CloudSat's Return to the A-Train

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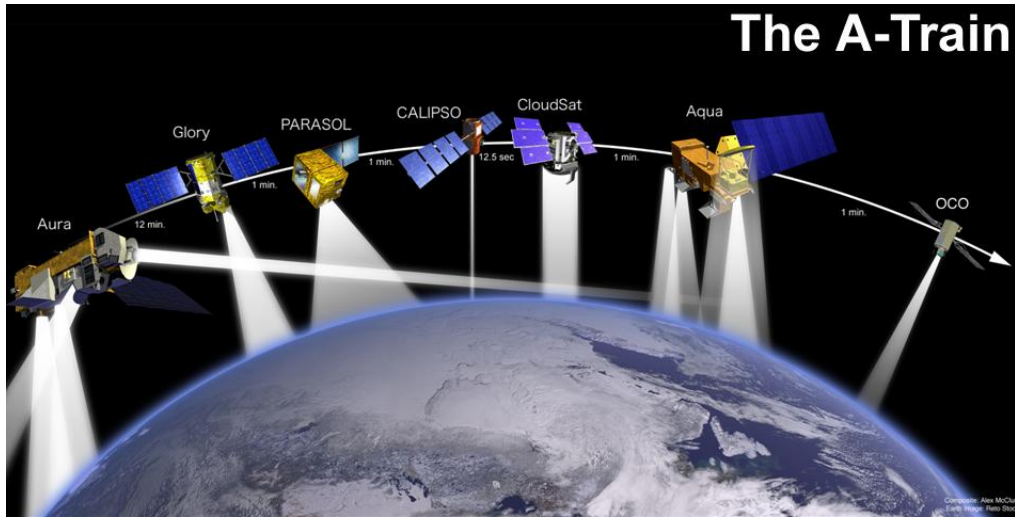
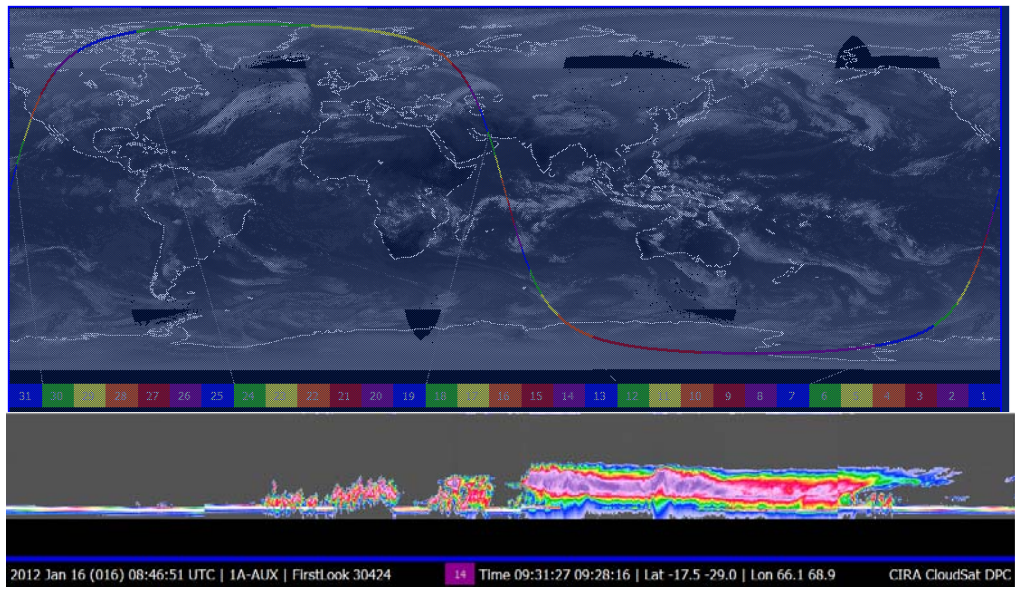
CloudSat Mission Overview

