FOUR YEAR EXPERIENCE OF OPERATIONAL IMPLEMENTATION OF AUTONOMOUS ORBIT CONTROL: LESSONS LEARNED, FEEDBACK AND PERSPECTIVES

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ABSTRACT

The implementation of the Autonomous Orbit Control (AOC) experiment on the CNES micro-satellite Demeter began in April 2005 and is still under way four years later. The purpose of this paper is then to provide feedback on the experience gained and to share the lessons learned during this time. It is also to discuss the use of autonomous orbit control for future missions.

The first part of the paper consists of an overview of the experiment. We'll describe how the system has been designed and implemented, emphasizing the most innovative aspects.

The second part of the paper is more specifically devoted to the lessons learned. These pertain to many different aspects: onboard software (regarding flexibility in particular), algorithms (and some of their desired properties), monitoring, etc…

In the final part of the paper we'll look into the use of AOC for future missions, and we'll investigate the more general question of the trade-off between AOC and more traditional ground-based solutions.

Acronyms and notations

AOC	Autonomous Orbit Control
FDIR	Failure Detection, Isolation and Recovery
ΔV	Velocity increment
LEO	Low Earth Orbit
LEOP	Launch and Early Operations Phase
SK	Station Keeping

1. INTRODUCTION

1.1 Autonomous orbit control

The purpose of Autonomous Orbit Control (AOC) is, not surprisingly, to control the orbit autonomously on board. The role of the control centre is then limited to monitoring the process without being in the control loop.

In this paper, autonomous orbit control is meant to concern the station keeping of one satellite only (still enabling limited orbit changes). AOC could probably be used for other mission phases as well (LEOP activities, de-orbiting), but this has not been considered in this paper as the manoeuvre strategies or the operations involved are somewhat different.

Autonomous computation and execution of manoeuvres may be of interest to simplify the ground segment and ease the operations, and also to improve orbit control accuracy, for instance for a very low orbit when solar activity is high.

In an ideal implementation (i.e. as it is imagined), the satellite accurately maintains its position and velocity close to reference values that are known and defined by the control centre. All the usual tasks habitually performed by the control centre (relevant to the platform, the ground stations, mission programming…) only depend on this reference orbit and not on the "actual" one (as determined classically using ground-based means).

The experiment on Demeter slightly differs from what could have been a truly operational implementation of AOC, even if most aspects have been demonstrated, at least for limited periods of time.

1.2 The objectives of the experiment and why it was initiated

The AOC experiment was proposed in 1998 within the framework of a CNES R&D program on autonomy. Its main objective was to show that AOC can be a reliable option for future missions, that is, that it can be implemented securely in an operational context.

In fact, other experiments have already been conducted (see [3,4,5]), but the one on Demeter is probably the closest to what a truly operational application might look like.

At the time the experiment was initiated, autonomy was a controversial topic and was often seen as taking unnecessary additional risks. Thus, in a context of rapidly improving on-board processing capabilities and the availability of off-the-shelf orbital navigators, it made sense to demonstrate that autonomy was not to be limited to orbit determination, but that it could be extended to other activities as orbit maintenance.

1.3 The Demeter micro-satellite

Demeter was the first satellite of the CNES Myriade series that was built and launched. More details can be found in [10].

2. EXPERIMENT OVERVIEW

2.1 Architecture

Figure 1 represents the typical tasks of an orbit control process.

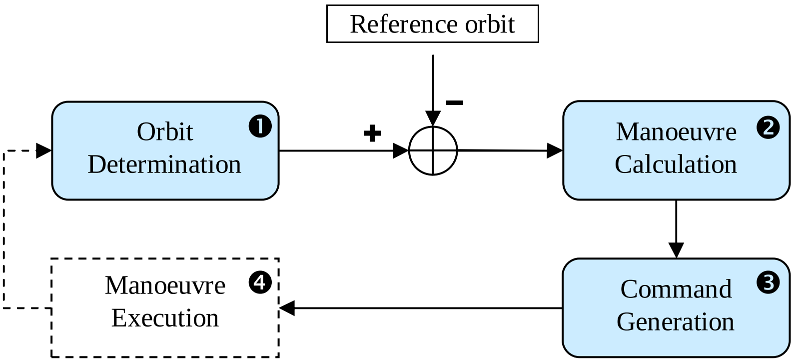

Figure 1: Typical orbit control loop

In the experiment on Demeter, these tasks are performed in the following way:

➊: A Topstar 3000 GPS receiver (from ThalesAleniaSpace) is used. It includes a “navigator” that generates time, position, velocity plus associated quality information.

➋: Manoeuvre computation is performed by a specific software installed in the GPS receiver. The receiver main software exchanges data with the manoeuvre computation software through a dedicated generic interface. The manoeuvre computation software outputs (that include the next manoeuvre date and velocity increment) are sent in the usual receiver telemetry.

➌: Command generation to the platform is performed by another specific software installed in the payload management unit. It transforms the manoeuvre date and velocity increment into adequate propulsion and attitude commands.

➍: Manoeuvre execution takes place provided the 3 previous steps have performed correctly and if the platform-dependent security mechanism (designed to prevent unwanted manoeuvres from being queued for execution) has not been activated.

