PARASOL and CALIPSO: Experience Feedback on Operations of Micro and Small Satellites

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I. Introduction

PROTEUS and MYRIADE are two satellites low cost product lines developed by CNES, the first one being a small satellite family, the second one a micro satellite family. PARASOL, launched in December 2004, is the second MYRIADE micro satellite and is operated from CNES Toulouse Space Center (CST). CALIPSO, from PROTEUS product line, launched in April 2006 is also operated from CST. PARASOL and CALIPSO are part of the A-TRAIN (Afternoon Train), which is a constellation of 6 satellites coordinated by the Constellation Coordination System (NASA Goddard).

CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations) is a three-year Earth science franco-american (CNES/NASA) mission. Its purpose is to study the clouds and aerosols radiative impacts which represent the main uncertainties about the climate evolution prediction. CALIPSO, as well as PARASOL, has integrated the Afternoon or "A-Train" satellite constellation with an orbit altitude of 705 km, and a nominal inclination of approximately 98.2 degrees, local time being around 13:30 UTC.

The PARASOL mission purpose is to perform measurements of the polarized and multi-directional reflectances, on ground areas previously observed by the Calipso Lidar.

The “LOA-CNRS” (Atmospheric Optics Laboratory) in the French city of Lille is the Parasol scientific principal investigator. For CALIPSO, there are two principal investigators, one American, the Langley Research Center, located in Hampton, the second located in the French city of Jussieu, the Pierre Simon Laplace Institut “IPSL/SA”.

The paper will first present PARASOL and CALIPSO satellites and operations, will present the combined station keeping operations, will briefly describe the ground segment and will present the chosen organisation to allow the good execution of all activities (manpower, planning, coordination meetings, resources sharing and operations priorities management).

Finally, the paper will be concluded with the presentation of futures missions for both product lines and their integration into the operational system, taking into account the experience feedback acquired during the operations of small and micro satellite.

II. Satellites description

A. PARASOL micro satellite

PARASOL satellite, launched the 18th of December 2004, stands about 80 cm tall and weights 120 kg at launch. The satellite payload consists of a digital camera with a 274x242-pixel CCD detector array, wide-field telecentric optics and a rotating filter wheel enabling measurements at different wavelengths and in several polarization direction. Because it acquires a sequence of images every 20 seconds, the instrument can view ground targets from different angles.

The satellite attitude control system, precise it within one-tenth of a degree, is built around a star sensor, four reaction wheels and three magnetic torkers. Three Sun sensors and a magnetometer are also used during the satellite positioning phase. The propulsion module is a blow down system using hydrazine, 4.5 kg of hydrazine which corresponds to speed increment of 85 m/s. It uses 4 thrusters, 1N thrust each. The solar array provides approximately 180 W of electric power at the satellite begin of life. A Li-ion battery provides power during eclipses. Onboard data handling is centralised and controlled by a 10-Mips T805 microprocessor. Data can be stored in a large mass memory (16 Gbits) and has a high speed telemetry system. Telemetry and telecommands use the CCSDS international standard.

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Telecommunications use S band transmission for the communication with the satellite, and X band to transfer the scientific telemetry.

The acquisition and safehold mode is used after separation from the launcher and later in case of anomaly detection. The normal mode is the mode in which the scientific mission is carried out (NADIR direction, 3 axes stabilized by three reaction wheels). The attitude is given by the star sensor. The Orbit Control Mode (MCO) is dedicated to perform the orbit maneuvers. During this mode, the attitude is just provided by the gyroimeters. Each burns sequence is preceded by an attitude maneuver, performed using reaction wheels as actuator, in order to steer the thrusters along the direction of thrust.

As the others MYRIADE satellites, the PARASOL redundancy philosophy is minimized: then, spare units exits only for very critical parts such as the Solar Arrays Drive Mechanism, onboard transmitter and receiver, and some internal components of the On Board Computer.

B. CALIPSO small satellite

CALIPSO is a 635 kg satellite with a power of 560 W based on a PROTEUS platform (« Plate-forme Reconfigurable pour l'Observation, pour les Télécommunications et les Usages Scientifiques »). It has been successfully launched on the 28th of April 2006 with a DELTA 2 launcher from Vandenberg in a double launch, associated with another “A-Train” satellite, CLOUDSAT.

