OPTIMISATION OF NS, EW STATION-KEEPING MANOEUVRES FOR GEO SATELLITES USING ELECTRIC PROPULSION (OPASKEP)

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ABSTRACT

Over the last decade, electric propulsion has become a good alternative to traditional chemical satellite propulsion, both for large and small GEO platforms. To take advantage of these new technologies, the existing control laws for the station keeping of GEO satellite shall be revised and adapted to the platform using electric propulsion. In the frame of the ARTES-5 program, OPASKEP tool has been developed. The objective of this work has been the development of an optimisation tool that allows the analysis of new station keeping strategies to be used for the control of the geostationary satellites using electric propulsion. The tool is based on numerical optimisation techniques and uses a thrusters-based model of the satellite to take directly into account the activity of each thruster used for the control of the satellite on the optimisation process.

1. INTRODUCTION

Over the last decade Electric Propulsion (EP) has become a good alternative to traditional chemical satellite propulsion, both for large and small GEO platforms. Two of the most promising technologies are Ion Gridded Engines and Hall Effect Thrusters, due to their high specific impulse compared to chemical thrusters. To take advantage of these new technologies, the existing control laws for the station keeping of GEO satellite, need to be revised and adapted to the platform using electric propulsion.

In the frame of the ARTES-5 program, OPASKEP tool has been developed by GMV with support from SENER and Astos Solutions. The objective of this work has been the development of an optimisation tool that allows the analysis of new station keeping strategies to be used for the control of the GEO satellites equipped with EP thrusters. The typical control laws for GEO chemical satellite are based on the separate control of the in-plane perturbations (eccentricity vector and longitude) and the out-of-plane perturbation (inclination vector). These E/W and N/S control strategies are based on the computation of manoeuvres along a principal direction and the translation of these control law on thrusters activation.

The current design and the technologies used for GEO satellite with electric propulsion typically provide a thrusters lay-out very different to the chemical ones. All the thrusters can have a significant component of the thrust vector in more than one direction, so the control shall be considered as a complete problem and cannot be split into out-of-plane and in-plane control.

The tool developed in the frame of this project is based on numerical optimisation techniques and uses a thrusters-based model of the satellite to take directly into account the activity of each thruster used for the control of the satellite on the optimisation process. This paper presents the tool design and the main principle of the optimisation algorithm. Usually, control strategies consider satellites as a point. The present work includes the mathematical definition and the satellite model that allow considering it as a system. The results of some simulations and their practical applications are presented. Finally, the new steps required for the transition to operational control tools are described.

2. TOOL FUNCTIONALITIES

OPASKEP tool is design to cope with the different operational scenarios that a geostationary satellite will found over its lifetime; from the station acquisition manoeuvres through the nominal Station Keeping (SK) manoeuvres to the manoeuvres transferring the satellite to its graveyard orbit as well as the repositioning manoeuvres if required.

From the operational point of view, the objective of this optimisation is the minimization of the propellant mass consumption under a given set of constraints, which can be orbital, attitude or power constrains. Furthermore, a set of additional cost functions permits to analyse the sensitivity of the propellant mass consumption related to multiple parameters. These cost functions are described in more detail in the section 7.

In addition to optimising the SpaceCraft (S/C) manoeuvres, the tool also permits the optimisation of the EP thruster layout (thruster position and orientation).

This functionality is particularly interesting when the orbit and attitude controls are combined to reduce the reaction wheel unloading manoeuvres propellant mass consumption.
OPASKEP, being a multi-satellite tool, supports the analysis of collocation problems. It permits, for example, the optimisation of the station keeping manoeuvres of a cluster of satellites taking into account minimum inter-satellite distance and/or radio frequency interference constraints.
The tool includes a Monte-Carlo analysis mode, which permits to simulate the optimised manoeuvres taking into account navigation inaccuracies, thrust level error and thrust pointing error.
In addition, OPASKEP tool permits to estimate the S/C mass at the beginning of the nominal station keeping phase by estimating the delta-V required by a GTO-GEO transfer using chemical or electric propulsion. The chemical transfer supports the subsynchronous and the supersynchronous transfer strategies. The electric transfer is based on the Pollard model [1].

