CALIPSO and CloudSat Coordinated Ascent Phase to the EOS Afternoon Constellation

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The CALIPSO spacecraft is currently in formation with the Aqua spacecraft in a frozen, Sun-synchronous orbit with a 705-kilometer altitude at the equator crossing. The CALIPSO mission, was launched on April, 28th 2006 on a dual launch configuration with CloudSat from Vandenberg, CA. The CALIPSO and CloudSat teams faced two challenges: coordinating their respective ascent to the Afternoon Constellation and ensuring a safe insertion in their final position without impacting any of the Afternoon Constellation missions. This paper describes the CALIPSO operations during the CALIPSO-CloudSat coordinated ascent and the lessons learned.

I. Introduction

THE Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission is jointly developed under partnership by NASA Langley Research Center (LaRC), the French Centre National D'Etudes Spatiales (CNES), Hampton University (HU), the Institute Pierre Simon Laplace (IPSL), and Ball Aerospace. The goal of the CALIPSO mission is to provide measurements of aerosols, cloud vertical structure and cloud optical properties. CALIPSO is a member of the Afternoon Constellation along with the Aqua, CloudSat, Parasol and Aura satellites.[1-3] To meet its science objective, the CALIPSO spacecraft has to fly in formation with the Aqua spacecraft in a frozen, Sun-synchronous orbit with a 705-kilometer altitude at the equator crossing.[4]

The CALIPSO mission was launched on April, 28th 2006 on a dual launch configuration with CloudSat from Vandenberg, CA. CALIPSO and CloudSat are nominally inserted into an orbit with a semi major axis 15 km (defined at SECO2 (Second Engine Cut-Off 2)) below their mission value by the Delta-II launch vehicle. This insertion orbit was chosen to allow both missions to catch up to Aqua within a reasonable amount of time assuming Aqua could be at any one of 16 different position in its repeat cycle.[5] All the other spacecraft members of the Afternoon Constellation are already in their final mission orbit. Consequently, the CALIPSO and CloudSat teams faced two challenges: 1) coordinating their respective ascent to the Afternoon Constellation while 2) ensuring a safe insertion in their final position without impacting any of the Afternoon Constellation missions.

This paper focuses on the CALIPSO aspect of the CALIPSO-CloudSat actual coordinated ascent operations and lessons learned. This paper is divided into four sections. The first section presents an overview of the missions' goals and the general ascent design. The second section discusses the ascent safety criteria that were developed prior to launch as well as the overall coordination and scheduled communications between CloudSat, CALIPSO and the EOS Afternoon constellation. The third section describes the actual launch and ascent operations in light of the pre-launch analysis. Finally, the last section summarizes the lessons learned and outcome of the CALIPSO and CloudSat coordinated operations.

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II. Missions' Overview and General Ascent Design

A. Missions' Overview
In this section, the general mission requirements are presented for the CALIPSO and the CloudSat missions.

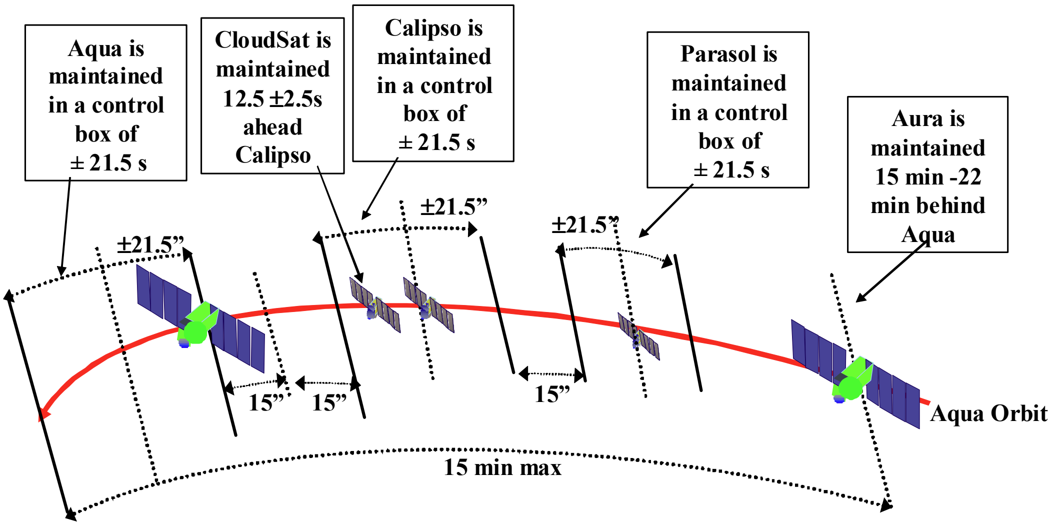

Figure 1. Afternoon Constellation Control Boxes (measured as time difference in the equator crossing).

CALIPSO and CloudSat along with the other members of the EOS Afternoon Constellation are flying nearly-identical orbits in order to perform quasi-simultaneous science measurements of the same geographical location. Figure 1 shows the relative equator time crossing locations of each member spacecraft and their control boxes in the Afternoon Constellation. The relative equator crossing times were designed to allow each member spacecraft to perform coincident imaging with the other constellation member's instruments while ensuring the health and safety of the constellation. The multiple coincident instruments measurements will be combined to provide the scientists with a unique insight into the Earth's climate. CALIPSO is required to be between 30 seconds and 116 seconds behind Aqua in Equator crossing time. In addition, it will be shifted 215 km East of Aqua (measured along the Equator) to perform coincident imaging with a portion of the AQUA MODIS swath free of Sun glint.[6] CloudSat is formation flying with CALIPSO such that it is between 10 seconds and 15 seconds in front of CALIPSO in crossing time at the Equator.[7]

B. CloudSat/CALIPSO General Ascent Design

Both ascent trajectories are designed such that the spacecraft achieve their final configuration in the Afternoon Constellation within the time allotted by mission requirements. For CloudSat, the requirement is 45 days or less with a goal of 30 days. For CALIPSO, the requirement is 45 days or less**.** The targeted orbit is a 16-day repeat cycle, Sun-synchronous frozen orbit with a 215-km cross-track separation with respect to "Virtual Aqua" at the Equator Crossing. Note that Virtual Aqua is defined as the center of Aqua's control box. CALIPSO targets the center of its control box which corresponds to a 73-second lag time at the equator crossing with respect to the Virtual Aqua spacecraft. CloudSat targets a location 10-second in front of CALIPSO's control box prior to initialization of its formation flying phase. Figure 2 shows a schematic of the CloudSat/CALIPSO coordinated ascent.

