ABSTRACT

Geostationary satellites that share the same longitude slot is being the most adequate solution for those satellite operators that need to cover a continuously increasing demand of broadcasting services. Mission analysis of geostationary satellites for single satellites and collocation scenarios become absolutely necessary to study the expected behaviour of the missions during their whole lifetime in terms of safety and performance.

The mission analysis of geostationary satellites demands studies that cover different manoeuvre control strategies, orbit prediction and collocation analysis of dedicated cluster configurations. focusgat is an improved geostationary analysis tool for station keeping and collocation under contract with the European Space Agency.

focusgat is the evolution of GMV’s commercial package matool. It allows the evaluation of the performance of the station keeping and collocation strategies for chemical and ionic strategies.

In this paper the new capabilities and algorithms will be described, among the basic capabilities provided by matool.

1. INTRODUCTION

focusgat incorporate the foremost features of its predecessor matool:

- Evaluation of out of plane control strategies North/South (N/S)
- Evaluation of drift and eccentricity control strategies East/West (E/W)
- Feasibility analysis of single burn strategies for eccentricity/drift control
- Manoeuvre planning for the implemented strategies
- Analysis and assessment of collocation scenarios for several satellites

- Analysis of delta-V and associated mass budgets for several configurations and control strategies
- Verification of the constraints associated with the control window
- Graphical representation of the outcome obtained in the mission analysis simulation for collocation and orbital evolution

The analyses are performed through three different execution modes [4]:

- Collocation parameters estimation mode: provides an initial estimate of the collocation control parameters for a cluster of satellites.
- Proximity analysis mode: performs a proximity analysis reusing ephemeris files generated in a previous execution or generated by a different system. This mode avoids the need to recompute the manoeuvres during a simulation.
- Complete execution: long term station keeping and collocation simulation. This execution mode is done by using generic manoeuvre planning and implementation algorithms based up propulsion characteristics to follow a control strategy defined by a set of parameters.

It is important to emphasize other additional capabilities of focusgat; it is possible to automatically execute a Montecarlo analysis for a configurable number of scenarios taking into account orbit determination errors and thrusters behaviour. Moreover focusgat supports the use manoeuvres given in external files where consequently only the propagation and the proximity analysis would be carried out.

focusgat development has been oriented to fulfil the requirements identified by the European Space Agency (ESA), extending the original capabilities in matool, as follows:

- Allow the analysis of a single satellite or a constellation of up to eight satellites on the same orbital slot.
• Implementation of a more flexible approach where each type of manoeuvre is associated to a dedicated control cycle.

• Simulation of electric propulsion system: implementation of Station-Keeping (SK) cycle for one day; eccentricity control based on N/S manoeuvres or drift control based on N/S manoeuvres.

• The ability to manage given “reactive constraints”. The new feature makes possible to include an algorithm that defines a maximum longitude drift and latitude, triggering an in-plane or an out-plane manoeuvre.

• Addition of new control strategies: Symmetric evolution versus move inclination pole for N/S control and minimum eccentricity versus Sun pointing strategy for E/W control.

• Simulation of wheel momentum dumps taking into account the associated consumption and the evolution of the satellite gravity centre.

• New data management capabilities: export of ephemeris files in STK format [6] and import CCSDS Orbital and attitude data ephemeris file [7].

• Implementation of different reference frames: QMOD, MOD, TOD and J2000.

• Possibility of performing parametric test cases.

• Implementation of eclipses model and batteries power charge cycle.

The modifications and algorithmic extensions of focusgat provide innovative capabilities to study station-keeping and collocation strategies for geostationary satellites.

2. FOCUSGAT NEW FEATURES

2.1 Day-by-day computation

The main difference in the focusgat design from the matool version is that the computation is made day-by-day instead of cycle by cycle. This means that the implementation of the tool is defined as follows [5]:

The orbit propagation is made each day of the station keeping cycle. This new approach allows two different calculations.

• To include separated station keeping cycles for the N/S and E/W manoeuvres.

• Check the reactive constraints that can plan a new manoeuvre for that day.

The first characteristic allows setting new control scenarios where the control cycles are different for N/S and E/W manoeuvres. The following test cases scenarios can be studied with focusgat:

• Set the same station keeping control cycle for the N/S and E/W manoeuvres (as the previous version matool).

• Set two station keeping control cycles, one for the N/S manoeuvres and a different one for the E/W manoeuvres.