3. TOOL DESIGN

OPASKEP tool is based on the COTS software General Environment for Simulation and Optimisation (GESOP [2]), an Astos Solutions products that has been developed for the European Space Agency, which provides the optimisation, simulation and plotting environment. OPASKEP can be run as a plug-in of GESOP or as a stand-alone application. In this last case, the use of GESOP is transparent for the user.

Fig. 1 depicts the general structure of the OPASKEP software design.

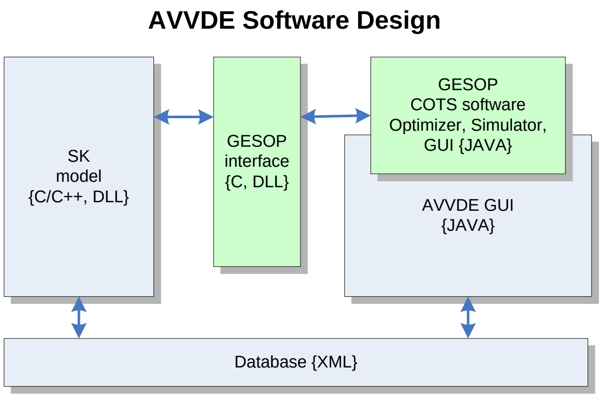

Figure 1. OPASKEP Software Design

The SK-Model provides the complete model for station keeping simulations, coded in C/C++. It is linked to the model interface of the GESOP software as a dynamic link library (DLL) under Windows or shared libraries under Linux and MAC OS platforms, which are the three platforms supported by the tool. It contains an initialization part and an evaluation part in which a loop over the simulation time is executed. The initialization part reads the SK-scenario defined by the user via the OPASKEP Graphical User Interface (GUI) and defines from this information all the states and control variables as well as the constraints and cost functions. The evaluation part is composed by a set of routines which are called by the integration step of GESOP to evaluate:

- the state vector derivatives (equations of motions);
- the control laws;
- the constraints;
- the cost function.

The GESOP components are interfacing with the OPASKEP specific modules, which are focusing only on the modelling of a station keeping simulation environment, but not on numerical functionalities, which are completely included inside GESOP.
By means of the OPASKEP GUI, the user may define the SK-Scenario, make modifications of optimisation and simulation settings, run any basic operations like initialization including initial guess computation, simulation, optimisation and Monte Carlo analysis and review numerical and graphical results. This component is coded in JAVA in order to reuse available packages of the GESOP GUI, like the whole plotting functionality.
All the relevant information required for the data driven initialization of the SK-Model is written in the SK-scenario file. This file provides information about the satellite platform, the propulsion system and the orbital environment, in a XML format. Settings related to the configuration of GESOP are written into a specific file called TOPS file, which is a JAVA data stream binary. Besides the GESOP configuration, it contains current values and bounds of all optimisable parameters and controls, a list of active constraints, the model description and the return code of the last optimisation or simulation. The simulation results are also written in a JAVA data stream binary file, called STRUCT file. This file is created by GESOP and is read by the OPASKEP GUI for plotting purposes. User actions like optimise or simulate or Monte Carlo analysis are invoked via the GUI. These commands are forwarded to GESOP using a command line interface.

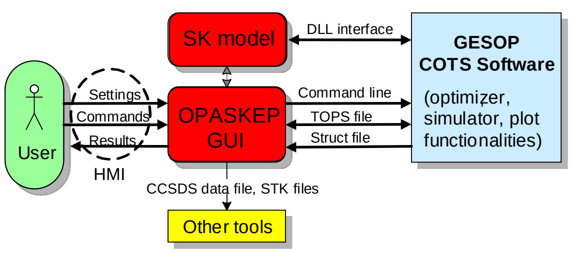

Figure 2. OPASKEP Tool Interfaces

4. SATELLITE MODEL

The current design and the technologies used for GEO satellite with electric propulsion typically provide a thrusters lay-out very different to the chemical ones. All the thrusters can have a significant component of the thrust vector in more than one direction, so the control shall be considered as a complete problem and cannot be split into out-of-plane and in-plane control. This implies a complete definition of the S/C thruster configuration.

