Operational Collision Risk Assessment of CALIPSO and LANDSAT-5 Crossings

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In late February 2010 the French Space Agency (Centre National d'Etudes Spatiales, CNES) and NASA (LaRC, Langley Research Center) operations teams in charge of the CALIPSO satellite were notified of an unfavorable spacecraft collision risk with the Landsat-5 satellite detected by the NASA Earth Science Mission Operations (ESMO) team. As a member of the Afternoon Constellation, CALIPSO is orbiting in a sun-synchronous frozen orbit following a repetitive ground track at a mean equatorial altitude of 705 km. Landsat-5, operated by the United States Geological Survey (USGS), is also orbiting in a sun-synchronous frozen orbit following almost the same ground track at the same mean equatorial altitude. Both orbits can be considered as nearly identical, the main difference between them being the mean local time of the ascending node. The assumed in orbit position difference between the two satellites was such that the relative phasing should not create any collision risk despite the orbit intersections. However, changes in mean local time of Landsat-5 and the Afternoon Constellation modified the orbital configuration and led to dangerous crossings during a significant period of time. This issue concerns not only CALIPSO and Landsat-5, but also all the current and future Afternoon Constellation missions. This paper will introduce the station keeping principles that led to the dangerous orbital configuration and the flight dynamics aspects taken into account to study the crossings. It will continue to present the CNES and LaRC tools developed to identify the crossings and to compute the maneuver trade space permitting to choose the maneuver parameters that mitigate the collision risk. Finally, it will describe the maneuver strategy agreed upon by all the concerned missions to manage the close approaches.

I. Introduction

THE main objective of the CALIPSO mission is to collect cloud and aerosol data for a better understanding of their role in climate and improve the ability to predict long-term climate changes and seasonal climate variability. A secondary objective is to provide a set of simultaneous coincident data with which to validate and improve data retrievals from both NASA's Earth Orbiting System (EOS) and Cloudsat satellite. To fulfill these objectives CALIPSO satellite was conceived as a joint NASA and CNES project flying as a part of the Afternoon Constellation. The mission is led by NASA whereas the satellite platform operations are under CNES responsibility.

The Afternoon Constellation (also known as A-Train) currently consists of four on-orbit missions in addition to CALIPSO: Aqua, Aura, Cloudsat and PARASOL. The first two are NASA EOS missions whereas Cloudsat is a joint mission with the Canadian Space Agency and the United States Air Force. Finally the PARASOL mission, operated by CNES, is still considered part of the A-Train but has dropped below the A-Train orbit altitude. There are two additional missions that are scheduled to join the A-Train between 2012 and 2013 (GCOM-W1 and OCO-2).

Landsat 5 was launched on March 1, 1984 and was the fifth satellite of the Landsat program. Its main objective is providing a global archive of Earth images. The Landsat Program is managed by USGS, and data from Landsat 5 is collected and distributed from the United States Geological Survey (USGS) Center for Earth Resources Observation and Science.

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To carry out their missions, the Afternoon constellation and Landsat-5 have to orbit at a mean equatorial altitude of 705 km following a repetitive ground track. The discriminatory parameter of the orbits is the right ascension of the ascending node (RAAN) also known as the Mean Local Time (MLT). Consequently both orbits have two points in common: the nodes corresponding to the orbit intersections. These intersections make a collision event possible if the satellites arrive simultaneously. The initial orbit parameters (MLT and relative phasing) were chosen to ensure that no collision risk was possible between Landsat-5 and the Afternoon Constellation. However, these parameters evolved throughout the operational lifetime due to modifications in the mission requirements leading to a dangerous situation for the satellites' safety.

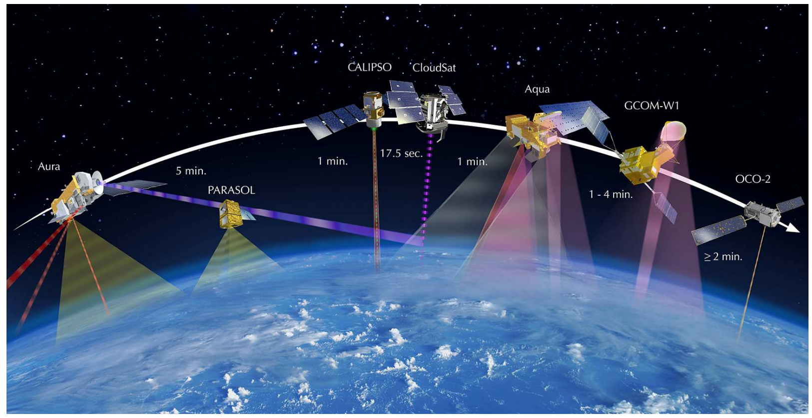

Figure 1. Afternoon constellation (Credits NASA). *The CloudSat spacecraft experienced an anomaly which led it to temporary exit the A-Train Orbit. Cloudsat return operations to the A-Train orbit are in progress.*

Handling this new configuration needed an international cooperation and coordination involving several teams from different countries. This paper describes the station keeping principles that led to the dangerous configuration and the flight dynamics concepts which permitted the characterization of the close approaches. The software tools developed by the flight dynamics teams from CNES and LaRC and the final long term strategy agreed to minimize the collision risk without interrupting the mission will also be discussed.