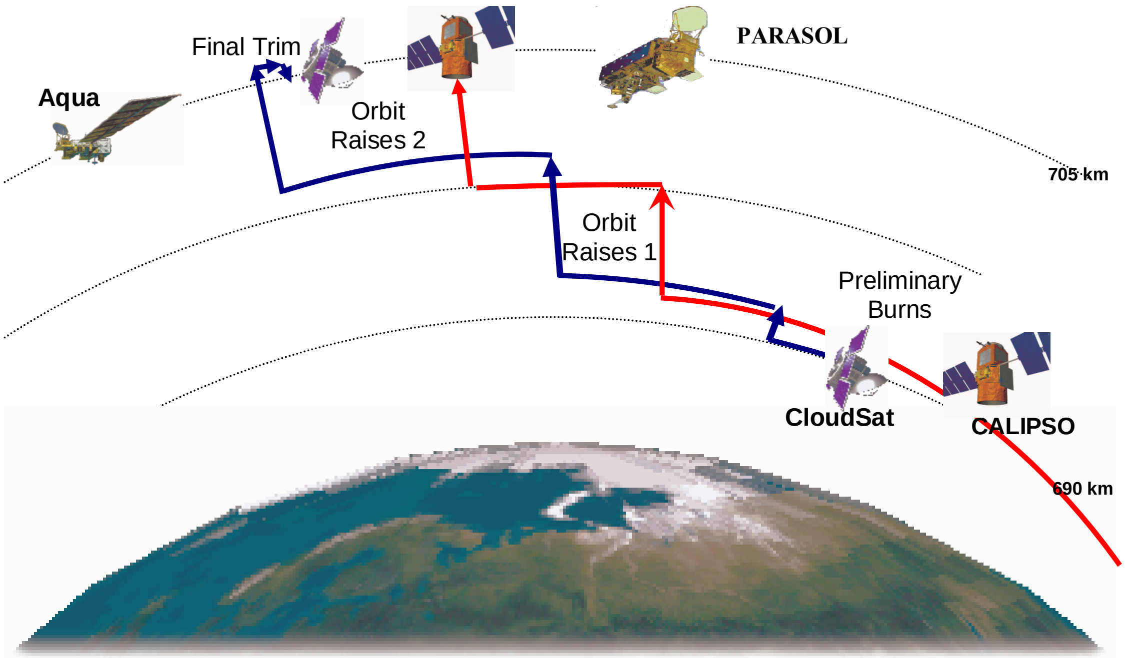

Figure 2. Schematic of CALIPSO/CloudSat Coordinated Ascent

The detailed ascent phase for each satellite is described in Ref. 4 and Ref. 8. The nominal coordinated and independent ascent mission phase has a high-degree of inherent safety due to the care taken in the design of the launch vehicle separation sequence and the coordination of plans for subsequent maneuvers. The ascent mission phase design is tolerant to 3σ errors relative to the nominal and accommodates most extreme circumstances where 3σ errors are cascaded. Additionally, mitigation strategies are available to maintain separation if required. The ascent maneuver sequence has been designed to prevent risk to the constellation, notably Aqua and/or partner satellites, if one or both the final ascent burns from either satellite fail by generally providing passive-aborts relative to these satellites

The following is a summary of the possible CloudSat maneuvers. For most days in the 16-day launch cycle, the maneuver sequence laid out below is in the order in which the maneuvers would occur during the ascent; for some exceptional days during the 16-day cycle, the order below is altered. More information can be found in Ref. 8.

- Check-Out Burn (CO)
- Closed-Loop Calibration (CLC) Burn
- Open-Loop Calibration (OLC) Burn
- Nodal Shift (DNo) Burn
- Inclination Injection Error Correction (DInc) Burn
- Orbit Raise 1 (OR-1) Maneuver consisting of two burns (OR-1A & OR-1B)
- Orbit Raise 2 (OR-2) Maneuver consisting of two burns (OR-2A & OR-2B)
- Trim Burn 1 (TM1)
- Node Shift Trim (TNo)
- Inclination Trim (TInc)
- Trim Burn 2 (TM2)
- Trim Burn 3 (TM3) (formation flying establishment burn)

The following is a summary of the possible CALIPSO maneuvers, given in the nominal sequence which they would occur. More information can be found in Ref. 4.

- Check-Out Burn (CO)
- Inclination Maneuver (DInc)
- Orbit Raise 1 (OR-1) Maneuver consisting of two burns (OR-1A & OR-1B)

- Orbit Raise 2 (OR-2) Maneuver consisting of two burns (OR-2A & OR-2B)
- Orbit Raise 3 (OR-3) Maneuver consisting of two burns (OR-3A & OR-3B) (if launch vehicle dispersions are low)
- Trim Burn 1 (TM-1)

In the following section, the coordination and safety of the CALIPSO and CloudSat nominal ascent plans are detailed.

III. Ascent Safety Criteria, Coordination and Communications

In this section, the safety criteria of the CALIPSO/CloudSat coordinated ascent are laid out as well as the general communication/exchange between the two missions during the ascent.

A. Coordinated Ascent Safety Overview

This section describes the general ascent safety criteria used by CALIPSO and CloudSat in developing their nominal ascent plans. The plan was designed such as to allow a coordinated yet independent ascent. In other words, unless there are extraordinary conditions which exceed 3σ deviations from the nominal, each mission will conduct its ascent to the operational orbit based on just the exchange of ephemeris data and pre-scheduled teleconferences exchanges. For conditions at the 3σ level (or greater) or for situations where a spacecraft contingency has occurred, these plans will be applied to the extent that they are still appropriate. Under the circumstances where the nominal plan must be abandoned because it is no longer applicable, the two missions formulate recovery plans independently but will discuss those plans with the other mission and ESMO before execution.