Therefore, the satellite is defined in OPASKEP tool by its general characteristics (S/C mass, etc.) but also by its thruster configuration, its attitude control system in order to analyse the possibility of combining orbit and attitude control as well as its power system.

The S/C thruster configuration is defined in a generic way. Each thruster mounted on the satellite is defined by the following properties:

- specific impulse;
- thrust level;
- thruster orientation (cant and slew angles);
- thruster position;
- power consumption;
- plume impingement effect: constant force and torque contributions due to fixed appendages and variable contributions as a function of the solar array position;
- range on thruster position;
- range on thruster orientation;

These two last parameters permit to optimise the thruster layout.

The S/C attitude is represented by its angular momentum vector components. Its reaction wheel system configuration may also be defined by setting for each reaction wheel their orientation, their inertia, their angular velocity range and their initial velocity.

The S/C power system is defined by the solar array configuration and characteristics, the platform and payload power consumption and the batteries characteristics.

5. OPTIMISATION PROBLEM

5.1. Optimisation Problem Formulation

OPASKEP tool is based on numerical optimisation techniques. The control problem, for which an optimal solution is searched, is defined by

- an objective function J

  $$\min J(\vec{x},\vec{u},\vec{p},t) = \phi(\vec{x}_f,\vec{p},t_f) \qquad (1)$$

- the independent variable t, which represents the simulation time
- the state vector $\vec{x}$, which has the dynamics

  $$\dot{\vec{x}} = f(\vec{x}(t),\vec{u}(t),\vec{p},t) \quad t_0 \le t \le t_f \qquad (2)$$

  This state vector is composed by the S/C equinoctial elements, the S/C angular momentum vector components and the amount of energy stored in the batteries. The time span [t_0; t_f] represents the simulation time span. The dynamic model is detailed in the section 6.
- $\vec{u}(t)$ is the time-variant control vector. The control laws to be optimised correspond to the acceleration profile of each S/C thruster.
- $\vec{p}$ are time-invariant parameters, which describe some system properties. Their values are optimisable, but do not change over time. The content of this vector depends on the SK scenario and on the cost function selected. Potential parameters can be, for example, thruster orientation, thruster position or SK deadbands.
- Path constraints

  $$g(\vec{x},\vec{u},t) \ge 0 \qquad (3)$$

- Final boundary constraints

  $$\psi(\vec{x}(t_f),t_f) \ge 0 \qquad (4)$$

- No initial boundary constraint is required in the SK problem.

5.2. Optimisation Method

The optimal control problem is solved by the GESOP optimisation software. As the optimisation problem is defined in a generic way, it could be solved by any optimisation method available in GESOP. Nevertheless, the performances of the different methods depend on the problem type and size. Therefore, a preliminary phase of this project has been devoted to the analysis of the different optimisation method performances and the most suitable method has been selected.

The method selected is the Collocation and Multiple Shooting Trajectory Optimisation Software (CAMTOS [3]) with SNOPT as nonlinear programming (NLP) solver. This method permits to combine direct multiple shooting and direct collocation methods to discretize the optimal control problem and transforms it to a nonlinear parameter optimisation problem. In this project, only the direct multiple shooting method is used to discretize the optimal control problem. The state of the art of the NLP solver permits to solve optimisation problems containing tens of thousands of optimisable parameters and constraints, which permits to optimise SK manoeuvres over a nearly half a year period. The main challenge is the definition of the problem in an appropriate way to minimise the CPU and memory used. For that purpose, a trade-off shall be performed between

- the minimum simulation period required to obtain representative results;
- the maximum time step that can be used to define the path constraint nodes in order to obtain a correct fulfilment of the path constraints;
- the maximum time step that can be used to obtain an accurate optimal control.