A NASA EARTH SYSTEM SCIENCE PATHFINDER MISSION

- Launched April 28th, 2006 along with CALIPSO
- Cost drove several programmatic decisions
  - 22 month planned mission
  - The rate sensor was also removed from the baseline pre-CDR due to cost
  - Battery showed aging prior to launch but it was decided not to replace it at that time due to cost
  - SWTB available for ground testing, but all components excepting the SCC are simulated
- Formation flies and follows CALIPSO's orbital trajectory in the A-Train
  - Flies 12.5 seconds ahead of CALIPSO
  - One minute behind Aqua
  - Historically has performed burns once every few weeks
    - Control box is relative to CALIPSO
    - Performs open and closed loop burns
      - Open loop burns change the vehicle's momentum set point





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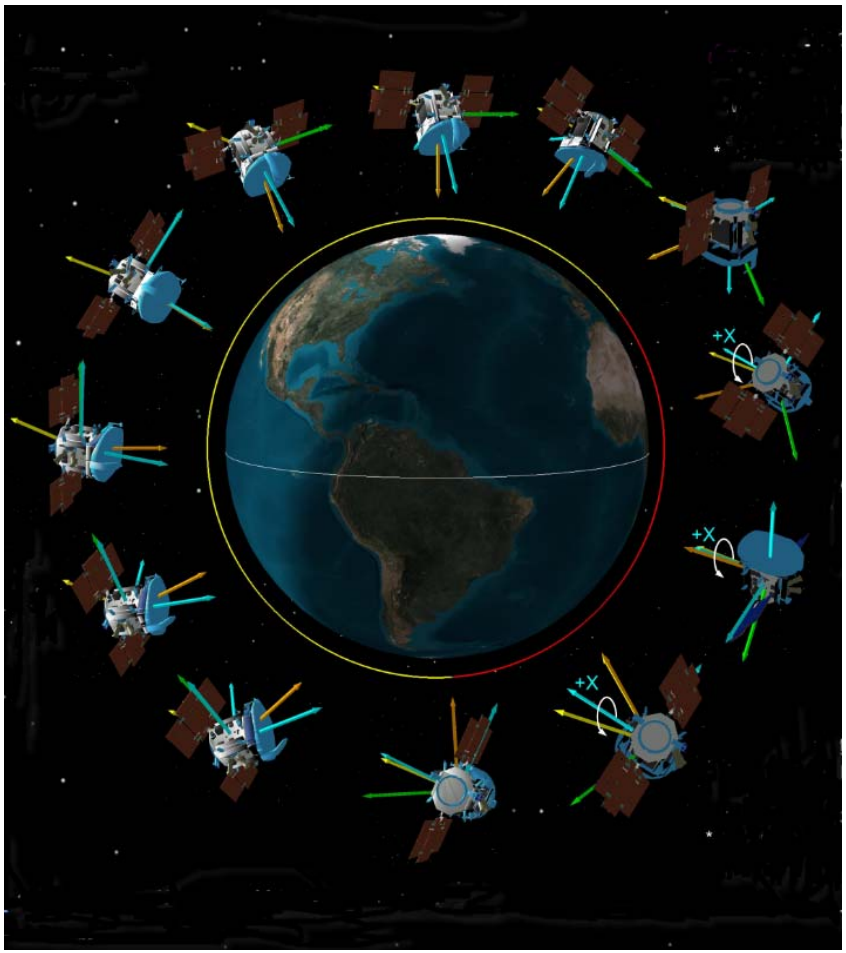
CloudSat New Operations Mode



- Redesign of CloudSat's operational modes driven by battery limitations
- Keep vehicle sufficiently warm by commanding heaters in sun to avoid survival heaters turning on in eclipse
- CloudSat collects science data for approximately 55 minutes of each orbit
- No active control – the vehicle hibernates during eclipse
- Exits eclipse with the arrays on the sun
- Spin the vehicle about the principal inertia axis