• Set free propagation for the inclination and a station keeping control cycle for the E/W manoeuvres.

• Set free propagation for the longitude and eccentricity and a station keeping control cycle for the N/S manoeuvres.

• Set no station keeping control cycles. The N/S and E/W manoeuvres are triggered if after checking the reactive constraints it is needed (i.e.: the satellite is out of the control window).

• Set the station keeping control cycles and the reactive constraints flag. If necessary the reactive constraints will trigger additional manoeuvres.

• As in the previous version matool the manoeuvres can be read from an external manoeuvres file. If that file is empty, free propagation will be computed.

The second characteristic allows studying any orbital constraints before checking if a manoeuvre has to be planned. This is carried out by propagating the orbit one day, check the reactive constraints, and if necessary trigger a manoeuvre.

The reactive constraints that have been implemented check if the satellite is out of the longitude or latitude window. If the satellite longitude is out of the window an E/W manoeuvre is computed on that day, using the control strategy selected (sun pointing perigee or minimum eccentricity). For the latitude, if the satellite is out of the widow a N/S manoeuvre is triggered.
2.2 Simulation of electrical propulsion system: Drift control based on N/S manoeuvres.

This strategy controls the satellite drift taking advantage of the N/S manoeuvres execution. The N/S thrusters must provide a tangential component to be able to compensate the drift perturbation. The eccentricity is controlled with E/W manoeuvres. During the SK cycle the inclination is controlled every day by means of N/S manoeuvres except the last days of the cycle when no manoeuvre is carried out to be able to do orbit determination. The minimum numbers of thrusters needed to control the satellite are six: two thrusters to control the eccentricity (E/W thrusters) and four N/S thrusters with a coupling angle in the tangential direction.

Making a comparison, in the station keeping by chemical control, during each station keeping cycle, the evolution of the satellite longitude as a function of the time corresponds to a parabola. During each station keeping cycle, E/W manoeuvres are performed in order to shift the sign of the longitude drift (and to correct the eccentricity).

In order to be able to shift the longitude drift sign by using continuous manoeuvre, a narrow margin of longitude has to be used. For a given station longitude, the drift to correct at the manoeuvre epoch depends on the difference between the longitude corresponding to the parabola vertex and the longitude at the manoeuvre epoch. The larger is this difference, the larger will be the drift to be corrected. Given this, the strategy is designed in such a way that those manoeuvres are performed frequently in order to maintain as much as possible the longitude inside the classical parabolic shape (external limit) of the station keeping longitude cycle, that is applied to control the satellites implementing chemical manoeuvres, and a defined internal parabola (internal limit).

The algorithm of the strategy of drift control based on N/S manoeuvres is based on the figure 1:

The parabolas show a theoretical evolution of the mean longitude of the SC versus the delta sidereal time (spacecraft (SC) sidereal time minus theoretical sidereal time).

In this strategy four delta-longitude limits must be defined (Δλ₁, Δλ₂, Δλ₃, Δλ₄). The first two limits correspond to the parabolas vertex. While the third one is a margin (if the SC is under that margin no manoeuvre is done). And the fourth one is a margin of the end of the control region.

The drift is corrected by N/S or E/W manoeuvres depending on the difference between the current mean longitude and the target longitude and the difference between the orbital revolution period and the sidereal day.

The first step is to calculate where the SC is in that picture at the beginning of the day, and then depending on the relative position of that point with the theoretical parabolas the needed ΔT is obtained in the diagram. (In that diagram the arrows show depending on the SC position the ΔT required. Depending on the case the required ΔT goes to the inner parabola or the x axis.)

The ΔT is then used to calculate the required delta time of the tangential thrusters that is needed to compensate the drift evolution, the following formula is used:

\[ t = \frac{\Delta T}{6\pi \frac{a^2}{\mu} g_y} \]  

Where, \( g_y \) is the thrusters’ acceleration component in the tangential direction.

The required \( dV \) needed in the N/S is calculated to counteract the secular variations of the inclination vector due to Luni-Solar perturbations. If that \( dV \) is \( A \), the total time that the thrusters must provide in the N/S and tangential direction can be obtained in the equation number 2:

\[ g_{y1} \cdot t_1 + g_{y2} \cdot t_2 = A \]
\[ g_{y1} \cdot t_1 + g_{y2} \cdot t_2 = B \]

A simulation using this strategy is in the fig. 2, 3, and 4:
2.3 Simulation of electrical propulsion system: Eccentricity control based on N/S manoeuvres.

