SSC22-VIII-02

ASTERIA in-orbit testing on OPSSAT: an on-board autonomous orbit control solution including collision risks avoidance

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ABSTRACT

For several years, CNES has been working on Flight Dynamics algorithms to ensure high level of autonomy for next generation of space missions. One example of these autonomous techniques is the Autonomous Orbital Control, which consists of delegating to onboard satellite system the identification, planning and realization of orbital corrections to stay in the mission reference orbit. ASTERIA, an application of on-board autonomy combining station keeping and collision risk management for the low earth orbit satellites, enables both in-track and cross-track control for different LEO missions. The on-board collision risk management process is fully integrated into the autonomous station keeping in order to maintain the satellite orbit as best as possible and to minimize mission unavailability resulting from the avoidance maneuvers.

The paper aims to show the completeness of the ASTERIA concept. First, the principles of on-board orbit control with collision risk management are described with the operational concepts of such a solution. Then, the ability to operate ASTERIA is demonstrated through an in-orbit experiment performed last year on the ESA OPSSAT 3-Units CubeSat.

Keywords: autonomous orbit control, autonomous collision avoidance, station keeping, LEO, collision risk, CCSDS Mission Operation, OPSSAT, mission optimization, space traffic management

ACRONYMS

ACA	Autonomous Collision Avoidance
AOC	Autonomous Orbit Control
AOCS	Attitude and Orbit Control System
API	Application Programming Interface
ASTERIA	Autonomous Station-keeping Technology with Embedded collision RIsk Avoidance system
CAM	Collision Avoidance Maneuver
CCSDS	Consultative Committee for Space Data Systems
CCSDS MO	CCSDS Mission Operation
CDM	Conjunction Data Message
CNES	Centre National d'Etudes Spatiales
CONOPS	CONcept of OPerationS
COPoC	CNES Operational Probability of Collision
CPU	Central Processing Unit
EUSST	European Space Surveillance and Tracking
ESA	European Space Agency
ESOC	European Space Operations Center
FDIR	Fault Detection, Isolation and Recovery
FPGA	Field Programmable Gate Arrays
GNSS	Global Navigation Satellite System
LEO	Low-Earth Orbit
LTAN	Local Time of the Ascending Node
NMF	Nanosat CCSDS MO Framework
OBC	On Board Computer
OD	Orbit Determination
PVT	Position, Velocity and Time
RAM	Random Access Memory
STM	Space Traffic Management
TCA	Time of Closest Approach
TRL	Technology Readiness Level
XML	eXtensible Markup Language

INTRODUCTION

The incidents of collision in orbit are recent in the great adventure of the Space Age. They highlight the real dangers related to the amount of objects in space and the reality of collision risks. The situation is getting worse and the amount of debris in orbit is constantly increasing (and sometimes skyrocketing after ASAT test…). In Low Earth Orbit (LEO), the emergence of large constellations of thousands of units and the miniaturization of satellites emphasize the risks. At the same time, the ongoing improved surveillance technologies enable more small debris to be reliably tracked and catalogued.

Regarding these facts, increase in the number of tracked and operational objects in space, new methods to deal with collision risk avoidance and day-to-day coordination between operators have to be find. It was the same assessment many years ago for the civil aviation control.

That is why CNES is developing an on-board solution named ASTERIA to directly manage collision risk embedded with station keeping loop on-board in full autonomy. In a second time, “road traffic regulations” lead by the Space Traffic Management is necessary.

ASTERIA (Autonomous Station-keeping Technology with Embedded collision RIsk Avoidance system) enables coupling station keeping on LEO orbit, collision risk identification and calculation, and implementation of avoidance maneuvers . This system is in complete autonomy on board based on some ground interface exchanges. The on-board management drastically reduces the ground operations for these activities. The system is based on the on-board information of navigation to benefit from a real time knowledge of the orbital state of the satellite. Free from ground link constraints, the system is able to have strong reactivity for the avoidance implementation and for the adaptation of the response to orbital evolution while having a good estimate of the risks. Moreover, the coupling between station keeping and collision risk management makes it possible to consider innovative solutions to minimize the impact of avoidance on the satellite mission. To recap the advantages of the solution: best reactivity, more anticipation and a better mission programing satisfaction.

Figure 1: ASTERIA and PATRIUS logo

ASTERIA is developed in Java language using CNES flight dynamics library named PATRIUS.

In order to test ASTERIA in-orbit and reach the maximum TRL, CNES worked with ESA (ESOC) to use OPSSAT experiment opportunity. In fact, OPSSAT has the perfect capacities and architecture for such an in-orbit experiment.

ASTERIA PRINCIPLES

Autonomous system added value

ASTERIA is a wink to Asteria, a deity in Greek mythology, personification of the starry night. She is an ideal symbol to represent the invisible hand guiding our satellites on secure trajectories. The ASTERIA concept is a crucial step to increase the on-board system autonomy for orbit control activities. The architecture enables a strong coupling between station keeping and collision risk management, in order to take advantage of synergies in maneuvers calculation and increase the reactivity and efficiency of the AOC. ASTERIA enables the satellite to autonomously maintain precise guidance of a reference trajectory (required by the mission needs) while controlling the risks of collision encountered on the trajectory. It assesses the risk of upcoming collisions, adjusts station keeping maneuvers and implements a dedicated avoidance strategy, if needed.

Collision risks in space are expected to grow. They are a major problem for the safety of satellites and require the implementation of a permanent monitoring and action capacity. The on-board autonomy of the collision risk management appears as a solution with positive effect on operational costs induced by the important increase of collision risks. In addition, the limited dependence of the ground segment and the good knowledge of the orbital dynamics enable an incomparable reactivity to the space environment while anticipating future events in order to satisfy the ideal orbit possible for mission needs.

The risks calculated on board are correctly estimated thanks to a knowledge of the current state of our satellite and related low uncertainties on its position, despite the use of simplified methods for trajectory propagation.