By default, the typical approach for solving an optimisation problem is to define equidistant control nodes from a user time step. This definition presents the disadvantage of defining a lot of useless control nodes. The control nodes located inside the time spans in which no manoeuvre can be performed are useless as the control values at these nodes are already determined (null value). In the same way, the optimality of North/South manoeuvres decrease with the extension of these manoeuvres around descending/ascending nodes. As South manoeuvre are optimal around the ascending nodes, the control nodes associated to these manoeuvres can be removed at least from 6 hours before the descending nodes to 6 hours after the descending modes (South manoeuvres performed around descending nodes would increase the inclination instead of reducing it). In the same way, the control nodes associated with the North manoeuvres can be removed from 6 hours before to 6 hours after the ascending nodes. This permits to divide by two the number of control nodes and thus the memory required. For that purpose, a functionality permitting specific control grid generation has been implemented in OPASKEP tool. This functionality is based on the concentration of the control nodes around initial guess manoeuvres, which can be provided by an external manoeuvre file or computed internally by the tool.

6. DYNAMIC MODEL FORMULATION

The mathematical formulation used to model the satellite dynamics can be split into four different parts: the orbital dynamics, the S/C mass evolution, the attitude dynamics and the power management.

6.1. Orbit Control

The equations of motions defined in the SK model are based on the integration of the classical non-singular equinoctial parameters, defined as

$$\begin{cases} a \\ e_x = e\cos(\omega+\Omega) \\ e_y = e\sin(\omega+\Omega) \\ h_x = \tan(i/2)\cos\Omega \\ h_y = \tan(i/2)\sin\Omega \\ \lambda = \Omega+\omega+\nu-GMSA(t) \end{cases} \quad (5)$$

where a is the semi-major axis, (e_x, e_y) are the coordinates of the eccentricity vector, e is the orbit eccentricity, ω is the argument of perigee, Ω is the right ascension of the ascending node, (i_x, i_y) are the coordinates of the inclination vector, i is the orbit inclination, λ is the true longitude, υ is the true anomaly, GMSA(t) is the Greenwich Mean Sidereal Angle at the epoch t.

The dynamic of a geostationary satellite is well known. The satellite state vector, position and velocity, will evolve under the effect of the attraction of the Earth as a point mass plus the effect of other perturbations. The perturbations considered are

- the non-spherical Earth gravity field;
- the Sun and Moon gravitational fields;
- the solar radiation pressure;
- the station keeping manoeuvres;
- the plume impingement effect.

6.2. S/C Mass Evolution

The main objective function of this optimisation problem consists in minimizing the fuel mass consumption. Indeed, a diminution of the propellant consumption permits to reduce the launch cost, to increase the payload mass, to increase the satellite lifetime or any combination of the above possibilities. Thus, the satellite mass will be a part of the dynamic model.

$$\frac{d\,m(t)}{dt} = \sum_{k=1}^{N} \frac{u_k(t)\,m(t)}{Isp_k\,g_0} \quad (6)$$

where m(t) is the S/C mass at the epoch t, N is the number of thrusters mounted on the satellite, u_k is the acceleration of the thruster k at the epoch t, Isp_k is the specific impulse of the thruster k, g_0 is the gravitational acceleration at earth's surface.

The thruster accelerations are defined as control laws in the optimisation problems. These control variables can thus take at any time any value comprised between zero and the maximum thruster acceleration, which can be computed from the thruster thust level (F_k), the S/C mass (m), the thruster cant (γ_k) and slew (σ_k) angles.

$$\vec{u}_k = \frac{F_k}{m}\begin{bmatrix} \sin\gamma_k\cos\sigma_k \\ -\sin\gamma_k\sin\sigma_k \\ -\cos\gamma_k \end{bmatrix} \quad (7)$$

6.3. Attitude Model

The S/C attitude dynamic is introduced in the state vector by the components of the total angular momentum vector in inertial frame. The attitude model implemented is a simplified model assuming that the S/C perfectly points to the Earth at any moment and that the satellite inertia tensor can be reduced to the principal moment of inertia values. This simplified model is sufficient to estimate the evolution of the total angular momentum vector and the reaction wheel angular velocities.

