CloudSat's Return to the A-Train

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Abstract: Since its launch in April 2006, the CloudSat spacecraft had been flying in the A-Train constellation in close formation with the CALIPSO spacecraft. On April 17th of 2011, CloudSat experienced a severe battery anomaly which caused the vehicle to fault into a passive, but power positive spin; however it could no longer maintain itself within its control box. Due to potential conjunctions with the Aqua spacecraft the CloudSat team initiated a series of burns which lowered the CloudSat spacecraft out of the A-Train in June 2011. Recovery required developing a new mode of operation dubbed DO-Op for Daylight-Only Operations as well as other new safing and preparatory modes required to support the new concept of operations. After recovering into a safe, consistent and reliable operational state, NASA, JPL, the A-Train spacecraft members and the CloudSat team determined that the CloudSat vehicle's operational capability was robust enough to perform a series of orbit maneuvers and return it to formation flying with CALIPSO within the A-Train. Since the CloudSat vehicle had drifted in an uncontrolled orbit for several months, a series of burns including orbit lower burns, orbit raise burns, and inclination increase and decrease burns had to be performed to return the vehicle to its new control box.

Prior to the anomaly, CloudSat performed orbit maintenance burns approximately every two to three weeks in order to maintain formation with CALIPSO. It also conducted larger inclination burns approximately once a year in concert with the other vehicles in the A-Train. Originally CloudSat had sufficient battery capacity to operate in eclipse and, for the most part, burns were performed in eclipse to avoid instrument and star tracker Sun in Field-of-View (FOV) constraints and thereby simplifying burn planning. Removing the Sun FOV constraints also made it relatively easy to avoid Moon and Earth FOV constraints.

After recovering from the anomaly the new DO-Op mode of operation imposed many more constraints on the CloudSat maneuvers into the burn attitude and on the orientation of the spacecraft during the burn. CloudSat is now required to hibernate through eclipse and all of the burns now must be performed while the vehicle is in the sun. The new limitation also included keeping the solar arrays pointed at the Sun at all times and keeping the momentum axis pointed within 90 degrees of the sun in order for the new safing, preparatory and delta-V modes to work properly.

The CloudSat team has developed a reliable and robust methodology for performing burns, and have also developed an accurate set of tools that can be used to verify all of the constraints will be met, effectively returning all of the orbit maintenance functionality that the vehicle had prior to the anomaly. This paper discusses the team's considerations required for performing burns to keep the vehicle within its control box in the A-Train and formation flying relative to CALIPSO in light of the mission's new set of constraints. In addition, the improved method of commanding small burns in order to keep the vehicle's momentum within its requirements is also outlined. Specific performance on the burns required to return the vehicle to the A-Train is discussed, as is the performance for smaller formation flying burns.

Keywords: *Formation flying, CloudSat, orbit maintenance, attitude control, A-Train constellation*

1. Introduction

CloudSat was co-manifested with CALIPSO and they were launched on April 28th, 2006. Both vehicles joined the A-Train approximately one month later, and CloudSat began formation flying operations with CALIPSO. In April of 2011, CloudSat experienced a severe degradation in battery capability, which required several months for the team to develop, test and implement a new approach for continuing the mission. The battery limitation caused the team to develop a new method of operations, which actively controls the vehicle during the daylight portion of the orbit, and leaves the vehicle in a very low power, passive spin, “hibernate” state during eclipse. However, before the recovery efforts could be completed, a potential conjunction between the CloudSat and Aqua vehicles forced the team to execute a sequence of burns to exit the A-Train. By November of 2011, CloudSat had returned to active operations, but had drifted for several months in an orbit separate from the A-Train.

Due to the constraints on the vehicle’s new mode of operation, modified methods of performing burns had to be developed. This required developing the capability of executing precise burns which adjusted the vehicle’s orbital semi-major axis, mean local time and inclination. This paper discusses the original approach with CloudSat followed for performing delta-Vs, the additional operational constraints which were imposed by the new operational modes, and how these constraints were met. Given the additional operational constraints on the mission, more sophisticated methods of modeling the maneuvers ahead of time also needed to be developed to predict the performance of the maneuvers to insure that none of the vehicle’s operational constraints are exceeded.

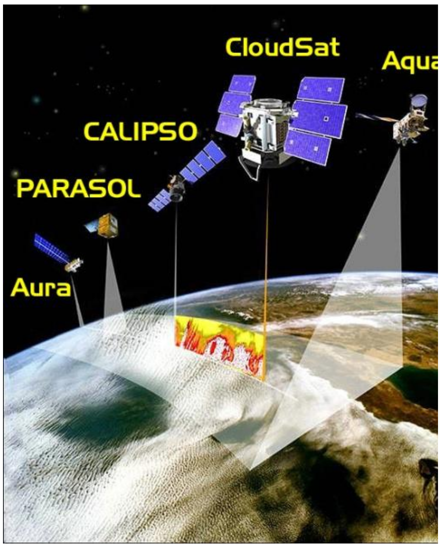

Figure 1 – This figure shows the A-Train constellation when CloudSat was launched. CloudSat originally flew approximately 12.5 seconds ahead of CALIPSO and, sixty seconds behind Aqua and performed propulsive maneuvers to maintain a 1 km ground track overlap between CloudSat’s and CALIPSO’s

2. CloudSat Operation Prior to Anomaly

Approximately one month after launch, CloudSat performed its final major propulsive maneuver to join the A-Train (Figure 1) and started formation flying with CALIPSO. The vehicle then began its mission operations phase, in which it was flown, fixed in the orbit frame collecting science data (Figure 2). Burns were performed approximately every two to three weeks in order to maintain CloudSat’s orbit track within +/- 1 km relative to CALIPSO ground track. CloudSat’s beta angle varied between approximately 20 and 30 degrees over a year, and the solar array orientations to the sun guaranteed that the vehicle had sufficient power to adequately charge the battery for operations during eclipse. When the battery was healthy, the ground operations team only had to consider star tracker outages due to the Sun, Earth and Moon in order to perform burns. The design originally included a gyro, but it had been removed as part of a cost cutting effort so it was necessary to keep the star trackers in the solution to meet the required burn accuracy. Burns were almost always performed in eclipse to minimize the difficulty of burn planning. Orbit maintenance burns were split between orbit raising and orbit lowering burns. Approximately once a year, CloudSat would perform a series of inclination adjust maneuvers in coordination with the rest of the vehicles in the A-Train. Previous papers on CloudSat’s recovery have emphasized returning to an operational state, and this paper is intended to focus on the Attitude Determination and Control ADCS aspects of returning CloudSat to within its slot in the A-Train.