2.2 Objectives of the orbit control

Because the main scientific mission does not require orbit maintenance, the control only needs to be representative enough, although in practice it is very close to what is usually done. Tangential manoeuvres only are performed in order to control the argument of latitude or the longitudes of the ground tracks. As inclination evolves freely, the longitudes of the ground tracks can be controlled at the equator only. The control of the argument of latitude (all along the orbit) is done by controlling the time at the ascending node and the mean eccentricity vector.

2.3 Experiment’s most original aspects

There are different levels:

On-board architecture:

The choices mainly originate in the fact that changes to the product line on-board architecture had to be minimised (in particular there could not be any changes to the main platform software). The commands that are generated on board are identical to those sent from the ground.

Ground architecture:

In “routine mode” the control centre (nearly) operates as if AOC did not exist. Doing otherwise (e.g. getting the control centre to use some reference orbit only) would have resulted in lots of changes (and analyses), which was not desirable in the framework of this experiment. The only impact on the control centre is the use of the manoeuvre execution times to improve the quality of the determined orbits, which, in any case, did not result in any ground software changes.

But this gave rise to additional constraints on the AOC. Autonomous manoeuvre amplitudes had to be bounded and manoeuvres forced to be close enough to ground station visibility passes so that the satellite acquisitions were not impacted (requirement: maximal along-track deviation from nominal position less than 500m). This also led to the definition of manoeuvre slots so that the ground could define the position of manoeuvres as required.

A second implementation mode (implying changes in the control centre) has been demonstrated but for a limited period of time.

Operations:

All the aspects relevant to the AOC experiment are dealt with either in the technological control centre (for routine aspects) and by the experiment team (using their own tools). The routine operations performed by the control centre are very little impacted. Only a few procedures are added to take account of the presence of the AOC experiment.

2.4 Experiment timeline

The main phases are summarised in Table 1 and detailed thereafter. The total active implementation period has lasted for 4 years so far (excluding the pause at the end of 2005), and was only interrupted for shorts periods of time for exceptional reasons unrelated to the AOC experiment.

Table 1: Experiment phases

29 June 2004	Launch of Demeter
July 2004 → March 2005	Passive phase: AOC flight validation (no AOC manoeuvres performed)
April 2005 → Oct. 2005 4 April → 20 Sept. 2005 25 Sept. → 20 Oct. 2005	**Active phase I**: Active phase I.A ("routine" mode) Active phase I.B ("continuous" mode)
April 2006 → August 2009…	**Active phase II** ("routine" mode)

Passive phase (no manoeuvres performed): As it was decided from the beginning that no manoeuvre should be performed for the first few months in orbit, an extended validation phase took place. This enabled us to check that the on-board software was behaving satisfactorily. Careful attention was paid to some more sensitive aspects, particularly with respect to some of the main requirements (positions of manoeuvres, maximum ΔV allowed, etc…).

Active phase 1: There were two sub-phases that took place in so-called "routine mode" and "continuous mode".

"Routine" mode: The AOC was first implemented with (at most) 2 manoeuvres per week for the control of the longitudes of the ground tracks. Demeter was then at the same altitude as the Aqua train, so that the AOC was also used to (loosely) control the satellite position (i.e. argument of latitude) with respect to the other satellites at the same altitude (to within a few degrees).

Duration	4.5 months
Manoeuvre rate	At most 2 per week
Manoeuvre slots	1 orbit period long time intervals. Every Wednesday and Sunday (unless cancelled). Uploaded and updated once a week (up to 6 at a time)
Control	Longitude of ground tracks at ascending node + mean eccentricity vector

"Continuous" mode: This mode has been implemented only once, and was more representative of what could be thought of as an ideal implementation.

The scientific mission was off during this period, and it was possible to make temporary changes to the ground segment. A reference ephemeris was defined consistently with the actual orbit as controlled on board, and used by the control centre. The control centre was still determining the orbit (as it routinely does) but for monitoring purposes only. Initially, the process was closely monitored as the number of manoeuvres could be (and in practice was) up to 2 per day.

Duration	3.5 weeks
Manoeuvre rate	At most 2 per day
Manoeuvre slots	1 orbit period long time intervals. Automatically generated on board
Control	Time at ascending node + mean eccentricity vector

Active phase II: From April 2006, thanks to the experience already gained, the AOC on Demeter has begun to be considered as a truly operational sub-system. But at the end of the first phase (end of 2005), new developments occurred.

The altitude of the orbit had to be lowered (and the inclination changed accordingly) in order to comply with debris regulations in case any problem should happen with the satellite. But more importantly, new analyses had to be conducted to ensure that the implementation of AOC could be carried on, as shadowing problems on the solar array that could endanger the satellite had to be dealt with.

This resulted in additional constraints on AOC. Manoeuvre slots had to be decreased in size and the direction of manoeuvres had to be constrained too (either in the direction of the velocity or in the opposite direction, but not either way as was the case before). After these new constraints were taken into account, the experiment could be resumed (in “routine mode”).

As a new operational sub-system (and effectively considered as such by the control centre operators), AOC has been used to successively:

- Control the synchronicity with Parasol (another satellite in the Aqua train) so that ground station visibility conflicts could be minimised.
- Manage 4 successive close approach occurrences with the Essaim 4-satellite formation (one every six months), each time in a different way (see [8,9]).
- Maintain the separation with the Essaim formation after the orbit of Demeter was changed once more to avoid any further close approach occurrences with Essaim.

