STENTOR STATIONKEEPING STRATEGY

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ABSTRACT *– The STENTOR satellite is an experimental spacecraft which will be used to demonstrate new technologies in geostationary orbit. It will use plasmic propulsion for its station keeping. This implies station keeping cycles and orbit control laws quite different from the classical ones.*

In addition, the goal for this kind of satellite is to be autonomous over a few weeks. Thus the planned station keeping maneuvers will be stored on board and executed without any ground updating.

This paper will describe how these station keeping strategies have been designed. Then, the principle results of the mission analysis of the Stentor satellite will be presented.

CONTEXT

Geostationary satellite stationkeeping consists in performing orbital correction manoeuvres to remain within a longitude and inclination window. Different types of manoeuvres are used each of which has a different effect on one or more orbit parameters.

The stationkeeping strategy organizes these manoeuvres into cycles over time i.e. in sequences of manoeuvres repeated throughout satellite life. In order to do this, it takes several criteria into account such as minimised consumption, resistance to different constraints and dispersions. This correction strategy may be very different depending on satellite characteristics (e.g. the type and orientation of onboard thrusters) and integrates miscellaneous satellite- or mission-related constraints.

The CNES SG department is responsible for the positioning and stationkeeping of geostationary satellites. For stationkeeping, it performs orbit control mission analyses and supplies the means for operationally calculating the necessary manoeuvres.

To this end, several Fortran applications are used, but they are constantly being modified to take the specificities of the different satellites or missions into account.

To limit the efforts for customising these applications, the department has conducted a study aimed at developing a generic toolbox for the easy production of geostationary satellite stationkeeping strategy simulators.

This study and the results are the subject of this article in which the main caracteristics of this toolbox (library bibSMAP) and an application on Stentor station keeping phase are presented.

STATIONKEEPING LIBRARY ARCHITECTURE

Design

The analysis phase was used to exhibit three-level architecture:

the first level groups all objects in the field: among these we can find all the components used to represent a geostationary satellite and its geostationary orbit (satellite, tanks, types of thrusters, attitude, orbit bulletin, satellite and mission constraints, etc.);

the second level defines the objects specific to the field of stationkeeping: we can find the components used to specify the stationkeeping strategies (strategy, manœuvre patterns, manoeuvres, types of manoeuvres, control laws, station windows, orbit determination periods);

and the last groups the objects implementing the simulation of stationkeeping strategies: manoeuvre simulators, orbit extrapolators, stationkeeping strategy simulators.

This three-level architecture is used in this way to identify conventional "Data", "Skill" and "User" services respectively.

Then the library has been designed using the objet oriented method UML (see [1] and [2]).

The following packets were used to logically group the identified classes:

- Stationkeeping satellites and orbits: this packet groups all the classes used to model a satellite and its stationkeeping orbit.
- Basic patterns: this packet is used to model manoeuvre patterns which are repetitive sequences of typed manoeuvres, spaced by random drift periods.
- Types of Manoeuvres: this packet is used to model types of manoeuvres covering the notions of thruster type, thrust characteristics, associated constraints.
- Stationkeeping strategies**:** this packet groups the classes used to model a stationkeeping strategy. This represents a global pattern application strategy throughout the simulation period. It is defined by an ordered list of patterns with which conditions of application are associated. The pattern applicable to a given date represents the first pattern in the list whose pre-requisites are met.
- Skill tools**:** this packet groups the skill components among which we can find **the control law modules** activated to calculate (date and amplitude) each pattern manoeuvre, according to specific control laws. We can also find orbit extrapolators, manoeuvre simulators (pulse, pseudo-pulse) and lastly, the different types of error models on different parameters.
- Stationkeeping strategy simulation: supervisor packet grouping the classes modelling the simulation of stationkeeping strategies. The main services provided are the initialisation of a stationkeeping strategy simulation session, pattern simulation, satellite evolution, orbit update planning, DV control laws and manoeuvre simulator activation.
- Constraint forecast: this packet groups the classes used to develop satellite constraint forecast applications (eclipses, sensor visibilities and glare, Earth-satellite-Sun alignment)
- Utilities: this packet groups all the required utility classes.