Both missions evaluated the safety of their nominal coordinated ascent using the following criteria:

- Maintaining a positive along-track separation (CloudSat always being in front of CALIPSO) after separation at all times during any nominal ascent.
- In case of a contingency (defined as a spacecraft losing its propulsive capability) leading to one spacecraft flying below the other spacecraft, the spacecraft will be in a passive abort configuration. This passive abort strategy was developed such as to not violate any constellation member Alert Zone-Of-Exclusion (ZOE) (Ref. 9) for most contingency cases.

The ascent plans are designed to ensure that two missions' ascents are essentially independent as:

- In the event of a CloudSat contingency, there is a minimal safety issue for CALIPSO, and CALIPSO can attain its mission requirements without CloudSat.
- In the event of a CALIPSO contingency, there is a minimal safety issue for CloudSat, and CloudSat can attain its mission requirements without CALIPSO.

In the event of a contingency scenario which would lead to the along-track separation going below 800 km prior to either spacecraft's first orbit raise**,** CALIPSO and CloudSat will discuss possible actions to be taken, if necessary. Possible actions are: (1) CloudSat will perform a small semi-major axis decrease maneuver or (2) CALIPSO will perform a small semi-major increase maneuver. In case of a non-resolution of the actions to be taken, the CALIPSO and CloudSat missions will adopt the resolution procedure outlined in Section 7.3 of Ref. 10.

B. Communication between missions during the ascent phase

CloudSat, CALIPSO and ESMO communicated at various stages during the ascent. CloudSat and CALIPSO have exchanged their final nominal ascent plan prior to launch and extensive contingency analysis has been performed.

After launch and separation, an initial teleconference was held between CloudSat, CALIPSO, and ESMO 2-days after launch and a follow-on the next week. The telecon agenda was the following:

- Review spacecraft status,
- Exchange each mission's assessed separation state, i.e., mean orbital elements at their separation epoch
- Describe each mission's assessment of launch injection errors relative to the nominal injection orbit parameters, and review each mission's assessment of the difference in mean semi-major axes between CALIPSO and CloudSat
- Confirm CALIPSO/CloudSat relative separation rates are as expected.

Based on these assessments CALIPSO and CloudSat made a preliminary determination of whether an additional maneuver might be necessary to ensure adequate separation between the spacecraft at the start of the orbit raise maneuvers. They also exchanged each mission's expected ascent plan, i.e., the maneuver sequence and timing, based on the observed injection errors and revisions to the original plan, if any, that result from the injection errors:

(1) CALIPSO described its ascent plan (including maneuver dates and times) with emphasis on whether 2 or 3 orbit raise maneuvers are needed and its plan, if any, to perform an inclination maneuver and (2) CloudSat specified its ascent plan sequence (including maneuver dates and times) from the options outlined in the CloudSat playbook (Ref. 8). In addition to the teleconference discussed above, CALIPSO and CloudSat exchange long term ascent ephemeredes.

At 15:00 UTC on the day before the first Orbit Raise maneuver for CloudSat, a joint telecon was held between CloudSat, CALIPSO, and ESMO (Earth Science Mission Operations) to discuss final plans for the Orbit Raise maneuvers. The agenda for this telecon was:

- Exchange their updated burn and no-burn ephemeris data via the Constellation Coordination System (CCS) from their current states through the second Orbit Raise maneuver
- Exchange their updated sequence of events (includes contact times, planned maneuver times, delta-V magnitude and direction)
- Discuss the spacecraft status and the maneuver performance, when appropriate, and any possible problems anticipated to occur during the Orbit Raise maneuvers

Two additional teleconferences with identical agendas were scheduled on the day before both missions' second Orbit Raise maneuver and on the day of the CALIPSO. Finally, an exceptional teleconference could have been scheduled to discuss a new course of action in the event of a contingency scenario. For example, an exceptional teleconference will have been held if either CloudSat or CALIPSO predicted that the separation distance was below 800 km prior to the first orbit raise maneuver.

C. Position Monitoring during the ascent phase

In addition to monitoring provided by the CCS (Constellation Coordination System)[11], both the CloudSat and CALIPSO missions monitored their along-track separation with respect to one another during the ascent. In the event of a contingency, if there is any concern about the predicted along-track separation between the two spacecraft, both missions were ready to communicate and take action to restore a safe distance between the two spacecraft.

IV. CALIPSO Ascent Operations

A. CALIPSO Operations Overview

The CNES component consists of the CALIPSO and Parasol ground control centers, located in France on CNES premises. The NASA component consists of the OCO, Aqua, CloudSat and Aura ground segments, located in the United States, at GSFC, LaRC, and JPL. During the LEOP (Launch and Early Orbit Phase), the main component was the Command and Control Center (CCC) located in France; CCC performed the orbit determination, the maneuver calculation and the telecommands. At the CCC, the ops team used the Flight dynamic software G2 to process the OD, compute the maneuvers and send the telecommands. Figure 3 shows a schematic of the CALIPSO CNES ground system.

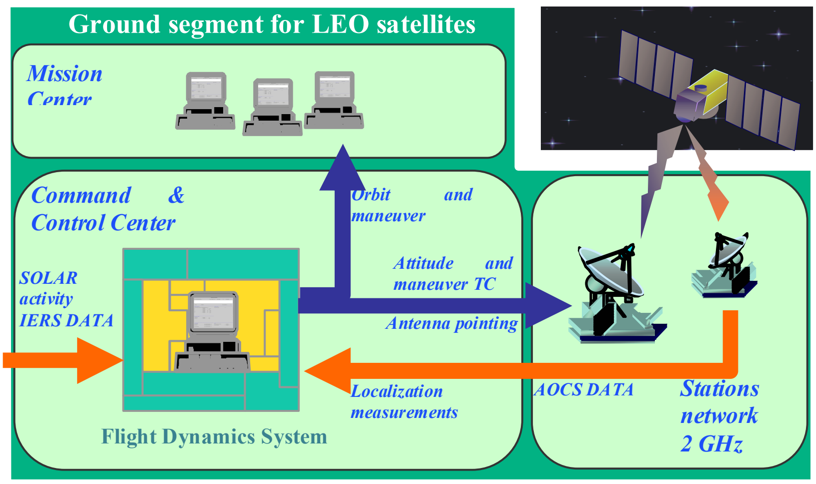

Figure 3. G2 Role in the Command and Control Center.