CLOUDSAT

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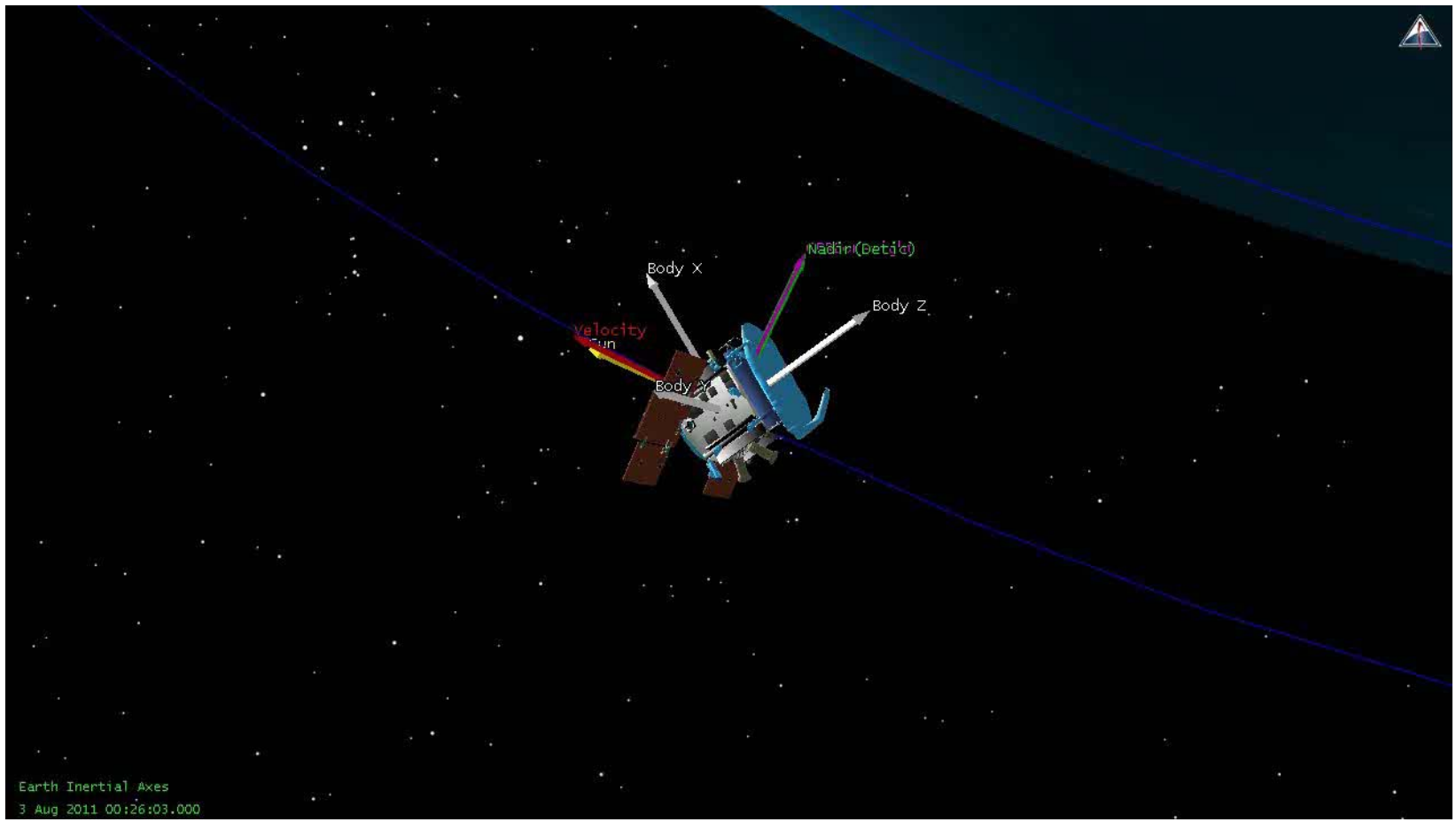
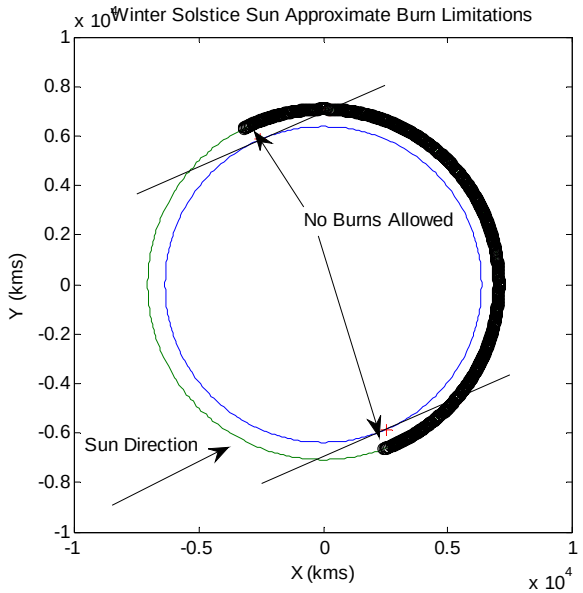
DO-Op Highly Robust Method for Controlling CloudSat