Remark: The Stationkeeping strategy simulation packet has the particularity of providing the generic operation of stationkeeping operation based on the others while the "skill tools" packet in this way defines a generic framework for all calculation modules, orbit extrapolators and manoeuvre simulators represented by abstract classes.

This organisation is used to facilitate the extensibility of the components library by allowing the specialisation of these generic tools without upgrading the other so-called generic components.

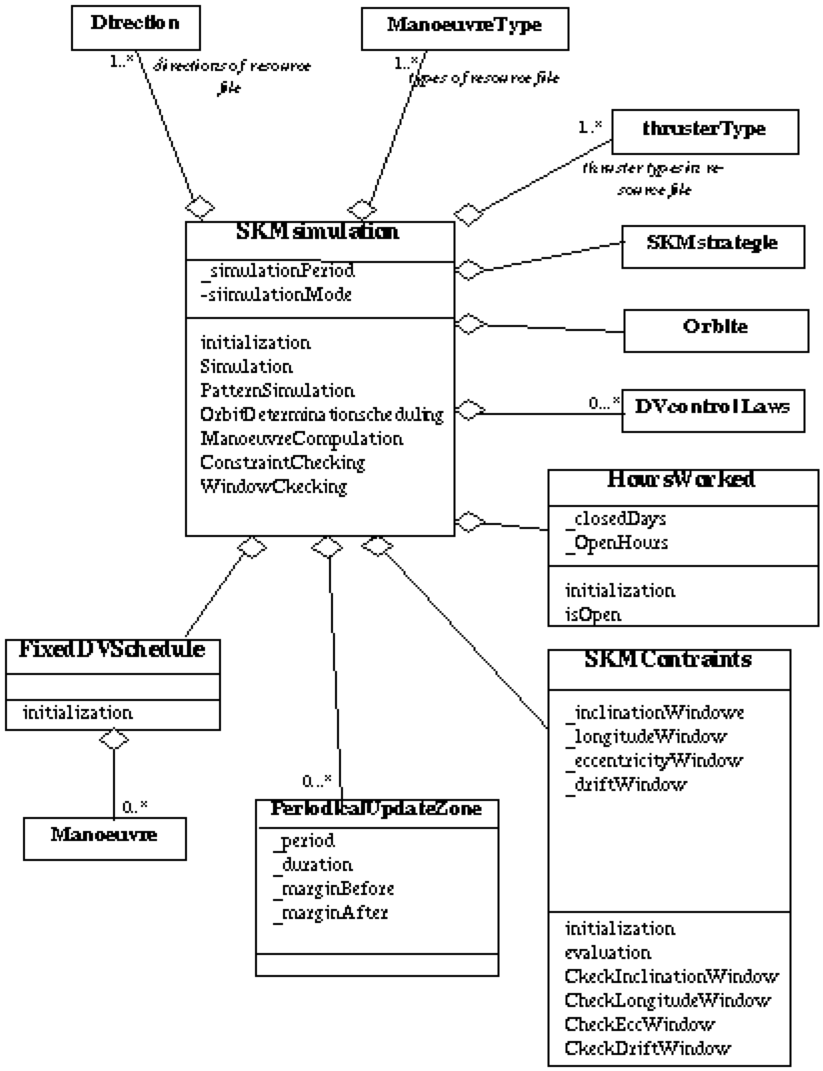

Fig 1. "Stationkeeping strategy simulator" packet

Operating principle

Stationkeeping strategy simulation

To explain the operating principle, we will describe the main component implementing the simulation of stationkeeping strategies.

The generic components library for the simulation of stationkeeping strategies is assimilated to a system whose main mission is to simulate the strategy for geostationary satellite stationkeeping under constraints. In reality, this library supplies the generic components for setting up such a system.

The general operation of the stationkeeping strategy simulator is based on the possibility of defining one stationkeeping strategy per parameter setting. Two operating modes are possible: *mission analysis* (where errors on different parameters are simulated) and *operations*(without error).