Duration	More than 3 years
Manoeuvre rate	At most 2 per week
Manoeuvre slots	~0.5 orbit period long time intervals.
Control	Time at ascending node + mean eccentricity vector

3. EXPERIMENT'S HIGHLIGHTS AND MAIN RESULTS

In this section selected results, which are among the most representative, are presented and discussed.

3.1 The first manoeuvre performed (10 April 2005)

Figure 2 shows some of the results corresponding to the first manoeuvre performed.

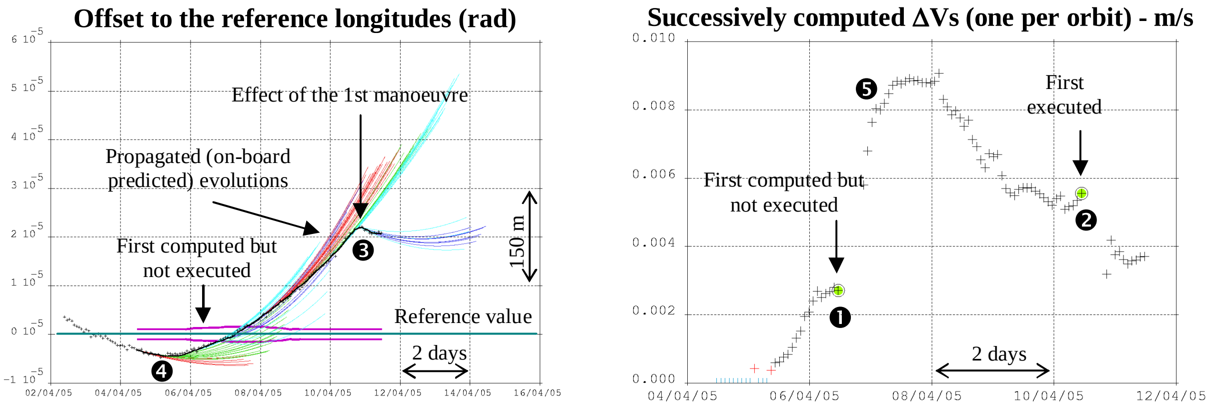

Figure 2: First executed manoeuvre

All the computations performed nominally. A first manoeuvre was computed in the first available manoeuvre slot (❶), and transformed into platform commands. But no manoeuvre occurred because of the platform security mechanism that prevented the commands from being put in the execution queue. Without the need for any specific action from the ground (except authorizing the manoeuvre), the on-board calculations continued without any problem (as the on-board algorithms had been configured to be tolerant to up to 100% manoeuvre execution error), which resulted in the first executed manoeuvre 4 days later (❷). The effect of the manoeuvre is visible through the change of slope (❸).

Another sudden change of slope can be seen without any orbit manoeuvre occurring (❹). It appears to be due to changes in atmospheric density. This resulted in variations in the once-per-orbit computed ΔVs (❺) until the value became stable again, but the manoeuvre that resulted appears slightly underestimated. The difficulty lies in the fact that these variations are not well taken into account in the on-board models (except as model noise). Designing algorithms that behave as well as possible in this kind of situation has probably been one of the most challenging aspects to deal with.

3.2 Synthetic view of all the manoeuvres performed

The results shown in Figure 3 are based on the satellite propulsion telemetry, and consequently correspond to the manoeuvres that were actually performed.

Time period analysed	4 years (from April 10th 2005 until August 5th 2009)
Number of manoeuvres performed	219

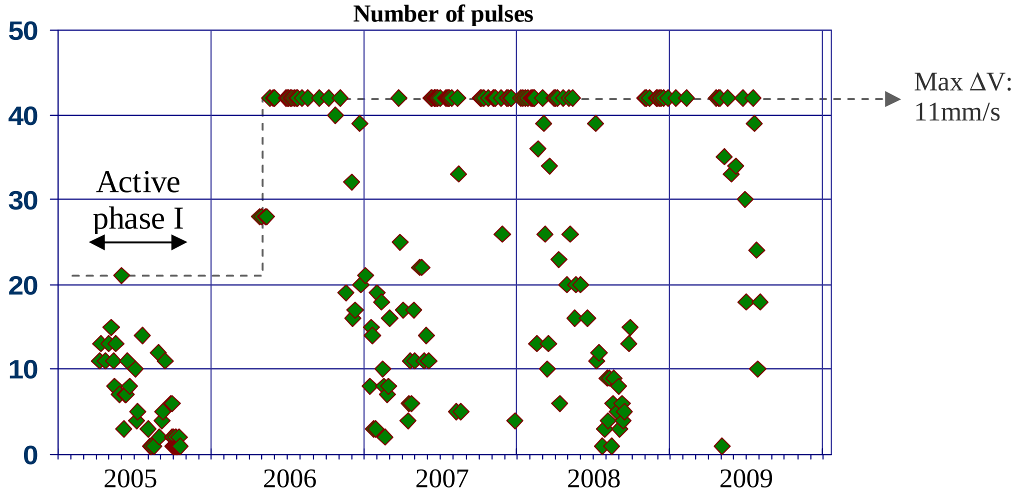

Figure 3: All the manoeuvres performed so far

3.3 Selected results from active phase I (2005)

For completeness, here is a summary of what happened in 2005. More can be found in [6,7].