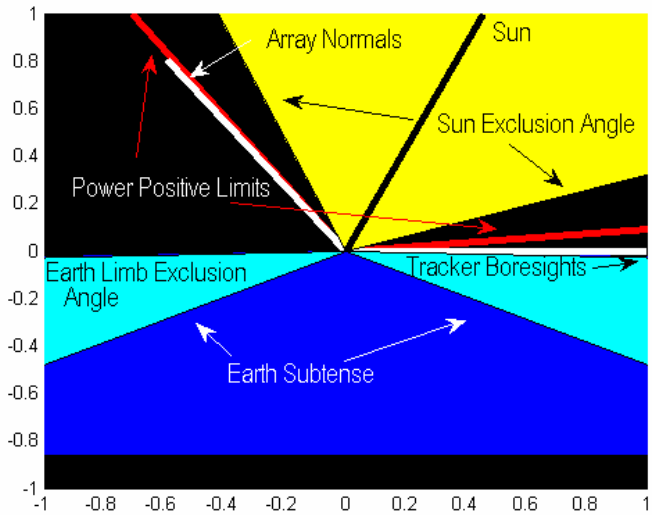


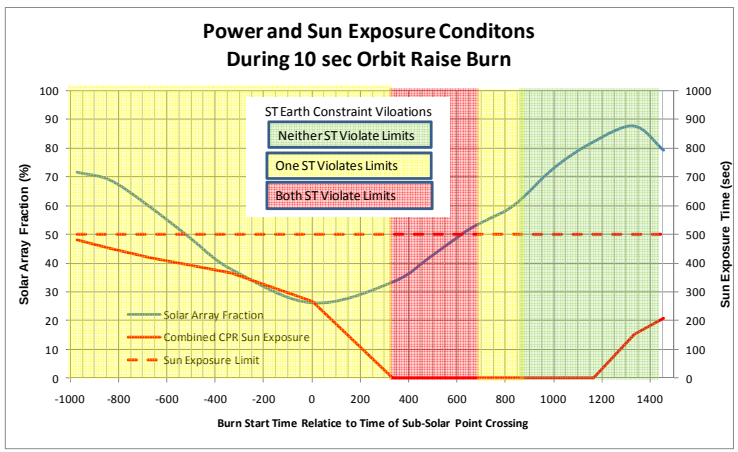
Maintaining Formation Flying Requires Several Specific Burns in Specific Locations



- Orbit raises and lowers required
- Inclination adjust burns also required
- Vehicle control inactive in eclipse
- Also requires sufficient time to exit from and prepare for eclipse
- Inclination adjusts require to perform burns at or near the equator
- To maintain the orbit's frozenness, must be able to perform orbit raises and lowers at specific locations in the orbit
- Team selected a new orbital location relative to Calipso – approximately 110 seconds behind it.