The general principle of the stationkeeping strategy simulator is as follows:

- Software initialisation aimed at integrating the parametering file(s)

- Initialisation of input data:
    - mode, simulation session
    - the initial satellite (orbit, tanks and masses, panels, attitude, orbit and attitude errors)
    - the station window (parameters concerned, thresholds)
    - propulsion systems and types of manoeuvres, associated constraints and errors
    - kinds of manoeuvres and associated precompensations,
    - the stationkeeping strategy: the list of patterns and associated conditions, the manoeuvres and groups of manoeuvres of each pattern, the control laws associated with the manoeuvres, the possible orbit updating zones on each pattern,
    - satellite constraints, mission constraints,
    - the fixed manoeuvre schedule (fixed manoeuvres to be inserted in the planning)
- Static control of correct parametering (pattern coherence, fixed manoeuvres and constraints)
- If an entry point is defined, it is simulated (associated with an imposed departure pattern)
- Then, up to the end of the simulation period:
    - select the pattern to be simulated on the current date according to the definition of the stationkeeping strategy,
    - simulate the pattern throughout the period corresponding to the duration of the pattern while taking elements outside the pattern into account (schedule of fixed manoeuvres),
    - generate output files.

Remark: if a failure is detected during the pattern simulation (non compliance with window, constraints not verified, control laws objective not reached), the pattern is rejected, and we then go on to select another pattern from the stationkeeping strategy list.

The advantage of this generic operation lies in the fact that the stationkeeping strategy simulator simulates a strategy supplied on input. The latter is defined by a text file in a highly specific format easily generated by users expert in the stationkeeping field.

Pattern simulation

The manœuvre pattern simulation principle over a given period is relatively simple:

the satellite evolves during free motion periods (between two pattern manoeuvres): orbit extrapolation, mass evolution and if any, simulation of fixed manoeuvre schedule. If necessary, an orbit update point is scheduled and orbit errors are then managed. Lastly, compliance with the stationkeeping window specified on input is checked.

for each pattern manoeuvre, call up the associated control law module to calculate the manoeuvre and verify the other associated constraints.

Manoeuvres are then simulated with the simulation model associated with the type of manoeuvre taking performance errors into account.

Calculation of a manœuvre pattern

A manoeuvre is calculated by a control law module. Here we will specify a few notions before describing the general principle.

- *Type of manoeuvre*: the types of manoeuvre are partitioned into *kinds of manoeuvre*. For example, the manœuvre kind *"inclination correction"* groups *North* and *South* types of manœuvre.

- *Pre-compensation*: used for a manoeuvre of a given kind, to define the list of manoeuvres designated by their kind, for which it must pre-compensate the effect. For example, tangential effect of North/South manœuvre are pre-compensated by the East/West manœuvres.
- *Group of manoeuvres*: some manoeuvres of a pattern can be grouped as they participate in the same orbit correction objective, they are then calculated simultaneously.
- *Control horizon*: this is the calculation horizon associated with the control law governing a manoeuvre (or its group), this is the time interval separating the manoeuvre from its objective (target date, target orbit). The target date can be defined either in terms of duration, with respect to the manoeuvre (or group) itself, or relatively, with respect to a future manoeuvre of a given type.

The manoeuvre calculation principle is therefore as follows:

- calculation of the control horizon (target date) of the manoeuvre or the group of manoeuvres to be calculated,
- calculation of the manoeuvres to be pre-compensated for the manoeuvre or group concerned: list of manoeuvres to be pre-compensated on the control horizon. The latter may be fixed, they are then given in the manoeuvre schedule or when they are undefined they are pre-estimated by invoking their mode of calculation.
- calculation of the objective to be reached (target obit) for the manoeuvre or group of manoeuvres concerned. This calculation is only performed once when called up by the calculation module for the first manoeuvre of the group.
- calculation of the current manoeuvre (date and amplitude) to reach the objective assigned to the group. This calculation takes the manoeuvres to be pre-compensated into account.
- verification of constraints to be complied with for this type of manoeuvre (date, amplitude, amplitude variation, etc.).

Development

The previously described design results in the definition of 81 C++ components i.e. 64 generic components and 17 space dynamics components.

The generic components perform strategy determination through pattern simulation and parameter read and result editing functions. They use skill components via abstract classes which enable the former to be independent of user choices as regards space dynamics algorithms.