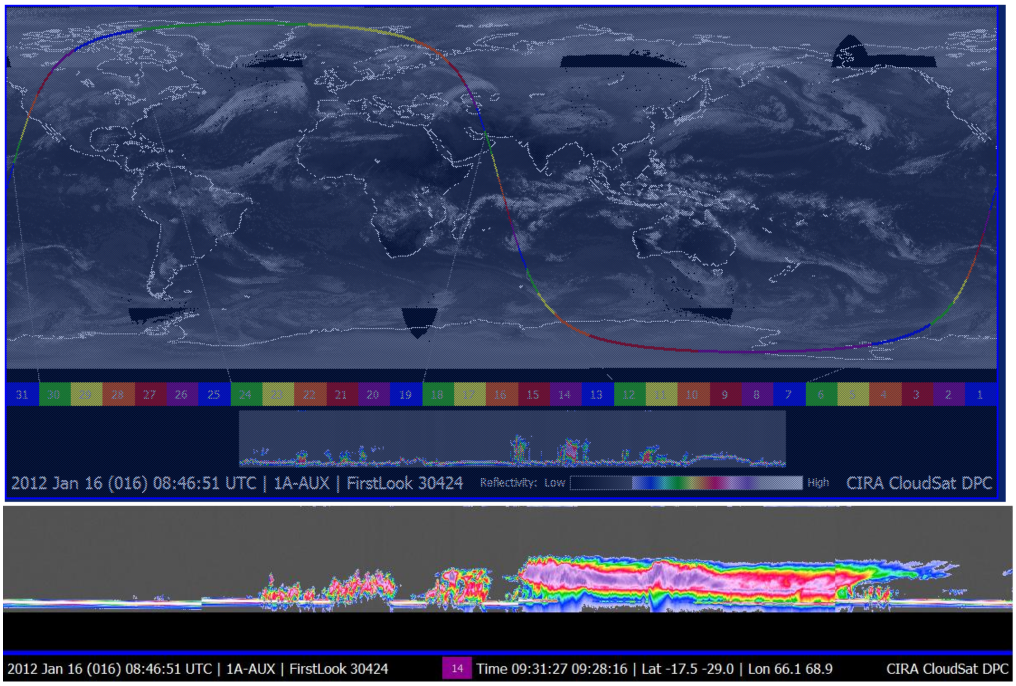

Figure 2 – CloudSat's science instrument provides data which is used to improve weather modeling and forecasting. Several phenomena which have been observed by CloudSat require significantly longer data sets than the initially planned 22 month mission. Understanding climate variability for certain phenomena requires multi-year data sets.

3. CloudSat's Original Operational Mode

The CloudSat ADCS subsystem provided three axis attitude control of the vehicle during Safe, Point, and Delta-V operations. Configuration of the vehicle's sensors, control gains, sensor operations and all ADCS functions are table driven and are easily modifiable without patching or uploading software from the ground. The flight software modes used a tiered method for controlling the vehicle, and faults or commands caused the system to regress to lower levels of control and promotion to higher levels of control can only occur via command (Figure 3). The attitude sensors on the bus include magnetometers and sun sensors for coarse attitude determination and a pair of star trackers for precision attitude determination. Reaction wheels are normally used for controlling the spacecraft's pointing, unless performing a large delta-V, while executing detumble, or initiating the emergency mode operations. Torque rods are used for momentum management and a GPS receiver is used for precision orbit determination. Momentum control nominally kept the vehicle's momentum below 1 Nms.

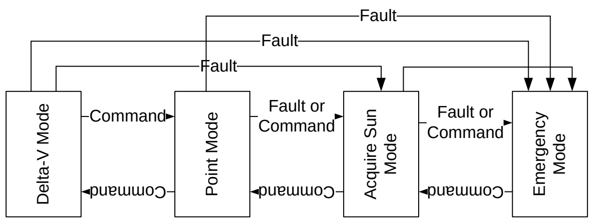

Figure 3 – This figure shows the hierarchy of operating modes for the vehicle. A variety of faults can cause the vehicle to safely transition to a lower level of control, and promotion to higher levels of control can only occur via command.

Maintaining formation with CALIPSO was one of the driving design considerations. CloudSat originally was able to maintain a 50% overlap of the footprint of its instrument with CALIPSO's instrument, and to achieve this, it was required to perform accurate burns at precise locations within the orbit and at exact times.

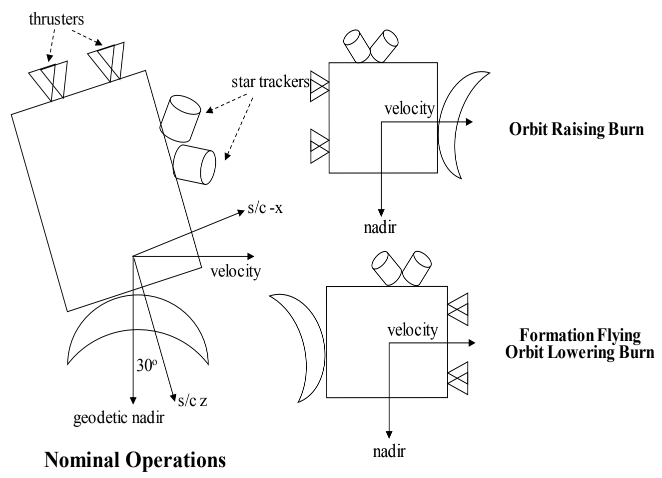

Figure 4 – This figure shows the vehicle's nominal orientation in the orbit frame for collecting science data and also the necessary orientations for orbit raising and orbit lowering maneuvers. Reorienting the vehicle for orbit adjusts were performed using simple targets in the orbit frame. Maneuvers requiring rotations larger than 120 degrees were accomplished using waypoints, and generally using a two maneuver sequence. In generally burns were performed in eclipse to avoid any potential limitations due to the sun entering into the star tracker fields of view.