II. Nominal station keeping

Landsat 5 and the Afternoon Constellation missions fly in 705 km, 98.2 degree, frozen, sun-synchronous, polar orbits which permit Earth observations under nearly identical lighting conditions every 16 days. The one exception is PARASOL, which lowered its orbit by 3.9 km in late 2009 due to insufficient fuel to maintain its location in the constellation, so it no longer maintains the same orbital relationship with the other Afternoon Constellation satellites.

Figure 2 illustrates the Afternoon Constellation spacecrafts' relative phasing (α). Aqua satellite follows a path along the World Reference System-2 (WRS-2) grid with a Mean Local Time of the Ascending Node (MLTAN) between 13:30 and 13:45 in a 43 seconds control box. CALIPSO flies in another 43 seconds control box placed 30 seconds behind the Aqua one. CloudSat was in the front of CALIPSO spacecraft by 17.5±2.5 seconds until an anomaly occurred in 2011 which led it to leave the A-Train orbit (Fig. 2 shows the Cloudsat position before the anomaly which corresponds to the position it occupied when managing the CALIPSO and Landsat-5 passings).

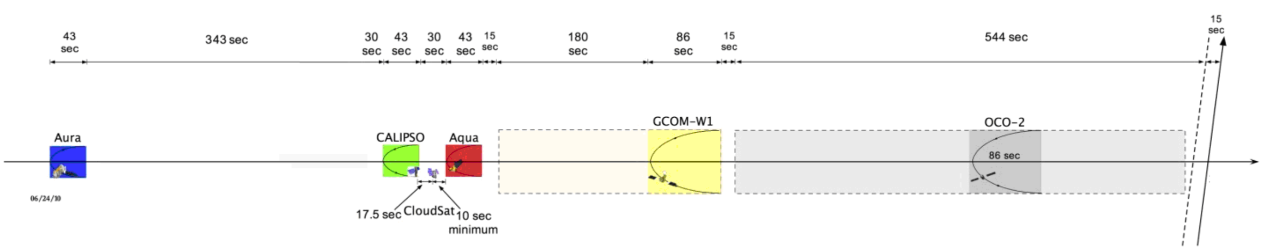

Figure 2. Afternoon Constellation spacecrafts relative phasing.

The Landsat-5 satellite maintained an initial Mean Local Time of the Descending Node (MLTDN) near 9h45 following a path along the WRS-2 grid (as explained later, the Landsat-5 MLTDN was moved to 10h00 causing the dangerous passings). In its nominal configuration Landsat-5 crossed the orbital intersection near the poles prior to the crossing by any Afternoon Constellation satellite. All the spacecrafts could co-exist without any interaction as they were all following a repetitive ground track with a MLT that guaranteed the correct phasing to avoid a collision in the orbit intersection. Table 1 summarizes the station keeping parameters values.

Table 1. Afternoon Constellation and Landsat-5 station keeping parameters.

	Aqua	CALIPSO	CloudSat	Aura	GCOM-W1	OCO-2	Landsat-5
Altitude	705 km						
Inclination	98.2 degrees						
Orbit Type	Sun-synchronous and frozen						
MLT at the ascending node	13:30 – 13:45	9 minutes later than Aqua	12.2s ± 0.4s earlier than CALIPSO	8 minutes later than Aqua	79.5-259.5 seconds earlier than Aqua	180.5-360.5 seconds earlier than Aqua	9:30 – 10:00 (Descending node)
Ground-track Reference	WRS-2	215 km East of Aqua WRS-2	N/A	One WRS-2 path + 25.4 km West of Aqua	WRS-2	WRS-2	WRS-2
Ground-track Error	± 10 km	± 10 km	± 1 km wrt the CALIPSO lidar ground-track	± 10 km	± 20 km	± 20 km	± 10 km

To achieve these station keeping requirements (ground track error, relative phasing and MLT) the spacecrafts perform various maneuvers. The ground track error and the phasing difference are primarily maintained by performing Drag Make-Up maneuvers (DMU) to compensate the atmospheric drag. These raising maneuvers increase the orbital period and make the spacecraft drift along its ground track and within its control box. The parabola represented in each control box of Fig. 2 symbolizes the effect of a DMU and the atmospheric drag on the spacecraft. After performing a DMU the semi-major axis is higher than the nominal (perfectly phased) one and the spacecraft drifts back in its control box. Under the effect of the atmospheric drag, the semi-major axis decreases reversing the drift forward until another DMU is needed.

To keep the MLT steady, a sun-synchronous orbit needs a given inclination in order to guarantee that the line of nodes rotates at the same angular velocity as the meridian plane containing the Sun. Perturbations, like the Sun, the Moon and the Earth potential, modify the nominal inclination forcing the MLT to drift. Inclination maneuvers shall then be performed to maintain the MLT requirements.

III. The dangerous configuration

For a given ground track path the MLT and the relative phasing are coupled[1]. Allowing the MLT to drift, while maintaining the same ground track path, implies that the relative phasing will drift as well. An example of this relationship is represented in Fig. 3. Y-axis ($\Delta\alpha$) represents the difference between the mean relative phasing and the nominal one. The x-axis (ΔMLT) represents the difference between the current MLT and the nominal one. The green dotted line represents the combination of $\Delta\alpha$ and ΔMLT corresponding to a 0 ground-track error (GTE) and the orange dotted lines represent the combination of $\Delta\alpha$ and ΔMLT leading to the maximum permitted GTE. The blue trajectory represents the satellite evolution performing DMUs to keep the GTE between the required boundaries without performing inclination maneuvers. As we can see in this figure, moving the MLT to a new value will force a new relative phasing in order to keep a ground-track error within the mission requirements.