Using this library, the Oskar software was made to calculate the stationkeeping strategy of the Stentor satellite. The particularities of its platform have led us to develop two specific manœuvre *control law modules* (cf. previous paragraph), which were simply added to all the other modules already available (chemical stationkeeping strategies).

APPLICATION TO STENTOR

Stentor stationkeeping (cf. [4]) is performed using 83mN plasma thrusters for North/South control, and 10N chemical thrusters for East/West control. The low thrust of plasma thrusters means frequent manoeuvres have to be performed (nearly every day). This is why it is planned to calculate these manoeuvres on ground over a certain duration, then to load them in "packets" for automatic onboard execution. The term "period of autonomy" is used to qualify the period between two loads, over which the satellite is autonomous.

Different strategies were studied by ASTRIUM and by CNES for Stentor stationkeeping.

North/South control may, in fact, be performed by several thruster configurations: on board there are two types of plasma thrusters (SPT100, PPS1350), whose characteristics and set-ups vary considerably. Moreover, it is also possible to perform this control with conventional chemical thrusters (backup).

The bibSMAP library and Oskar software were used to simulate the different types of strategies envisaged for these different configurations.

Here we only present strategies in the case of plasma propulsion, those that have been adopted for the Stentor mission analysis.

In this part we will describe the characteristics of these strategies. Beforehand, we must indicate the dimensioning data and constraints which oriented their preparation:

Main characteristics

General constraints

- two manoeuvres must be spaced by a minimum duration
- the duration between manoeuvres and eclipses is also limited (depending on the type of manoeuvre)
- calculations and reloading of manoeuvre plannings must be made in days and hours worked.

Types of manoeuvres envisaged:

ISKM: Ionic StationKeeping Manoeuvre, plasma North/South control manoeuvre.

PEWM: Pulsed East West Manoeuvre: pulsed chemical manoeuvres ensuring East/West control.

PPOL: Pulsed Pitch Off Loading, pulsed chemical pitch desaturation manoeuvres.

ISKM characteristics and constraints:

- North/Radial or South/Radial control
- low thrust (~ 83 mN)
- major variation of thrust throughout life (~ 7%)
- 2 types of plasma thrusters (SPT100, PPS1350) whose directions and thrusts differ considerably.
- For reasons of electrical power specific to the Stentor satellite, thrust durations are limited depending on the time of the year (within or outside eclipses period). Order of magnitude 100 mn outside eclipse period, 30 mn during eclipse period.

PEWM characteristics and constraints:

- East or West control
- pulses are spaced by 300 s (long thrusts)
- constraint linked to moment of momentum management: East/West manoeuvres are calculated in pairs to limit disturbing torques: for each East/West pair,
- both manoeuvres are identical (DV1 = DV2) and they are spaced by (2k+1)*1/2 orbit
- their amplitude is limited as is their amplitude variation (from one pair to another).

Pulsed Pitch off loading: PPOL

These manoeuvres are programmed by ground and loaded in packets at the same time as the other manoeuvres. They are then adjusted onboard according to the real cinetic momentum. General constraints also apply to these manoeuvres.

Control strategies

Combined inclination and eccentricity control

The plasma thrusters on Stentor have a high radial component, which will be used to control eccentricity for the least cost. Consequently, North/South plasma manoeuvres control inclination and eccentricity, East/West manoeuvres then control longitude only.

The necessary inclination correction is mainly due to the Moon-Sun attraction, it is composed of a secular drift (preponderant term) and two periodical terms. Order of magnitude: the secular drift of the inclination vector varying between 0.753 and 0.952 deg/year, the cost of correcting this drift also varies between 40 m/s/year and 52 m/s/year.

The latitude window is +/- 0.5 deg, therefore inclination in the ix-iy plane must remain within a circle with centre (0,0) and radius 0.05 deg inclusive of all errors. Given the very low thrust of plasma thrusters and the limited durations for each, inclination manoeuvres will need to be performed practically every day.

Optimally, the inclination correction manoeuvres take place on the line of nodes (ascending node for South manoeuvres, descending node for North manoeuvres). As we dispose of North and South thrusters on Stentor, the North/South correction strategy will be composed of North and South manoeuvre pairs spaced every (2k+1)*1/2 orbit. i.e. a Δv of approximately 0.2 m/s at each manoeuvre (for manoeuvres spaced by 36 h and for an annual correction of 50 m/s).