<u>“Routine” mode</u>:

Duration	4.5 months
Max. manoeuvre frequency	2 per week
Number of manoeuvres	28 (1 every 5 days as an average)
Total |ΔV|	~0.1 m/s
Station keeping accuracy	100–200m on the ground tracks at ascending node.

<u>“Continuous” mode</u>:

Duration	3.5 weeks
Max. manoeuvre frequency	2 per day
Number of manoeuvres	29
Total |ΔV|	~0.02 m/s
Station keeping accuracy	Less than 0.01s on the time at ascending node. 3D position accuracy < 500m (comparison with ground reference ephemeris)

3.4 Selected results from active phase II (considered as more operational)

Figure 4 shows results obtained from mid 2006 to mid 2007, in particular:

- The computed ΔVs (upper graph),
- The time offset to the reference time at the ascending node (lower graph).

These results come from the AOC telemetry only (i.e. without using any additional data).

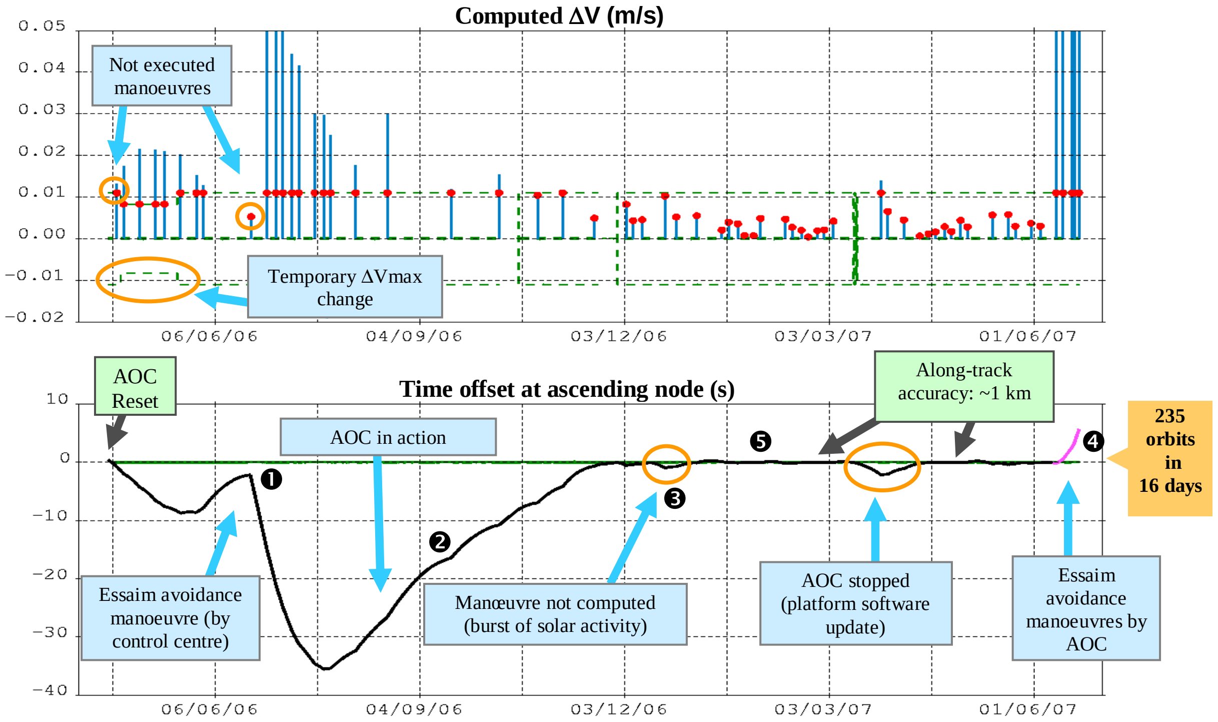

Figure 4: Results from phase 2 (mid 2006 - mid 2007)

❶: Impact of the first Essaim avoidance manoeuvre performed by the control centre (at which time the AOC was stopped). AOC was used to bring the satellite back to its reference position (❷). We see that the return was very slow: about 4 months. More efficient return strategies have been implemented in the management of the following close approaches to improve this point.

❸: Illustrates the effect of a solar activity burst (around 15 December 2006). This event is detailed later on (see sub-section 3.5).

❹: Illustrates the strategy implemented for the 3rd Essaim close approach: AOC was used to generate manoeuvres so that a secure enough radial/tangential separation at close approach could be guaranteed.

❺: The performance has been nominal at times (see at end of 2006 / beginning of 2007) despite all the events that occurred, with an along-track accuracy of about 1 km.

Figure 5 shows some results obtained in 2008 (same data plotted as in Figure 4, again coming from the AOC telemetry only).

❶: We can see that the ΔVs, habitually positive in order to increase the semi-major axis have negative values for a limited period of time, and then are positive again. This comes from the strategy implemented after the 4th Essaim close approach for which a specific reference law has been defined (see below and Figure 6). The return time has been as quick as possible given the strict limitation on the ΔV amplitudes (11 mm/s).

❷: The altitude of the orbit was slightly lowered (by the control centre) and the reference AOC parameters changed accordingly, which is not visible, except through the degradation of the control accuracy. Another period, about 3 months long, with nominal performance can be seen (❸). The accuracy may occasionally degrade (❹,❺) depending on other priorities in the control centre (e.g. ❺: inclination manoeuvre impacting the semi-major axis), or because other constraints apply (e.g. no manoeuvres allowed when the star tracker is dazzled by the moon).