The timeline of the operations was scheduled according to passes over the CNES and NASA 2 GHZ ground stations. The upcoming operations were written in the SOE (Sequence Of Events). After the injection by the launch vehicle, the CALIPSO LEOP lasted 4 days. The first Orbit determination was done using Doppler and ranging measurements by the Operational Orbit Centre (OOC) and by the NASA GSFC FDF. Both entities compared their results. During the LEOP period, the onboard equipments were turned on. The engineers followed the health of the equipment using telemetry data in real-time or recorded. Then the G2 will compute the orbit and the guidance telecommands for attitude acquisition. Figure 4 illustrates the CALIPSO ground system main flight dynamics functions. At the end of LEOP, the payload was in a passive state, all units off. In order for CALIPSO and CloudSat to transfer from the injection orbit to the operational orbit and to initiate formation flying together, the two missions executed coordinated planning but independent execution. In addition to the CALIPSO and CloudSat verifications that the implementation was safe for the constellation, the NASA GSFC ESMO Constellation Coordination System (CCS)[11] checked the safety of the orbit raise sequence. The flight dynamic team computed the maneuvers and processed the telecommands using the G2. The efficiency of the maneuvers was estimated by the G2 through AOCS (Attitude and Orbit Control System) data and orbit determination.

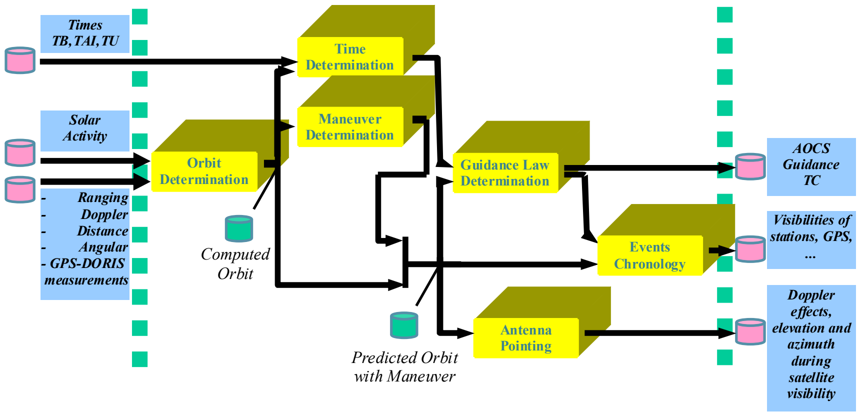

Figure 4. Main CALIPSO Flight Dynamics Functions.

B. Nominal vs. Actual CALIPSO-CloudSat Coordinated Ascent

This next section compares the nominal coordinated pre-launch ascent to the actual ascent and provides a summary of the lessons learned during operations.

1. Pre-Launch Nominal Ascent

The nominal ascent scenario was designed to ensure positive satellite separation during all phases of the ascent. Coordinated and independent simulations based on an April 28, 2006 nominal launch were performed to model the spacecraft separation. Table 1 lists Aqua, CloudSat and CALIPSO initial states used for this simulation. Those states were specified at a common epoch shortly after both spacecraft separation and were derived from the Boeing DTO results and the Aqua weekly predicted ephemeris update provided on 04/24/2006 on the CCS.

Table 1. Predicted Nominal Aqua, CloudSat and CALIPSO Brouwer-Lyddane J2 Only Mean Elements in MJ2000 Earth Equator coordinates on April 28th, 2006*.

	Epoch	A	E	I	RAAN	W	MA
AQUA	Apr 28 2006 12:00:00	7077.851	0.001179	98.268	59.524	90.392	193.869
CALIPSO	Apr 28 2006 12:00:00	7063.538	0.001020	98.267	61.564	83.781	126.438
CloudSat	Apr 28 2006 12:00:00	7062.153	0.000955	98.266	61.563	89.273	120.994

**Values based on the Boeing DTO results and Aqua Data 04/24/2006 Weekly Update*

Note that the CALIPSO nominal semi-major axis targeted for the insertion orbit was about 14.3 km below Aqua's orbit, the 15-km value being defined at SECO-2. For a nominal separation, CloudSat is 1409 m below CALIPSO in mean semi-major axis which will create the spacecraft to initially separate from one another. This statement should always be true as the allowed 3σ dispersion in delta semi-major axis is ±100 m. Figure 5 shows the predicted nominal along-track separation between CloudSat and CALIPSO during the ascent. Figure 6 presents the mean semi-major axis history for CALIPSO, CloudSat and AQUA during the ascent. For this simulation, the ascent starts at a common epoch after Launch and ends about 2 days after CALIPSO's last orbit raise. For a nominal ascent, CloudSat and CALIPSO orbit raise OR1/OR2 maneuvers are on May 24/ May 26 and May 24/May 27 respectively as laid out in references 5 and 8.