The layout of thrusters is such that each plasma thrust will induce a radial thrust along the -R(or Z) axis which can be used for the eccentricity control. As the N/S manoeuvres of a pair are separated by π, the effect, due to the radial component of the manoeuvres, on eccentricity should cancel out. We will, however, obtain an effect on eccentricity by:

- slightly deoptimising the date of N/S manoeuvres to correct eccentricity in one direction,
- making each North and South correction with slightly different durations to make an eccentricity correction in the other direction.

To correct eccentricity, we will therefore symmetrically move the centre of the thrust of each manoeuvre by δS: S1 = $(S-\delta S)$ and S2 = $(S+\pi+\delta S)$, then split both manoeuvres into two different durations: $\Delta t1 = \Delta t-\delta t$ and $\Delta t2 = \Delta t + \delta t$.

Both manoeuvres of a pair then become slightly closer under the effect of this demodulation.

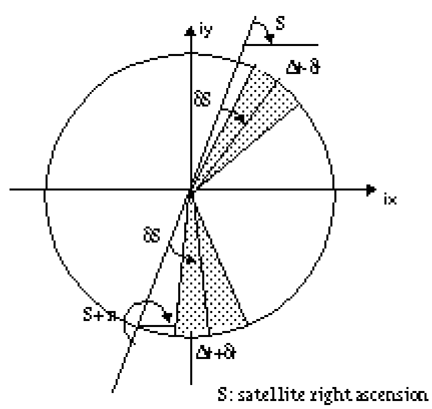

Fig 2. Demodulation for eccentricity control

The target eccentricity control consists in cancelling the latter, i.e. centring the travel along e produced by each plasma manoeuvre on ec = 0

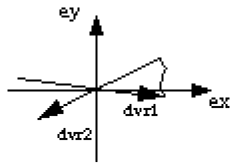

Fig 3. Eccentricity control

Maximum thrust durations change according to the period, if we do not proportionately modify the number of manoeuvres according to the periods, the inclination control capacities then vary seasonally. It is not always possible to completely cancel the inclination drift (eclipses periods, years with a high North/South cost), whereas at other times there is enough of a margin for this control (outside eclipses periods).

This is the reason why the strategy adopted for the inclination control is, whenever possible, to anticipate i.e. at each manoeuvre use the maximum thrust capacity authorised, while complying with the demodulation necessary for the eccentricity control. Low capacity periods are thus compensated by the others.

This control period is obviously limited by the maintaining of the satellite in its inclination window. The effect of this is to keep or bring the inclination to the bottom of its control circle (when the N/S capacity is sufficient) and to let it rise slightly in the other periods.

Longitude and drift control

Once we have controlled inclination and eccentricity, only longitude (and implicitly its drift) remain to be controlled to ensure that the satellite remains in its window. This control performed by the chemical East/West manoeuvres must take the following into account:

- the natural evolution of longitude which is mainly characterized by a longitudinal acceleration due to the Earth's potential, and its value and its speed depend on the station point (cf. [3]) . For Stentor,1 = -11 deg, the natural movement of the longitude is practically nil, this is a stable point.
- the tangential torquing of the North/South manoeuvres. As the North/South cost is greatly preponderant, even a low tangential torquing of these manoeuvres may have a strong impact on East/West control.
- the longitudinal movement induced by the radial component of each plasma manoeuvre.

Moreover, margins must also be planned to take the non-corrected periodical terms, and the manoeuvre and orbit errors into account. This amounts to reducing the control window.

Keeping the satellite in its longitudinal window consists in controlling the evolution of the longitude in a reduced window given the high density of North/South manoeuvres and the constraints linked to East/West manoeuvres: these manoeuvres must be calculated in pairs of identical manoeuvres spaced by 2(k+1)*1/2 orbit. Four manoeuvres (two pairs) are required to control longitude and drift. Each of these is calculated separately to ensure a longitude rendezvous at the date of the next rendezvous, given the plasma manoeuvres occurring within this time interval (as they induce longitudinal travel through their Δvr and a tangential torquing to be pre-compensated), next they are smoothed to reveal two pairs with conservation of the final longitude and drift.