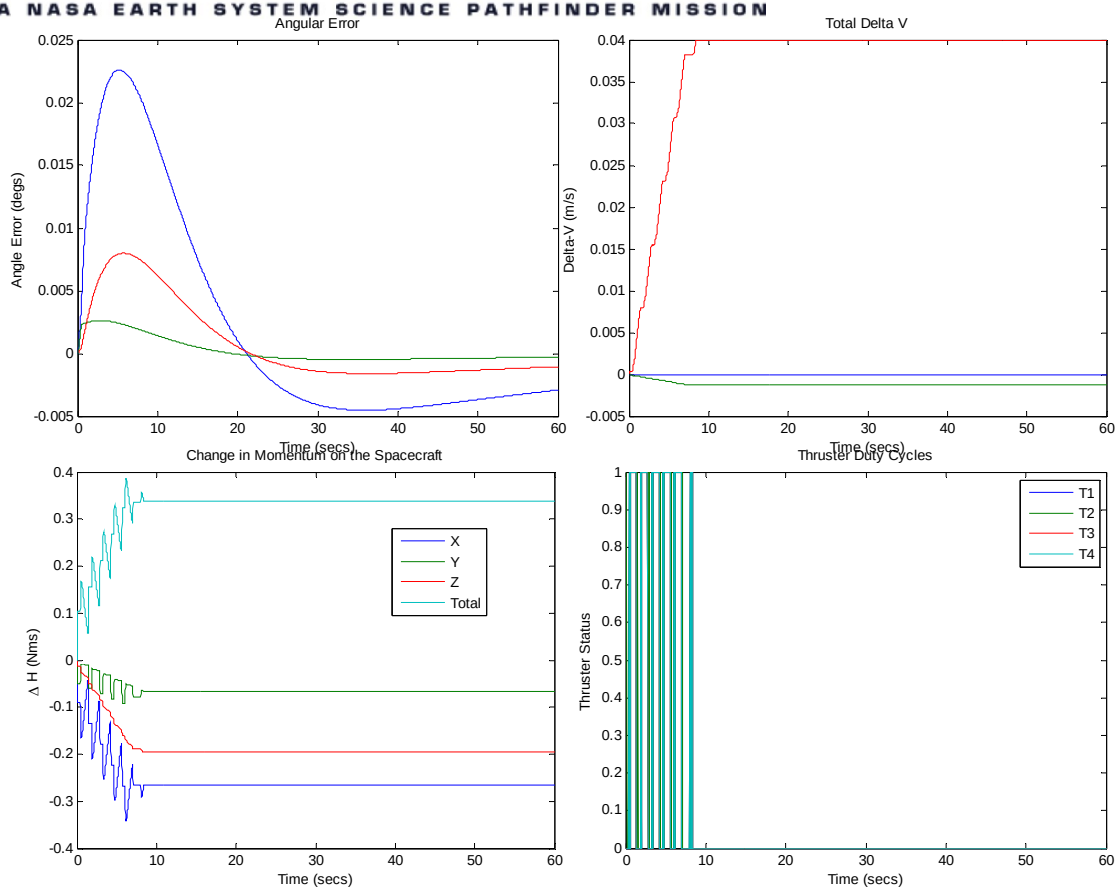
Spacecraft Constraints Must Be Met During Burns





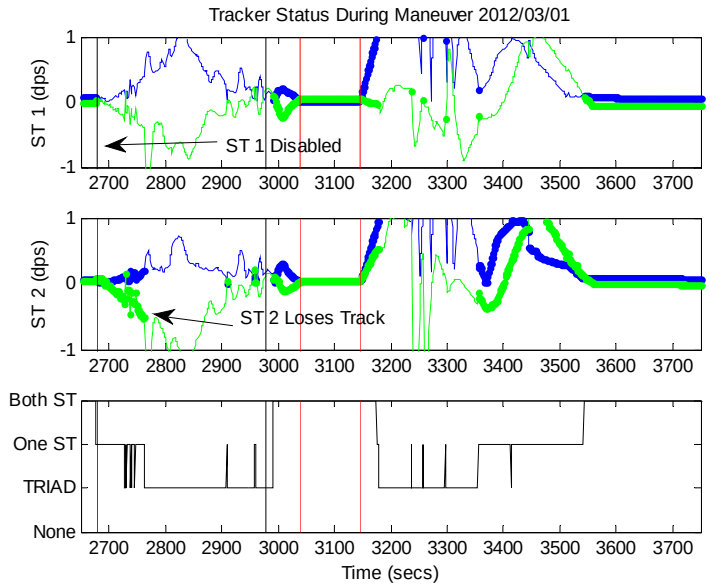
- Meet or exceed at 40% solar array fraction
  - Short transients can be tolerated
- Keep the vehicle's +X axis within 90 degrees of the sun in case of an anomaly during the burn.
- Align the star trackers away from the Earth, the moon and the Sun during all of the burns.
- Keep the tracker rates below 0.75 degs/sec
- Keep the instrument boresight pointed generally away from the sun, and don't violate any of its sun constraints.
- Don't change the vehicle's momentum set point due to thruster pulsing during the burn.