AOC basics

Collision risk management activities are linked to orbit control activities because they are based on knowledge of the future satellite trajectory. As a result, the autonomous avoidance management operation is strongly linked to the use of an AOC. This enables the on-board system to have control and knowledge of the future trajectory with a timing and reactivity that would not be possible with ground based station keeping management. The satellite, thanks to its on-board navigator, has up-to-date information on its current state and can therefore adjust its correction needs more precisely, both for station-keeping management or for mitigating collision risks. The coupling of the two functionalities makes possible to obtain a highly autonomous system. It provides the possibility to jointly address the correction needs related to orbit keeping and those related to trajectory securing. The orbit control activities are thus considered as a whole.

The set of orbital parameters used in ASTERIA AOC loop is:

$$\begin{pmatrix} a \\ e_x = e.\cos(\omega) \\ e_y = e.\sin(\omega) \\ i \\ \Omega \\ \alpha = \omega + \nu \end{pmatrix}$$

The purpose of AOC is to calculate a maneuvers plan that enforces the satellite to stay within a defined station keeping range. The station-keeping window is defined as allowable along-track and cross-track errors ranges.

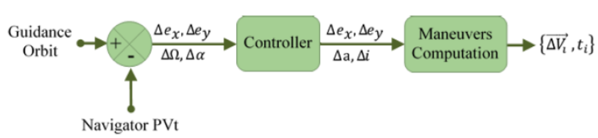

Figure 2: AOC general architecture

The different AOC steps, computed at each ascending nodes, are:

1. On-board navigator determines orbit using the last GNSS data (typically with least squares method or Kalman filter).
2. The guidance orbit used by AOC for its control is an analytical 1D guideline, consistent with the reference orbit. The AOC reference orbit is a 2D simplified analytic model (depending on both the argument of latitude and the longitude of the ascending node) used by the mission for long-term planning. Reference and guidance orbits take into account the Earth potential effects (J40×40 models typically).
3. The comparison with the guidance orbit is used to define the orbital deviations ($\Delta e_x, \Delta e_y, \Delta\alpha$ *and* $\Delta\Omega$) and their derivatives (using polynomial curve fitting).
4. The AOC controller sets the orbital increments ($\Delta e_x, \Delta e_y, \Delta a$ *and* Δi) using a Gauss analytical orbit prediction (using the same polynomial curve fitting propagator as for the comparison). The main orbital perturbations taken into account include the effects of solar and lunar gravitation, solar radiation pressure and atmospheric drag. Note that geopotential effects are already included inside reference and guidance orbit models.
5. Orbital increments are converted to commanding maneuvers $\{\overrightarrow{\Delta V}, t\}_i$ by taking into account the constraints on the maneuver positioning.

Both independent controllers manage the in-plane and out-of-plane station-keeping, leading to two kinds of maneuvers that can be coupled and spread. In order to take into account the use of a low-thrust engine, the computed maneuvers can be considered as impulsive maneuvers spread in time on several allocated time slots along an orbit. Thanks to its high control reactivity, AOC enables precise station keeping. Therefore, the satellite remains very close to its reference orbit on which mission and ground station scheduling activities are based, regardless of the knowledge of the actual trajectory.

Maneuvers uncertainties and adjustability

Considering low thrust propulsion, two types of maneuver errors are taken into account. The first one is the magnitude error, which is defined as a percentage of the nominal maneuver magnitude. It is assumed to follow a normal distribution law. The second one is the direction error, which is defined as a deviation angle around the nominal thrust direction. It is assumed to also follow a normal distribution law defined around the nominal direction. The magnitude error is easy to consider, as it is only distributed on one direction, along the maneuver vector.

Assuming these maneuver uncertainties, CNES has developped a new method based on the initial formula proposed by Gates, in order to compute the maneuver uncertainties contributions to the covariance matrix conserving the gaussianity of the propagation. In fact, that is an important hypothesis for the analytical collision risks determination method used by ASTERIA and hereafter details.

The effects of maneuvers are not considered in the same way depending on their position in the on-going maneuvers plan horizon:

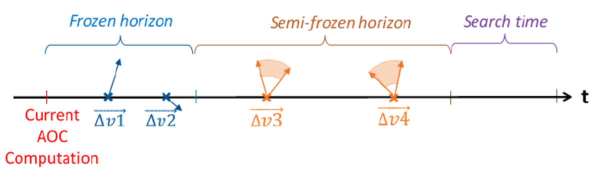

Figure 3: maneuvers horizons

The closest maneuvers of the maneuvers plan are frozen and can already be commanded by the AOCS. Their realization errors are taken into account in the covariance matrix. Maneuvers positioned further away in the semi-frozen horizon can be adjusted in amplitude and direction to better satisfied the reference orbit (or collision risks avoidance as further explained) but remain positioned in their previous computed slots in order to minimize mission programming impacts. This variability for non-fixed maneuvers is considered as a maneuver execution error and can then be added to the uncertainties. Finally, the search horizon is the new period added at each AOC loop to looking forward new maneuver slots needs.

ACA coupling

The orbit control of ASTERIA has to anticipate station keeping corrections over a sufficiently long time horizon to enable the identification of possible collision risks. As an output of the AOC calculations, the trajectory with station keeping maneuvers is checked by the ACA module to ensure that it does not generate any unacceptable risks. Depending on the result of this verification, a loop is made between the AOC and the ACA leading to modification on station keeping maneuvers plan or to the implementation of a specific avoidance maneuvers strategy. The AOC and ACA iterations are also performed at each ascending nodes.