Since the ADCS did not have a gyro, more care must be exercised when executing maneuvers to perform a burn than on other similar vehicles to insure that the star trackers continue to provide valid data. Figure 4 shows a how the vehicle was oriented relative to nadir for normal science operations, and also for orbit raising and orbit lowering burns.

Pre-anomaly all burns were performed using two different methods onboard the vehicle: closed-loop and open-loop burns. Burns larger than 1 m/s were performed using closed-loop control, where the thrusters are used to control the attitude and rate on the vehicle as well as provide the required delta-V to the spacecraft. Closed-loop burns have larger command quantization, and do not provide the high accuracy required for small formation maintenance burns. Conversely, open-loop burns are intended for short, precise burns. For open-loop burns, the vehicle fires specific thrusters for a precise length of time and uses the reaction wheels to control the vehicle's pointing while the thrusters are firing. Since the thrusters aren't perfectly balanced, the torques they introduce can quickly become larger than the torque supplied by the reaction wheels, so this method of control is only suitable for short duration burns. Depending upon the size of the burn, either 1, 2 or 4 thrusters are used during open-loop burns. Knowledge of the individual thruster performance as a function of tank pressure and temperature allowed precise burns to be achieved. Before launch, CloudSat required the accuracy on all burns to be within 6% 3σ of the planned delta-V.

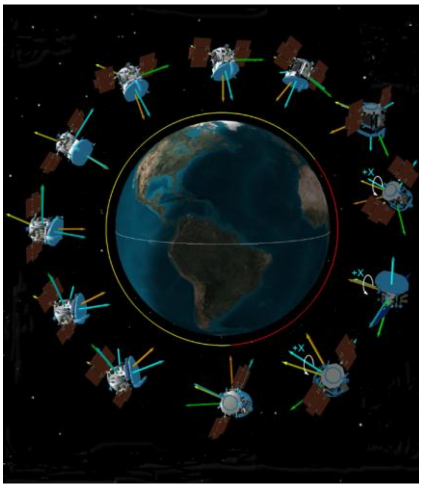

Figure 5 – This figure shows the vehicle's orientation over an orbit during the new DO-Op mode. The vehicle collects science data for approximately 54 minutes, hibernates during eclipse, and has brief recovery and setup periods just after eclipse exit and just before eclipse entry.

Attitude control during the maneuvers to the burn and during the burns was also significantly less complicated than in current operations. The commands for orienting the vehicle aligned the vehicle's thrust direction with the orbit frame axes, and the vehicle was rolled about that thrust line in order to point the star trackers towards zenith. Since the burns were done in eclipse, the sun wouldn't interfere with the trackers. Also, during science operations the vehicle flew in a fixed orientation in the orbit frame, and any maneuvers to and from the burn attitude would have the same tracker to Earth limb geometry regardless of when the burn was performed.

One other point which is worth highlighting: prior to the anomaly scheduling and performing burns could be turned around fairly rapidly – it only required a few commands, and the mission operations team could quickly check the maneuver against tracker and instrument constraints without needing sophisticated simulations .

4. CloudSat's Updated Operational Mode

Post-anomaly, the team developed a new method for operating CloudSat. Given CloudSat's battery limitations, it was necessary to have the vehicle hibernate while in eclipse and only perform active operations during the daylight portion of the orbit, and it was imperative to exit eclipse with the arrays on the sun. Keeping the vehicle in an ultra low power, stable and predictable orientation through eclipse was accomplished by carrying momentum in the system so that its spin direction stays fixed in inertial space during eclipse (Figure 5). Holding this fixed direction requires the vehicle to actively control its momentum state. During normal operations, any momentum changes due to environmental disturbances are small and are easily offset by modulating the torque rods. However, firing the thrusters can significantly perturb the vehicle's momentum state unless care is taken to balance out the torques from each of the thrusters. Also, during science collection the vehicle performs a slow roll about the instrument boresight, so any maneuvers performed for a delta-V have to take into account the vehicle's starting attitude for the maneuver. Any changes in the vehicle's momentum state could result in the vehicle exiting eclipse without the solar arrays on the sun, which would most likely result in a fault.

The new method of controlling and operating the vehicle also induced new requirements on performing burns on the vehicle. Some of these new constraints are shown in Figure 6 and include:

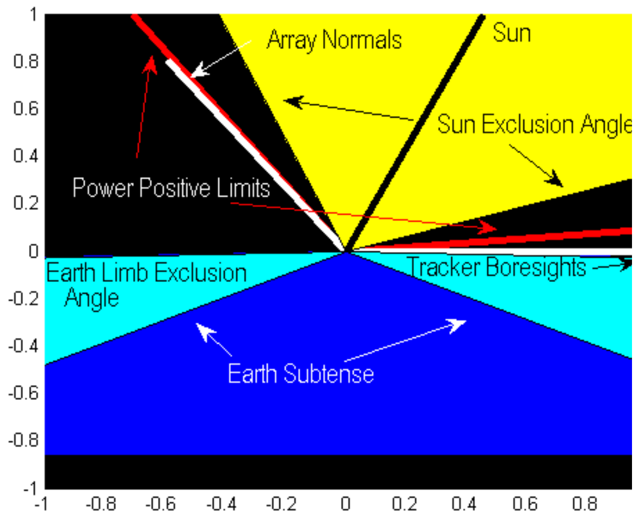

Figure 6 – This figure shows the tracker and solar array normal alignments at the sub-solar point. In order for the trackers to function properly the boresights must be kept away from the sun, the Earth and the moon. For the system to remain power positive, the solar array normals must be kept within a set angle from the sun. Slight discharges from the battery are allowed, but lengthy maneuvers off the sun can't be tolerated by the system. Also, the vehicle must keep its +X axis within 90 degrees of the sun for the safe mode to work, so the vehicle is left with a narrow keyhole where the star trackers need to be kept in order to support the mission requirements and stay operational. All of CloudSat's planned maneuvers are orbit raises, lowers, inclination changes or mean local time adjusts, so the vehicle can meet all of its required burns when the trackers are kept at the same angle relative to nadir.