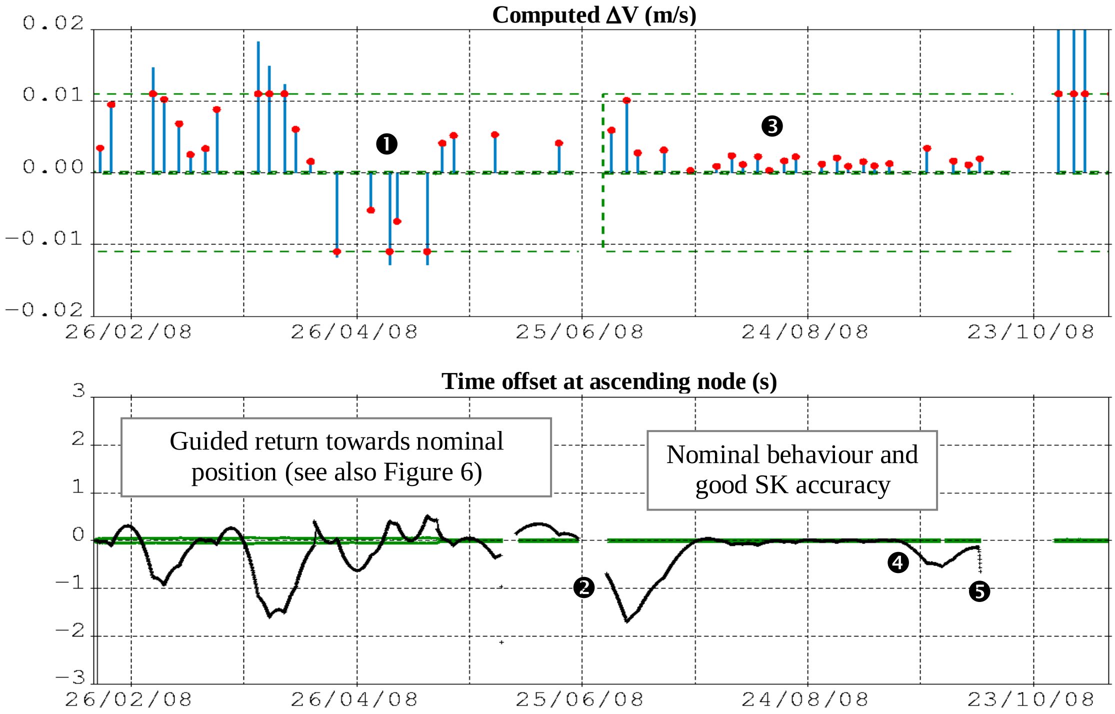

Figure 5: Results from phase 2 (2008)

The guidance law defined for the return to the nominal position after the 4th Essaim close approach is illustrated in Figure 6. It has been possible to devise such a guidance law because the algorithms enable the definition of a quadratic law (as a function of the orbit number) for the reference time at the ascending node. The quadratic law corresponds to having the semi-major axis increase or decrease at a constant rate. Two parabola arcs have been adjusted to meet continuity requirements.

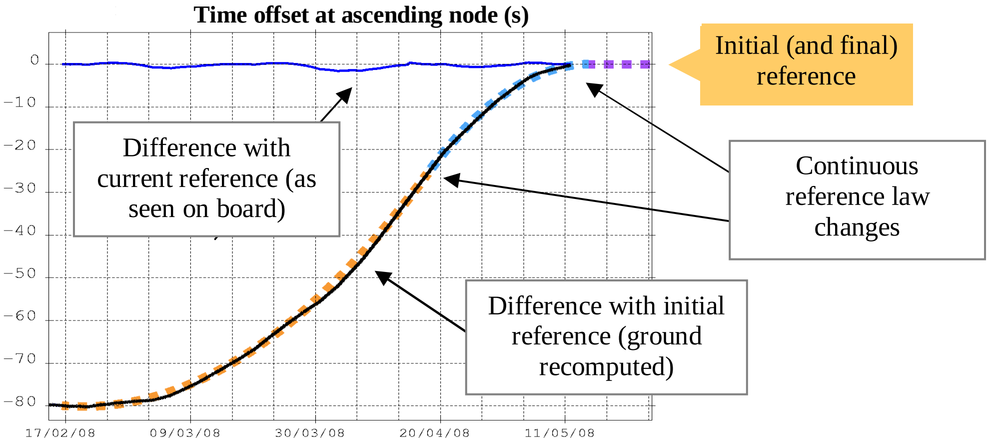

Figure 6: Guided return towards reference position

3.5 Other on-board results

Figure 7 illustrates what happened on the 15th December 2006 (see also ❸ in Figure 4).

- ❶ represents the slope of the curve as derived from the on-board calculated model (red curve),
- ❷ corresponds to what really happened as derived from the instantaneous (once per orbit) data (dotted line).

The difference of slope is similar to the effect of a tangential manoeuvre, except that no manoeuvre occurred. The phenomenon originates in rapid changes in solar and more particularly geomagnetic activity: a powerful solar flare resulted in a magnetic storm and the Ap index going to more than 200. From the change of slope, an equivalent semi-major axis change can be computed: about 11m, which is not insignificant.