The total angular momentum vector in inertial frame $\vec{h}$ can be obtained by integrating the sum of all the disturbance torques $\vec{T}$.

$$\frac{d\,\vec{h}(t)}{dt} = \sum \vec{T}_{Disturbance} \quad (8)$$

The disturbance torques considered are

- solar radiation pressure disturbance torque;
- magnetic torque due to the S/C interaction with the local Earth magnetic field;
- gradient gravity torque;
- RF emission torque;
- SK manoeuvres torque (due to the thruster

positions and orientations with respect to the S/C centre of mass) and due to the plume impingement effect.

The total angular momentum vector is composed by the satellite angular momentum vector and the angular momentum vector associated with the reaction wheels. The angular velocity of each reaction wheel can thus be deduced from this last vector.

6.4. Power Management

The power system is introduced in the state vector by the amount of energy stored in the batteries at a given epoch.

At a given epoch, the power margin without taking into account the energy stored in the batteries is given by the difference between the power generated by the solar arrays P_{SA} and the power consumed by the active thrusters P_{th}, by the S/C payload P_{PL} and the S/C platform $P_{S/C}$. These two last consumptions are assumed constant.

$$P(t) = P_{SA}(t) - P_{th}(t) - P_{PL} - P_{SC} \qquad (9)$$

The variation of the amount of energy stored in the batteries (E_{batt}) depends on the current power margin (P), the maximum amount of energy storable in the batteries (E_{batt}^{max}) and the minimum power needed to charge the batteries (P_{ch}).

$$\frac{dE_{batt}}{dt} = \begin{cases} 0 & if \quad E_{batt} \geq E_{batt}^{max} \\ P & if \quad P < 0 \\ P_{ch} & if \quad P > 0 \quad and \quad P > P_{ch} \end{cases} \qquad (10)$$

7. COST FUNCTIONS

From the operational point of view, the main cost function to minimize is typically the propellant mass consumption as a reduction of the propellant mass consumption permits to increase the satellite lifetime and/or increase the S/C payload and/or reduce the launch cost. Nevertheless, it could be very useful to have additional cost functions to refine the control strategy once a “minimum fuel” has been reached. These additional cost functions should be combined with a “maximum fuel consumption” constraint to analyse the possibility to optimise some parameters assuming a certain propellant mass over-cost.

The cost functions available in OPASKEP tool are

- Minimization of the propellant mass consumption;
- Minimization of the inclination control circle radius;
- Minimization of the eccentricity control circle radius;
- Minimization of the latitude deadband;
- Minimization of the longitude deadband;
- Minimization of the thrust acceleration needed;
- Minimization of the maximum S/C angular momentum vector magnitude value;
- Maximization of the minimum inter-satellite distance value;
- Minimization of the transfer duration (basically applicable to station acquisition and repositioning phases);
- Minimization of the distance to target orbit (transfer phases);

8. CONSTRAINTS

The constraints available in the tool can be divided into two different categories: constraints applicable to all scenarios and constraints only applicable to a specific scenario.

8.1. General constraints

The constraints applicable to any scenario are

- Eclipse constraint: manoeuvres should be avoided in eclipse periods;
- Orbit determination: manoeuvres should be avoided during some periods in order to perform orbit determination;
- Colinearity Angle (CA): depending on the satellite platform, it can be prohibited to perform manoeuvres when the angle between the sun and Earth vectors, as seen from the spacecraft is smaller than a certain threshold.
- Power management: The energy stored in the batteries energy shall be higher than a given minimum.
- Attitude management: A maximum allowed S/C angular momentum vector magnitude or a constraint on the reaction wheel angular velocities can be imposed to the solution.
- Minimum allowed satellite mass: This constraint permits to define a maximum allowed propellant mass consumption. It is very useful in case of optimising a cost function different than the minimum propellant mass consumption to set a maximum propellant mass consumption overcost.

The constraints defining time spans over which no manoeuvre can be performed directly apply on the control variables. Over these time spans, the thruster nominal, lower and upper bounds acceleration values are set to zero. All the other constraints are defined as inequality path constraints.