1) Keep a 40% solar array fraction on the Sun during the maneuver to the burn, the burn itself and the recovery back into normal science operations. Transients that exceed this for a short time are allowed, but the vehicle cannot dwell in this state.
2) Keep the vehicle's +X axis within 90 degrees of the sun in case of an anomaly during the burn.
3) Align the star trackers away from the Earth, the moon and the Sun during all of the burns.
4) Keep the instrument boresight pointed generally away from the Sun and don't violate any of its sun constraints.
5) Don't change the vehicle's momentum set point due to thruster pulsing during the burn.

The team also wanted to insure that the vehicle transitions from hibernate to active control, and from active control to hibernate were sufficiently fast to maintain the freedom to perform burns over as large a segment of the orbit as was possible.

Also, post-anomaly designing a burn required a longer and more involved development schedule. During the current state of operations all of the maneuvers which are performed on CloudSat are simulated in a high fidelity Matlab simulation to verify constraints are not violated. In addition, since the command sequences for executing the burn and keeping the vehicle in a stable power and thermal state require over 100 commands, these have to be developed at Ball, tested on the software test bench, and uploaded to the vehicle prior to the maneuver being performed. The power demands of heaters on the power bus supporting the GPS receiver also drive the team to disable the GPS prior to performing any burns and also require multiple orbit to raise the temperature above the trip point of these heaters before power to the GPS receiver can be restored.

4.1 Angle considerations

Within the new operational constraints, the angles of several components relative to various vectors needed to be considered. The new mode of operations requires the star trackers to avoid the Earth, Moon and Sun while oriented during any delta-V operations. It is also required to keep the instrument boresight from dwelling on or near the sun, and keep the solar arrays oriented such that the array fraction on the sun is at least 40% for extended periods of operations. Occasional pointing deviations away from this can be performed, but will discharge the battery during the off-pointing. In addition, the safe modes require the +X axis of the vehicle to be within 90 degrees of the sun in case a fault is tripped during the burn. Given the schedule constraints required for preparing for the burn campaign, it was decided that during the maneuvers the vehicles would need to meet the instrument and power constraints during the maneuvers to the burn attitude, and the star tracker constraints relative to the other celestial bodies would be ignored. It was thought that if the maneuver rates were sufficiently slow, the vehicle could maintain a star tracker solution with only a single tracker in the loop, but the trackers were not able to maintain track during single tracker operations, except when the rotational rate of the vehicle was within a factor of three of the orbital rate. The maneuvers were also designed so that the vehicle would dwell for at least 60 seconds to allow the trackers time to recover a valid attitude solution after a maneuver to the burn attitude was performed.

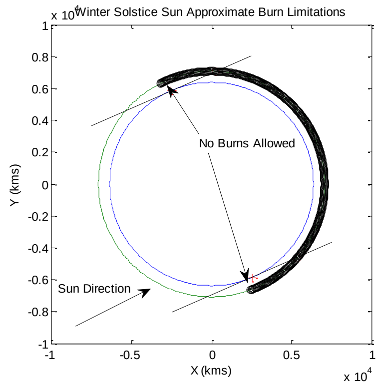

Figure 7 – This figure shows a representative section of the orbit which could be used for performing burns. CloudSat's new operations methodology requires it to hibernate in eclipse and also allows a period of time just before and after eclipse to prepare for and recover from hibernate. Even with these constraints, burns are possible over nearly half of the orbit.

4.2 Where burns can be performed

Preserving as much of the orbit as is possible for performing burns was greatly desired for CloudSat. Since CloudSat flies in a frozen, sun-synchronous orbit, maintaining this orbit requires burns be performed at specific locations. In addition to hibernating in eclipse, CloudSat requires a certain period of time to prepare for and recover from eclipse. Excluding these times, CloudSat still has approximately 50 minutes per orbit over which it can perform burns (Figure 7). It is also required for the vehicle to reorient itself before reentering eclipse so that the vehicle will achieve a power positive state at eclipse exit. Although about half of the orbit is preserved for performing burns, there are secondary limitations which may guide the team towards choosing a specific set of maneuvers. Instrument thermal constraints make burn orientations where the instrument sees the sun for an extended time period less desirable, so orbit raises in the southern hemisphere or orbit lowers in the northern hemisphere are limited by instrument constraints. Maneuvers that are performed near the sub-solar point are generally avoided because they can have the worst sun to solar array geometry, which taxes the battery. Achieving specific delta-V's can generally be performed, but may require care in designing the maneuver sequence.

4.3 Off-pulsing the thrusters for open-loop burns

During open-loop burns it is necessary to avoid significantly changing the momentum set point on the vehicle. Given CloudSat's momentum state, it was necessary keep any disturbances from the thrusters below a total effect of 1 Nms to keep the burns from significantly perturbing the vehicle's momentum state when it enters into eclipse so the solar arrays would be pointed at the sun at eclipse exit. By looking at the expected torques on the body from each thruster, it is possible to derive a set of thruster duty cycles that would keep the vehicle's momentum state relatively unchanged. Given the quantization in the thruster burn time, the torques can't be perfectly balanced, but the prebuilt sequences are sufficiently accurate to insure that the vehicle's momentum state isn't affected by more than 1 Nms for even the longest anticipated open loop burn. To compensate for the difference in thrust, a sequence or thrust commands are issued which fires all four thrusters, then only three thrusters are fired, then two, and finally one thruster. The length of time the each group of thrusters is fired is selected to minimize the net torque on the vehicle. In cases where more delta-V is required than is provided by a single block of firings the firing sequence will be repeated multiple times. If the required delta-V falls between the delta-V provided by an integer number of full blocks, a cleanup block with appropriately smaller fire times is built. Using this technique, pre-anomaly delta-V accuracy has been achieved. Before launch, the Ball team used thruster vendor data to develop accurate total thrust equations as a function of pressure, on-time and temperature for each thruster, which was instrumental in making this approach work.