Off Pulsing Thrusters Minimizes Momentum Change on Vehicle



- Maintaining CloudSat's location within the A-Train requires precise burns.
- Also need to keep the momentum change on the vehicle due to the burn below 1 Nms.
  - Insures that the vehicle will exit the next eclipse with the solar arrays facing the sun.
- Off-pulsing the thrusters keeps vehicle's momentum set point relatively unchanged

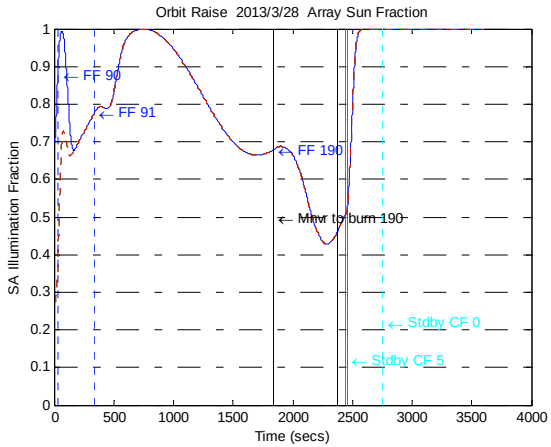
Disabling Star Trackers Insures Vehicle Will Achieve Burn Attitude

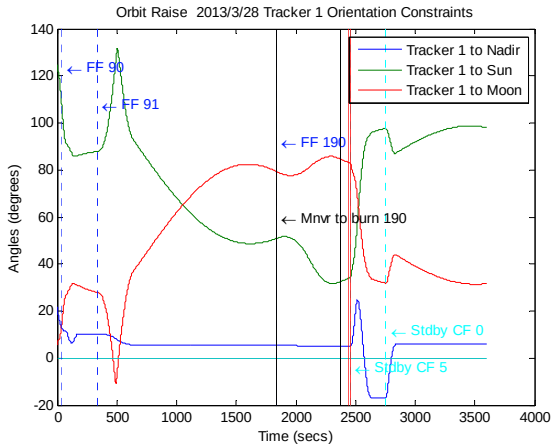


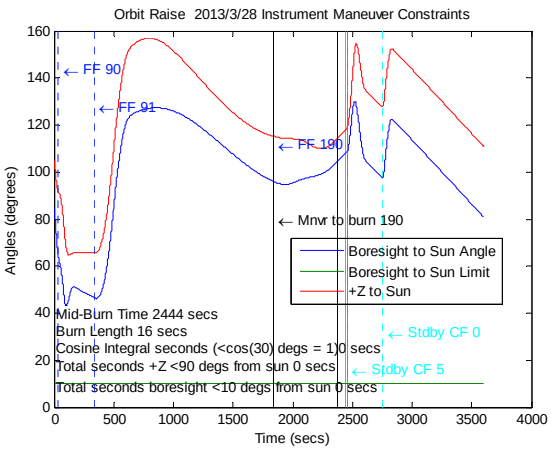
- An early attempt to perform a large burn aborted due to a falsely tracked star getting into the attitude solution
- An issue when the trackers sweep across the Earth
- Trackers are now disabled in command sequence if the vehicle sweeps the boresight over the Earth limb
- Maintaining track more difficult with only one tracker enabled
  - If vehicle rates exceed ~ 4x orbit rate, remaining tracker may lose track
- Trackers nearly always lock up quickly once reenabled and rates are slowed
- Allow 60 seconds for trackers to recover a valid attitude solution prior to executing burn