CALIPSO provides atmosphere vertical profiles measured by a payload composed by an active Lidar (Light detection and ranging), an Infrared Imager Radiometer and a visible Camera.

The attitude control shall maintain a pointing accuracy better than 0.025°. It is performed using magnetometers, gyros, coarse sun sensors, star trackers and GPS sensors and magnetotorkers, reaction wheels and thrusters as actuators. The actual use of the sensors and of the actuators depends on the satellite modes. The orbit control can use up to 4 thrusters for performing maneuvers. Electrical power is provided either by the solar cells of the two identical wings of the solar generator, or in case of lack of sun, by the Li-ion battery. The command-control is based on a fully centralized architecture, using a µcs 31750 processor and a mass memory including 6 stacks of 512 Mbits. As Parasol, Calipso Telemetry and telecommands use the CCSDS international standard; satellite and mission telecommunications use S band transmission and dedicated mission transmission using X band.

As far as possible, the spacecraft is considered as built with 2 independent half satellites: one nominal half and one redundant half. However, critical equipments or equipments of more than 2 units (for instance: gyros, reaction wheels) are shared by both half satellites. This architecture allows to cope with the satellite performances and the low cost target.

The two Calipso main modes are:

- the safe mode, used after separation or in case of satellite failure detection (generally speaking, any satellite failure leads to safe mode, while any instrument current anomaly leads to the instrument passive state, platform remaining nominal),
- the nominal mode in which, as Parasol, the scientific mission is carried out.

The onboard failure detection and recovery function is aimed at setting the satellite in a secure state in case of failure, while being robust to spurious events in order to preserve the mission availability.

III. Parasol and Calipso operations

Operations can be divided in four parts:

- LEOP operations including the Launch Phase,
- Begin Of Life operations, including activities linked to the ascent phase (maneuvers) as well as assessment tests for the whole satellite including the payload,
- The Mission phase itself,
- The End Of Life operations, which can be ended by a re-entry phase for the satellite.

All these phases are prepared before launch, operations are validated and teams are prepared during training phases and general rehearsals. These training phases begin about one year before launch.

The LEOP phase is a relatively short (about 3 days) but a very intensive phase is terms of activities to be performed. For PARASOL, this phase was also critical since the satellite was launched with 5 other satellites by an ARIANE 5 launcher, and that 5 of them were also operated at CNES. A specific attention was taken concerning the
collision risk between these satellites and the launcher third stage. The consequence being that spacecrafts were not
allowed to perform their maneuvers simultaneously for the first days in orbit. For CALIPSO a same criticism exists
since the launch is shared with CLOUDSAT.

The mission phase is of course the main part of the satellite on-orbit life, and consists of repetitive tasks needed
to maintain the satellite in nominal conditions to satisfy all requirements in order for the mission to become a
success. This phase includes all maneuvers needed for the station keeping, as well as exceptional operations.

C. The operations linked to the A-TRAIN

PARASOL and CALIPSO are part of the A-TRAIN (Afternoon Train), which is a constellation of 6 satellites
coordinated by the Constellation Coordination System (CCS at NASA Goddard). The Begin Of Life activities
includes all manoeuvres required to join the Constellation.

For PARASOL it has been necessary to perform 5 maneuvers (semi major axis combined to inclination
maneuvers) to join the A-TRAIN, since it had to comply with the main passenger injection orbit: minus 43 km
above AQUA altitude, minus 0.08° for the inclination, and minus 3.25° for the right ascension of ascending node
with respect to AQUA plane. This phase lasted about 4 weeks, and began after the assessment tests were completed,
about 2 weeks after launch.

CALIPSO has joined the A-TRAIN in less than one month, performing two maneuvers achieved end of May,
nearly one month after launch.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{A-Train.png}
\caption{A-TRAIN Constellation}
\end{figure}

Once arrived in the constellation, CALIPSO station keeping is obtained by following a reference grid with
maintenance of the ground track at the equator. For PARASOL, the choice was to implement slavery on relative
orbital position. Station keeping between a target (AQUA) and a chaser (PARASOL). In addition, CLOUDSAT and
CALIPSO respect the formation flying rules, with CLOUDSAT slaved to CALIPSO, CLOUDSAT being located
within CALIPSO control box limits.