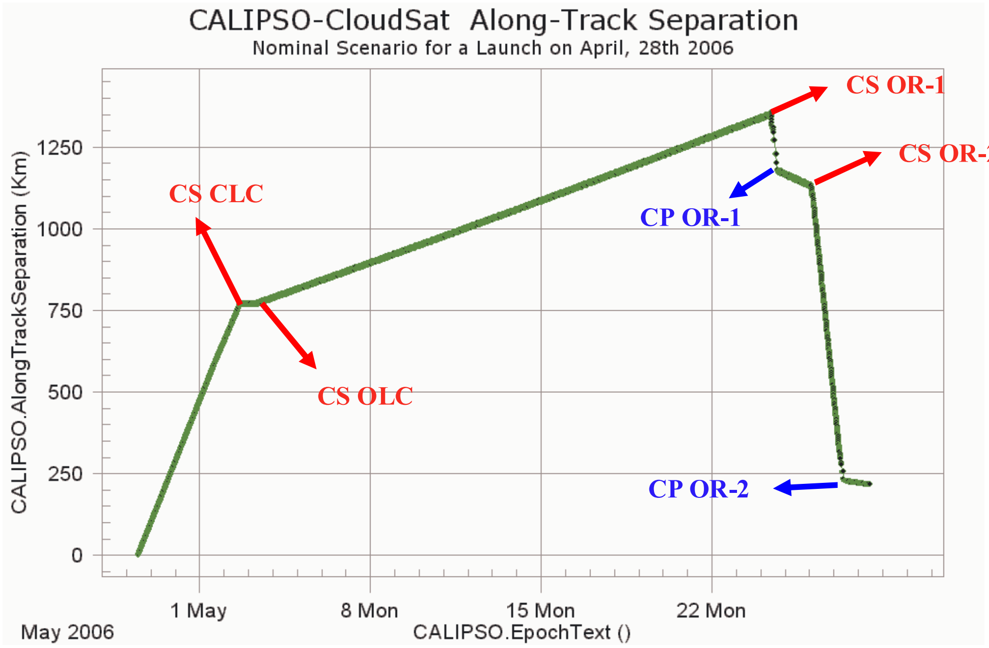

Figure 5. CloudSat Along-Track Separation with respect to CALIPSO.

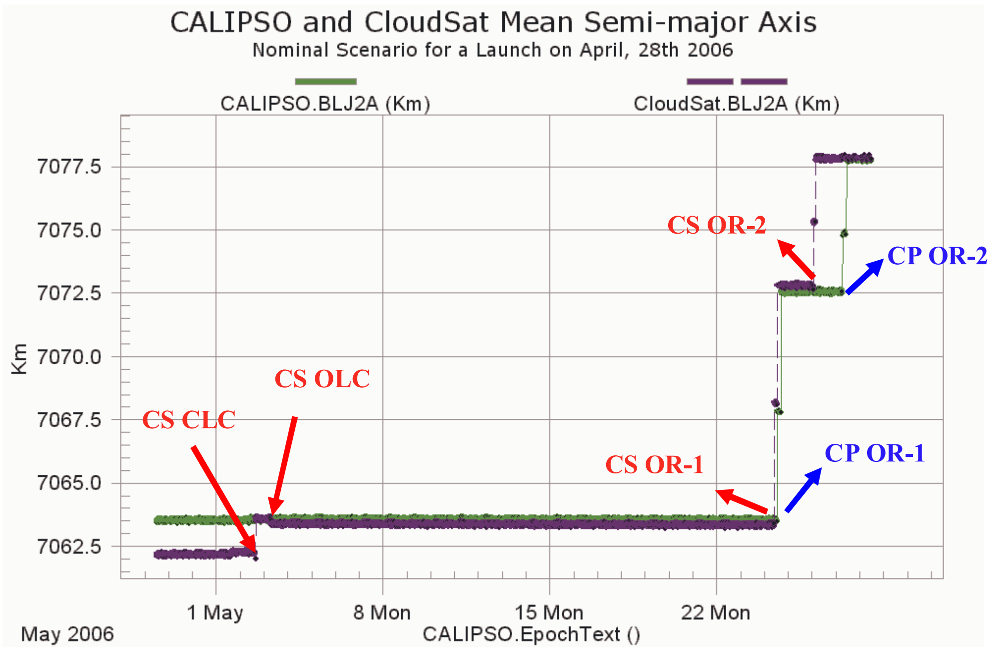

Figure 6 CloudSat, CALIPSO and Aqua Mean Semi-Major Axis.

The following ascent design features are evident from the analysis:

1. CloudSat is deployed into a slightly lower orbit than CALIPSO which causes the along track separation to continually increase.

2. Adequate separation exists between CloudSat and CALIPSO in the along-track direction and between CALIPSO/CloudSat and Aqua in the radial direction which minimizes the risk of a close approach if one or both orbit raise maneuvers fail for either or both satellites.

2. Actual Coordinated Ascent

After several launch delays, CALIPSO and CloudSat successfully launched on April 28th, 2006 at 10:02:16 UTC from Vandenberg, CA. The resulting insertion orbit had about a $+1\sigma$ dispersion on semi-major axis. Table 2 shows the CALIPSO nominal state provided before Launch by Boeing versus the actual CALIPSO state after separation (extracted from the first orbit determination solution). The CALIPSO inclination difference in the true-of-date with respect to Aqua is about -0.0026 deg which is 0.0016 deg less than the targeted value of -0.001 deg. All the remaining elements were close to their targeted value. The higher semi-major axis meant that the orbit raises maneuvers would be delayed which provided both teams with more time to plan for the best maneuver sequence.

Table 2 CALIPSO Actual Separation versus Nominal Separation in Mean Brouwer-Lyddane J2 Only in the MJ2000 Earth-Equator Frame

	Epoch	BLJ2A [km]	BLJ2E	BLJ2I [°]	BLJ2RAAN [°]	BLJ2W [°]	BLJ2MA [°]
CP Nominal (BET)	Apr 28 2006 17:00:00	7063.500	0.001034	98.266	61.771	84.805	136.156
CP Actual (First OD solution)	Apr 28 2006 17:00:00	7064.713	0.001044	98.264	61.760	91.193	134.18
		+1.213 (+1 sigma)	1.093E-05	-0.00265	-0.0111	6.388	6.388

A few changes were also made to the nominal maneuver sequence of both missions due to some operational issues. The CALIPSO spacecraft moved their check-out maneuver by 24 hours to accommodate for additional passes to perform some postponed earlier activities. More information on the CALIPSO operations can be found in Ref. 12. CALIPSO decided to not perform any inclination maneuver correction since the dispersion was small enough to compensate for the mean local time error by changing the final ground-track error target. This strategy allows for reaching the required Equator-Crossing Time difference with respect to Aqua via the ground-track control algorithm implemented in G2. If a nominal 2.5 days between CALIPSO orbit raises had been scheduled, the orbit raises would have occurred on May 27th and May 30th. However, the first CALIPSO orbit raise was advanced by one day to mitigate any risk of a once-around. This scenario also had the advantage to maintain a larger separation with CloudSat in between their orbit raises. The CloudSat spacecraft moved their check-out and calibration maneuvers by about a week due to some difficulties in acquiring their nominal pointing mode. They divided their large DNo maneuver in two smaller maneuvers (DNo1 and DNo2) to both minimize and analyze any eventual out-plane dispersions due to large pointing errors. These changes were discussed at the scheduled L+2 coordination teleconference and at a follow-on teleconference the following week. They were agreed to by all participants since CALIPSO and CloudSat were in a healthy and safe separation configuration and there was no need for a quick maneuver response. Indeed, the actual mean semi-major axis difference with CloudSat was very close to the nominal target as shown in Table 3.

