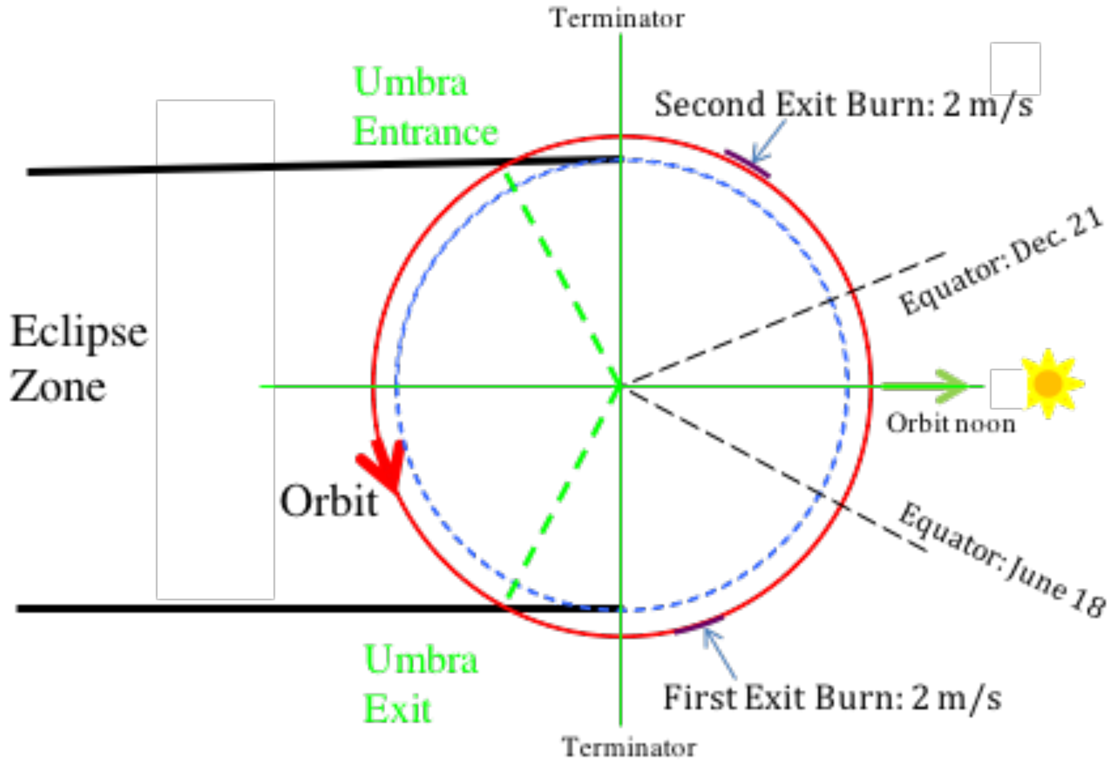

Figure 6. A pair of finite-duration maneuvers sized to each decelerate CloudSat by 2 m/s at widely separated points on the sunlit side of the orbit suffice to lower the entire orbit by at least 4 km. ***(Drawing derived from original courtesy of Ron Boain.)***

regular, but not continuous overlap by other members of the A-Train. Some data products currently produced will be adjusted for radar-only data, and other data products will not be possible at all.

Until the reaction wheel failure in June, the dominant issue for CloudSat was how to continue joint science with CALIPSO. After 11 years, CALIPSO has only enough propellant remaining to perform one more annual inclination adjustment, in the spring of 2018. This means that toward the end of 2018, the CALIPSO MLTAN would begin to drift eastward. The CloudSat team had just begun serious consideration of strategies to preserve joint measurements with MODIS while continuing to overlap data with CALIPSO for as long as possible when the RWA-1 problem occurred. (At about the same time CALIPSO's backup laser accumulated enough loss of pressure to cease operating—but that's a story for another time.)

CloudSat is currently operating on three wheels in DO-Op mode and is collecting and distributing science data. It failed to execute last month's planned drag make-up maneuver because executing the maneuver on three reaction wheels proved to be more difficult than we had realized. As a result the spacecraft has drifted out of its control box and continued to drift toward CALIPSO. A revised maneuver sequence was developed and tested for three-wheel operations, and the maneuver was successfully executed on 24 August 2017, well before CloudSat encroached on CALIPSO's territory. As a result of this maneuver CloudSat will return to its control box toward the end of September 2017 and would stay in its control box until late January 2018 in the absence of intervening maneuvers.

The CloudSat spacecraft is operating well, and mission operations are being adapted to the reduced attitude control capability of three-wheel system.