These choices need a “close” coordination of satellites operations, as well as very good exchanges with NASA
Constellation Coordination System. This is achieved using daily ephemeris automatic exchanges between AQUA,
CALIPSO, CLOUDSAT and PARASOL Satellites Operation control Centers via a NASA dedicated server, and
monthly teleconferences between satellite operation managers and with the CCS team. Meetings are also planned to
coordinate some specific operations concerning the whole constellation. The global surveillance of the A-TRAIN is
insured by the CCS at NASA Goddard Space Center in Washington.

When needed, a DMU (Drag Make Up) maneuver is programmed, so that PARASOL (respectively CALIPSO)
stays within it’s A-TRAIN control box limits. For PARASOL, these maneuvers are actually realised every two or
three months.
D. The routine operations

For MYRIADE micro satellites, the operations are based on three basic concepts:
- the first one is that all ground processes shall be automated and routine operations shall be performed during working hours of working days,
- the second one is that MYRIADE satellites shall have the sufficient level of autonomy to support several days in-orbit without being operated from the ground: a high level of autonomy during acquisition / safehold phases, low redundancy level and few ground interventions during LEOP phases. and if an anomaly that could endanger the satellite occurs, it shall be designed to enter in a secure safehold mode, and support several days without any ground intervention.

Then, if these concepts are respected, micro satellites activities planning becomes quite simple. And this is the case for PARASOL. Indeed, these rules being respected, ground operations are minimised.

The On-Board Transmitter is programmed twice a week (switched-on before a pass and immediately switched-off after the pass, 7 days planned), and the TC plans for the satellite attitude control (satellite guidance and SADM guidance) are also uploaded twice a week (8 days planned). The mission program is uploaded once a week (8 days planned each time). The on board UTC time is also refreshed once a week. Every day, the orbit determination is automatically computed, the PARASOL location within its A-TRAIN control box is calculated and the mission scientific products are automatically generated. After each pass, the telemetry is automatically monitored to check the satellite general status and archived on dedicated computers.

Once a month, when the Moon enters in the star tracker field of view (two times per orbit for 5 up to 10 days), the satellite attitude control is modified so that it is achieved with the gyroometers instead of the star tracker which is no more able to fulfill its requirement. During this time period, programming a Drag Make Up (DMU) maneuver is not allowed, even if it is still possible to perform a contingency maneuver if needed.

Monthly, the calibration need is evaluated for some units such as Gyros and magnetometers, and the Solar Sensors status is checked.

For PROTEUS satellites the operation strategy is very similar to the MYRIADE one, the differences are mainly linked to the fact that PROTEUS satellites have more on board redundant units (implying more operations, more monitoring).

CALIPSO routine activities will also be performed automatically. The on board transmitter is never switched-off (then no TC plan linked to this activity), the satellite guidance and SADM guidance is uploaded every day, and the mission plan is uploaded once a week. The on board UTC time is also refreshed once a week. The automatic orbit determination, associated to the PARASOL – CALIPSO orbits comparison allows to check that satellites local times respect the scientific requirement (PARASOL shall be maintained 11 minutes behind CALIPSO in local time). And of course CALIPSO position within its A-TRAIN control box limits is verified.

CALIPSO others occasional activities consists of equipment or subsystem expertises (in order to check the spacecraft integrity and performed a trend analysis), temporary spare equipment switching on, Payload managing during Sun eclipse by the Moon and randomly, Solar flares management, Hubble Space Telescope avoidance and maneuver according to other A-TRAIN satellites.

Since the ground stations are shared by the PROTEUS and MICROSAT missions, the passes planning is realised once a week, taking into account all on-orbit missions requirements. This is achieved partly by an automatic process, but it also requires to be modified by hand to take into account all exceptional satellites (ex. Maneuvers) or ground activities (ex. Ground station maintenance). Today, the pass plannings, managed by a software called ARAMIS, takes into account three satellites, PARASOL, CALIPSO and DEMETER (the first MYRIADE satellite, in orbit since two years), and 5 ground stations.