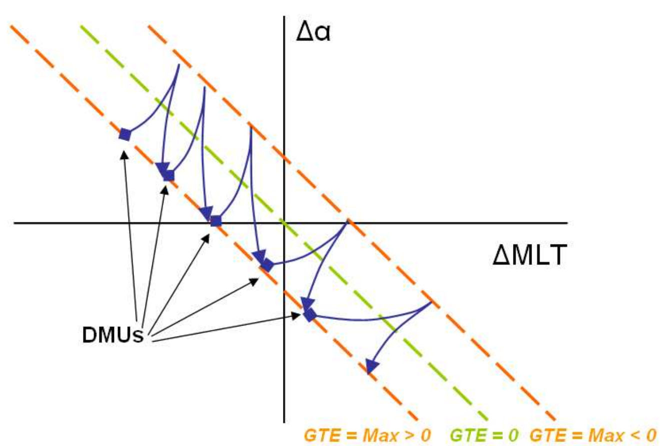

Figure 3. Example of relationship between relative phasing and MLT drift

In 2002, USGS initiated a series of inclination maneuvers in order to increase Landsat 5's MLT from 9:45 a.m. to 10:00 a.m. Consequently, in order to maintain its ground track, Landsat-5 gradually decreased the relative phasing with respect to the Afternoon constellation. Eventually, Landsat-5 went from crossing through the orbit intersections several hundred seconds before the A-train satellites to crossing at almost the same time and then crossing well after the A-train. It is when Landsat-5 goes from crossing the intersection prior to an A-train satellite to crossing it after that A-train satellite (or vice versa) that there is potential for a high risk of collision. While every orbit has 2 crossings (northern and southern nodes) of the orbital intersection, the transitions from satellites exchanging the order in which they cross the nodal intersections are referred to as passings.

IV. Close approaches characterization

As mentioned earlier, when the relative phasing between Landsat-5 and The Afternoon Constellation is such that the satellites reach the orbits crossing points at the same time, there is a high risk of collision generated by close approaches repeated at a frequency of twice an orbit (one at the North and the other at the South hemisphere). Because the orbits are so similar, the phasing change between an orbit and the following one can be less than the along track uncertainty. Therefore, the risk can be high for several consecutive crossings through an orbit intersection. CNES characterizes a close approach event by computing its probability of collision[2]. It can be demonstrated[3] that, in case of consecutive close approaches, the classical method to compute the probability of collision used at CNES may not be applicable. Consequently we had to find new elements to identify and characterize these close approaches.

The first element is the radial separation at orbits crossing points. Analyzing both Afternoon Constellation and Landsat 5 orbits we can see that the Landsat-5 frozen orbit has a much larger libration than that of the Afternoon Constellation. The Landsat 5 perigee and apogee (and thus its eccentricity) and its argument of perigee each oscillate over a wider range than those for the Afternoon Constellation satellites. Consequently, the radial separation at the orbits crossing point raises and falls following a well known cycle of 118 days. The eccentricity requirement of the Afternoon Constellation is 0.0012 +/- 0.0004 deg. However, in practice, eccentricity deviation is less than 0.0001 degrees. Actual Landsat-5 eccentricity deviation is around 0.0003 degrees which produces radial separation with respect the Afternoon constellation orbits to oscillate between +/- 2km. Figure 4 shows a simplified analytical computation of the radial separation at CALIPSO and Landsat-5 orbits crossing points.

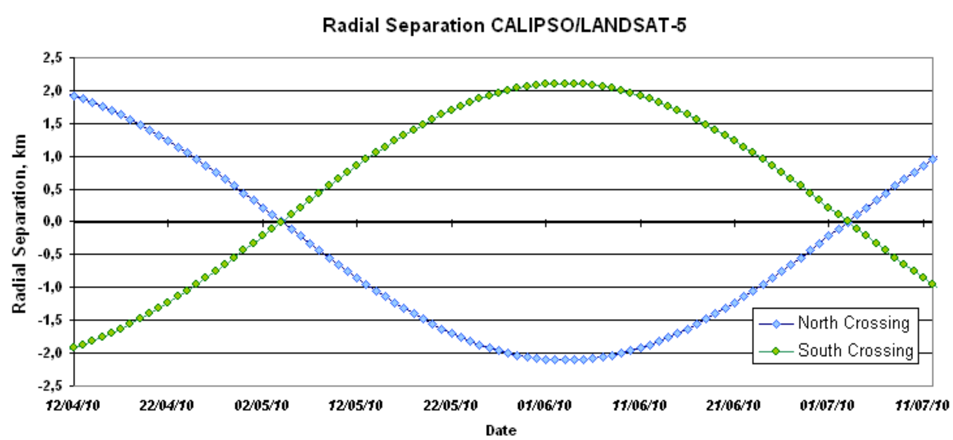

Figure 4. Analytical computation of the radial separation at orbits crossing points between CALIPSO and LANDSAT-5.

The second element permitting the characterization of the close approaches is the crossing time difference, i.e., the period of time between the passage of one of the satellites through the orbits crossing point and the passage of the other.

By computing the dates when the crossing time difference is close to 0 we can identify the passings. The radial separation at the orbit's crossing points is then the criteria used to define whether a given passing event is a dangerous conjunction. Then these dangerous conjunctions can be mitigated by maintaining the orbit so a passing does not occur during a period of low radial separation.

V. Developed Software Tools

To handle the CALIPSO and Landsat-5 crossings two dedicated tools were developed. The first one computes the crossing time difference and the radial separation at orbits crossing points in order to identify the passing periods. The second was used to compute the maneuver trade space allowing a shift of a dangerous passing period to other favorable dates.