8.2. Station keeping constraints

The main constraints applicable only to the station keeping scenarios are the control box deadbands (inclination and eccentricity control circles, latitude and longitude deadbands). They are inequality path constraints as the satellite has to remain in its SK box over its entire operational lifetime.

In case of collocation, additional path constraints may be taken into account to assure a minimum inter-satellite distance and to avoid radio frequency interferences.

8.3. Station Acquisition and repositioning constraints

Specific station acquisition and station repositioning constraints are:
- Maximum time of transfer;
- On-station control box: At the end of the transfer phase, the satellite shall be located inside its SK box (final boundary constraint).
- Avoidance of other GEO satellite boxes: The control boxes of other satellites located in the transfer path have to be avoided.
- Time span in which no manoeuvre can be performed due to operational constraint (final Earth acquisition during the station acquisition phase, etc).
- If the satellite shares its station keeping box with other satellites, a minimum inter-satellite distance constraint shall be defined to assure that no collision will occur during the satellite insertion/extraction in/from the cluster.

8.4. Disposal constraints

The constraints applicable to this scenario are
- avoidance of other GEO boxes ;
- safe satellite extraction from the cluster in case of collocation;
- reach of the target graveyard orbit.

The two first constraints are inequality path constraints and the last one is a final boundary constraint.

9. SIMULATIONS

Two specific missions have been analysed with this tool: Orbital Life Extension Vehicle (OLEV) [4] and SmallGEO [5]. The OLEV satellite is a life extension spacecraft, which will be attached to an existing “client” satellite to extend its operation for a longer time in case of nominal end of life or in case of some technical problem. The Small GEO programme is aimed at the development of a small, general-purpose geostationary satellite platform, which will enable European industry to compete effectively in the commercial telecom market for small platforms.

For both satellites, the impact of a set of parameters have been analysed, such as the epoch of the year, the simulation year, the S/C mass and the integration of orbit and attitude control on their nominal optimal station keeping strategies. The results of some of these scenarios are presented in this section showing the main conclusions and the practical applications of these results.

9.1. OLEV nominal orbit control

Several scenarios varying the client S/C mass, the station longitude and the simulation year have been optimised by OPASKEP tool and compared to the OLEV nominal control strategy. OPASKEP tool demonstrated that is capable to optimise and reduce the propellant mass consumption from 8% to 17% depending on the scenario. The solutions provided should be refined to be usable in operation because in some cases the inclination daily manoeuvres are split into several manoeuvres, which can increase too much the number of EP cycles and in some other cases, the manoeuvres are not using the maximum thruster acceleration. The modelling and the optimisation grid used can be tuned to get better results. The main challenge is the definition of the problem in an appropriate way to minimise the CPU and memory used. Nevertheless, the general conclusions are fully applicable independently of this behaviour.

9.2. OLEV thruster layout optimisation

OLEV EP thrusters are mounted on Thruster Orientation Mechanisms (TOM), which permit to orient the thrusters in such a way that the thrust directions pass through the mated centre of mass when OLEV is attached to a client in order not to generate any disturbance torque. The degrees of freedom allowed by the TOMs have been introduced in OPASKEP tool by defining a margin on the thruster cant and slew angles. The introduction of these degrees of freedom permits to considerably reduce the propellant mass consumption. More than a 20% of fuel saving is obtained.

Nevertheless, if the cant and slew angles are freely optimised without setting any constraint between them, the thrust directions will not pass anymore by the mated centre of mass and will thus generate disturbance torque. Hence, the fuel saving will be partly compensated by the increase of Reaction Wheel (RW) unloading manoeuvres due to the generation of additional disturbance torques.

Fig. 3 compares the evolution of the S/C angular momentum vector magnitude obtained
- in the nominal optimal strategy in which the tool only optimise the thruster acceleration profiles (blue curve);
- when the tool optimises the thruster acceleration profiles and the thruster orientation (black curve).

Without optimising the thruster layout, the magnitude of the S/C angular momentum vector is about 200 Nm after 3 months of SK; whereas it reaches 1000 Nm in case of thruster layout optimisation.