During the mission lifetime, an Operations Coordination meeting, involving all the mission team is held once a week for each mission. During this meeting, all the operations carried out since the last meeting are summarized, the exceptional activities for the week following are planed and coordinated, the earth terminals reservations are approved on ARAMIS in coordination with other mission, the Sequence Of Events describing all the activities of the next week, as well as the weekly sequence to be uploaded the day after and pertains to the week following are approved.

After the Operations Coordination meeting all processes are programmed by the operator for the next 7 days, thanks to a task scheduler software called “AGENDA”. The daily or weekly TC are automatically generated. The
telemetry is also automatically stored and is available to the experts on an internal server. Therefore, all daily and nominal activities are performed thanks to automatic processes, all being under the operator control. If an anomaly occurs, an alarm is generated and the operator is automatically informed by phone. Then, after a first investigation he calls the adequate expert (ground engineer, flight dynamics …). At least one pass per day and per satellite is also followed by an operator, who can contact the satellite responsible if an on-board alarm is detected. In any case, the mission operation manager is informed.

IV. Ground segments

CALIPSO and PARASOL ground segments are both composed of a Mission Operations Ground System (MOGS) and a Satellite Operations Ground System (SOGS).

The CALIPSO MOGS includes two major sub-systems: the Mission Operations Control Center located at the NASA Langley Research Center in Virginia and the Payload Data Delivery System (X band station and Network).

The PARASOL MOGS is divided in two parts. A first part called “Mission Center Level 1” located in CNES Toulouse Space Center, and which is dedicated to the nominal payload management (checking the Payload status, programming the payload, getting the raw mission and process the telemetry to get the level 0 and 1 products, delivering and archiving the Data). A second center, called “ICARE”, located in the city of Lille, which one of aim is to pool data and provide shared services enabling the scientific community to exploit the huge volumes of data derived from the A-TRAIN.

Both PARASOL and CALIPSO SOGS are based in CNES Toulouse Space Center. This part of the Ground segment is used to operate the satellites, perform the monitoring and platform controls, orbit and attitude control, payload service and satellite expertise.

CALIPSO and PARASOL SOGS are very similar and use the following components:

- A common network of S-Band Earth Terminals called TTCET (Telemetry and TeleCommand Earth Terminal) located at Kiruna (Sweden) and Aussaguel (France). They are all based on the same architecture, insure the TM/TC link with the satellites, and can download Doppler measurements for the orbit control.
- One or more CNES 2 Ghz stations which can be “kitted” to be adapted to the small and micro satellites ground constraints (e.g. one station located in Hartebeesthoek (South Africa) another one in Kiruna).
- A X-Band station called “TETX” which is dedicated to the acquisition of high rate mission telemetry. This station is located in CNES Toulouse Space center and is only used by the MYRIADE satellite product line.
- A common mean called “ARAMIS” used to plan passes for all in-orbit PROTEUS and MYRIADE satellites.
- A common archiving system,
- A common configuration management system,
- Two separated Satellite Operation Control Centers (SOCC). These SOCC are designed to support up to 7 on-orbit satellites belonging to 5 different missions (belonging to the same satellite family). But due to the actual difference between PROTEUS and MYRIADE satellites, these SOCC are not shared, even if they are very similar. PROTEUS and MYRIADE SOCC have the same architecture, based on the use of Personal Computers. The main functions are: TM/TC real time management, telemetry display using mimics, orbit and guidance management, telemetry monitoring and archiving, file transfer management. In a general manner, ground software are shared between PROTEUS and MYRIADE, but their configuration are different, satellite data base management is specific to each family. Moreover, the mission interface management is specific to each mission.
- A common Data Transmission Network (RTD) which provides the connexion between the stations and the CCC, the stations and the missions centers, the SOCC and the mission centers. The network architecture relies on the multi-missions resources at CNES.

For LEOP phases, as well as for Commissioning, this system can be completed by Earth Terminals of the 2 Ghz network, which provide additional angular measurements used by the Orbit Operational Center for the orbit determination.
There are three SOCC (or CCC) per satellite family (PROTEUS and MYRIADE), one used for the routine operations for all the satellites of a same product line (with respect to the limitation of 7 satellites or 5 missions per SOCC), one for used for qualification and LEOP phases and the last one dedicated to testing phases with satellites simulators.