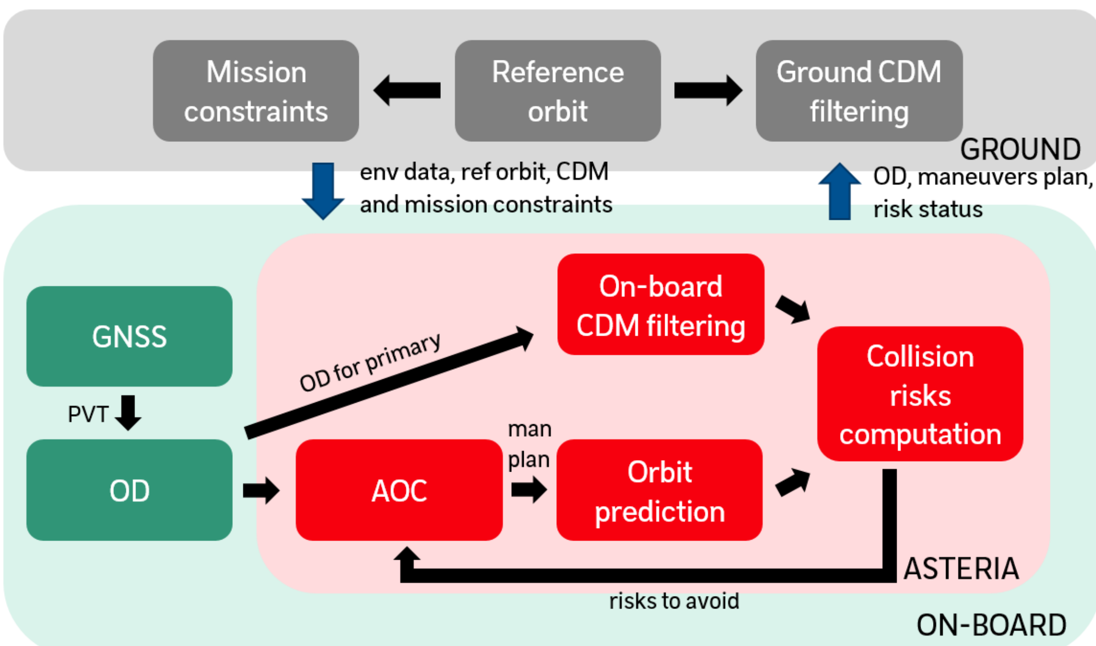

Figure 4: ASTERIA overall architecture

Asynchronous interfaces exchanges between ground mission operations center and satellite are:

- From ground: solar activity and Earth orientation poles environment data, lighted Conjunction Data Messages (CCSDS format), maneuver allocated slots by mission constraints and sometimes reference orbit update.
- From satellite: last OD with covariance matrix, maneuvers plan and risk mitigation status.

On-board synchronous activities at each ascending nodes are:

1. Orbit determination from last GNSS data (orbit and covariance matrix).
2. CDM filtering thanks to the last OD assumed as the primary object: numerical prediction taking into account Earth gravity model (J40×40), solar and lunar gravitation, atmospheric drag and solar pressure forces.
3. AOC and ACA iterations:
   a. AOC maneuvers plan computation as previously explained and, if necessary, considering all collision risks to avoid.
   b. Orbit prediction through the new maneuvers plan: same numerical prediction assumptions as for CDM filtering.
   c. Collision risks computation on the overall horizons using filtered CDM (hereafter detailed).

Collision risks determination

Conjunction Data Messages (CDM) are XML files containing information related to a risk of collision between a satellite (called primary) and an object (called secondary), which can be another satellite or a space debris. These files are generated through catalogs of space debris and by various space organizations or agencies, which are referred to as the originators of CDMs.

A CDM is divided into two parts: a header and a body. The header contains information related to the message itself (creation date, sender, etc.). The body, on the other hand, contains information related to the encounter of the two objects, as well as two segments describing each object individually. The first part, named relativeMetaData, contains for example the Time of Closest Approach (TCA), which is the time where the distance between the two objects is minimum. This is a key element, because it corresponds to the date of the risk, and all the data of the CDM are expressed at this date. This part also contains the minimum distance between the two objects, their position and relative velocity, as well as the dimensions of the satellite screening box. The two following segments contain the data related to an object (the primary or the secondary), and this, always at the TCA. Each presents the object (its type, its name) and the choices of computation that have been made for the propagation of the position, velocity and covariance (force model, ephemeris, reference frame). It also contains the Cartesian coordinates of the position and the velocity, as well as the coefficients of the covariance matrix.

The CDM catalog is obtained from the ephemeris of the reference orbit. The real trajectory will be really close to the one of the reference orbit, but it will be necessary to recalculate the conjunctions from the more precise OD information available on board. To reduce the volume of the CDM catalog to be uploaded on board, it is necessary to add a filtering and data reduction step on-ground:

- The first step of this filtering consists in selecting the objects in the vicinity of the satellite.
- The second step of ground filtering consists in removing the duplicates in order to avoid the same risk to be calculated several times. Indeed, CDMs on a detected risk are issued every day during the 7 days preceding the TCA. In addition, several originators can each send a CDM for the same risk and finally, an orbital evolution can lead to the generation of a new version of the CDM.
- The third filtering step will sort the CDMs by secondary and select only one per group. For each group, the choice of the CDM to keep is a compromise between the one whose creation date is the most recent and the one whose TCA is in the ASTERIA scanning facility. The most recent creation date ensures that the information is as up-to-date as possible. The TCA as close as possible to the scanning interval makes it possible to limit the backpropagation of covariance which are costly in terms of computation time and whose physical meaning is limited.
- The CDM data reduction step of 64% on average: some information which are not directly necessary for the calculation of the risk of collision itself, but which can become necessary for a relevant analysis of the risk of collision, have been kept in order to help make the decision to maneuver if the risk is greater than a fixed threshold. These include, for example, the number of observations available and used, as well as the header and relativeMetaData data.

Thus, by sorting the catalog by secondary, and by simplifying the CDMs, it is possible to reduce the total number of files by 97% and the total data size by 99%. These modifications make it possible to easily go below the 3MBytes mark, which is necessary to guarantee the data being uploaded on board within a single station pass per day.

