

GEOSTATIONARY SATELLITE MISSION ANALYSIS WITH *focusgat*

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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 satellite 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 [2]. *focusgat* is an improved geostationary analysis toolkit for station keeping and collocation strategies 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. During a simulation period, it evaluates the inter-satellite distances and angles, which can be exported in easy to handle data files or plotted for analysis and easier understanding.

In this paper the new algorithms will be described in detail and the main features will be applied to selected problems to demonstrate the improvements in fuel efficiency that can be accomplished.

1. INTRODUCTION

focusgat incorporate the foremost features of its predecessor *matool*:

- Evaluation of out of plane control strategies (N/S)
- Evaluation of drift and eccentricity control strategies (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 ESA. The new implementation in *focusgat* extends the original capabilities in *matool* and improves the performance are as follows:

- The manoeuvre cycle computation for N/S and E/W control is generated referred to the day rather than to the cycle. This enhancement allows the implementation of a more flexible approach where each type of manoeuvres is associated to a dedicated control cycle.
- Possibility to swap control cycles for N/S and E/W strategies. This feature provides more flexibility in station keeping operations
- The ability of manage reactive constraints. The new “day-reference” feature implemented makes possible to include an algorithm that defines a maximum longitude drift and triggers an in-plane manoeuvre. In addition the simulation can be forced to finish in case of any violations of a defined geostationary station keeping box.
- Different control modes are available:
 - Symmetric evolution and move inclination pole for N/S control
 - Minimum eccentricity and Sun pointing strategy for E/W control
- Planning of wheel momentum dumps taking into account the associated consumption.
- Generation of ephemeris files as export product in STK format.
- Import CCSDS OPM orbital data ephemeris file.
- Allow the study of parametric cases using the external manoeuvres files.

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 as defined as follows [5]:

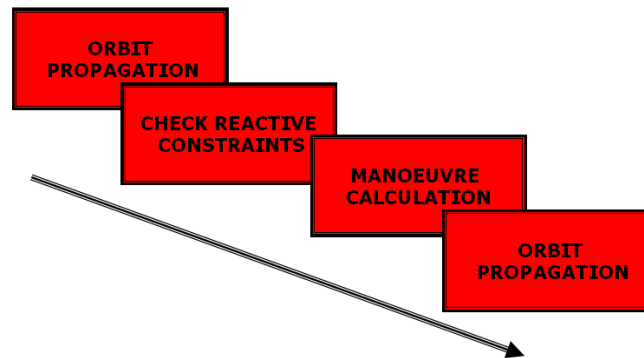


Fig. 1. Algorithm sketch

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 window a N/S manoeuvre is triggered.

In the following figures it can be seen a simulation not using station keeping cycle and only triggering a manoeuvre when the satellite is out of the longitude and latitude windows.

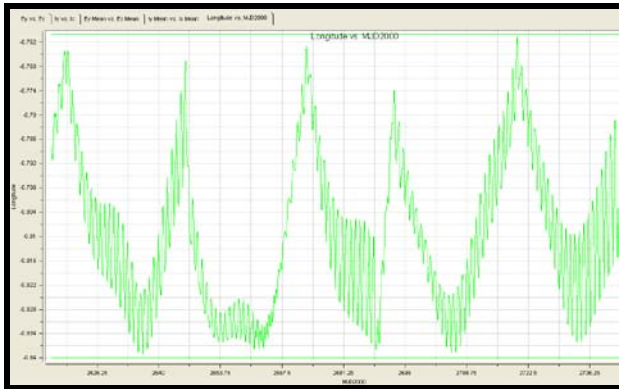


Fig. 2. Reactive constraints: longitude

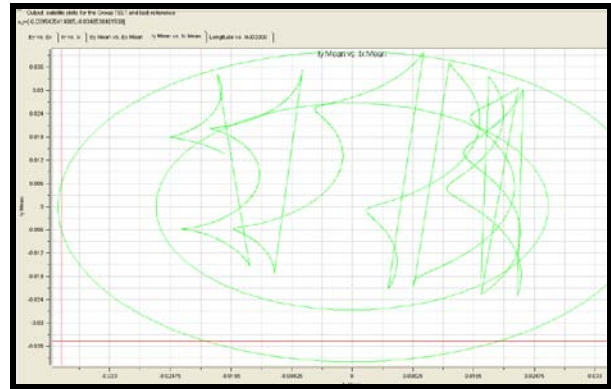


Fig. 3. Reactive constraints: inclination

In the above simulation the duration of the prediction is 150 days. For that time and for a longitude and latitude window of 0.04 deg, seven E/W manoeuvres are computed and the same for N/S.