V. Operation management and associated manpower

The operation team for each mission is composed of a satellite responsible, a ground responsible, a flight dynamics engineer, the mission programming specialist (if needed) and an operator for the routine monitoring, this team being managed by the mission operation manager. When needed, the team can be completed by satellite experts (e.g. thermal control, power, orbit and attitude, software, command and control experts) and ground system experts (e.g. Network, Ground Station experts).

Ground experts can intervene independently on PROTEUS ground segment or MYRIADE ground segment, since both ground segments are very similar. Moreover, to respect this similarity, one engineer is responsible for the whole coherency and the operational management of both ground segments (SOGS).

Flight dynamics engineers are also able to intervene on both CALIPSO and PARASOL missions, as well as operators. As for satellite responsible, there are two teams, one dedicated to micro satellites and the other to small satellites. Indeed, PROTEUS and MYRIADE platforms are too different to be compatible with a shared team of satellite experts.

This organisation allows to work with a minimum manpower available only during working hours of working days. During week-ends and days off, processes are entirely automatic. Moreover, the telemetry is automatically monitored after each pass, and if some predefined critical anomalies are detected, a dedicated software called SYGALE phones automatically a 24/7 manpower and delivers the appropriate message to this person, so that he can intervene on the next pass. Some actions may be needed to put the satellite in a secure safe-hold mode, a first
investigation is made to prepare the activities of the next working day. This is only possible thanks to these specific platforms which are designed to withstand a safe-hold mode of several days without damages.

When CALIPSO and PARASOL are in nominal mode, the routine operations, has described here above, can be foreseen and performed automatically. During nominal activities, spacecrafts status are checked automatically by monitoring telemetry, and in case of non compliance, alarms are raised. These alarms are shared into two categories: yellow and red alarms. If yellow alarms lead only to expertise during working hours, some specific red alarms may require a rapid intervention from the ground, even during days off.

During working hours of working days, should any red anomaly be encountered (ground or on board anomaly), a hotline is automatically called. In this case, an expertise shall be performed and actions are undertaken to recover a nominal functioning.

The most important red alarm corresponds to the safe mode (transition performed automatically by the on board software in case of main failure detection). The return to nominal mode is performed according to a dedicated sequence, shorter on MICROSAT satellites as PARASOL (2 days) than on PROTEUS satellites as CALIPSO (5 days).

During nights, week-ends and days off, MYRIADE and PROTEUS families have different levels of intervention. Indeed, the only sequence for which a rapid intervention is needed for MYRIADE micro satellites is the detection of a safe hold mode. In this case, some telecommands shall be sent to the satellite in order to protect the battery capacitance. Then, if a reset of the on board software is detected during the TM monitoring (done automatically after each pass), an on call 24/7 satellite responsible is contacted by the hotline. This person shall intervene on the next pass to send the correct TC. If the ground processes are blocked, a ground responsible is also contacted to secure the operation. On PROTEUS satellites, other red anomalies could need a rapid intervention of satellite responsible, typically those which could impact the availability of scientific products (in addition to those which can lead to the safe mode).

Other extra activities are always performed with manpower, for obvious safety reasons. Depending on the activity itself, they can be performed either during working hours or non working hours (nights, week-ends and days off).

This is the case for the launch phase, the begin of life activities, the rise up maneuvers which can be undertaken nights and days. For PARASOL and CALIPSO, due to the location of the ground stations, all passes are in the range of 10:00 PM to 2h00 AM (no pass between 2h00 AM to 10h00 PM). This explains why the begin of life activities requires bigger teams since the working hours are not sufficient to follow all passes.

Other unusual activities (e.g. On Board Computer new software upload, emergency maneuver) are planned, as possible, during working hours, and with a re-enforced team.

VI. Experience feedback

Since June 2004, where DEMETER, the first micro satellite from MYRIADE product line, has been launched, until today, six micro satellites and one PROTEUS small satellite, CALIPSO, are operated from CNES Toulouse Space Center (JASON, the first PROTEUS satellite is operated in partnership with NASA). For one of them, the first telemetry has been received 20 hours after launch, the acquisition sequence being completely automatic for the six micro satellites.