Table 3. CALIPSO and CloudSat State State Comparison in Mean Brouwer-Lyddane J2 Only in the MJ2000 Earth-Equator Frame

	Epoch	BLJ2A [km]	BLJ2E	BLJ2I [°]	BLJ2RAAN [°]	BLJ2W [°]	BLJ2MA [°]
CS Actual	Apr 29 2006 00:00:00	7063.314	0.0009852	98.26651	62.062	86.891	231.725
CP Actual (First OD solution)	Apr 29 2006 00:00:00	7064.711	0.0010409	98.26679	61.756	91.193	134.186
		+1.397					

The first CALIPSO maneuver was the check-out maneuver which was performed on May 3rd, 2006. This maneuver was implemented to check the overall propulsion system as well as the perturbation torques due to Thruster's misalignments. The maneuver behaved nominally with a total change in semi-major axis of +49 meters. The maneuver was composed of two burns of about 1.53 cm/s each. Since there was no scheduled inclination maneuver, the next maneuver was the first orbit raise on May 26th, 2006. This maneuver was composed of two burns of 2.06 m/s and 2.49 m/s respectively for a total commanded semi-major axis change of +8.6 km. The burn size and location were chosen so as to achieve a frozen orbit configuration. The actual semi-major axis value reached was 98.6% of the commanded value (i.e., 1.4% cold). The next maneuver is the second and last orbit raise on May 31st, 2006. This maneuver raises the semi-major axis by 4.6 km to the CALIPSO operational orbit. There is no eccentricity correction so the maneuver is divided in two equal duration burn of about 1.2 m/s each. The actual semi-major axis value reached was 100.2% of the commanded value (i.e., 0.2% hot). In light of the OR-2 maneuver performance, the CALIPSO team decided that the trim maneuver was no longer needed. Table 4 lists all the performed CALIPSO maneuvers along with their corresponding efficiency.

Table 4. CALIPSO Maneuver Performance Summary.

Date	Maneuver	Predicted Change Semi-major Axis	Actual Change Semi-major Axis	Efficiency
05/03/2006	Check-Out	+58 m	+49 m	0.85
05/26/2006	Orbit Raise 1	+8.6 km (Eccentricity=+0.000137)	+8.476 km	0.986
05/31/2006	Orbit Raise 2	+4.6 km	+4.611 km	1.002

Figures 7 a-f show various CALIPSO parameters from launch through the end of the ascent phase. Figure 7a represents CALIPSO and Aqua mean semi-major axis history. Figure 7b exhibits the Equator Crossing Time (ECT) separation as measured from the back of Aqua's control box. Recall that CALIPSO targets the center of its control box which corresponds to an ECT of 51.5 seconds from the back of Aqua's control box. However, there could be a variation of up to ± 3.5 seconds due to some operational constraints on the burn location. Figure7c presents the ascending node Ground-Track Error (GTE) with respect to CALIPSO customized WRS-2 grid. Figure 7d shows the difference in seconds between the ECT separation and the separation measured using the GTE value. Since CALIPSO uses the GTE to control the ECT separation, this value translates to a correction to apply to the control boundaries. Finally, Figures 7e and 7f represent CALIPSO and Aqua mean argument of perigee and mean eccentricity respectively.

At the end of the ascent, CALIPSO is at 54.5 seconds behind the back of Aqua's control box (ECT value) and drift slowly toward Parasol. The achieved GTE value is of -3.1 km which corresponds to a correction of -3.75 seconds. Preliminary long term predictions show that a Drag Make-Up maneuver is not required until end of August. Finally, CALIPSO reached a frozen orbit configuration after its first orbit raise as shown on Figures 7e and 7f. There was no need for further eccentricity correction on the second orbit raise.

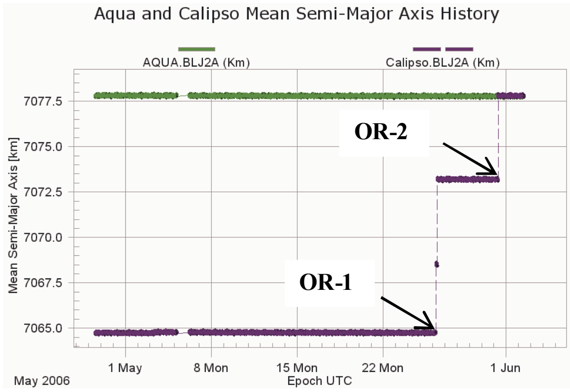

Figure 7a. CALIPSO and Aqua Mean Semi-major Axis History.