In case of using an external manoeuvre file and checking the reactive constraints, if the satellite is out of the control window the simulation is stopped.

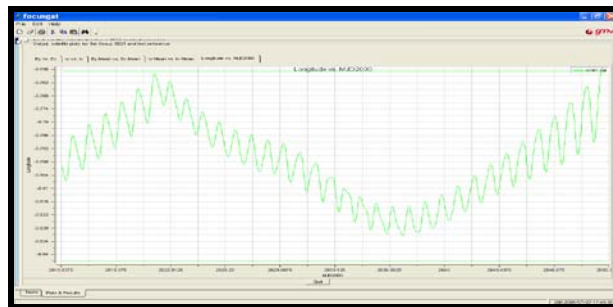


Fig. 4. Simulation stops when satellite is out longitude window

2.2 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.

Below are presented the same test case using the different station keeping strategies.

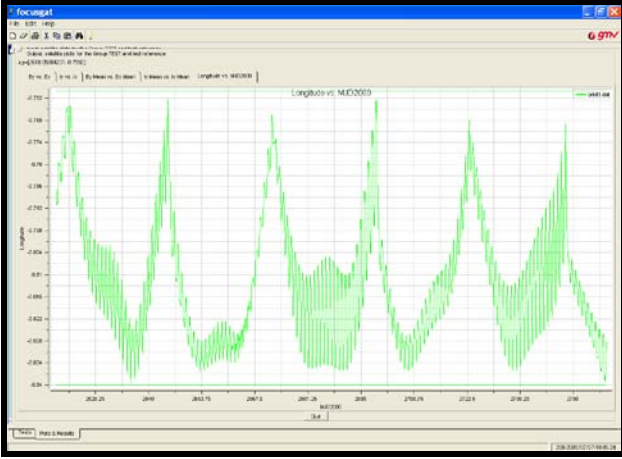


Fig. 5. Sun pointing perigee strategy

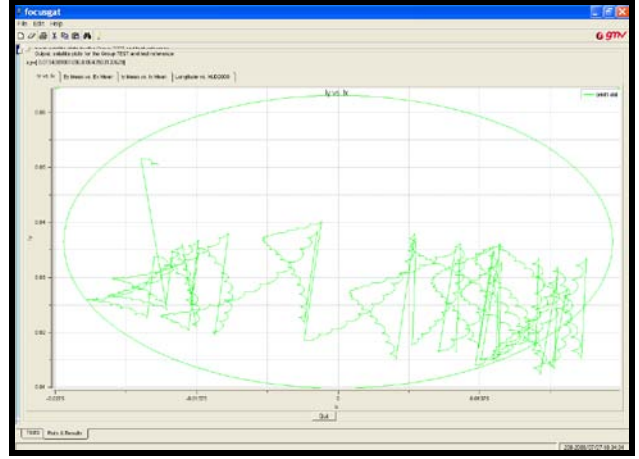


Fig. 6. Symmetric evolution strategy

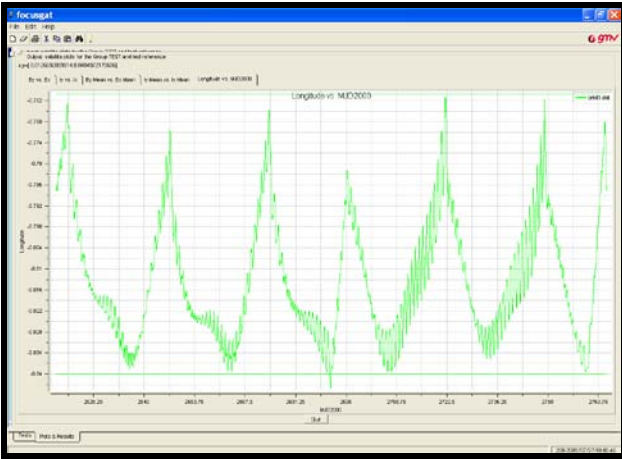


Fig. 7. Minimum eccentricity strategy

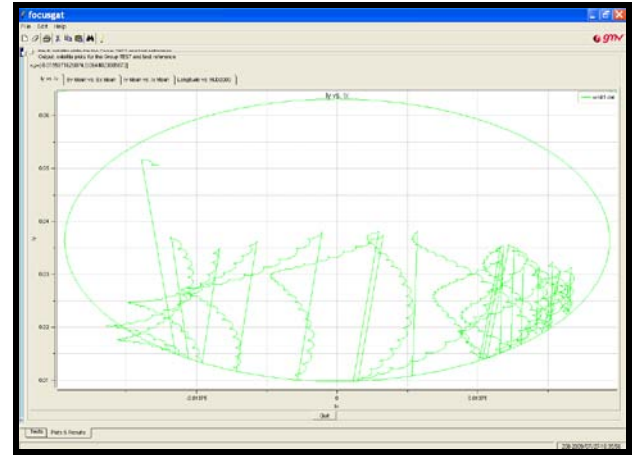


Fig. 8. Move inclination pole strategy

2.3 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 how many wheel unloading manoeuvres 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.

$$\vec{T}_{SunPr} = \vec{d} \times (c_p SA_{eff} P) \vec{u} \quad (1)$$

- Gravity gradient torque.

$$\vec{T}_{GG} = \frac{3\mu}{R_{S/C}^3} [\vec{u}_N \times (I \cdot \vec{u}_N)] \quad (2)$$

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]:

$$\frac{d}{dt}(I\omega) = N_{DIST} + N_{CONTROL} - \omega_{ROT} \times I\omega - [\omega_{ROT} \times h + N_{Wheel}] \quad (3)$$

$$L = I\omega + h \quad (4)$$

$$\frac{d}{dt}h = N_{Wheel} \quad (5)$$

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

$$0 = N_{DIST} - \omega_{ROT} \times h - \frac{d}{dt}(h) \quad (6)$$

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 the results can be summarize in the following graphics:

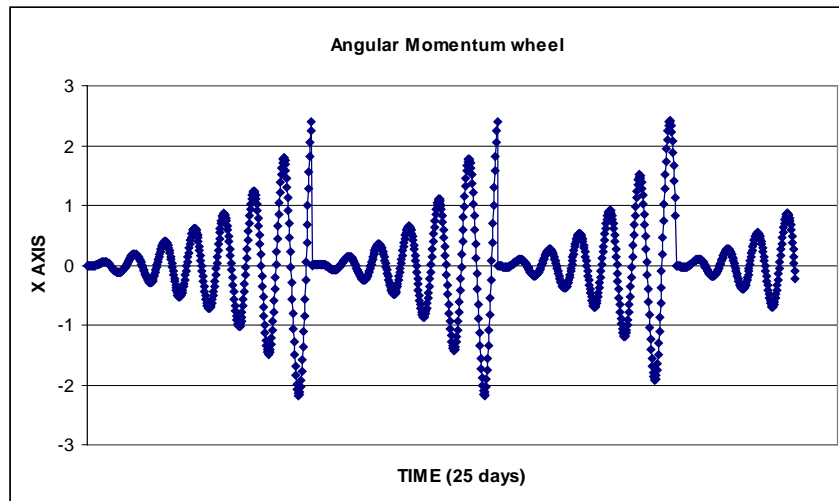


Fig. 9. X Axis Angular momentum wheel evolution

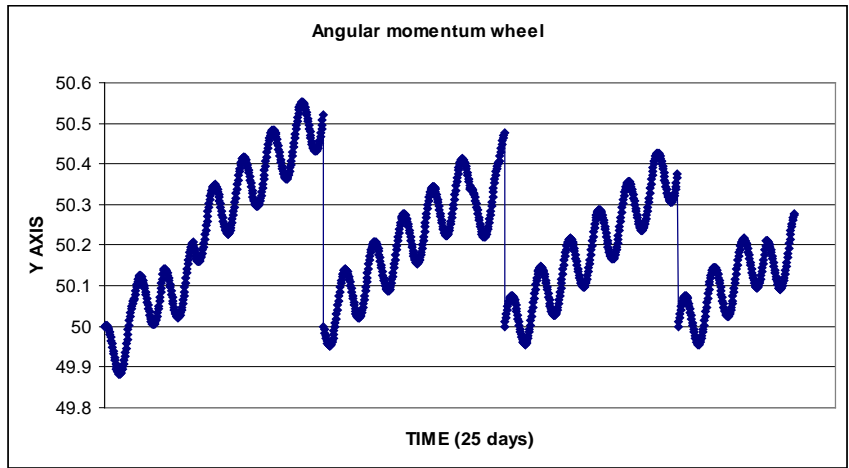


Fig. 10. Y Axis Angular momentum wheel evolutions

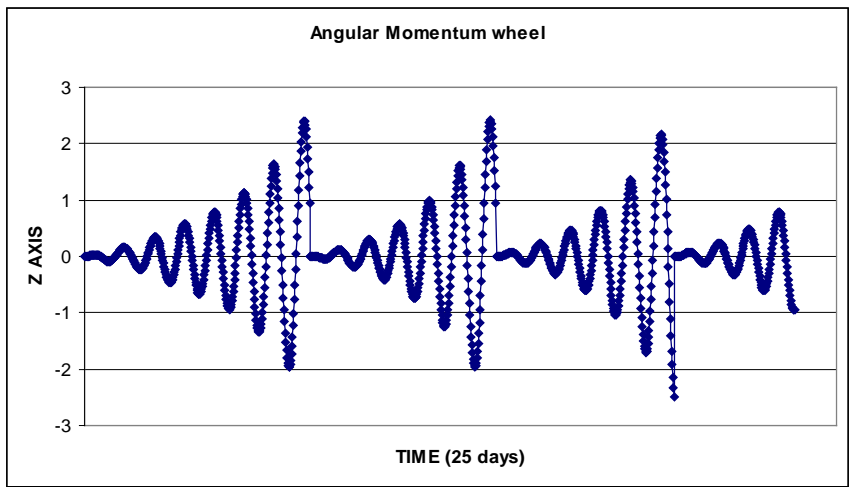


Fig. 11. Z Axis Angular momentum wheel evolutions

2.4 Compatibility with other commercial products

- 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 below:

```

stk.v.4.0
BEGIN Ephemeris
  NumberOfEphemerisPoints 1022
  ScenarioEpoch 1 MAR 2007 0: 0:0.0
  EphemerisECITimePosvel
    0.000 -38987728.0920 16057706.8820 8256.2817 -1170.9981265 -2842.9666551 -0.9240020
    1800.000 -40754123.3975 10816934.0471 6533.6154 -788.8451829 -2971.7515576 -0.9874324
    3600.000 -41819425.4573 5390094.0718 4711.3235 -393.1244309 -3049.4112182 -1.0345552
    5400.000 -42165313.0340 -129452.3098 2819.4165 9.3563077 -3074.6109756 -1.0646864
    7200.000 -41785841.0880 -5646751.9566 888.9204 411.6732619 -3046.9186472 -1.0773803
    9000.000 -40687542.0821 -11066892.7204 -1048.6061 806.9060365 -2966.8117990 -1.0724658
    10800.000 -38889313.3301 -16296635.5195 -2961.4741 1188.2565521 -2835.6693068 -1.0500488
    12600.000 -36422090.2501 -21246017.8183 -4818.5094 1549.1658828 -2655.7474713 -1.0105186
    14400.000 -33328314.3714 -25829899.9548 -6589.4668 1883.4268373 -2430.1410916 -0.9545400
    16200.000 -29661203.1808 -29969428.6531 -8245.5396 2185.2904896 -2162.7302220 -0.8830466
    18000.000 -25483835.1395 -33593392.4297 -9759.8339 2449.5648326 -1858.1135129 -0.7972269
  END Ephemeris