The consistency checks performed by the on-board algorithms resulted in the rejection of all the data following the event and the cancellation of subsequent manoeuvre computations. This was unlucky as the AOC was used at this time to ensure no collision risks with the Essaim formation. In fact the model remained valid for about 2 days (see the red curve following the event), after which time no model was considered valid any longer. The AOC software was finally reset (by sending one command only), and the situation became nominal again (❸), except for the degraded control accuracy.

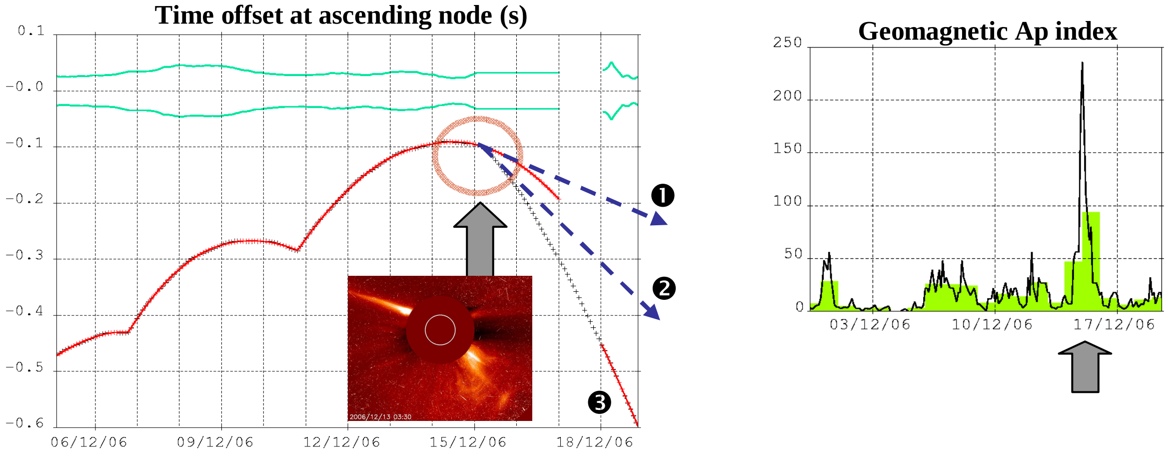

Figure 7: Effect of strong magnetic storm

3.6 What about now?

Autonomous manoeuvres are still being calculated and executed. At the moment, the semi-major axis of Demeter's orbit is forced to increase slowly (at a rate of about 1m/day) in order to adjust the orbit period. The AOC on Demeter is expected to remain active until the end of the scientific mission.

4. FEED-BACK, EXPERIENCE GAINED AND LESSONS LEARNED

4.1 Anomalies detected

Very few anomalies (three) have been detected.

1) Only one (minor) anomaly originated in the manoeuvre computation software. The consequence was that uploaded manoeuvre slots were not always sent back in the telemetry, which made

impossible to check they had been correctly uploaded. But it has been possible to get round this minor problem by removing already present slots before adding new ones.

Two more serious problems were the following:

2) The command generation software erroneously rounded off the first one-pulse manoeuvre duration to 0 before sending it to the GPS receiver (to notify it with this manoeuvre to come). But the “0” value meant an endless thrust to the receiver. This resulted in a divergence of the navigator as the GPS measurements did not match its internal model. The quality indicators transmitted with the position and velocity to the AOC algorithms soon had values above normal, so that the corresponding data were eliminated by the AOC algorithms. This resulted in no AOC models updated and no manoeuvre computed (so the situation was safe). Two days later, the navigator was reset. Without any command sent to the AOC software, manoeuvre calculations resumed immediately as the software had remembered everything (including model data, associated covariance…), which resulted in a manoeuvre successfully executed shortly afterwards.

Thus, this anomaly turned out to be positive as it showed that the AOC algorithms were able to handle this situation securely. The anomaly was corrected by not notifying the GPS receiver of the next manoeuvre to come, which had no impact because of the small manoeuvre amplitudes.

3) A third anomaly was discovered at the beginning of 2009, nearly 4 years after the beginning of the implementation. From February 2009, manoeuvre dates in generated commands were erroneous and were offset by one year. This was due to incorrect handling of non leap years (2009 was considered as one). The situation was corrected by resetting the payload management unit which houses the software.

Thus, the 3 anomalies that occurred could be corrected without any change to the on-board software. None had serious consequences. The only impact was the prevention of the computation or execution of manoeuvres, which resulted in a degradation of the station keeping accuracy, but this was not critical for Demeter.

4.2 Safety aspects

The implementation of AOC has proved very secure. But many precautions had been taken during the design process.

No problem related to propulsion or manoeuvre execution as such ever occurred (but this would have been no different if manoeuvres had been computed in the control centre). In addition, the GPS receiver has behaved perfectly.

One initial fear was that the onboard algorithms might generate manoeuvres without the ground being able to cancel them (in case of up-link loss). This is the reason why an additional platform-dependent security mechanism was added. In reality everything went fine.

The separation between the 2 different onboard tasks: manoeuvre computation on the one hand (for the computation of manoeuvre time and ΔV), and command generation on the other (that also performs additional consistency checks: manoeuvre time close to current time, ΔV less than threshold…) has also contributed to making the AOC secure, all the more so as the different situations that occurred over time proved that everything worked well.