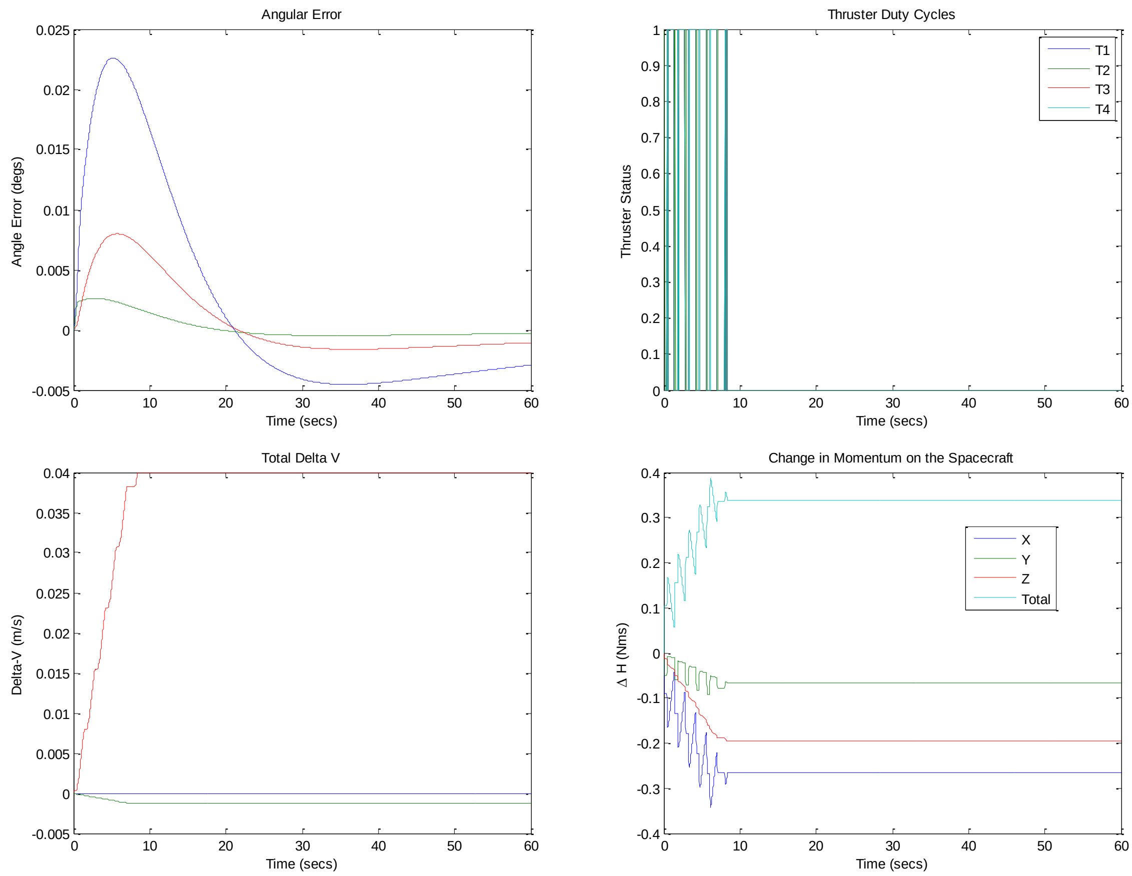

Figure 8 – This set of figures show the predicted angular deviations during a burn, the thruster duty cycles, the predicted delta-V that is applied to the vehicle and the expected change in the vehicle' momentum state.

Modeling of the burns showed that the vehicle could perform open loop-burns in this manner and not adversely affect pointing or the vehicle's momentum state. One of the known effects of performing burns in this manner was that the off-pulsing would cause the thrusters to cool down during the burn, and the resulting efficiency of the burn would be degraded. Initial tests revealed that the off-pulsing reduced the thruster efficiency by approximately 40%, but the open loop burns are a small contributor to the budget, and the vehicle has sufficient fuel margin to meet the mission needs for another seven years, and operating the vehicle in this manner allows CloudSat's new operational constraints to be met. Figure 8 shows a prediction of the vehicle's performance during one of the open loop burns.

The simulation results are examined to insure that the vehicle maintains accurate pointing, provides the correct delta-V, and doesn't significantly perturb the vehicle's momentum.

4.4 Disabling the star trackers

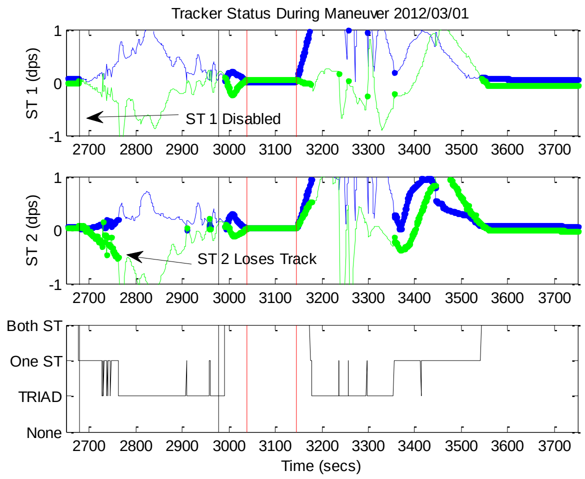

Figure 9 – This figure shows the tracker behavior during a representative maneuver on 3/1/2012. Simulation results indicated that star tracker 1 would be swept across the Earth during the maneuver to the burn attitude, and was disabled when the maneuver was commanded. Star tracker 2 fell offline as the rotational rate of the tracker exceeded its ability to track at rate. The blue lines show the tracker cross-axis rates, and the green lines show the tracker about boresight rates. It is also worth noting that the star trackers recovered during the 60 second wait prior to performing the burn.