A. Computation of the crossing time difference and the radial separation

The two spacecrafts will reach the orbit crossing point at the same time for a given difference in the in-orbit position $\Delta\alpha_{critical}$. Assuming that orbits are not coplanar, the direction from the center of the Earth and the orbits crossing point is defined by the vector $\vec{c}$ perpendicular to the kinetic momentums of both orbits $\vec{n}_1$ and $\vec{n}_2$.

$$\vec{c} = \frac{\vec{n}_1 \wedge \vec{n}_2}{\left\| \vec{n}_1 \wedge \vec{n}_2 \right\|} \tag{1}$$

Letting $\Delta\Omega$ be the difference in RAAN of the orbits and $\overrightarrow{AN}_i$ the unitary position vector of these Ascending Nodes, it can be proven[4] that:

$$\alpha_i = \arccos\left(\overrightarrow{AN}_i . \vec{c}\right) \quad \alpha_i \in [0;\pi] \quad \text{if} \quad \Delta\Omega \in [0;\pi[$$

$$\alpha_i = -\arccos\left(\overrightarrow{AN}_i . \vec{c}\right) \quad \alpha_i \in [0;\pi] \quad \text{if} \quad \Delta\Omega \in [-\pi;0[\tag{2}$$

$$\Delta\alpha_{critical} = \alpha_2 - \alpha_1 \tag{3}$$

Where α_i is the in-orbit position of the crossing point of each spacecraft. With Eqs. (1), (2) and (3) we can compute the crossing point position.

The software implements two computation modes: the long-term mode and the accurate mode (for short-term analysis).

1. *Long-term mode*

The radial separation (ΔR) is computed in mean parameters using Eqs. (4) and (5) :

$$\Delta R = r_2 - r_1 \tag{4}$$

$$r_i = \frac{a_i \cdot (1 - e_i^{\ 2})}{(1 + e_i \cdot \cos(\alpha_i - \omega_i))} \tag{5}$$

Where:

r_i is the distance between the center of the Earth and the intersection of the vector $\vec{c}$ with the corresponding orbit *i*.

a_i is the mean semi-major axis of the orbit *i*

e_i is the mean eccentricity of the orbit *i*

ω_i is the mean argument of perigee of the orbit *i*

The crossing time difference (CTD) is computed as follows:

$$CTD = \frac{\Delta\alpha_{critical} - \Delta\alpha}{\sqrt{\dfrac{\mu}{a^3}}} \tag{6}$$

Where:

$\Delta\alpha$ is the actual difference in the in-orbit position of both spacecrafts
μ is the Earth standard gravitational constant

In the long-term mode the radial separation and the crossing time difference are computed with a given time step, typically 12 hours. Thus, the accurate passing dates throughout the crossing points cannot be identified but it permits long term computations (two years) to be performed in a few seconds. Figure 5 shows an example of the results of the April 2010 passing, the first one detected (see section VI).

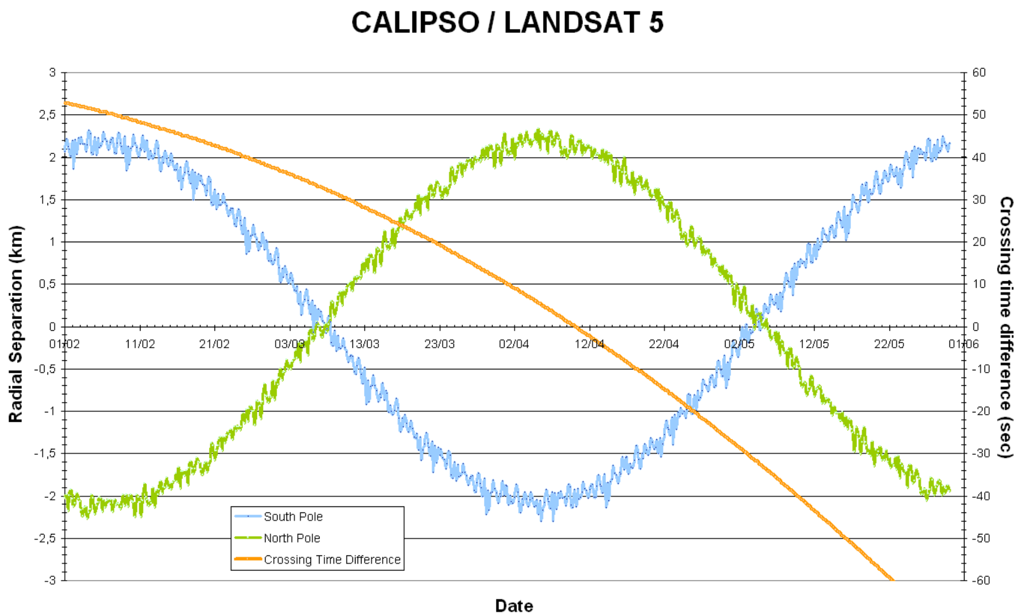

Figure 5. Crossing time difference and the radial separation computed with the long-term mode.

2. Accurate mode

In this mode the software identifies the first satellite to pass through the orbits intersection point (α_1) and it computes the distance between the center of the Earth and the satellite at the passing instant (r_1). Then, again for the other satellite, it computes the time (*CTD*) taken to reach its orbit intersection point (α_2) and computes its distance to the center of the Earth (r_2). The radial separation is then $\Delta R = r_2 - r_1$. In this mode all the computations are made in osculating parameters and passing dates and times are estimated with a precision better than 0.001 seconds. The radial separation is as accurate as the ephemeris used for the computations. The computation time for one month analysis is approximately 1 minute.