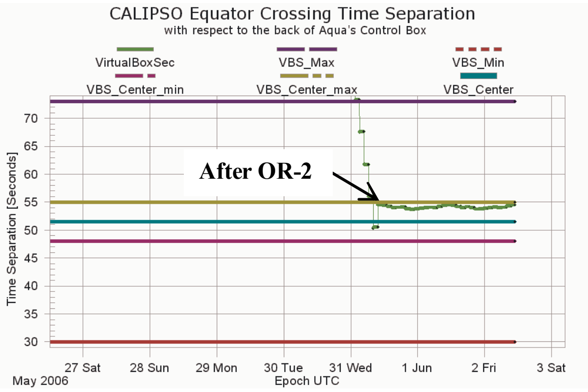

Figure 7b. CALIPSO Equator-Crossing Time (ECT) Separation wrt. the back of Aqua's Control Box

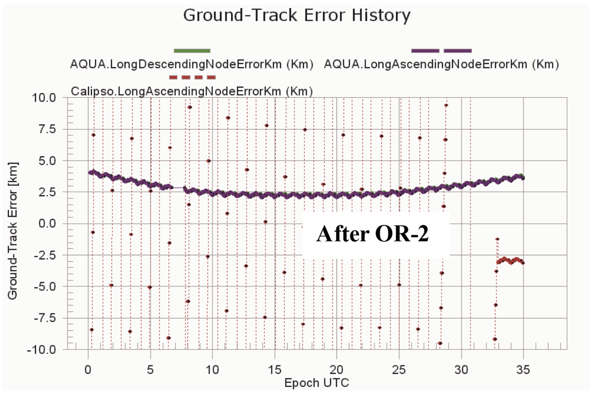

Figure 7c. Aqua and CALIPSO Ground-Track Error (GTE) History.

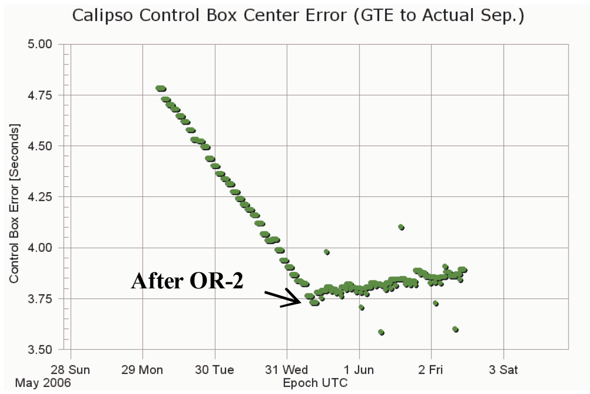

Figure 7d. Difference between CALIPSO ECT and GTE control box positions in seconds

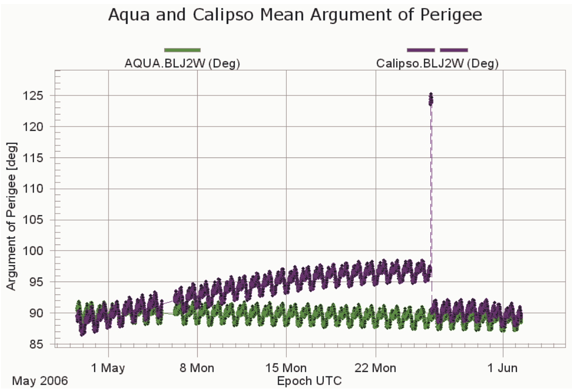

Figure 7e. Aqua and CALIPSO Brouwer-Lyddane J2 Only Mean Argument of Perigee History.

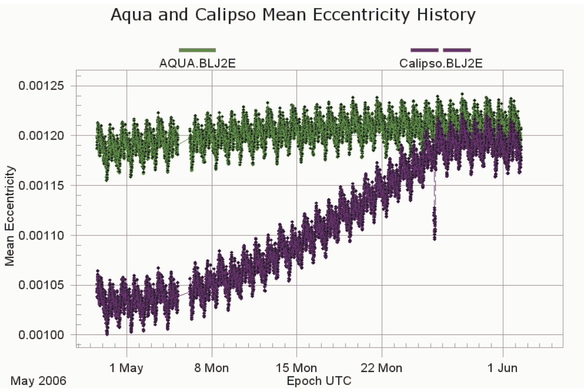

Figure 7f. Aqua and CALIPSO Brouwer-Lyddane J2 Only Mean of Eccentricity History.

While planning and executing the above maneuver sequence, CALIPSO coordinated with CloudSat as per the previous agreements. Each mission updated ascent plan were communicated and checked by both teams as well as the ESMO (Earth Science Mission Operations) team. The complete CALIPSO and CloudSat final maneuver sequences as they occurred is summarized in Table 5 along with the various coordination teleconferences scheduled during the ascent phase.

Table 5. CALIPSO and CloudSat Ascent Maneuver Summary.

Event (Elapsed Day from Launch)	Event Date (Calendar UTC)	CALIPSO Maneuvers	CloudSat Maneuvers	Coordination Teleconferences
Launch Day	April 28th, 2006 10:02:16			
L+2	April 30th, 2006 16:00:00			L+2 - Part 1
L+5	May 3rd, 2006 08:38:46	CO-A		
	May 3rd, 2006 11:06:45	CO-B		
L+12	May 10th, 2006 16:00:00			L+2 - Part 2
L+13	May 11th, 2006 14:50:19		CO	
L+14	May 12th, 2006 13:52:47		CLC	
L+15	May 13th, 2006 07:15:44		OLC	
L+20	May 18th, 2006			
L+24	May 22nd, 2006 11:24:05		DNo-1	
L+25	May 23rd, 2006 10:24:36		DNo-2	
L+26	May 24th, 2006 15:00:00			Pre-OR1
L+27	May 25th, 2006 20:45:37		OR-1A	
	May 25th, 2006 23:13:23		OR-1B	
L+28	May 26th, 2006	OR-1A		
	May 26th, 2006	OR-1B		
	May 26th, 2006 15:00:00			Post-OR1
L+29	May 27th, 2006 10:12:19		OR-2A	
	May 27th, 2006 12:40:30		OR-2B	
L+30	May 28th, 2006 10:55:34		TInc	
L+33	May 31st, 2006 05:48:00	OR-2A		
	May 31st, 2006 08:15:00	OR-2B		
	May 31st, 2006 15:00:00			Post-OR2
L+35	June 2nd, 2006			
L+36	June 3rd, 2006 07:13:11		TM2	

Figure 8 represents Aqua, CALIPSO and CloudSat mean semi-major axis history during the coordinated ascent phase. Figure 9 shows the corresponding CALIPSO-CloudSat along-track separation. The separation profile is consistent with the safety design developed prior to launch. The spacecraft initially separates at a rate of about 190 km/day after Launch which decreases to about 20 km/day after the CloudSat calibration maneuvers. The spacecraft separation reaches about 3,000 km prior to the orbit raises which is well above the set 800 km safety threshold. Due to CALIPSO moving its first orbit raise a day earlier in the sequence, the CALIPSO-CloudSat along-track separation remains between 2,500 km and 3,000 km up until CloudSat last orbit raise. CloudSat achieved its temporary waiting position 10 seconds in front of CALIPSO box on May 27th. The along-track separation then decreases until CALIPSO performs its final orbit raise. As soon as CALIPSO is declared safe in its own control box, CloudSat will start its formation flying maneuvers to establish its final configuration with CALIPSO.