In this strategy the N/S thrusters must provide a radial component in order to be able to control the eccentricity. That is why the N/S thrusters have a coupling angle in the YZ plane. The N/S thrusters give a normal component (positive or negative, depending on the thrusters used) and a radial component that is oriented towards the Earth.

The radial component has an influence on the mean longitude, therefore when a N/S manoeuvre is performed an eastwards shift in longitude appears. This effect can be control using the E/W manoeuvres. The radial component of the N/S has also an influence on the eccentricity and it is used to control it. To control only the inclination N/S manoeuvres are done in pairs (one south and one north with same magnitude and separated by half a day).

If instead of performing two manoeuvres with the same duration and separated half of the sidereal day, the manoeuvres done have different duration, the overall effect on the inclination will be the same, but not in the case of the eccentricity.

Therefore, there is an overall $\Delta e$ in the same direction as the direction of the secular perturbation of inclination.

To achieve a variation of eccentricity in the direction perpendicular to the secular inclination perturbation, it can be modified the manoeuvre times.
2.4 Different station keeping control strategies:

There are four implemented station keeping control strategies for calculating the N/S and E/W manoeuvres.

- Sun pointing perigee strategy.
- Minimum eccentricity strategy.
- Symmetric evolution strategy.
- Move inclination pole strategy.

In fig. 16, 17, 18 and 19 are presented the same test case using the different station keeping strategies.

2.5 Planning of momentum dumps:

To improve the performance in the geostationary mission analysis a simplified model of planning of momentum dumps have been implemented in focusgat. With this new approach it can be estimated the number of wheel unloading manoeuvres that have to be planned and the total mass consumed during that specific manoeuvres.

The wheel unloading model takes into account the main disturbance torques that affects a standard geostationary satellite.

- Solar radiation pressure torque.

\[ \vec{T}_{\text{SunPr}} = \vec{d} \times (c_p S A_{\text{eff}} P) \vec{u} \]  

- Gravity gradient torque.

\[ \vec{T}_{\text{GG}} = \frac{3 \mu}{R_{3/c}^3} \left[ \vec{u}_N \times (I \cdot \vec{u}_N) \right] \]  

It can be simulated that the centre of pressure could change during the whole life of the satellite,
interpolating from the beginning of life (BOL), middle of life (MOL) and end of life (EOL) as well as the centre of gravity that can be simulated as a constant or as function of the mass consumed.

To model or predict the time evolution of the angular momentum of the reaction wheels it can be used the dynamic equations of motion of a rigid spacecraft given by Euler’s equation [1]:

\[
\frac{d}{dt}(I_\omega) = N_{DIST} + N_{CONTROL} - \omega_\text{rot} \times I_\omega \cdot \left[ \omega_\text{rot} \times h + N_{\text{wheel}} \right]
\] (5)

\[
L = I_\omega + h
\] (6)

\[
\frac{d}{dt} h = N_{\text{wheel}}
\] (7)

Taking into account the characteristics of a geostationary orbit and assuming that the attitude is in nominal pointing mode, the implemented algorithm is:

\[
0 = N_{DIST} - \omega_\text{rot} \times h - \frac{d}{dt} (h)
\] (8)

This equation is solved using an Euler numerical method and taking into account the disturbance torques considered above.

In this model it is assumed that during the N/S and E/W manoeuvres the attitude thrusters keep the satellite pointing to the Earth and no wheel momentum dumps are carried out in that situation. To compensate the momentum produced by the station keeping thrusters it is assumed that the attitude thrusters are in charge of that compensation while pointing to Earth.

The main results that have been computed with this algorithm show the evolution of the angular momentum of the satellite reaction wheels. For a standard geostationary satellite not taking into account the centre of pressure or gravity centre evolutions in the model, the results can be summarize in fig. 20, 21 and 22:

2.6 Compatibility with commercial products.

2.6.1 Generation of the ephemeris files in STK format:

One more additional capability of focusgat is to export the orbital data ephemeris file in the STK format [7]. An example of this format file is shown in fig. 23:

2.6.2 Import CCSDS OPM orbital data ephemeris file format.

focusgat allows to read the initial state vector of the satellites from the main input menu or to import the initial ephemeris in the CCSDS OPM ephemeris format [6] in the way specified in fig. 24.
2.7 Parametric studies

This section describes the parametric studies functionality that is included in the new software focusgat. The objective of creating this new feature is to perform automatically a set of test cases where the input data file can be edited and changed as well as the external manoeuvres files. With this improvement it can be analyse the influence of any of the input data parameters in the evolution of the satellites ephemeris computation. The results of the simulations are copied in the different test cases folders where the inputs were previously read.