Then, the on-board CDM filtering, using the last OD and a numerical propagation (whose assumptions have been detailed in the previous chapter), is applied in order to only focus on the potential risks during the AOC-ACA iterations. The detector has been defined to detect only minima and to stop the propagation at each minimum. Thus, data of the primary and the secondary at this time t are stored as a potential risk. It is therefore necessary to propagate the secondary ephemeris at the same time in order to be able to recover all the data at t if there is an event detection. This data is then stored and makes it possible to restart the propagation on the date on which it stopped. We therefore obtain, over the entire interval considered, a list of potential risks based on the minimum distances between the two objects. This list will then be sorted by a purely geometric criterion on the minimum Euclidean distance considered dangerous: a filtering is performed in order to select only the local minimums of relative distance within a sphere enclosing the satellite monitoring window. This filter volume is included in the screening box, possibly of the same size. Each selected encounter is then considered as a risk to be characterized during next ACA loops.

For each encounter, the CNES Operational Probability of Collision (COPoC) is calculated using a CNES 2D method which transforms the integral into a sum of terms whose number varies according to the precision required. This transformation makes it possible to obtain a low computation time with good computational precision, which is interesting in our case. To apply this method, the covariance of the two objects at the TCA is required, and a collision plane, is created. For reminder, this 2D method assumes the gaussianity of the covariance at stake and is well suited for short-term encounters with a high relative velocity, which represent the vast majority of real-life cases. Once the list of potential risks has been determined, it is necessary to start again from the covariance data of the CDM (expressed at the TCA), and to propagate them until the date of each risk to recover the covariance of both the primary and the secondary at this date. Covariance dilatation coefficients (kp for the primary and ks for the secondary) are applied to optimize the reality of the probability of collision. The collision plane is then created from the primary and secondary orbits and the reference frame. The relative position between the two objects is projected onto the collision plane, along with the covariance matrices, which are then added together to form a single matrix which will then be used for the collision calculation. Finally, the collision probability is calculated and stored for each encounter.

The disadvantage of estimating the risk of collision on board is that it is based on a simplified propagation model (the 2D COPoC method previously mentionned). However, calculation are done as close as possible to the risk, and benefit from a very good knowledge of the current orbit of the primary. In order to ensure that the advantages of on-board estimation outweigh the disadvantage, a comparison with a classic CNES EUSST ground-based risks estimation solution has been performed. The exercise is based on a real satellite, ANGELS, operated by CNES, using a fully determined trajectory and from real conjunctions. For the conjunction selected for the study, the risk estimate taken as reference is the one calculated from the known state of the most up-to-date primary and the last information on the secondary state. The realistic operational timeline is: two station passes and one ground orbit determination per day.

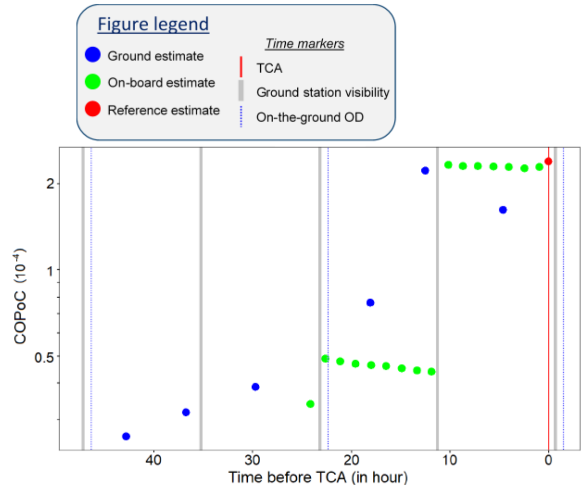

Figure 5: conjunction example without avoidance maneuver

The value of the risk estimated on board from 10 hours before the TCA is very close to the reference value derived from the most up-to-date information available. On-board COPoC computation does not show any over- or underestimation due to a simplified propagation model or the late on-board availability of secondary information.

Many real cases have been studied, and led to similar conclusions, showing that collision risk estimates are in equivalent order of magnitude between a complete ground-based process and an on-board estimate, and that the on-board provides a better short-term estimate, close to the TCA. ASTERIA therefore has reliable information, as close as possible to the encounter, and enough response time to implement a risk mitigation solution if necessary.

Collision risks avoidance

Collision risk mitigation is managed on board through iterations between AOC and ACA:

- As a first step, an alternative station-keeping strategy is evaluated. This strategy consists in adjusting, advancing or delaying an in-track correction maneuver depending on the impacted horizon.

- When this solution is not advisable or does not mitigate the risk, a specific avoidance strategy is implemented. This strategy is designed to minimize the effect on the mission and on the station-keeping window. If required, the avoidance solution includes the return corrections into the station-keeping window.

After the implementation of the avoidance strategy, the collision risk on the new trajectory is re-evaluated on board. The correction maneuvers are small and short term; the primary remains contained within the screening window. Thus, ASTERIA already has all the information required to re-estimate the conjunctions. It is not necessary to loop back to the ground.

The approach of the implemented avoidance strategy is to increase the radial separation between the primary and the secondary at the TCA date, by changing the semi major axis of the primary orbit:

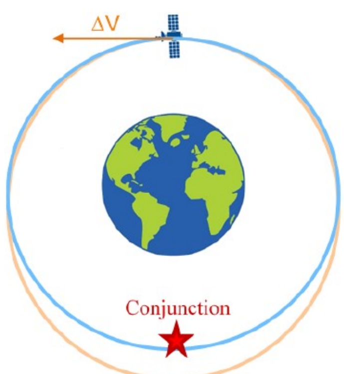

Figure 6: avoidance tangential maneuver for radial separation

The figure shows the effect of an impulsive thrust on the radial deviation at the TCA. The optimal maneuver would be an impulsive maneuver only tangential and performed n + 1/2 orbits before the TCA. The radial separation is a basic approach commonly used in operations. But the theoretical maneuver is generally not possible to be implemented because of the non-availability of the optimal thrust slots and because of the low-thrust propulsion which needs several thrusts to perform the suitable radial sepration at TCA. The advantage of the radial separation heuristic approach is that it provides a fast analytical calculation of the maneuver, with the assumption that the initial orbit of the primary is quasi-circular. The main focus of the optimization is on finding the most suitable sets of thrust regarding the AOC mission and platform constraints.