During one attempt to perform a maneuver, one of the trackers was swept over the Earth's surface and subsequently picked up a star. The image in the tracker passed all the checks for a star. The overall amount of light also saturated some of the masked pixels on the star tracker and the perceived background measured in the tracker read as a low value. The erroneous star corrupted the attitude solution and both trackers were gradually pulled offline and induced an attitude error on the bus. As a result, the spacecraft didn't converge to the desired attitude target in time to execute the burn as desired. Therefore, CloudSat implemented a rule that disabled any tracker that was swept across the Earth during any maneuver.

Subsequent burn attempts showed that once the first star tracker was disabled, the second star tracker isn't able to track, unless the vehicle is rotating very slowly (Figure 9).

4.5 Tool Development

Although a maneuver tool had been developed for performing maneuvers to burn attitudes and then performing burns, the updates to CloudSat's operational modes required an enhanced tool for modeling the maneuvers and insuring that all of the vehicle's power, payload and ADCS requirements were satisfied during any maneuvers (Figure 10). Prior to performing any burns with CloudSat, the maneuvers are modeled in Matlab using a dynamics model, and the flight sequences are also tested on a software test bench. The software test bench contains an engineering model of the computer and all of the inputs are simulated. The dynamics model is used to check for the length of time the instrument sees the sun, the observed solar array fraction during the maneuvers, tracker rate and exclusion angle violation, reaction wheel rates and the correct spacecraft orientation during the burns. The updated tool also includes other methods of maneuvering and can be used to simulate all the standby frame maneuvers.

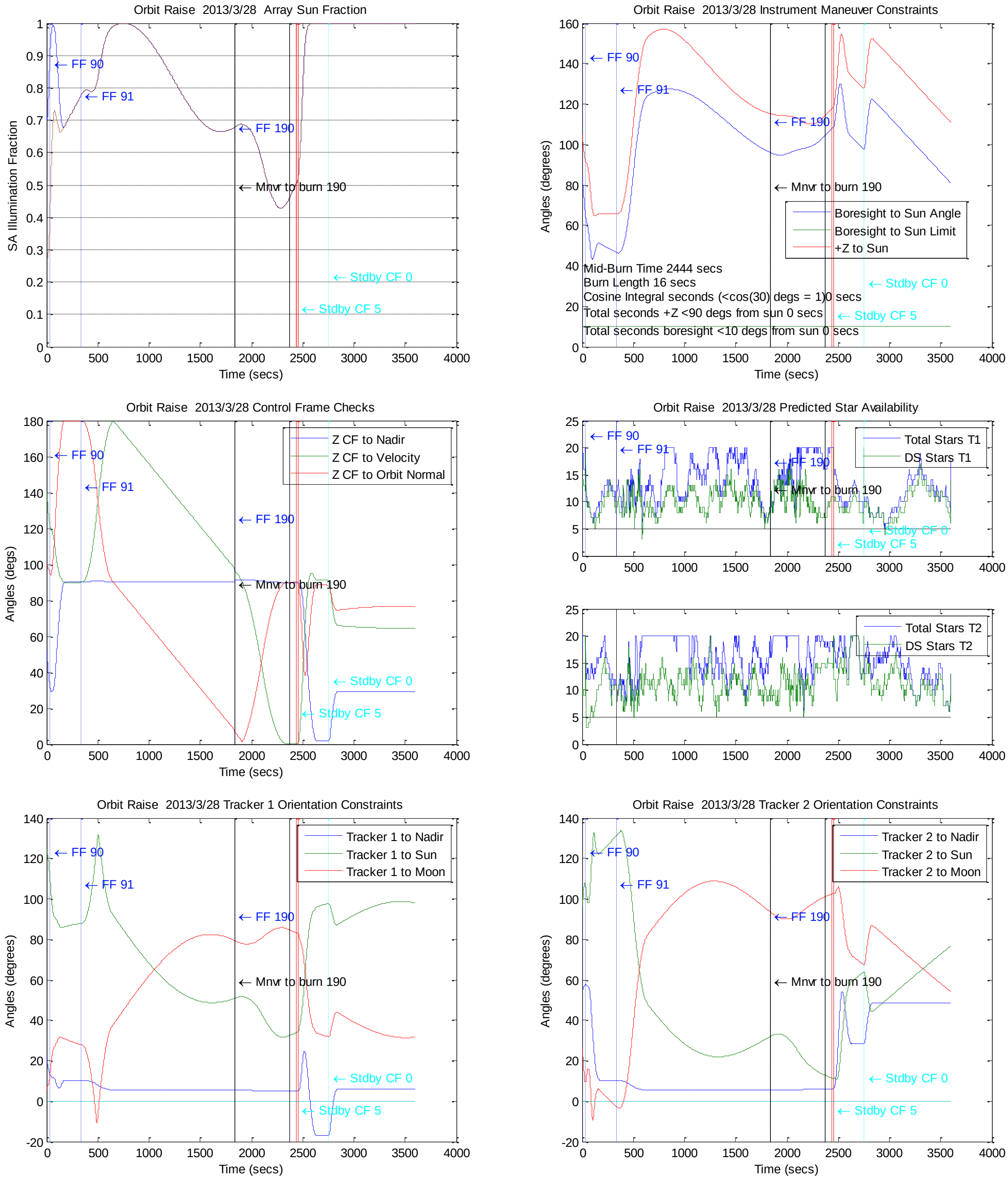

Figure 10 – Sample output from CloudSat's maneuver tool. This tool shows the kinematic predictions of the vehicle's solar array angles relative to the sun, the instrument angles relative to the sun, the control frame's orientation to the orbit frame during the entire maneuver sequence, the predicted number of stars tracked in each star tracker, the expected angles of each star tracker relative to the Earth, Moon and Sun.