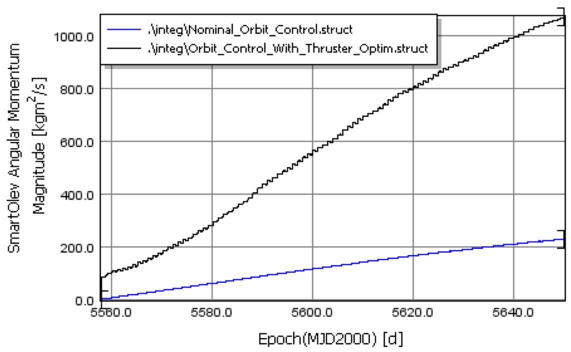

Figure 3. Impact of thruster orientation optimisation on angular momentum vector magnitude

9.3. OLEV integrated orbit and attitude control

One of the main concerns of satellite operator is to try to find some kind of synergy between orbit and attitude control. In the classical satellite architecture with chemical thruster an important amount of fuel is spent on attitude control, basically when reaction wheels are unloaded. This project has shown, in the case of electric propulsion satellite, that there is an advantage to consider both problems together. The main withdrawn of this approach is the need to increase the complexity of the control software to consider a satellite model with thruster and reaction wheel also as part of the orbit control problem, rather than considering the satellite as a punctual mass for orbit control.
In the OLEV mated configuration, OPASKEP tool demonstrated the possibility of using EP depointing strategy to generate some torques which permits to remove reaction wheel unloading manoeuvres. The solution consists of optimising the thruster orientations in addition to the thruster acceleration profiles as presented in the previous section but setting a constraint on the maximum allowed S/C angular momentum vector magnitude. Fig. 4 demonstrates that OPASKEP tool is able to optimise the design parameters and the control strategy to fulfil the maximum allowed S/C angular momentum vector magnitude of 20 Nm. This illustrates the possibility of combining orbit and attitude controls to avoid RW unloading manoeuvres.

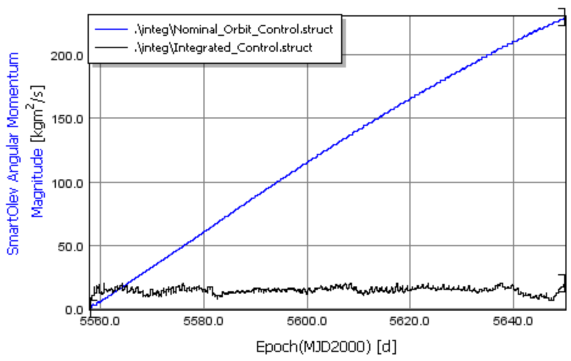

Figure 4. Constraint on S/C angular momentum vector magnitude

The propellant mass consumptions obtained for a 2300 kg S/C client are reported in the Tab. 1. It is interesting to note that in this scenario the orbit and attitude controls integration do not increase the propellant mass consumption with respect to the nominal orbit control in which the thruster layout is not optimised.

Table 1. Impact of orbit and attitude control integration on propellant mass consumption

	Propellant mass consumption (kg)
Nominal orbit control	2.104
Orbit control with thruster layout optimisation	2.024
Combined orbit and attitude control (Max. S/C angular momentum vector of 20 Nm)	2.070

9.4. Collocation

OPASKEP tool permits to optimise the SK manoeuvres of several satellites to get minimum propellant mass consumption while fulfilling collocation specific constraint such as minimum inter-satellite distance.
Several scenarios based on the collocation of two SmallGEO satellites have been run to analyse the impact of the minimum inter-satellite distance constraint on the control strategies and on the propellant mass consumption. The collocation method selected is the eccentricity-inclination separation method [6].
In absence of inter-satellite distance constraint, as expected the satellites, having the same characteristics, are controlled with similar control strategies. Fig. 5 shows the longitude evolution of both satellites.