B. Computation of the maneuver trade space for the passing shifting

The purpose of the maneuver trade space is to help determine maneuver plans to shift a passing event to a larger radial separation while reducing the number of simulations runs. The objective is to represent a given passing event by simple analytical equations in order to evaluate the effects of a maneuver on the passing dates and on the radial separation.

If there are no scheduled maneuvers on the study period, the crossing time difference (CTD) as a function of time can be adjusted by a parabolic function using the least squares method

$$CTD = at^2 + bt + c \tag{8}$$

Where:
t is the time from the initial passing date
a, b & c are the coefficients determined with the least squares method

The effect of a maneuver (*ΔV)* on the crossing time difference can be represented by a linear function of time :

$$CTD_{Man} = \begin{cases} 0 & \text{if } t < t_{man} \\ 3\Delta V \cdot \sqrt{\dfrac{a}{\mu}} \cdot (t - t_{man}) & \text{if t} \geq t_{man} \end{cases} \tag{9}$$

Where:
t is the time from the initial passing date
t_{man} is the number of days between the initial passing and the maneuver execution ($t_{man} < 0$)
ΔV is the velocity change due to the maneuver

Then, we can compute the number of days shifted by a ΔV maneuver (t_{shift}) by solving Eq. (10). Doing this for different values of ΔV, we can find out the maneuver trade space in terms of days shifted.

$$a{t_{shift}}^2 + bt_{shift} + c + 3\Delta V \cdot \sqrt{\frac{a}{\mu}} \cdot (t_{shift} - t_{man}) = 0 \tag{10}$$

As we can see in Fig 5 the radial separation as a function of the time can be adjusted by a sinusoidal function:

$$\Delta R = \Delta R_{Max} \cdot \cos(\frac{\pi}{T} \cdot (t - \Delta t_c)) \tag{7}$$

Where:
t is the time from the initial passing date
Δt_c is the number of days between the passing and the date of the maximum radial separation.
ΔR_{Max} is the maximum radial separation
T is the radial separation period

Assuming that the semi-major axis change induced by the ΔV is negligible with respect to the maximum radial separation, the corresponding radial separation of the shifted passing can be estimated using Eq. (7) replacing t with t_{shift}. For a given crossing, the developed tool automatically estimates all the parameters of the equations above and computes the maneuver trade space in terms of days the passing is shifted and the radial separation obtained. For example, Fig. 6 shows the values of the parameters of the April 2010 passing.

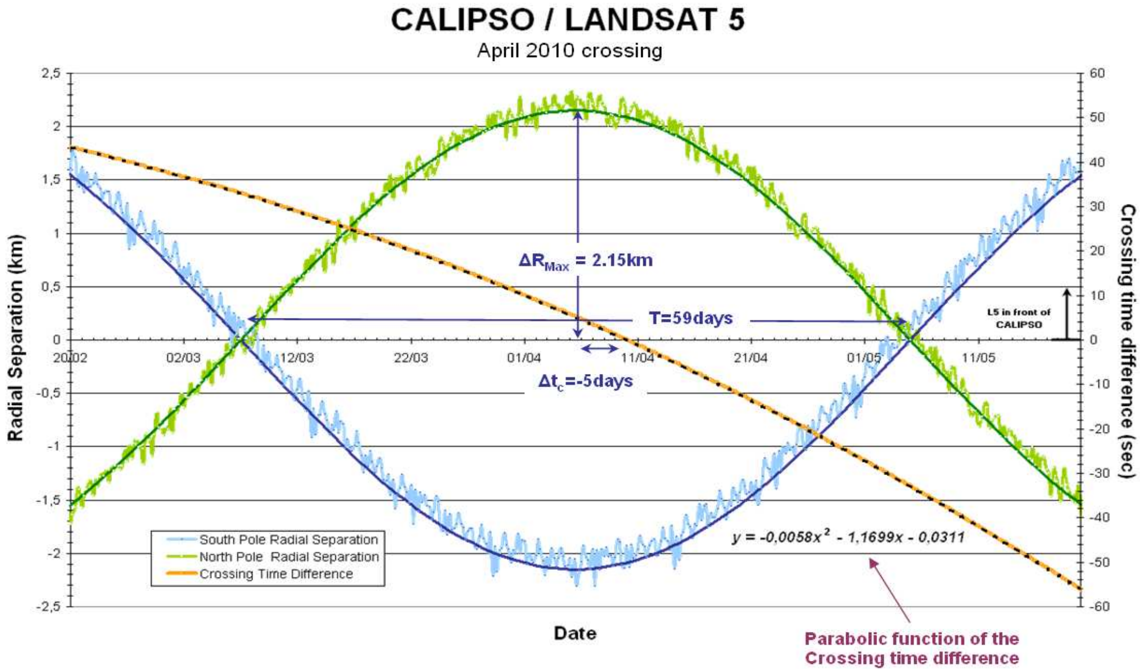

Figure 6. Passing parameters of April 2010.

Figure 7 shows the resulting maneuver trade space. The user can obtain the maneuver set of parameters (*ΔV* and number of days before the initial passing date to execute the maneuver) that permit obtaining a desired radial separation.