4.6 Developing pre-canned COLA sequences

Since CloudSat's launch in 2006, the spacecraft has performed a handful of collision avoidance maneuvers. CloudSat has a flight rule which specifies that the vehicle must perform a maneuver to avoid a possible conjunction if the probability of collision exceeds a certain threshold. The collision probabilities are published by JSPOC and CARA, and if necessary CloudSat will perform a propulsive maneuver to decrease the probability of collision to an acceptable threshold. These potential conjunctions can appear fairly rapidly, and if a rapid response is needed, the team has insufficient time to perform the normal maneuver schedule. In order to mitigate this, the team has developed a pair of prebuilt collision avoidance maneuvers which are onboard the vehicle and can be executed with a minimum of planning.

5. Burn Sequence for Rejoining the A-Train

Several burns were required to return CloudSat to the A-Train. Given that CloudSat had drifted for several months in a non-sun-synchronous orbit, orbit raises were required to return CloudSat to the A-Train's orbital altitude, and in addition other maneuvers were executed to adjust CloudSat's inclination or Mean Local Time and achieve formation flying with CALIPSO. A preliminary look at the current orbit location indicated that the most efficient adjustments could be made to CloudSat's orbit by adjusting the inclination and changing the vehicle's rate of precession. The timing of the maneuvers also needed to be very precise in order to achieve formation flight relative to CALIPSO. Once a preliminary plan was developed, it became apparent that GCOM-W was scheduled to launch in mid-May and achieve orbit in the A-Train, and CloudSat needed to be at the correct orbital altitude before this vehicle launched. Therefore, CloudSat also performed an orbit lowering maneuver to start the sequence to return to the A-Train and decrease the burn timeline to return to the A-Train.

In order for CloudSat to achieve its location in the A-Train, all of the significant maneuvers needed to be performed at the correct times – any delays that exceeded more than an orbit or two would require reworking the entire approach sequence. In order to mitigate any risks associated with performing the maneuvers, the CloudSat team took a conservative approach in that all of the maneuvers were tested with the Matlab simulation and then on the software test bench. Finally, the attitude maneuvers associated with the burns were also demonstrated on the vehicle a week or two before the actual burn was planned. Figure 11 shows data from the 1st large burn to return to the A-Train.

Table 1 – This table contains a summary of the primary burns which were performed to rejoin the A-Train. Even with the new required modes of operations, highly accurate burns were still attained.

Date	Burn Type	Desired Magnitude (m/s)	Achieved Magnitude (m/s)	% Error
4/6/2012	Orbit Lowering Burn	-2.1	-2.1029	0.14
4/13/2012	Inclination Decrease A	-4.02	-4.045728	0.64
4/13/2012	Inclination Decrease B	-4.02	-4.045728	0.64
5/3/2012	Orbit Raise Burn	2.2	2.2114	0.52
5/15/2012	Orbit Raise Burn	2.82	2.8139	-0.22
7/18/2012	Inclination Increase	2.72	2.700705	-0.71

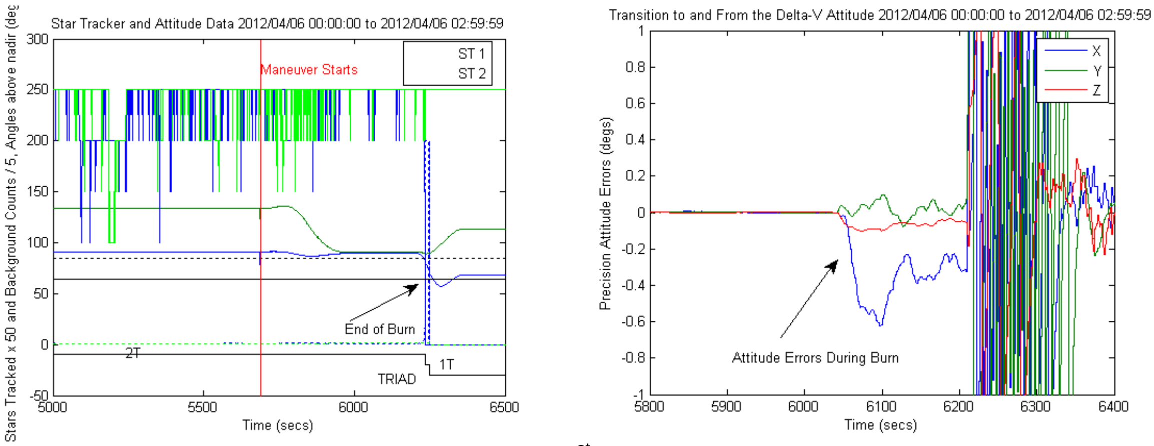

Figure 11 – Sample performance plots from the 1st orbit lowering burn to rejoin the A-Train. During this burn, CloudSat maintained a two star tracker solution through the burn, and the measured attitude errors about each axis were less than 0.7 degrees during the burn. As is shown in Table 1, the burn results were highly accurate, and the delta-V error was 0.14%.

Since CloudSat rejoined the A-Train, it is now approximately 105 seconds behind CALIPSO. The more involved method of performing burns also caused the ops team to ask for a waiver for the ground track overlap on the vehicle – if CloudSat is going to reasonably maintain a 1 km overlap with a high degree of likelihood, the ops team would probably need to be able to turn around most of the maneuvers within a 48 hour period, in order to account for any planned or unplanned adjustments to CALIPSO's orbit. However, the team requires approximately one week to prepare for and execute each formation flying burn. With these new limitations, some margin has been added to the formation flying requirements in order to allow the team some flexibility in planning and scheduling the maneuvers.