Manoeuvre (or pattern) sequence cycle

The choice of nominal pattern was motivated by the following aspects:

- avoid eclipses by the earth or the moon for all manoeuvres,
- comply with spacing constraints between two manoeuvres,
- minimise the number of actuations by maintaining a sufficient control capacity,
- free periods with no manoeuvres to optimise the accuracy of orbit updating,
- comply with the operational constraint: ground calculations are made in worked hours and days.

North/South thrust centres (lines of nodes) and eclipse zones are naturally practically in quadrature as indicated in the next figure:

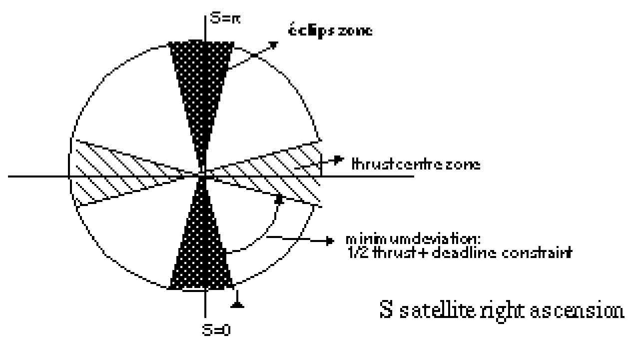

Fig 4. Eclipses zones – thrust centre zones

Given that North/South manoeuvres operate in pair and that four East/West manoeuvres (two pairs) are required to ensure longitude and drift control, one pattern proposed is as follows:

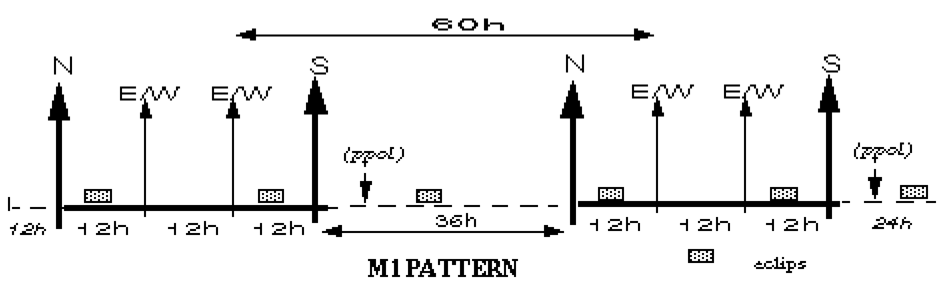

Fig 5. M1 manœuvre pattern

This is a 6 sideral day pattern, with the following characteristics:

the number of actuations is minimal, given the inclination correction requirements,

manoeuvres are sufficiently spaced out to verify time constraints, they are a priori correctly positioned with respect to eclipses as indicated in the figure below:

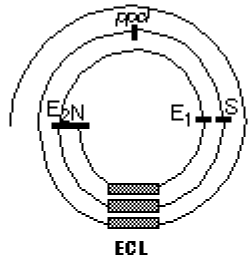

Fig 6. Eclipses location with respect to manœuvre ones

Every three days a 36 h arc with no manoeuvre appears. This is used to have the possibility of calculating and reloading the manoeuvres every k*3 days. The duration of an operational cycle with such a pattern will therefore be a multiple of 3 days. It can be adapted to each cycle at packet loading, so that the next calculations are performed in administrative hours.

A second pattern (directly derived from the M1 pattern) is also envisaged when N/S thrust capacities are insufficient (given the technological characteristics and constraints). It may be used during an eclipse, if necessary to compensate for the strictly limited duration of plasma thrusts in these periods (30 mn). It has a stronger North/South control capacity (twice as many manoeuvres as M1), but has the disadvantage of loading the cycle more and no longer preserving the long arc without any manoeuvres to update the orbit.