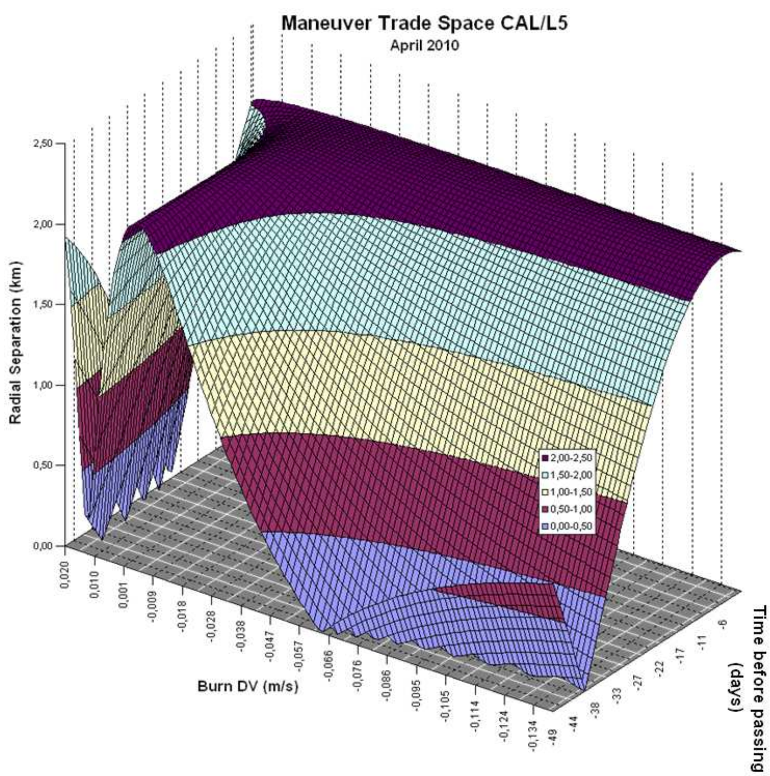

Figure 7. Maneuver Trade Space of the April 2010 passing.

To validate the software we generated six CALIPSO ephemeris containing maneuvers of different sizes and execution dates. We compared the actual shifted passing dates and radial separation with those estimated by the tool. The results are shown in Table 2.

Table 2. Maneuver Trade Space estimation accuracy.

Crossing Event Date : 10/04/2010 01:46

Maneuver Date	Days out	DV (m/s)	Estimated Days Shifted	Estimated Radial Separation (km)	Actual Days Shifted	Actual Radial Separation (km)	Days Shifted Error	Radial Separation Error (km)
01-mars-10 01:46	40	0,010	15,22	1,06	14,97	1,04	-0,25	-0,02
01-mars-10 01:46	40	-0,042	-23,29	1,16	-23,55	1,02	-0,26	-0,14
20-mars-10 01:46	20	0,010	8,38	1,69	8,53	1,7	0,15	0,01
20-mars-10 01:46	20	-0,042	-11,32	2,01	-11,60	1,97	-0,28	-0,04
06-avr-10 01:46	4	0,010	1,72	2,03	1,97	2,1	0,25	0,07
06-avr-10 01:46	4	-0,042	-2,20	2,13	-2,07	2,25	0,13	0,12

As we can see, the new passing date is estimated with an error smaller than 0.3 days and the radial separation error is less than 150 meters, even for maneuvers performed up to 40 days before the initial passing date.

VI. CALIPSO and Landsat-5 agreed strategy to mitigate the collision risks

The passing of the satellites was first discovered in February 2010. Landsat 5 was crossing through the orbit intersections in the space after Cloudsat and before CALIPSO. Additionally, it was learned that in the next several weeks it would pass behind CALIPSO. Further analyses revealed that 2 other Landsat-5 passages had already occurred. A backward-moving passage (from in front of the A-train to behind it) had occurred in late 2004while a second, forward-moving passage (from behind the A-train to in front of it) had occurred in 2008. The third passage (backward-moving) was underway (Figure 5). This passage was managed by computing the radial separation during the passing period. As shown in Fig. 4, the nominal passing date was such that the radial separation was large enough to guarantee the satellites safety. No special mitigation actions were needed. However, both CALIPSO and Landsat-5 rescheduled their planned DMUs to move the passing date forward in order to obtain the maximal possible radial separation of 2 kilometers.

A fourth passage of Landsat-5 (forward-moving) was expected to take place in 2011 involving all the Afternoon Constellation missions. A Red Team, with members of Landsat-5 and the A-Train missions, was formed to analyze the crossing situation and determine the best courses of action to minimize risks while continuing to provide the most science return from all the satellites. It was agreed that all transits with A-Train missions should be managed to an acceptable probability of collision (P_c) less than 10^{-5}. Internal analysis showed that the acceptable P_c would be obtained when the radial separations at the orbital crossing points are 400 meters or greater. The DMU maneuvers had to be coordinated between Landsat-5 and the concerned A-Train mission to ensure that the passing times would occur when the radial separations were safe.

Analysis performed on January 2011 showed that, with properly designed and coordinated Landsat 5 and CALIPSO maneuvers, a passing window of acceptable radial separations (i.e., greater than 400 meters) would occur from mid-August to late September. The maneuver strategy, designed to permit Landsat-5 to pass CALIPSO during this safe window, was as follows :

- Prior to the mid-August passing, CALIPSO should ensure that the passing would not occur before the passing window opened. Additionally, it should maintain a 10 second separation at the orbital intersections. To accomplish that, it positioned itself in the second quarter of its control box. Since this was a forward-moving passing, Landsat-5 would be entering from the back of CALIPSO's control box. Landsat-5 was expected to enter the CALIPSO control box weeks before the actual passing. Positioning itself in the 2nd quarter delayed the passing while also giving the mission the ability to perform an additional maneuver to retard the passing with less chance of going out of the box. It could also delay a planned maneuver and still have margin before going out of the front of its control box.