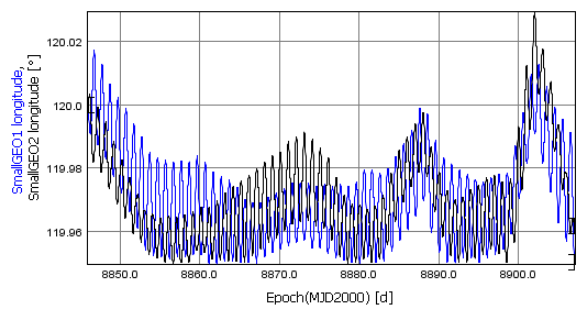

Figure 5. Longitude evolution in absence of inter-satellite distance constraint

The definition of specific inclination and eccentricity control circles for each satellite assures a minimum inter-satellite distance. Nevertheless, it could be interesting to define a more restrictive minimum inter-satellite constraint in order to determine how the control strategies can be modified, without modifying the collocation parameters, to increase the minimum inter-satellite distance and thus reduce the collision risk. A trade-off shall then be performed between the decrease of the collision risk and the propellant mass overconsumption due to the increase of the minimum inter-satellite distance value.

Fig. 6 illustrates the change in the longitude evolution due to the introduction of a 15 km minimum inter-satellite distance.

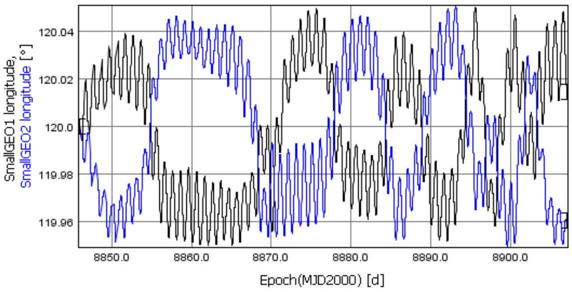

Figure 6. Longitude evolution with a 15 km minimum inter -satellite distance constraint

Table 2. Impact of inter-satellite distance constraint on propellant mass consumption over 2 months of SK

Minimum inter-satellite distance (km)	Propellant mass consumption (kg)
0 km (no constraint)	1.544
10 km	1.570
15 km	1.587
20 km	1.615

The main drawback on the collocation problem is that the increase of the optimisation problem is not linear with the number of satellites but quadratic. This imposes a major constraint for this type of scenarios. In any case, this problem is more linked to the sparsity management problem on the NLP solver than to the optimisation problem itself.

10. CONCLUSIONS

The simulation results assess the capability of using optimisation techniques based on NLP solver to optimise all the kinds of manoeuvres that a geostationary satellite shall perform over its lifetime. The state of the art of the NLP solver permits to solve optimisation problems containing tens of thousands of optimisable parameters and constraints which permits to optimise SK manoeuvres over a nearly half a year period.

The possibility of optimising very different cost functions and constraints has been demonstrated.

It has been also concluded that the use of this kind of optimisation techniques are not only useful for satellite control but also for satellite design. The tool is able to benefit from the design parameters optimisation such as thruster positions and orientations to reduce the amount of propellant required by the orbit control and/or to combine orbit and attitude controls.

11. FUTURE ENHANCEMENTS

Some of the limits found on the optimisation problems defined during the project development were related to the limitation of the current NLP solver to manage problem that requires a significant amount of memory or CPU time. The current NLP solver permits to optimise SK manoeuvres over several months, and that duration is expected to increase furthermore in the future. That could be made feasible by improving the NLP solver so that it can take advantage of the sparsity of the problem and can provide a more stable behaviour on the computation of gradient and hessian matrices.

Concerning the transition from the current status to operational software and the integration on the current or future development of ground segment, two different approach can be foreseen, the first one is the use of this kind of techniques directly on operations, but the stability and robustness shall be improved to an operational level, the second one is that the conclusions of these analyses shall be used to develop new control software applying the main conclusions as for example the integration of the orbit and attitude control on the same framework.

The development of this technology to higher level on the Technology Readiness Level (TRL) scale will require the development of specific control software, based on the operational requirements, and using ad-hoc development for this purpose. This software should be compatible with the operational loop and should include the integration of attitude and orbit control, the use of specific tools and libraries but without the dependencies of general scientific software, and the definition of a close-loop strategy that can tackle with contingency operations.

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