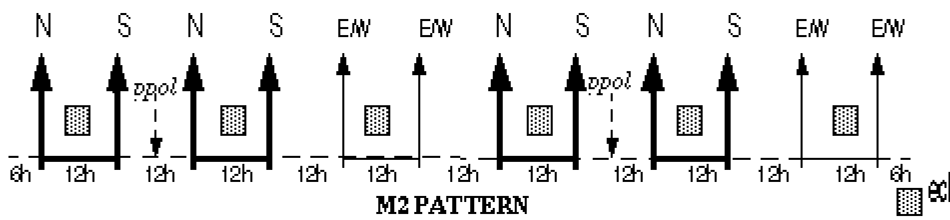

Fig 7. M2 manœuvre pattern

Simulations

We have chosen to present two simulation cases taken from strategy research for Stentor stationkeeping mission analysis:

- simulation1: a strategy for North/South control using type SPT100 plasma thrusters, where only the M1 (cf. previous paragraph) pattern is used.
- Simulation2: a strategy for North/South control using the SPT100 plasma thrusters, M1 pattern is used during the two first years out of eclipses periods, M2 pattern is used during eclipses periods the two first years, and always after two years.

For both test we have introduced dispersions and a period of autonomy of 15 days (orbit update frequency).

Modelled dispersions are applied:

- to orbital parameters,
- to the satellite attitude in the form of short and medium term errors and periodical errors in the day,

- to manoeuvres in the form of short and medium term errors applied to the thrust direction and the amplitude (via the specific pulse of the thrusters).

Both simulation cases are parameterised in a similar way for Oskar, only those parts relating to patterns differ.

Plots

The following plots were produced from the processing results of the simulation cases described previously by Oskar over 9 years from 8st April 2002.

The curves given the following in succession:

- the amplitude of true longitude vs time
- inclination in plane (i_x, i_y)
- eccentricity in plane (e_x, e_y)
- drift vs mean longitude

The "Results" table totals the speed increments per type of manoeuvre (North/South, East, West).

The statistics on the sizes of manœuvres, and general results about consumption are also given.

Results of simulation1:

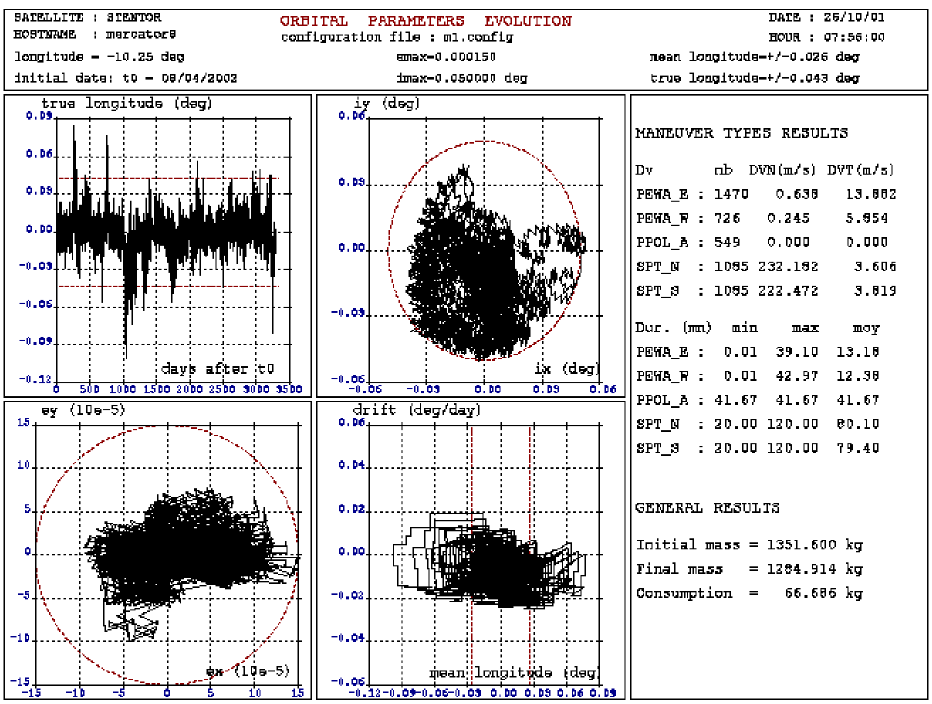

Fig. 8 - M1 pattern all the time

This plot shows that this strategy allows a control of the satellite in its window with a few margins for the orbit, attitude and manoeuvre errors (it can, however, be noted that the margin is relatively low as regards the inclination, which takes up approximately 80% of its window).