```

Fig. 12. STK ephemeris data format

- 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 in the way specified below ([6]):

```

CCSDS_OPM_VERS = 2.3
CREATION_DATE = 2009-05-22T05:35:22.166000Z
ORIGINATOR = GMV_AD
OBJECT_NAME = OB1
OBJECT_ID = A
CENTER_NAME = ESOC
REF_FRAME = J2000
TIME_SYSTEM = UTC
EPOCH = 2007-03-01T00:00:00.000000Z
X = -38965.214251831
Y = 16116.3703100188
Z = 1.58804434983080
X_DOT = -1.1751211088360
Y_DOT = -2.8411372821690
Z_DOT = -0.0011958847620
MASS = 2951.
SOLAR_RAD_AREA = 1.00000000000000
SOLAR_RAD_COEFF = 0.00000000000000
DRAG_AREA = 1.00000000000000
DRAG_COEFF = 0.00000000000000

```

Fig. 13. CCSDS OPM Ephemeris file format

2.5 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 picture it is shown the new feature:

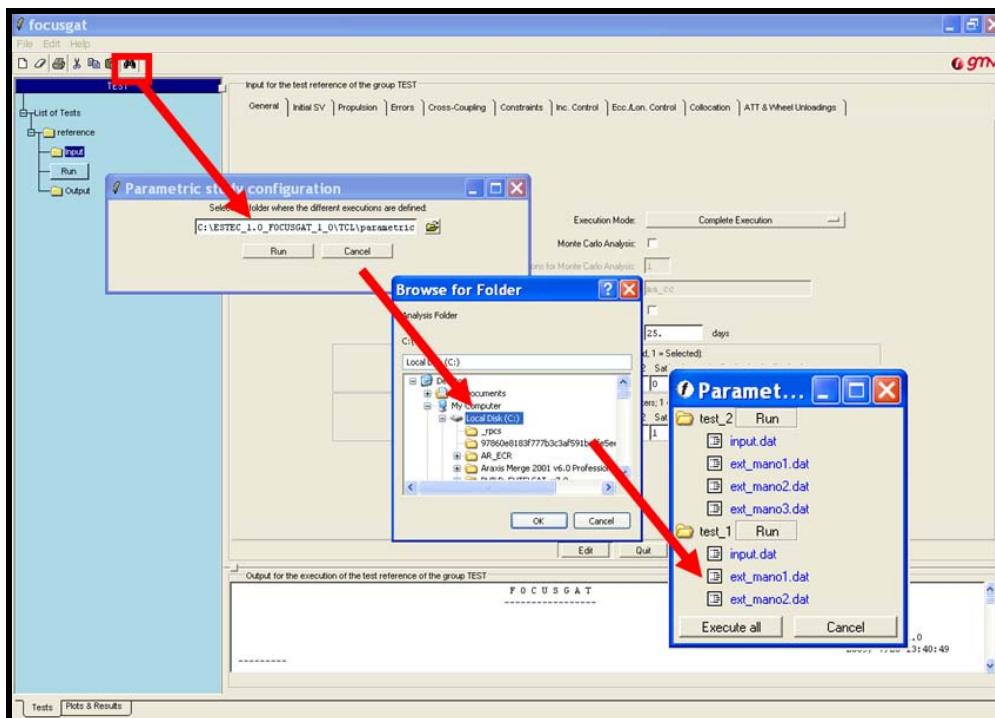


Fig. 14. Parametric studies functionality

2.6 Manage up to eight satellites

A new feature of *focusgat* is that it can perform mission analysis and collocation studies up to eight satellites. Below there are some figures of a cluster of eight satellites:

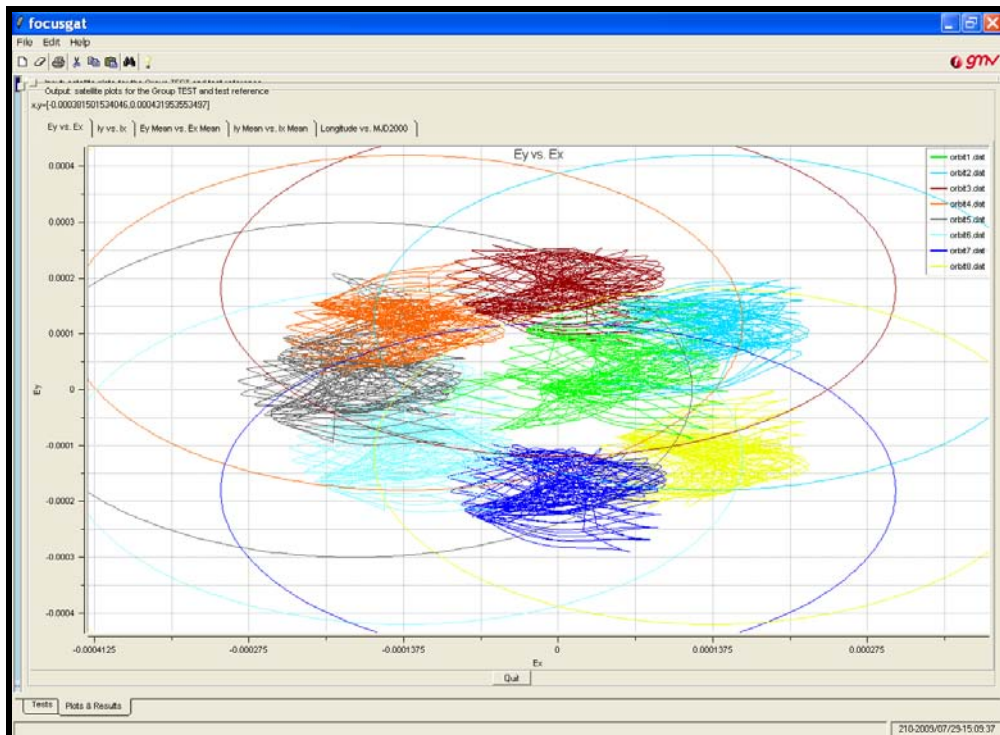


Fig. 15. Eccentricity vectors of 8 satellites

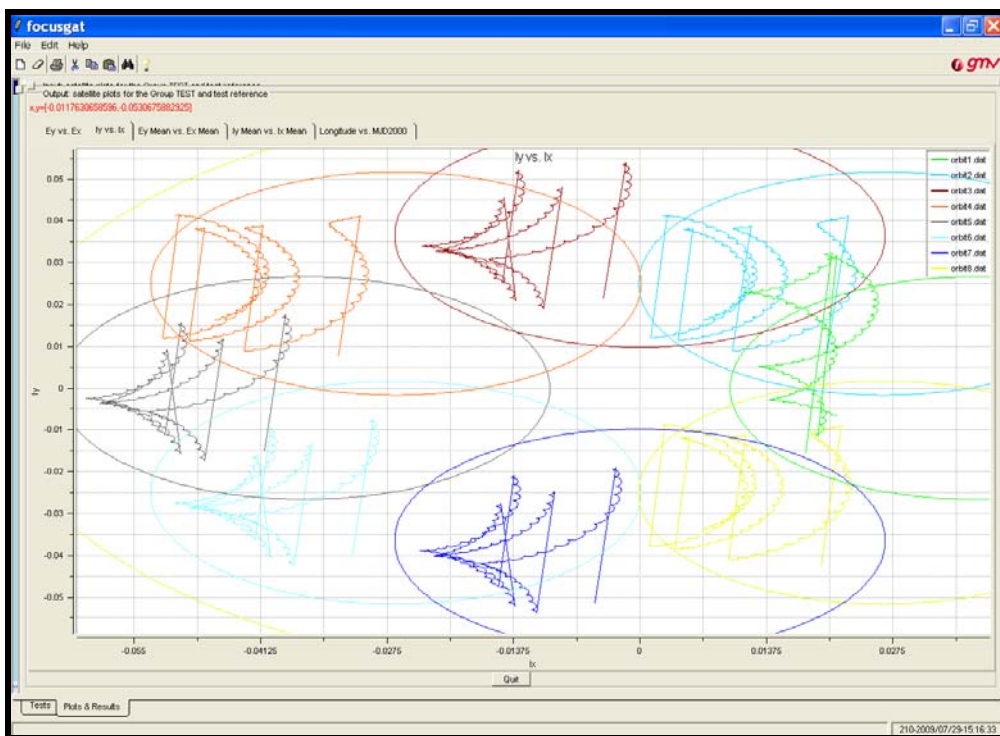


Fig. 16. Inclinations vectors of 8 satellites

3. RESULTS

By the time this paper has been written the new implemented features of *focusgat* have not been tested in detail in an operationally environment. The new implemented changes allow making a great number of different geostationary mission analysis configurations. These new features allow innovative investigations as it is shown in the following example:

- Simulation of one satellite for 56 days. The initial state vector is the same in both cases, the eccentricity/longitude control strategy is sun pointing perigee and the inclination strategy is the symmetric evolution. The initial mass of the satellite is 2951kg. No cross coupling effects.
 - Case 1: The geostationary station keeping cycle is 14 days; the N/S manoeuvres are scheduled on the 5th day and the E/W manoeuvres on the 7th of the cycle. The manoeuvres results can be summarize in the following chart:

SATELLITE MASS AND MANOEUVRES DV SUMMARY	
TOTAL NS DV:	4.98317419000000
TOTAL EW DV:	0.365703910000000
TOTAL TANGENTIAL N/S CROSS COUPLING:	0.000000000000000E+000
TOTAL RADIAL N/S CROSS COUPLING:	0.000000000000000E+000
REMAINING FUEL MASS:	2650.99998386093
NUMBER OF WU	7
TOTAL WU MASS CONSUMED	7.000000000000000E-003
EW MANOEUVRES 1 burn:	3
EW MANOEUVRES 2 burns:	1
EW MANOEUVRES 3 burns:	0

Fig. 17. Station keeping results

- Case 2: There is no station keeping cycle and the N/S and E/W manoeuvres are triggered when the satellite is out of the control window of 0.04 longitude and latitude degrees.

SATELLITE MASS AND MANOEUVRES DV SUMMARY	
TOTAL NS DV:	4.93535199000000
TOTAL EW DV:	0.328685840000000
TOTAL TANGENTIAL N/S CROSS COUPLING:	0.000000000000000E+000
TOTAL RADIAL N/S CROSS COUPLING:	0.000000000000000E+000
REMAINING FUEL MASS:	2650.99998411692
NUMBER OF WU	8
TOTAL WU MASS CONSUMED	8.000000000000000E-003
EW MANOEUVRES 1 burn:	1
EW MANOEUVRES 2 burns:	1
EW MANOEUVRES 3 burns:	0

Fig. 18. Reactive constraints results

In the second case the consumption of fuel mass and the number of manoeuvres carried out is lower than the common station keeping strategy and the longitude and latitude of the satellite is in both cases inside the control window.

The longitude evolution of these test cases examples are presented in the following pictures:

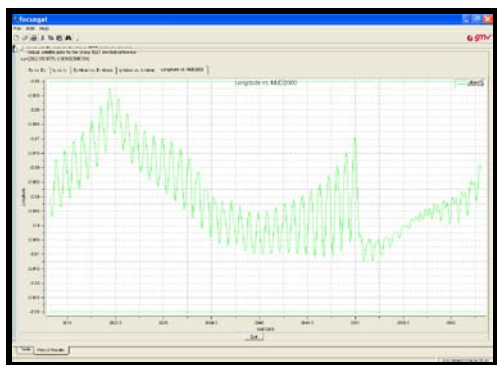


Fig. 19. Case 1: Station keeping cycle

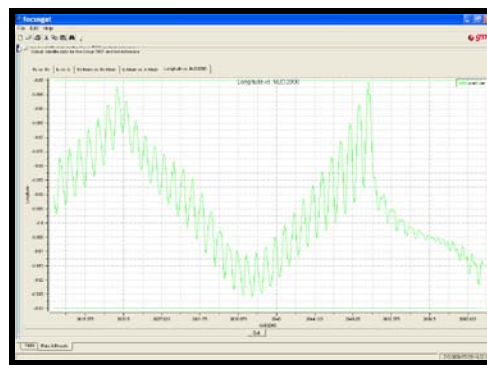


Fig. 20. Case 2: Reactive constrains

4. FUTURE ENHANCEMENTS

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

- Implementation of the station keeping cycles for one day.
- Introduction ionic manoeuvres control.
- Dynamic computation of the eccentricity control cycle along the whole simulation.

5. CONCLUSIONS

focusgat, the evolution of GMV's commercial package *matool* is a new software 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 GEO satellites [3].

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

6. ACKNOWLEDGEMENTS

The *focusgat* development has been financed by ESA Contract "New features for TEC-ECM guidance tool: *Matool*" study.

7. REFERENCES

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