- The Landsat 5 maneuvers were designed to keep the spacecraft within a restricted portion of its control box so that CALIPSO had a relatively stable reference to use in planning its maneuvers. Landsat-5 maintained itself within a 5 second control box. This was a relatively small slice compared to CALIPSO's 43 second control box.

- As the mid-August 2011 passing window opening approached, CALIPSO planned its DMU maneuvers in such a way that it would be in front of Landsat 5 at both the northern and southern orbits crossing points when the passing window opened and behind Landsat 5 at both crossing points when the passing window closes in late-September. While in the passing window, as Landsat-5 approached the 3rd quarter of the CALIPSO control box, CALIPSO planned and performed a DMU maneuver targeting the back of its control box (Figure 8). This maneuver allowed the crossing to occur at the time of maximum radial separation between the 2 spacecraft. An increase in solar activity beginning in late-August 2011 kept CALIPSO from fully realizing the back of its control box. However, the maneuver proved sufficient enough to achieve a safe passing. When the safe passing window closed in late-September, the spacecraft were crossing the orbital intersections over 10 seconds apart. CALIPSO would maintain this safe phasing separation until Landsat-5 exited the front in early-October 2011.

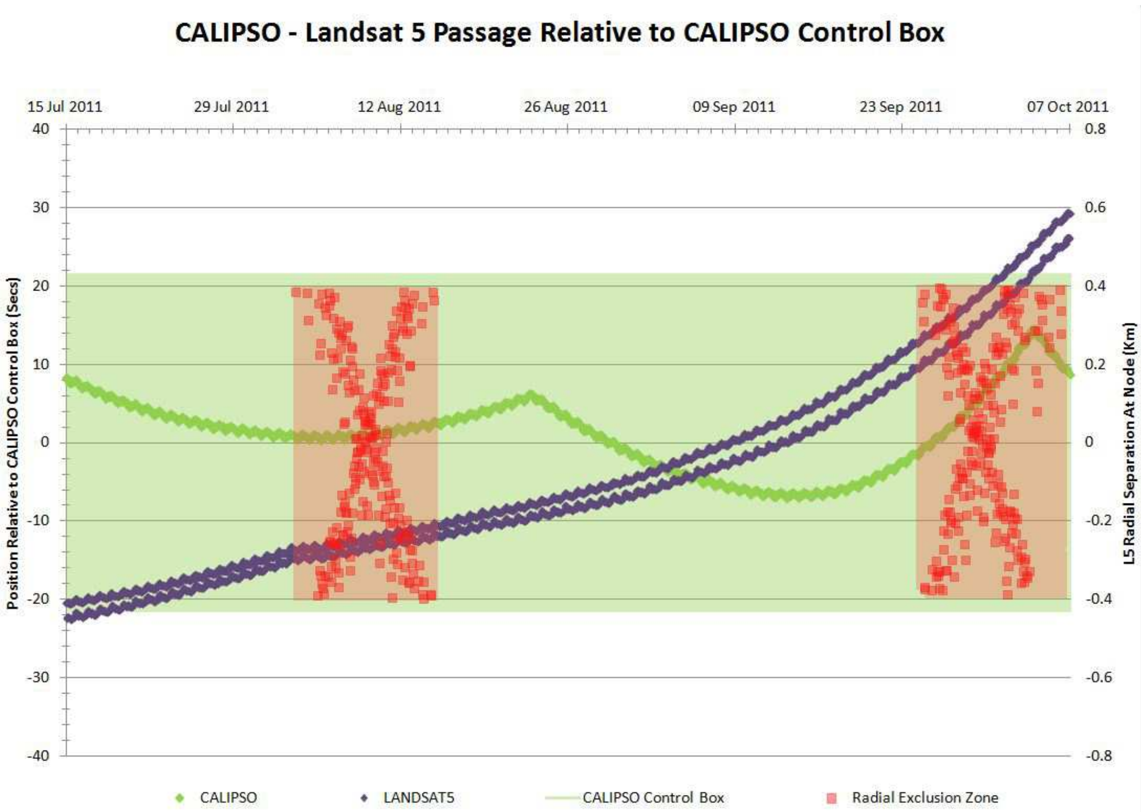

Figure 8. CALIPSO/LANDSAT-5 passing relative to CALIPSO control box

Figure 9 shows the January prediction and the final actual passing. The red zones represent the periods where radial separation is less than 400 meters. As we can see, the analyses performed in January predicted the passing to occur just before the window opening with a radial separation smaller than 400 meters. Thanks to the coordination and cooperation of the Landsat-5 and CALIPSO teams, DMUs performed from January to August permitted the shift of this initial passing date to the September 3rd and 5th with a larger radial separation (approximately 1.5 km).