For the near term: exiting the A-Train

Sometime in the next month, then, CloudSat will follow its exit strategy and perform two maneuvers on successive orbits to move to an orbit that is safely below the A-Train, which is considered to be an orbit that is at least 4 km below the nominal A-Train orbit all the way around the Earth. The ideal maneuvers would be equal decelerations on opposite sides of the planet, like a Hohmann transfer between circular orbits. Because of operational constraints discussed above, this is not possible for CloudSat. The furthest apart the maneuvers can get is if one maneuver is done as soon as reasonable after eclipse exit and the other is done as late as reasonable before the eclipse entry. CloudSat will use those locations, which are about 120 deg apart, for finite tangential maneuvers that each give 2 m/s reduction in velocity. After the second maneuver, the point on the exit orbit closest to the A-Train is between the two maneuver locations and about 4 km below the initial CloudSat orbit, which has continued to be close to the nominal A-Train orbit; the other side of the exit orbit will be about 10.8 km below the initial CloudSat orbit.

Longer-term option considerations

Once CloudSat has arrived in its safe exit orbit, we will temporarily resume DO-Op and the production of science products—the lower orbit altitudes are within the operating range of the CPR instrument without modification to any of the flight software. At the same time, the project will consider and decide on one of three options for going forward:

- Demonstrate that the spacecraft can reliably perform maneuvers (in particular, exit maneuvers) with fewer than three reaction wheels so that return to the A-Train might be allowed. Such a demonstration, performed early enough, might even allow CloudSat to forego exiting the A-Train.

- Move the spacecraft to a frozen sun-synchronous orbit between 4 km and 15 km below the nominal A-Train orbit and continue science operations from there until an end of mission is declared, at which time the spacecraft orbit will be lowered to an orbit which meets NASA's orbital debris requirements.

- Lower the spacecraft to a frozen orbit about 60 km below the nominal A-Train orbit, which is low enough to meet NASA's orbital debris requirements, and continue science operations from there.

Two considerations from orbital dynamics have significant implications for the options being considered. One is that lower orbits have shorter periods, so CloudSat will not be in synch with the A-Train. It will pass below the A-Train and move ahead in its orbit until it goes all the way around and catches up again. The lower the orbit, the shorter this synodic period, so CloudSat will be back in synch sooner, but for a shorter duration. The phasing of CloudSat with respect to Aqua is close enough to permit the generation of science products that combine CloudSat measurements with MODIS measurements for about 20 minutes out of a 99-minute orbit, limited by a need for a time difference of less than 10 minutes between the measurements. This gives combined science for about 20% of the synodic period, independent of the synodic period. That is true as long as

CloudSat's MLTAN is within about 12 minutes of Aqua's MLTAN so that CloudSat's groundtrack is within the 40 deg look-angle of the MODIS swath; if the MLTANs differ by more than about 12 minutes, then the duration of useful measurement synchronicity is reduced accordingly (e.g., a MLTAN difference of 17 minutes results in only 15 minutes of good-enough synchronicity out of a 99-minute orbit).

The need for close MLTAN values leads to the other orbital consideration: when the orbit is lowered, the inclination must be changed to keep the orbit sun-synchronous, i.e., keep the MLTAN constant. Every 10-km drop in the orbit without changing the inclination gives a 1.17-s eastward shift in the MLTAN every day (so a 20-km drop gives a 2.34-s daily shift, etc.); the amount of inclination decrease needed to counteract a 1.17-s/day drift is 0.04 deg, which takes 5.2 m/s cross track velocity change at the equator and is close to the inclination change needed in the IAM campaign every year.

The first option above is highly desirable, but depends on whether the CloudSat spacecraft design includes the capability for reliable two wheel operation given the time constraints of DO-Op. An alternative possibility for backup maneuver capability is using thrusters for attitude control on orbits containing maneuvers, but the flight software implications of this strategy are unknown and would need to be determined.

The second option above gives a synodic period of 84 days at the high altitude (4 km below the A-Train) and 21 days at the low altitude. A current estimate of the propellant available for future IAM campaigns gives roughly four or five more years that CloudSat can maintain its MLTAN. Going to a lower frozen orbit within the exit-orbit altitude range reduces the propellant available for MLTAN maintenance, subtracting about a year's worth of capability, because of the propellant needed to perform both any needed orbit raise and inclination decrease. The propellant needed is approximately independent of the frozen orbit altitude within the exit-orbit altitude range because a higher orbit raise corresponds to a lesser inclination decrease. Frozen orbits lower than that do not require an orbit raise, but the inclination decrease needed for the 15-km lower orbit to be sun-synchronous reduces the MLTAN maintenance capability by about one and half years.

The third option above would require so much propellant to restore sun-synchronicity that there would not be any left for IAM campaigns. After about a year and a half the CloudSat MLTAN would drift out of range of allowing combined measurement products with the MODIS instrument. Some time after that the orbit geometry with respect to the Sun would change too much for continued DO-Op, and we would have to end the mission.

CONCLUSION

The first two options above—returning to the A-Train with a revised exit strategy or continuing radar measurements in an orbit not too far below the A-Train—offer the possibility of multiple years of continued CloudSat operations. It is likely that this time next year CloudSat will be operating in a frozen orbit in or just below the A-Train, and the mission will be generating valuable science products (Lord willing and the creek don't rise, as the saying goes).

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