6. Open Loop Burn Performance

The new method of performing open loop burns were initially tested on 3/8 (Figure 12). The new method of maneuvering and burning was successful – the spacecraft could point itself to sufficient accuracy, the power balance was acceptable, and the spacecraft's momentum state remained unchanged. Figure 12 contains a summary set of plots from the initial open loop test. Since the checkout burn, the vehicle has performed another nine open loop burns for orbit maintenance. Since recent changes to command sequences have been made to account for the internal propulsion tank temperature and pressure, the largest burn error seen to date is 2.3%.

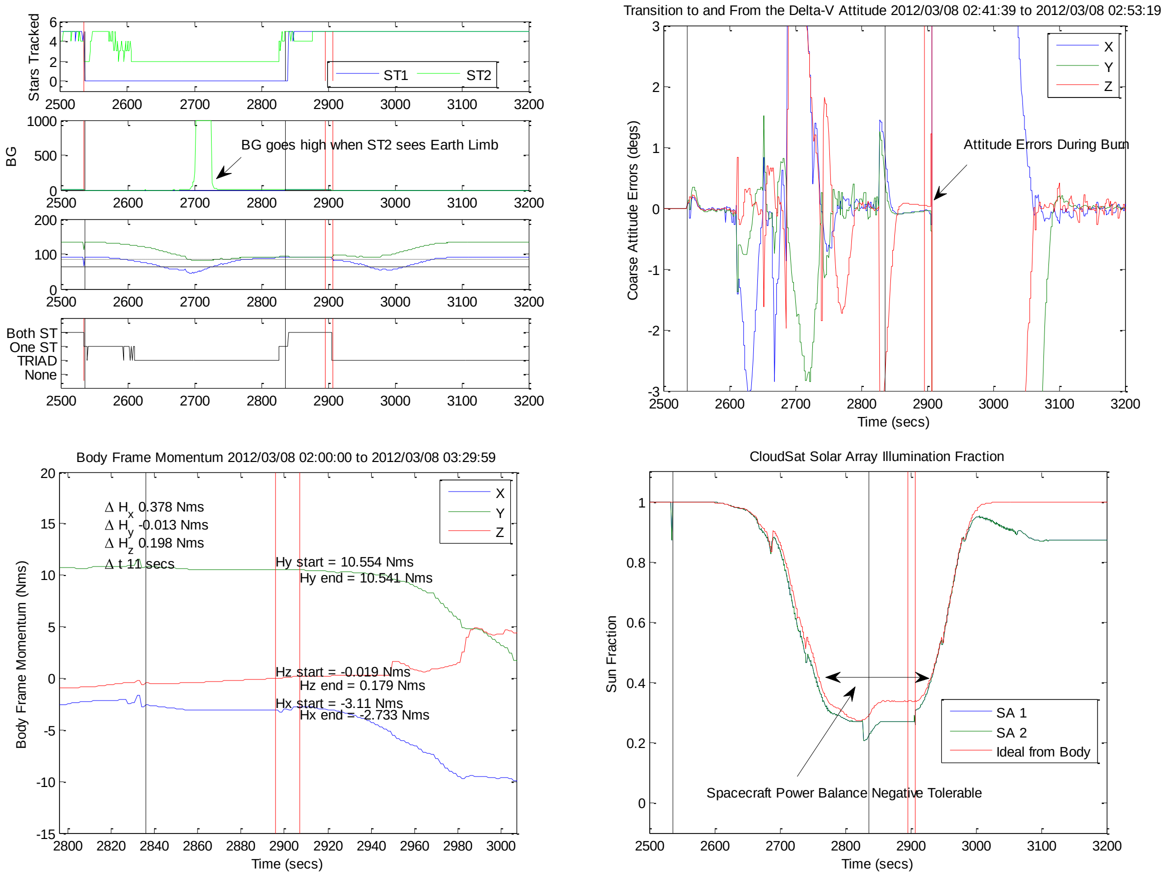

Figure 12 – This set of figures show that the methodology for performing open loop burns could operate within the spacecraft's limitations and also still achieve high accuracy results.

Table 2 – Summary results for orbit maintenance burns since CloudSat rejoined the A-Train. The results shown here assume that the higher accuracy thrust equations were used to calculate the burn efficiency. Very consistent values are seen in the burn magnitudes, excepting the over performance on January 15th, which is a result of a shorter than normal delay in the command sequence for the burns.

Date	Type	Expected DV (m/s)	% Error	Attitude Solution During Burn	Peak Attitude Error (degs)	Change in H (Nms)
7-Sep-12	Orbit Lower	0.040	-0.04	2 Star Trackers	0.05	0.2
21-Sep-12	Orbit Raise	0.070	-1.1	2 Star Trackers	0.03	0.2
18-Oct-12	Orbit Raise	0.058	0.5	2 Star Trackers	0.03	0.2
9-Nov-12	Orbit Raise	0.060	-1.3	TRIAD	0.4	0.9
4-Dec-12	Orbit Lower	0.055	-1.6	2 Star Trackers	0.3	0.4
14-Dec-12	Orbit Raise	0.104	2.3	2 Star Trackers	0.08	0.7
15-Jan-13	Orbit Raise	0.041	13.6	2 Star Trackers	0.005	0.1
28-Mar-13	Orbit Raise	0.079	-0.2	2 Star Trackers	0.04	0.4

7. Conclusions

Despite a serious battery anomaly, CloudSat has returned to normal operations and has also rejoined the A-Train. The team had to extensively modify the method of operations, including the plans for performing burns. On-orbit data has demonstrated a robust system that is capable of maintaining formation relative to CALIPSO. CloudSat expects to be operational for many additional years – the remaining fuel onboard the vehicle should last for approximately another 7 years, and no other components on the spacecraft have shown any measurable degradation.

8. Acknowledgements

I'd like to thank the extended team that helped to support CloudSat's return to the A-Train – there were many individual contributors to the mission's success including people from JPL, Ball, the RSC and the Aerospace Corporation. In particular I would also like to thank Deb Vane, Tom Livermore, Mona Witkowski, Ted Sweetser and Ron Boain for JPL's willingness and support in helping CloudSat return to the A-Train.

9. References

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