In the next fig. 25 it is shown the new feature:

![Figure 25. Parametric study functionality](image)

2.8 Manage up to eight satellites

A new feature of focusgat is that it can perform mission analysis and collocation studies up to eight satellites. In fig. 26 and 27 is shown a cluster of eight satellites:

![Figure 26. Eccentricity vectors of 8 satellites](image)

![Figure 27. Inclinations vectors of 8 satellites](image)

2.9 Using of different reference frames:

It can be selected the reference frame in which it is going to be done the orbit calculations during the simulation: QMOD, MOD, TOD, J2000.

2.10 Eclipse model and power charged cycle

The spacecraft power subsystem is comprised of two parts of elements, the power generator and the power consumers. A list of the most relevant systems is presented below:

- Elements generating power
  - Solar Array \( P_{SA} \)
  - Batteries \( P_{BATT} \)

- Elements consuming power
  - Propulsion system \( P_{TH} \)
  - Payload \( P_{PL} \)
  - S/C platform \( P_{SC} \)

A simplified model of the power balance can be expressed as follows:

\[
P_{\text{batt}} = P_{SA} - P_{ch} - P_{PL} - P_{SC}
\]  

(9)

If the value of \( P_{\text{batt}} \) is positive that means that the batteries will not be used, so this power is used to recharge the batteries if they are not completely recharged and the available power is higher than the power needed by the battery regulator to recharge it. On the contrary, if the value is negative that means that the energy available on the batteries is used to feed the satellite systems. This use will be possible until all the available energy on the batteries is finished.

The dynamic model of the tool includes the energy available on the batteries:

\[
\frac{dE_{\text{batt}}}{dt} = \begin{cases} 
0 & \text{if } E_{\text{batt}} \geq E_{\text{max}} \\
P_{\text{batt}} & \text{if } P_{\text{batt}} < 0 \\
P_{\text{ch}} & \text{if } P_{\text{batt}} > 0 \text{ and } P_{\text{batt}} > P_{\text{ch}}
\end{cases}
\]

(10)

The energy stored on a battery depending on the different situations is expressed by:

\[
E_{\text{batt}} = \begin{cases} 
E_{\text{batt\_nominal}} & \text{if battery charged} \\
P_{\text{batt}} t & \text{if } P_{\text{batt}} < 0 \text{ and } P_{SA} = 0 \text{ discharged condition} \\
P_{b} t & \text{charged conditions}
\end{cases}
\]

(11)

It is assumed that the case of discharging conditions corresponds when the satellite is on eclipse conditions so \( P_{SA} = 0 \). The battery power depends on the power used by the thrusters, the payload and the spacecraft. In this
simplified model those values are assumed as constant. (As well as the $P_{CH}$ and $E_{batt\text{, nominal}}$).

The graphical pattern of this model is:

![Figure 28. Charge conditions](image)

When the eclipses are computed, apart from the start and end time of the eclipse, the energy of the batteries in that moment is also shown in the standard output. In case that the thrusters’ manoeuvres will be done during minimum battery energy (user configurable) a warning message is shown in the standard output.

3. **ENHANCEMENTS AND CONCLUSION**

Several enhancements are envisaged for *focusgat*, some of them are presented here below:

- Study the way to implement eccentric orbits, not only geostationary.
- Dynamic computation of the eccentricity control cycle along the whole simulation.

*focusgat*, the evolution of GMV’s commercial package *matool* is a new software, developed under contract with ESA, for performing mission analysis and collocation of a geostationary cluster of satellites. It has been developed to be part of *focusGEO*, GMV’s Flight Dynamics solution for geostationary satellites [3].

The new enhancements make possible the study of different station keeping strategies with ionic and chemical configurations and collocation performances, as well as a preliminary way to predict the wheel unloading manoeuvres.

4. **REFERENCES**

1. James R. Wertz, *Spacecraft Attitude determination and control*.

2. Lindsay Pattinson, Vladimir Chechik, Eutelsat *Satellite Collocation*.