4.3 Software concerns

The algorithms on Demeter are rather complex, although the orbit control principles are not very complex in reality and could be easily simulated using Scilab or Matlab. The complexity can be measured by the number of commands than can be uploaded (32), each one containing several parameters.

One reason for this complexity was the changes that occurred during the design phase. For example, at one point in the development phase, the receiver was supposed to be turned on above the poles and for a few minutes only. The algorithms had to be adapted so that the data could be processed correctly.

Until the very end, changes were made to the software and new features added (but only after a first version gave satisfactory results). The motivation for these changes was to minimise the risks of not being able to run the AOC. Among the last changes made were the addition of an explicit model error on the semi-major axis drift (which proved useful, but which also led to complete rewrite of big chunks of code in charge of filtering), and the addition of checks concerning the evolution model for the mean argument of latitude (which proved unnecessary after all as everything worked fine).

Adding extra features near the end of the development process could have been risky as no software correction was possible after launch. But it could be made secure enough thanks to:

- the structure (and object-like design) of the manoeuvre computation software, made up of many independent parts that exchange information through well defined interfaces,
- the partly generated code of the on-board software and monitoring tools (related to the processing of commands and telemetry), which made changes to the software inputs and outputs easier.

But some features have not (yet) been implemented, except in simulations. Among these:

- the control of the mean semi-major axis (included because it was supposed to be simpler, in case something went wrong with the control of the other parameters).
- the use of instantaneous position and velocity instead of navigator solutions.
- the definition of manoeuvre slots as orbit number and argument of latitude. In practice they have been defined as date intervals as they are easier to define this way.
- the possibility of having more than one internal model update per orbit.

4.4 Flexibility / adaptability

This is the kind of feature that is highly desirable but hard to achieve. In practice it means having sufficient configurable aspects in order to adapt to unexpected situations (but as they are unexpected, it’s difficult to be prepared to cope with them).

In the case of Demeter there are several examples that could be given. Here is one:

From the beginning, it was decided that manoeuvres would occur on Wednesdays and Sundays (in routine mode), and that manoeuvre slots would be one orbit period long (from one ascending node to the next one). All this could have been hard-coded. Instead, defining manoeuvre slots of (possibly) variable length made it possible:

- to add manoeuvre opportunities when required (and this was required when controlling the close approaches with Essaim),
- to adapt to the end-of-2006 changes when manoeuvre slots had to take shadowing constraints into account (which could not have been anticipated before launch).

Without manoeuvre slots, the implementation of AOC would have had to stop at the end of 2005.

4.5 Monitoring

There are 2 aspects related to monitoring worth developing here:

- about the data that are (should) be transmitted to allow for the monitoring,
- about the monitoring activities: what should be done, and how.

In the experiment, lots of data are transmitted to the ground. They consist of:

- GPS and navigator telemetry,
- telemetry related to command generation (so that it is possible to check the on-board generated commands),
- telemetry related to manoeuvre computation, that consists of all the software configuration parameters (including manoeuvre slots…), the main computation results (once per orbit), essential information about each navigation data set (every 30s) and various status indicators that provide information about what is happening on-board.

As a matter of fact it has been chosen to transmit as much information as possible for checking purposes.

Thanks to all these data, it is for instance possible to run the onboard software on the ground in order to check the results obtained on board. And thanks to all this information at hand, all the exceptional situations that occurred could be explained rapidly.

At the beginning of the experiment everything was checked in detail. As confidence in the onboard software was increasing, the monitoring could become lighter and lighter. Thus, routine monitoring now consists in checking a few results from the manoeuvre computation telemetry only, mainly related to:

- the models computed on board (including offsets to the reference parameters) and associated consistency information,
- the (next planned) manoeuvres as computed once per orbit (which gives explanations why manoeuvres may not be needed),
- the manoeuvre slots present on board (in case something suspicious has happened),
- possible errors encountered.

All these data are checked using a few predefined plots, and doing so only takes a few seconds once the telemetry has been decoded and installed where appropriate. There is no need (any longer) to check that on-board calculations are correct. And there is no need (any longer) to evaluate the control accuracy except by checking appropriate data in the telemetry.

After 4 years of implementation, the monitoring of the AOC experiment has proved really secure, even though it is now limited to essential aspects most of the time. In practice the data as listed above are checked once a week on average, sometimes less often. This is made possible because the control centre would be directly informed of any critical situation related to the GPS receiver or to manoeuvre command generation or execution.

4.6 Control algorithms

A certain number of features proved useful and would be needed in some other AOC implementations (provided the algorithms' principles are kept close to what they are on Demeter), particularly:

- checking the navigation confidence data (i.e. the confidence data as estimated by the navigator)
- checking internal consistency between the internal models and the new computed data to be added to them.

Both features have been triggered at some point (see explanations on filter divergence or surge in solar activity in the previous sections) and contributed to inspiring confidence in AOC.

Another aspect that is critical is how the algorithms react to variations of solar and geomagnetic activity. The features that have been designed proved satisfying, although improvements are certainly possible.

4.7 Monitoring tools

The tools used on Demeter proved efficient.

It is difficult to describe what makes tools efficient or convenient, and what makes them well suited to the purpose.

In the experiment, there are various tools written in various languages (Perl, C, Matlab). Perl has been used for the processing of the telemetry coming from the manoeuvre computation software (and also to generate manoeuvre slots operationally on a weekly basis). It has enabled the design of both flexible and reliable tools.