Operations of these seven satellites are reduced to a minimum, and this, thanks to autonomous platforms and ground automatic processes. For each satellite, the number of passes have been reduced to a minimum, for example, 4 passes per day above S Band Ground stations for PARASOL, that is 25 minutes of visibility for the platform telemetry and telecommand, and 4 passes per day above X Band Ground station, that is 20 minutes of visibility, to download the scientific data.

A lot of lessons have been learned these last years, on several domains as well as on board operations, ground activities, organization and management.

For MYRIADE product line, the safe mode robustness has been tested several times in orbit. Nevertheless, this way of functioning has an interest only if the operations needed to recover the nominal operating mode are reduced. For micro satellites, these operations can be managed in two days (with less than ten passes).
The DEMETER on orbit experience feedback, has allowed to upload corrections on the PARASOL platform software, very soon after its launch. On the contrary, anomalies appeared firstly on PARASOL have been corrected on DEMETER very rapidly. This were also made easier because the team was shared between these micro satellites.

Operations preparation is less important on this kind of platforms since redundancy philosophy is reduced. This is not the case for the functional “end-to-end” tests which are under the satellite project team responsibility.

Concerning the ground segment, the automation of daily sequences is a great success. However, the major difficulty was to obtain an actual routine mode, with fully operating automatic processes and minimum manpower. Indeed, if ground tests before launch are sufficient to assess that processes are secure, they are not close enough to the actual daily life where unexpected external noise (such as network problems) can easily disturb the whole system and by the way stop the process.

It has taken a long time to come to a stable mode, and the PARASOL first 6 months in orbit has required a significant (and in fact non anticipated) manpower. Moreover, the ground system is complex, with a great number of interfaces, and it needs to have a permanent capability of adaptability, development and expertise. And even is the system is fully automatic, this functioning requires to have operators during working hours, for the global monitoring, and also needs permanent updating of software and computers.

One more difficulty was the implementation of an automatic process for the passes reservation. Today the software developed and called ARAMIS is not fully capable to insure the compliance with all mission needs. Then, if the first loop of reservation is automatic, a manual verification is unavoidable.

For the management of the whole activity, the Operation Coordination meeting, hold once a week is in accordance to the need. This meeting is also held each time an unplanned and urgent activity has to be discussed (for example if a safe hold mode occurs). Moreover, all topics cannot be discussed during this meeting which shall be hold in less than 2 hours, then other meetings have been created to coordinate activities and priorities between the different missions, should they be under preparation or already in orbit.

One major challenge is to have relatively short preparations phases, and to enter rapidly into a routine mode with a fully performing system, since micro and mini satellites in orbit lifetime is short (from 1 to 3 years, compared to telecom platforms). Then all begin of life on board or ground anomalies have to be solved as soon as possible. This is facilitated by the organization itself, since the satellite project team is shared between new satellites under development and satellite under exploitation, and since the operational team is involved in the very beginning of the project.

The Future - Conclusion

If 2004 was the year of micro satellite launches (6 satellites launched and operated at CNES Toulouse), 2006 in the year of small satellites: indeed, CALIPSO launched in April and COROT mission 6 months later will increase the operational activity. Then from 2007 to 2010, several others satellites should join the pool (SMOS and JASON2 satellite belonging to the PROTEUS family and PICARD, MICROSCOPE, the four ELISA of micro satellite family).

During this period, some processes need to be reviewed, in order to improve the tasks automation. In particular, the passes reservation loop, achieved with the software called ARAMIS, will have to take into account in the near future several other satellites such as COROT, SMOS, PICARD and MICROSCOPE.

Another important work concerns the unification of the different CNES networks used for the data transmission between ground stations, SOCC and MOGS of satellites operated by CNES. The major advantage is the improvement of the network supervision for micro and small satellites, especially during week-end and days off. Until now, this task is not programmed for MYRIADE and PROTEUS family, and its implementation will increase the data availability.

Today, the MYRIADE and PROTEUS satellites operation management (automation of ground processes, project team and operation team organization…) is a great success. Indeed, after some problems essentially linked to the youth of satellite families and operating systems, the scientific data availability is now greater than 95 % for on orbit satellites. Scientific products are available to the scientific community the day after their generation in orbit. This shows that this kind of operation management of low cost satellite families can be fully compliant to scientific requirements.

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