The collision multi-risks are partially managed using secondary management. Thus, the avoidance solution implemented enables the efficient management of several risky conjunctions from the same secondary. For multiple risks from different secondary objects, the method currently implemented in ASTERIA manages the risks independently by defining priorities. Improvement solutions are being considered using various works in progress.

ASTERIA CONOPS

The proposed operational concept assumes that the ground mission operations center is responsible for the pre-filtering of the debris data, given the high computing power capacity, in order to reduce the load on the on-board/ground link and the use of on-board resources. The execution of the ground activities is dependent on the visibility of the stations and on the supplying of CDM data by the Space Surveillance and Tracking service. The tasks performed on the ground are:

- Several times per day: conjunctions filtering
- Once per day: mission planning generation
- Once or both per day:
  - CDM, mission planning and space environment data (solar activity and Earth orientation poles) uplink
  - Maneuver plan, risks status and telemetry downlink

On-board activities of ASTERIA are synchronized with the activation at ascending nodes crossing, making computational allocations predictable. Theses activities are therefore not synchronized with those carried out on the ground, in line with the concept of on-board autonomy. The tasks performed on-board are at each orbit:

- OD
- AOC maneuver plan computation
- CDM filtering
- Primary and secondary objects orbit propagations
- Collision risks assessment
- AOC-ACA avoidance iteration (when required)

AOC and ACA monitoring is performed both on-board thanks to the FDIR and on ground through the telemetry status.

Let us compare the CONOPS of an avoidance management with a legacy ground-based concept and with the use of ASTERIA:

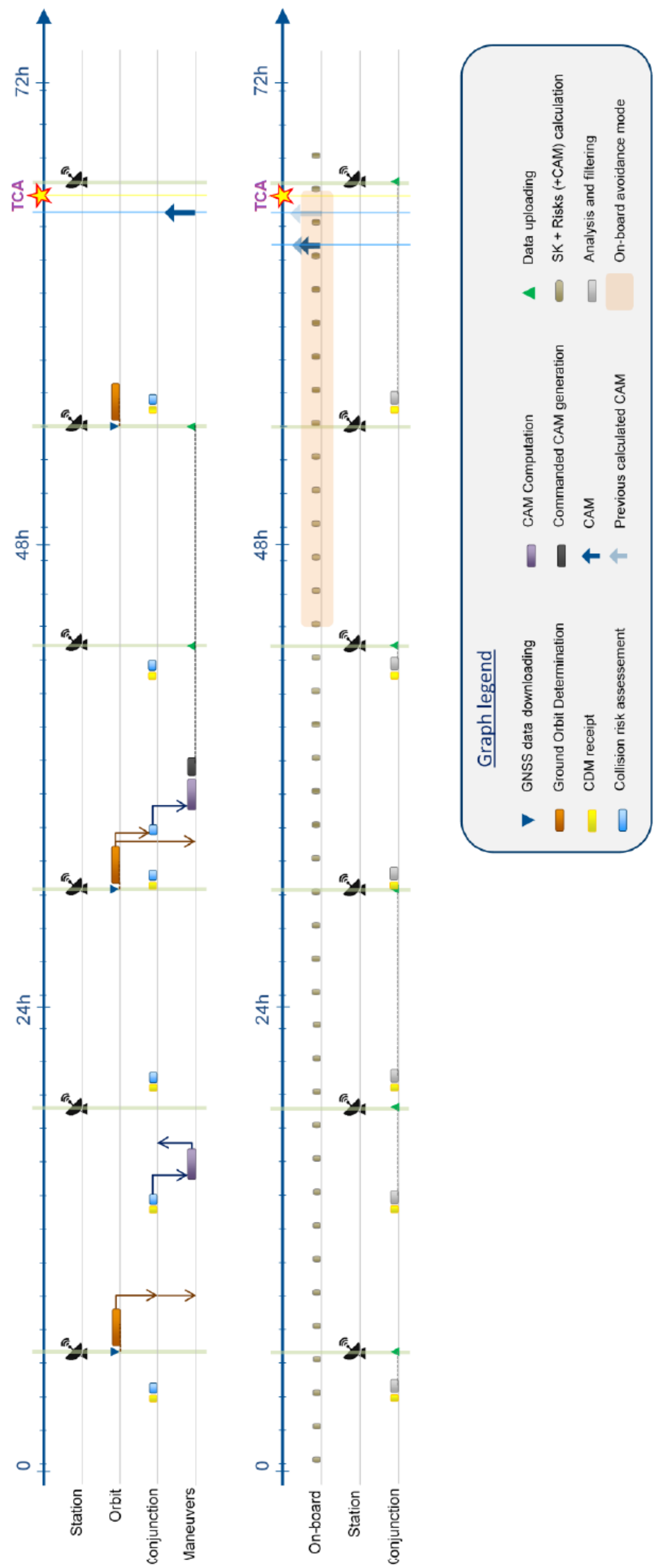

Figure 7: conjunction CONOPS comparison between ground legacy CONOPS (at the top) and ASTERIA CONOPS (on the bottom)

The diagram clearly highlights the responsiveness and strong adjustability of the on-board solution. Despite a computational limitation on the accuracy of on-board propagation of orbital states and covariance objects, the frequent updating of orbit determination data enables a relevant estimation of the collision risk. On the contrary, the legacy ground-based solution requires to command a maneuver calculated further upstream with older information. The inertia of the process linked to the dependence of the ground link and the availability of the operators strongly limits the optimization.