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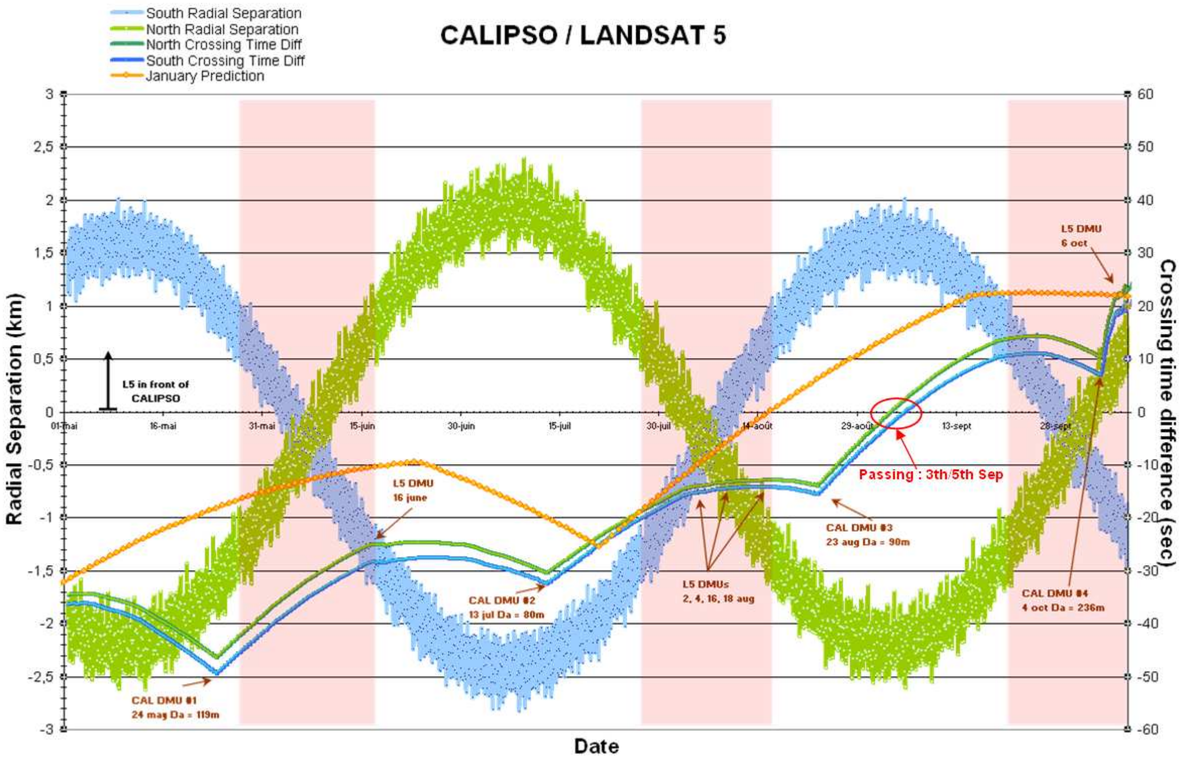

Figure 9. January 2011 prediction and final CALIPSO/LANDSAT-5 passing.

VII. Conclusion

The management of the Afternoon constellation and Landsat-5 crossings is an innovative example of collision risk assessment in constellation flying. Thanks to an international cooperation and coordination, Landsat and Afternoon Constellation teams ensured the safety and continuation of their missions. The activities carried out demonstrated the importance of the communication in order to handle the close approaches by agreeing upon a common maneuver strategy.

The flight dynamics aspects considered to study the crossings, as well as the developed tools, can be used to manage other cases of repetitive conjunctions with long and short term analyses. CNES applied these principles for long-term analyses when decommissioning ESSAIM[5] and HELIOS-1A satellites in order to ensure that the final orbits were not generating dangerous fly-bys with operational satellites.

LEO satellites are often required to have a repeated Earth coverage but the number of phased orbits are limited. Consequently, there are some altitudes, such as the CALIPSO one, where we can find a high concentration of operational spacecrafts which are all performing station keeping maneuvers. Changing the initial station keeping requirements of a satellite can create a dangerous configuration with respect to the other spacecrafts orbiting at the same altitude. Before changing its requirements, missions in phased orbits, should analyze the risks associated to the alteration of one of their orbital parameters, especially those related to the orbit plane. A collision in one of the Earth observation altitudes would be catastrophic, not only for the involved satellites, but also for the satellites orbiting in the same altitude.

Appendix A
Acronym List

CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations
CNES	Centre National d'Etudes Spatiales
CTD	Crossing Time Difference
DMU	Drag Make-Up Maneuver

EOS	Earth Orbiting System
ESMO	Earth Science Mission Operations
GTE	Ground-Track Error
LEO	Low Earth Orbit
MLT	Mean Local Time
MLTAN	Mean Local Time of the Ascending Node
MLTDN	Mean Local Time of the Descending Node
PARASOL	Polarisation et Anisotropie des Reflectances au sommet de l'Atmosphère, couplées avec un Satellite d'Observation emportant un Lidar
RAAN	Right Ascension of the Ascending Node
USGS	United States Geological Survey
WRS-2	World Reference System-2
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations
CNES	Centre National d'Etudes Spatiales
CTD	Crossing Time Difference
DMU	Drag Make-Up Maneuver
EOS	Earth Orbiting System
ESMO	Earth Science Mission Operations
GTE	Ground-Track Error
LEO	Low Earth Orbit
MLT	Mean Local Time
MLTAN	Mean Local Time of the Ascending Node
MLTDN	Mean Local Time of the Descending Node
PARASOL	Polarisation et Anisotropie des Reflectances au sommet de l'Atmosphère, couplées avec un Satellite d'Observation emportant un Lidar
RAAN	Right Ascension of the Ascending Node
SSAI	Science Systems and Applications, Inc.
USGS	United States Geological Survey
WRS-2	World Reference System-2

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