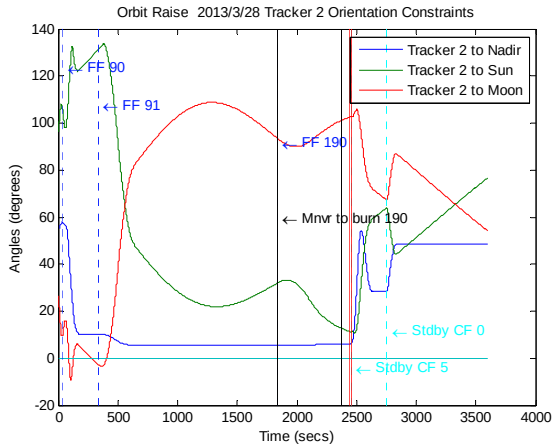
Tool Development for Maneuver Prediction

- Given the burn limitations and constraints, it was necessary to enhance CloudSat's maneuver planner tool
- Takes into account different methods of controlling the vehicle during operations
  - Standby vs. fixed frame pointing
- Used to insure that the vehicle meets all of its requirements on-orbit
- Tool results match on-orbit performance
  - Tool confirms that the spacecraft will remain in a safe state during the maneuvers







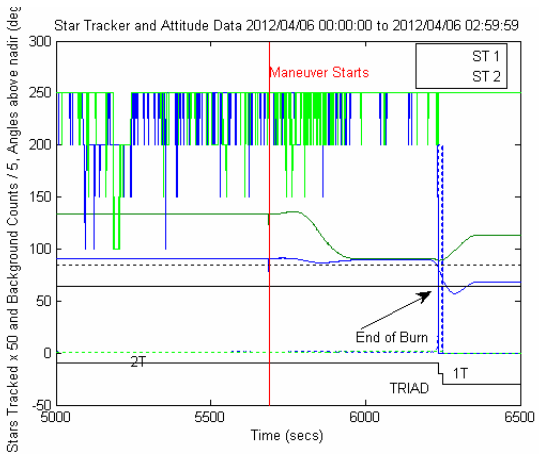


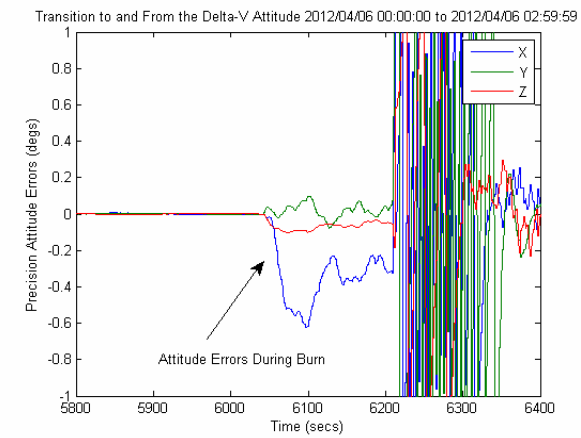
Burn Sequence to Rejoin the A-Train

Date	Burn Type	Desired Magnitude (m/s)	RSC Estimated 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

- Precise burns which occur at specific times were required to rejoin the A-Train
  - Missing a burn would require CloudSat to delay its entry into the A-Train by four months or longer
- No-fire maneuvers were tested onboard the spacecraft prior to executing them onboard the vehicle
- Even with current vehicle limitations, precise burns were achieved
- CloudSat rejoined the A-Train on 5/15
- MLT attained on 7/18