Collision avoidance with ground-based concept:

- The time required to implement the avoidance maneuver is directly dependent on the on-board/ground link to upload the command to the satellite. Additional organizational limitations can constrain and increase the timing of the sequence.
- The knowledge of the orbit of the primary is obtained from an orbit determination carried out on ground, itself dependent on the on-board/ground link. It is therefore not updated as close as possible to the TCA.
- The risk is identified earlier than with an on-board solution, but needs to be confirmed or invalidated with regard to the evolution of the orbital knowledge of the two objects in conjunction.
- After the CAM computation, it is necessary to ensure that the modified trajectory does not generate new collision risks.
- It is recommended to upload the commanded maneuvers on the second to last pass before the execution date in order to have a back-up in case of uploading problems.

Collision avoidance with ASTERIA:

- The system benefits from a very frequent orbit determination (at each orbit), providing it with precise and regular information.
- The on-board availability of updated secondary data is dependent on the on-board/ground link.
- The risks scanning horizon is shorter (around 24-48 hours) due to the reactive capacity of the system and the validity of the predictability horizon of the primary trajectory.
- ASTERIA can adjust the collision avoidance strategy at each new primary orbit determination and at each update by the ground of the conjunction data.
- It is not necessary to loop back to the ground for the impact of the avoidance solution on the other risks because the data available on board are sufficient to make this check.

OPSSAT EXPERIMENT

In spite of many simulation tests performed on ASTERIA with several CNES satellites data, CNES AOC-ACA roadmap is looking for every in-orbit testing to get the TRL top level. Firstly, without maneuverable capacity to test every modes without endanger the satellite.

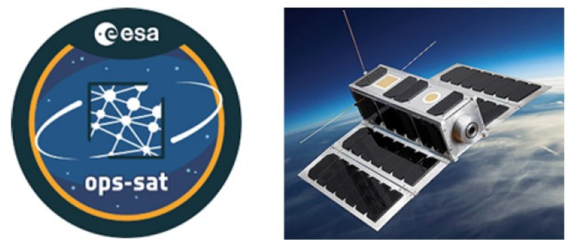

Figure 8: OPSSAT logo and artist view

The ESA OPSSAT mission offered us an opportunity to test the ASTERIA operational concept directly in flight. It made it possible to validate the CONOPS, the volume of board/ground data exchanges and to validate the computing load. Besides, with no direct links with ASTERIA, it was also helpful in learning how to use the protocol CCSDS MO on-board in order to develop and operate an embedded and autonomous solution. In fact, as detailed hereafter, OPSSAT architecture was the perfect client for our needs.

OPSSAT environment

OPSSAT is an ESOC 3U sun-synchronous orbit nanosatellite launched in December 2019 into a circular, polar orbit at 515 km altitude. OPSSAT project offers the opportunity to test in-flight experiments (software or FPGA) with the main aim to remedy to "has never flown, will never fly". Therefore, thanks to ESOC, CNES has joined OPSSAT experimenters in 2018 mainly to develop and test ASTERIA application.

Thanks to its hybrid architecture OPSSAT allows leading software experiment, using payload equipment and high performance CPU, without compromising the FDIR and critical sub-systems of the satellite. OPSSAT implements new CCSDS Mission Operations ground/on-board and on-board/on-board services oriented protocols that allow to easily develop and upload on-board software application using payload equipment API. ESOC Java code of CCSDS MO on-board/on-board nanosat is open-source and named Nanaosat MO Framework (NMF). Through this, ASTERIA has access to the GNSS API for on-board orbit determination. The light Linux operating system is able to execute Java language and all the NMF is running Java allowing to easily embedding ASTERIA code into an ASTERIA NMF application. The CPU and RAM of the test platform propose high capacities: ARM dual-core Cortex A9 800 MHz and 1Gb of RAM respectively.

Moreover, OPS-SAT project offers a suitable development, testing and operational environment:

- A Java software development kit.
- The open-source NMF.
- Light OPS-SAT software simulator and mission control segment (named CTT).
- A flat-sat at ESOC remotely accessible for test sessions
- A remotely web accessible mission operations segment to lead the operations (named EUD4MO, very useful during Covid-19 lockdowns)

OPSSAT dedicated station is at ESOC Darmstadt Germany. The quasi sun-synchronous 6h LTAN 515 km orbit makes it possible to obtain 3 to 6 passes per day with a correct elevation.

ASTERIA application

The main challenge of the OPSSAT ASTERIA application is to embed the ASTERIA flight dynamics core into an NMF application using the on-board time and the GNSS localization data, as external API.

The next figure explains how ASTERIA application interacts with satellite services (on-board time, GNSS data from AOCS API and CCSDS engine to deal between CCSDS telemetry/telecommand frames and MO services) through ESOC Supervisor code mainly running NMF framework:

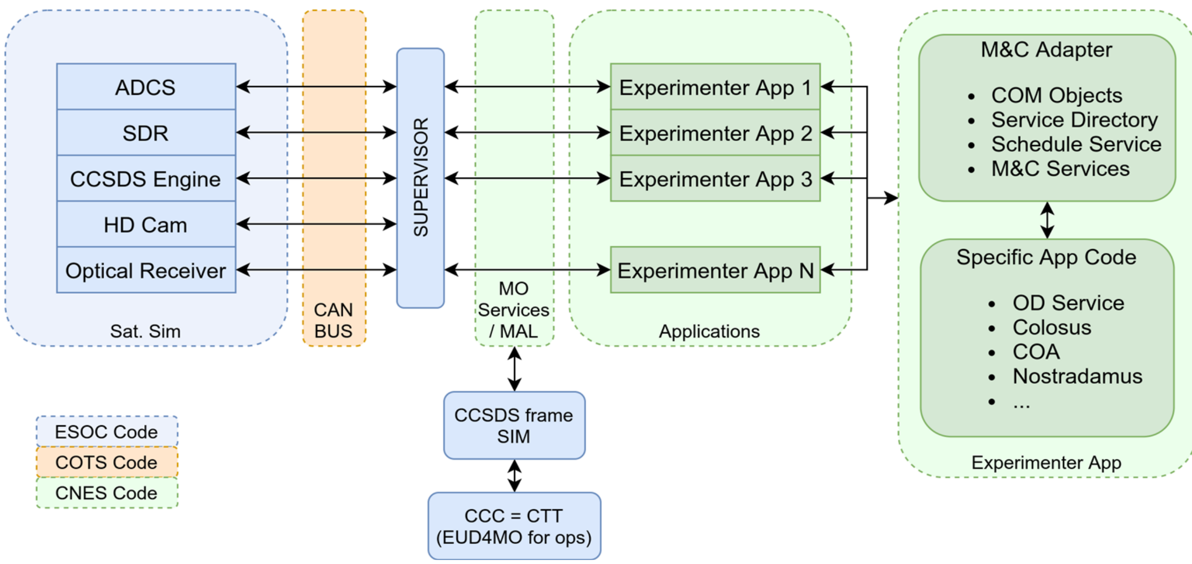

Figure 9: OPSSAT application architecture

ASTERIA application code is also split into two parts:

- Monitoring and Control (M&C) common code: is in charge of the scheduler allowing to execute time-tagged actions, of the parameters registration (such as GNSS data listening and archive) and of the application services specification. The main available services are: GNSS data query, OD, upload schedule, update CDM or configuration, perform ASTERIA core loop and prepare outputs to be downloading.
- Specific code: contains OD algorithm, ASTERIA core and the overall ASTERIA loop management.

ASTERIA core code is also services oriented, coded in Java language and mainly based on CNES flight dynamics PATRIUS libraries. The application also used PATRIUS to perform on board orbit determination using least-square QR decomposition method with GNSS API angular CIRF frame positions.

ASTERIA application outputs to download are Java logs and maneuvers plan at each activation and also ephemeris propagations on board computed for comparison with the reference trajectory.

The overall experiment schedule on few days of testing was:

Figure 10: OPSSAT operational schedule

With only two passes per day dedicated to the ASTERIA mission data exchanges.

Indeed, for ASTERIA application uplink (and modifications), it is clearly a key point to have such a light solution:

ASTERIA package	
coa_cnes-1.0.jar	87 Ko
coa_cnes_utils-1.0.jar	29 Ko
core-0.0.1-SNAPSHOT.jar	120 Ko
asteriaApp-0.0.1-SNAPSHOT.jar	139 Ko
patrius-4.4.jar	4 320 Ko
opssatConfigASTERIA.zip	750 Ko
TOTAL	**5.32 Mo**
Compressed ASTERIA package	
asteria_1.93_cnes.zip	**4.92 Mo**

Figure 11: ASTERIA application package

The application code is composed of:

- Some librairies:
  - AOC-ACA ASTERIA services
  - AOC ASTERIA tools
  - PATRIUS including space environment data over the experiment horizon
  - COLOSUS (CNES collision risks PATRIUS based library)
- ASTERIA NMF application
- ASTERIA configuration: properties, reference orbit

The total size inferior to 5Mbytes fills the objective and is quite similar to classic on-board software platform or payload solutions.

Experiment definition

The ASTERIA functions are directly related to station-keeping objectives, mission constraints and platform constraints such as instrument glare or propulsive capabilities. In order to be placed in a realistic operational context, it was necessary to define the associated mission and to configure ASTERIA:

- It is an ocean observation mission positioned on a sun-synchronous LEO orbit, as close as possible to the OPSSAT orbit.
- The station keeping is performed finely around the reference orbit created for the occasion.
- The mission is voluntarily busy, thus making available only a set of reduced slots dedicated to orbit control.
- 3 days testing horizon
- The propulsion system is electrical: virtual propulsion system has been defined with a maximum thrust of 0:25 mN, an ISP of 2100 s and a thrust spreading of 95% of performance compare to impulsive thrust (Robbins penalty).
- The on-board orbit propagation model includes the Earth gravity potential (J40×40), Moon and Sun gravity potentials, atmospheric drag and solar radiation pressure as explained before. Solar activity and Earth orientation poles data are real data over the experiment horizon.
- For the purposes of the experiment, the ground CDM filtering from the known reference guidance trajectory is performed from the CDMs provided by CNES EUSST entity from a screening around the reference orbit. Over the time span, a catalog of 893 CDMs is obtained. The ground filtering process implemented has reduced the number of CDMs to 20 corresponding to 20 secondary objects listing 55 risks in total. Rewriting the CDMs in light format led to obtain a CDM list to be uploaded with a size about 114KBytes. In order to test the complete algorithm sequence of ASTERIA, including the avoidance management mode, a fictitious secondary object has been added during the third day of the experiment. It generates a high probability risk with a TCA at 12 h from upload.
- Collision risk probability threshold is equal to $5e^{-5}$

Experiment results

ASTERIA ran more than 3 days with 46 consecutive activations at each ascending node crossing. Due to the miss of propulsion capacities of OPSSAT, the calculated maneuvers could not be executed and this led to the calculation of 17 in-plane station keeping maneuvers plus 4 dedicated to the avoidance of artificial risk added to the activation #36 (this activation led to test all ASTERIA avoidance modes overs all the AOC horizons as explained before).