It also shows that:

- following applications of dispersions, inclination is always correctly maintained in its 0.05 degree window,
- the evolution of eccentricity is not very sensitive to dispersions,
- true longitudinal movement slightly exceeds the allocation of +/- 0.043 degrees despite maximum use of the control capacity of East/West manoeuvres.

<u>Result of simulation2</u>

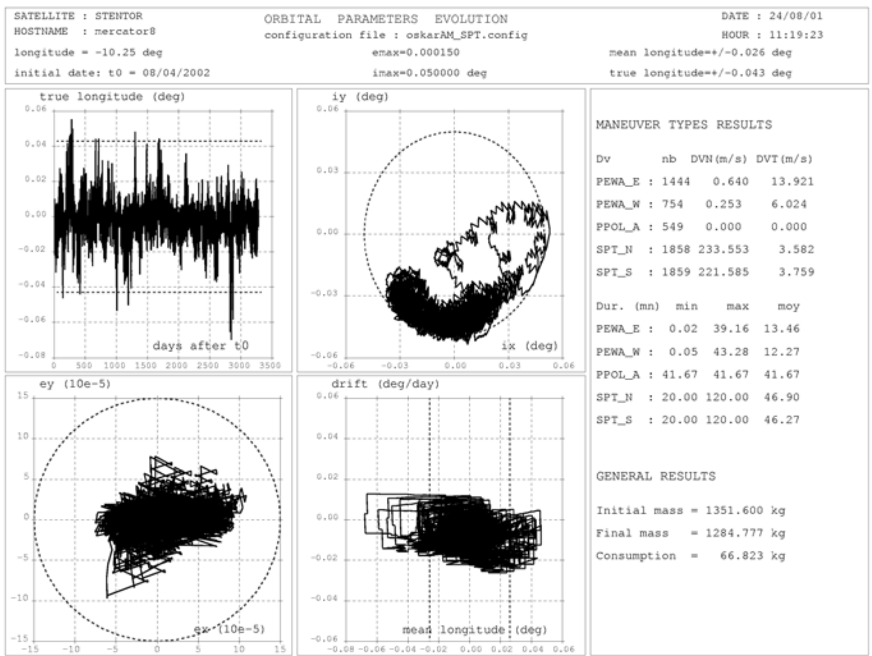

Fig. 9 - M1 and M2 patterns

This plot highlights the fact that the introduction of the M2 pattern during the period of eclipses and after two years improves inclination control in its window. It remains more easily in the bottom of the window.

Conclusion on the results of the Stentor stationkeeping strategy

Our mission analysis shows that the use of the strategy based on the M1 pattern can be used to keep the station in its inclination window with the SPT100 thrusters over a period of 9 years from 8st April 2002. Using this pattern alone has the great operational advantage of being unique and minimizing the number of manoeuvres. Moreover, it offers great flexibility for ground segment operations and provides for fairly long periods with no disturbances for orbit updating.

Using the M2 pattern, increases the frequency of North/South manoeuvres and improves the correction capacity of the inclination, which is found to be necessary in the case of stationkeeping with PPS1350 type thrusters.

The different simulations show that control of eccentricity and inclination resists dispersion well. However, longitude and drift control is highly sensitive to cumulative errors.

These simulations are nonetheless used to make a positive conclusion on the feasibility of Stentor satellite stationkeeping with plasma propulsion. The real characteristics observed in flight will be used to consolidate these results and adjust the strategy with a view to maximising the period of autonomy.

CONCLUSION

The bibSMAP library and associated Oskar software have met the Stentor mission analysis requirement. Several control laws were implemented and tested by simply adding the corresponding manoeuvre control law modules.

We henceforth dispose of generic stationkeeping tools compatible with all the satellite configurations listed to date. The genericity and the completeness of the components implemented are used to easily integrate new evolutions. We felt this for the analysis of the Stentor mission, during which many evolutions had to be integrated.

ACKNOWLEDGEMENTS

We would like to thank other members of the Stentor mission analysis team, in particular Dominique Delmas and François Desclaux for their invaluable advice and active support in this study.

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