Another aspect is that most tools are used both for simulation and for flight data analysis. As a result, they have been widely used over time. Most tools that process the telemetry (and also the command generation) were themselves partly automatically generated (along with the on-board software), which dramatically limited bug risks.

4.8 Confidence in AOC

All the aspects listed above made the confidence in the AOC increase progressively, until AOC was considered (by the control centre personnel themselves) as a truly operational entity.

Confidence has increased because: very few anomalies have been encountered, everything that happened could be explained easily, AOC has never had any negative impact on the rest of the system, …

All this has resulted in AOC being more operationally useful than was initially envisaged.

5. BEYOND THE EXPERIMENT

The experiment on Demeter has been very successful. But how useful would AOC be for future missions? This part attempts to give guidance to help answer this question.

5.1 When could AOC be useful?

There is (at least) one case when AOC should be considered seriously: when the altitude of the orbit is low and solar activity high, in which case the number of required station keeping manoeuvres may increase beyond what could reasonably be computed by the control centre. At an altitude of 500km, and given strong solar activity, the frequency can easily reach 3 per week (considering standard station keeping requirements). A simulation case performed using the AOC software showed that, under these hypotheses, the along-track accuracy could be kept below 1.5 km with 5 manoeuvres per day.

5.2 Questions about AOC

On Demeter, there is no strict station keeping requirements, and nothing serious normally happens if autonomous manoeuvres stop being executed. It would not be the case in a “real” implementation for which only the reference orbit would (supposedly) be used by the control centre.

Here are examples of the questions that immediately arise, as well as possible answers (which would actually require more detailed analyses):

- Is AOC an option?

One answer is that orbit manoeuvres must be possible, which implies that the satellite must be equipped with a propulsion system (obviously!), and that there exist adequate time slots that enable performing the needed manoeuvres (which may depend on the mission's characteristics). One convenient way is to define manoeuvre slots, but this may imply reserving too many slots. It may also be required that the time needed to perform the manoeuvres (including possibly implied attitude changes) be as short as possible.

- How to make AOC most worthwhile?

By including out-of-plane control so that all the needed manoeuvres are performed on board. And also by a control accuracy as good as possible so that the (3D) reference orbit can effectively be used (and also defined as simply as possible).

- How to make station acquisition secure?

One day or another the satellite may have to transmit data to ground stations. It then means that the acquisition by the ground stations strongly depends on how well AOC behaves. One way to make acquisition (far) less sensitive to along-track errors (and consequently to AOC outages), at least for low Earth orbits, is to have the station wait for the satellite at one fixed point of the orbit.

- What if AOC fails?

One could wonder: can AOC fail? But there exist situations independent of AOC that may prevent manoeuvres from being executed: satellite going to safe mode… In this case backup strategies are needed in order not to lose track of the satellite (see previous point) and to allow for return to nominal mode. A certain flexibility in the definition of the station keeping reference orbits, so that AOC would restart immediately even if the orbit were not exactly the nominal one, would be beneficial.

- What if the satellite needs to perform an avoidance manoeuvre?

If a manoeuvre needs to be performed by the control centre, it certainly means that the mission has to be interrupted. We are then close to the situation described above.

5.3 AOC for future missions: conclusions of an FDIR analysis

Earlier this year, a working group has been set up at CNES to decide about the use of AOC for some future project(s). The group was composed of many specialists from many expertise fields, including operations. Of particular concern was the comparison with more traditional (ground-based) solutions and FDIR aspects in relation to AOC. Even if the experience on Demeter was of course very beneficial to this kind of analysis, the objectives were to cover all aspects from a general point of view: overall system design, operations, on-board architecture, ground segment, FDIR, etc… Here are some of the conclusions that have been drawn and that may be of interest for future projects:

- The concept of a reference orbit to be used throughout the ground segment makes sense, as well as the use of manoeuvre slots in order to define where manoeuvres can be performed. This of course assumes that it is possible to define manoeuvre slots that don't have too much impact on the main mission.
- There are no specific (and critical) failure cases related to AOC.
- AOC monitoring would be implemented in a similar way as for any other on-board sub-system. In particular it is not necessary to do the same computations in the control centre as done on board. For specific purposes (optimisation of the performance, tuning), long-term monitoring capabilities are required.

Even if the conclusions may not be universal as they were drawn within the context of some specific project(s) and with specific constraints and objectives in mind, on the whole, the conclusions tend to be in favour of AOC, which means that AOC was considered secure enough to be envisaged as an alternative solution.

6. BRIEF CONCLUSION

As shown in this paper, the AOC experiment on Demeter has been a success. Having achieved its initial objectives, the experiment has been subsequently implemented far beyond what was initially planned. The conclusion is that AOC is reliable and can be considered in an operational context.

Regarding future missions, AOC may not always be the preferred option depending on specific constraints that may apply. However, situations where AOC seems most useful are when the orbit altitude is low and solar activity high, in which case classical (ground-based) solutions are harder to implement (because of the increased manoeuvre frequency, the increased impact of associated manoeuvre errors, the less accurate orbit predictions and the consequences on ground station pointing, etc…). But even under such severe conditions, a sufficient level of flexibility is necessary in order for the AOC to adapt to the mission's requirements.

In any case, if the conclusions of the CNES working group on AOC are anything to go by, autonomous orbit control is at least one option worth considering.

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