The computational load of ASTERIA has been monitored. The next figure shows the calculation time for each activation of ASTERIA. The monitoring gives an average calculation time for each activation of about 7 minutes:

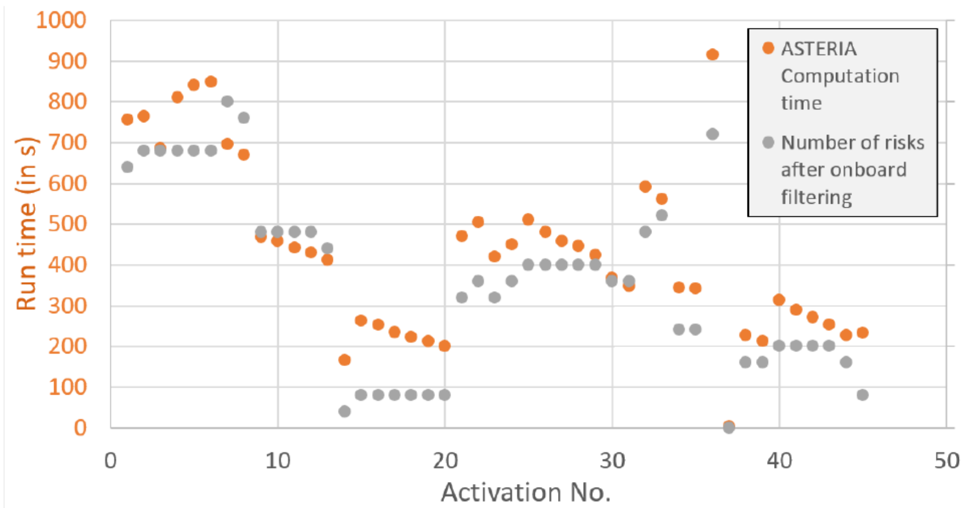

Figure 12: ASTERIA computation time depending on CDM

This time goes up to 15 minutes in case of complete calculation sequence with avoidance strategy, as for activation #36. The graph also shows the number of collision risks to deal with after the on-board filtering step. The number of risks to be processed is in the order of 10 to 15 dangerous encounters for each activation. It should be noted that the calculation time correlates rather well with the number of risks to be processed on board.

The next figure shows the distribution of the computational load during the execution of the ASTERIA application. As we expected, most of the load is dedicated to the calculation of state propagation and covariance propagation. This computational load explains the correlation of the computational time with the number of collision risks.

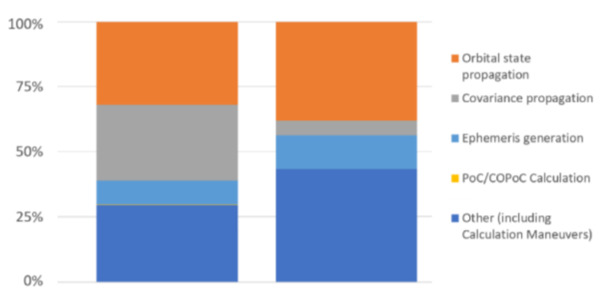

Figure 13: computational distribution without risk mitigation (on left) and with a risk to avoid at activation #36 (on right)

As it is possible to see on the next figure, the CPU usage obtained by OPSSAT telemetry showed peaks of load corresponding to ASTERIA computation. The graph displays 4 hours of measurements including 2 activations of ASTERIA. The CPU has never been saturated during the entire experiment.

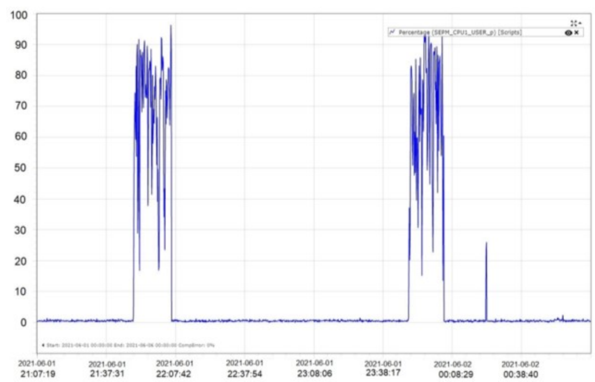

Figure 14: CPU charge during ASTERIA both activations

The calculation tasks of ASTERIA are synchronous and allocable, making the computation process of ASTERIA compliant with space avionics requirements.

All the experiment objectives are fulfilled successfully as we show ASTERIA capacities to:

- Be a light, "packageable" and patchable on-board application
- Assure AOC-ACA requirement in respect to mission and satellite constraints
- Having a fully operational CONOPS
- Not having too much CPU/RAM consumption

CONCLUSION

By coupling AOC with ACA, ASTERIA considerably increases the autonomy of orbit control for the benefit of the mission and of the ground operations for activities dealing with collision risk management.

The station keeping is accurate and efficient. The on-board risk calculation is relevant, based on a good knowledge of the orbit. The on-board management enables an increased reactivity and an adaptation to the right need of the collision risk mitigation actions.

The experiment on OPSSAT was a decisive step to validate the reliability of the operability process and the ability to implement such a system in a modern and disruptive on-board architecture.

Improvement activities will continue, with, in particular, ongoing works on multi-risk management and on the optimization of avoidance solutions thanks to CNES research projects with our industrials. Another really significant point to address is the Space Traffic Management necessity associated to such an ASTERIA solution: actually, it is necessary to coordinate operations between maneuverable satellites in case of risk conjunction between them with new "road traffic regulations" to avoid increasing the risk.

With the multiplication of mega-constellations, the improve of satellite computing capacity and disruptive on-board architecture, space domain is reaching a new era of advanced on-board autonomous and Space Traffic Management.

Acknowledgments

Authors would like to address thanks to all those people who provided technical support during design, development, test phase and operations of ASTERIA/OPSSAT, in particular, to the trainees Alix, Sara, Irene, Juliette, Alejandro, Chiara, Clément, Anthony and Baptiste for their contribution and their good mood. Authors would also like to thank David Evans from ESOC and his team (Tom, Dominik, …) for making the ASTERIA experiment on OPSSAT possible and successful.

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