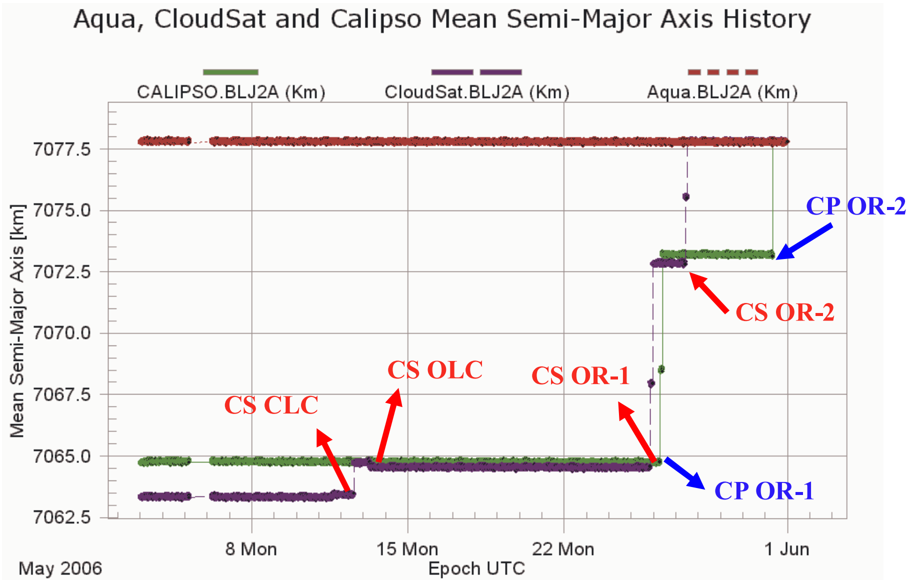

Figure 8. Aqua, CALIPSO and CloudSat Mean Semi-Major Axis History.

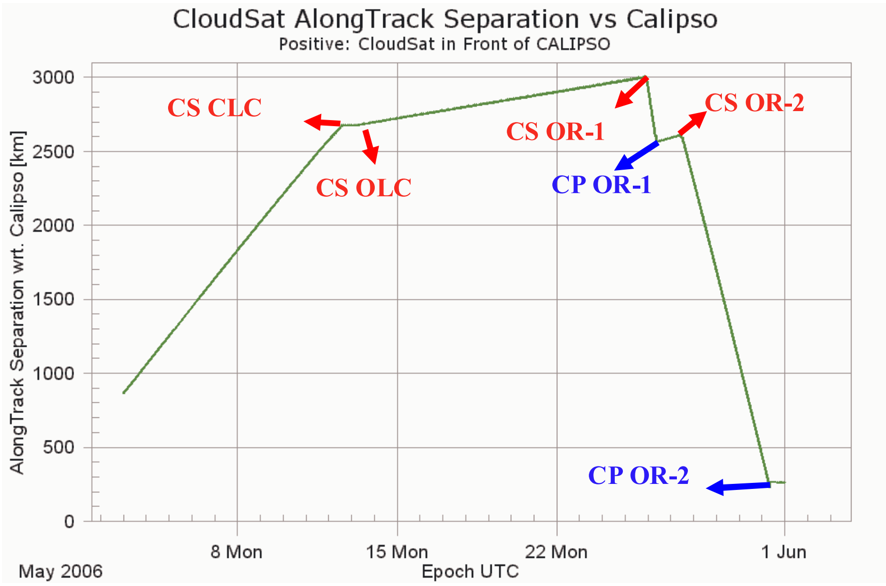

Figure 9. CALIPSO-CloudSat Along-Track Separation History.

V. Conclusions

This paper presented the CALIPSO-CloudSat coordinated ascent operations after their dual launch from Vandenberg on April, 28th 2006. Thanks to a careful design developed by the CloudSat and CALIPSO teams, the spacecraft simultaneous ascent to the Afternoon constellation was achieved successfully and safely. This design guaranteed that there would be no crisscrossing of the two spacecraft orbits during their ascent and that in the contingencies involving a spacecraft flying under another spacecraft it will only violate the Alert ZOE (Zone-Of-Exclusion) in very specific cases and even then the penetration would be small relative to the size of the Alert ZOE.[9] This paper also outlined the basic agreements which ensured the proper coordination between the two missions' ascent plans in spite of the changes made to their respective nominal plan. Overall, both the CALIPSO and CloudSat spacecraft behaved nominally with thruster performance on the order of 2% and 0.5% respectively. This better-than-expected maneuver performance simplified greatly the overall operations and coordination. However, both spacecraft had developed ascent plans which were resistant to cascaded +3-sigma errors along with mitigation strategy if required.

In addition, the ascent maneuver sequence had been designed to prevent risk to the constellation, notably Aqua and/or partner satellites, if one or both the final ascent burns from either satellite fail by generally providing passive-aborts relative to these satellites.
Both missions, as well as the ESMO team, were well informed and prepared during the past ascent operations. The changes made to the nominal plans further increased the overall safety with higher along-track separations, and additional back-up days in case of missed maneuvers. At the time this paper is written, CALIPSO is at the center of its control box, preparing the remaining instrument activities so as to start science measurements. CloudSat will soon perform maneuvers to initiate the formation flying with CALIPSO. After those last maneuvers, both satellites will start their routine operations up until Fall 2006 where they will get ready for a series of coordinated inclination maneuvers with all the members of the constellation. After the inclination maneuvers completion, they will resume nominal operations for their two-year and three-year mission respectively within the EOS afternoon constellation.

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