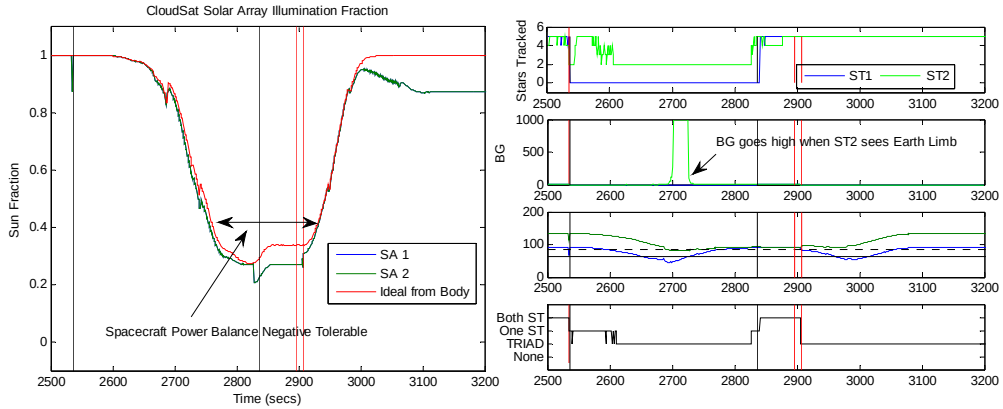
Spacecraft Performance Highly Successful During Campaign to Rejoin the A-Train

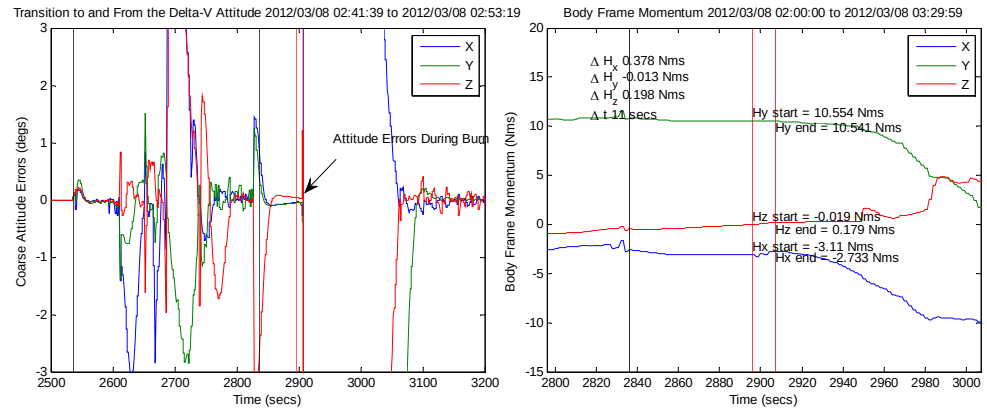




- Entire campaign of burns to rejoin the A-Train were highly successful
- Vehicle performance was consistent through the entire sequence of burns
- Attitude errors were kept below 0.5 degrees in all axes
- Spacecraft maintained power positive state through burns
- Maneuver sequence kept the instrument away from the sun

Open Loop Burn Performance – Initial Test





- Initial test of open loop burns was successful
- Burns approximately 40% less efficient due to planned off times for each thruster
- Attitude errors small
- Power profile acceptable
- Momentum change on the vehicle acceptable
- Maneuvers predictable
  - Trackers that approach the Earth's limb are disabled
- Maneuver predictions also match achieved on-orbit results

Highly Accurate Open Loop Performance Achieved

- With precise modeling, CloudSat has achieved highly repeatable open loop burns
  - Burn accuracies well within requirements
  - Demonstrated capability for burns from 4 cm/s to 11.9 cm/s
  - Acceptable change in momentum onboard the vehicle

Date	Type	Expected DV (m/s)	% Error	Attitude Solution During Burn	Peak Attitude Error (degs)	Change in H (Nms)
13-Jun-12	Orbit Raise	0.119	-0.2	2 Star Trackers	0.005	0.2
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

Conclusions

- The CloudSat team has restored all necessary functionality to the mission to perform all types of maneuvers which are associated with formation flying
- CloudSat continues to fly in the A-Train and the team expects CloudSat to remain in formation for several more years