LOW THRUST ORBIT TRANSFER OPTIMISER FOR A SPACECRAFT SIMULATOR (ESPSS -ECOSIMPRO® EUROPEAN SPACE PROPULSION SYSTEM SIMULATION)

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ABSTRACT

The paper describes the general strategy for electric propulsion orbit transfers, an open source optimiser for orbit transfer based on averaging techniques and the integration of such trajectory optimiser into EcosimPro® ESPSS (European Space Propulsion System Simulation). EcosimPro® is a Physical Simulation Modelling tool that is an object-oriented visual simulation tool capable of solving various kinds of dynamic systems represented by a set of equations, differential equations and discrete events. It can be used to study both transients and steady states. The object oriented tool, with the propulsion libraries ESPSS from ESA for example, allows the user to draw (and to design at the same time) the propulsion system with components of that specific library with tanks, lines, orifices, thrusters, tees. The user enhances the design with components from the thermal library (heaters, thermal conductance, radiators), from the control library (analogue/digital devices), from the electrical library, etc. The use of the new feature included into ESPSS, the satellite library is particularly interesting for orbital manoeuvres because the satellite library includes the flight dynamic (orbit and attitude) capabilities for a full spacecraft including orbital, attitude perturbations and power concerns during Sun's eclipse phases. In order to simulate realistic missions, an optimiser for orbit transfer has been integrated thanks to the design of few new components for interfacing the optimiser and the existing library. Hence the simulations take into account the interactions between the AOCS and the optimal thrust direction wanted to perform the orbit transfer and real strategies for power management during eclipses. Full satellite missions, for example continuous electric orbit transfer from super-GTO to GEO is presented and particular behaviours highlighted.

Index Terms— Optimiser, low thrust, orbit transfer, EcosimPro

1. INTRODUCTION

The paper describes the integration of a trajectory optimiser into EcosimPro® *ESPSS* (European Space Propulsion System Simulation).

EcosimPro® is a Physical Simulation Modelling tool that is an object-oriented tool dedicated for system assessments and analyses. That is a visual tool capable of solving various kinds of dynamic systems represented by writing equations and discrete events. It can be used to study both transients and steady states. Such object oriented tool, with the propulsion libraries *ESPSS* from ESA for example, allows users to draw (and design at the same time) the propulsion system with components of that specific library with tanks, lines, orifices, thrusters, tees. The user enhances the design with components from the other libraries (thermal, control electrical, EP, etc).

Into the last release of ESPSS [**16**], new features address "Evolutionary behaviour of components" and "Coupled Simulation of Propulsion System and Vehicle Dynamics" , which is actually a "Satellite library" that includes the flight dynamic (orbit and attitude) capabilities for a full spacecraft including orbital and attitude perturbations.

In order to simulate realistic missions, an optimiser for orbit transfer has been integrated thanks to the design of few new components for interfacing the optimiser and the existing libraries of *ESPSS*.

A first very general review of the orbit transfer strategies is presented with some useful bibliography for references.

A second part deals with the low thrust optimiser principles without any boring large set of equations that are generally used for the description of such optimisers.

The integration of the optimiser into *ESPSS* is presented before a detailed example of application in the case of an orbit transfer from super-GTO to GEO with all the possible orbital and attitude perturbations and with a kind of worst case eclipses.

2. GENERAL STRATEGY FOR ELECTRIC PROPULSION ORBIT TRANSFERS

The main drawbacks of Electric Propulsion using High Specific Impulse Thrusters is the low thrust and the associated long duration of an orbit transfer.

A. STRATEGIES FROM GTO TO GEO

Lots of strategies [**3**] to [**7**] have been investigated before finding a valid continuous thrust strategy between GTO and GEO which can minimise the orbit transfer duration.

First studies were based on the thrust arcs strategy around the apogee (similar to the high thrust chemical propulsion "apogee burns"). The results indicated a slight increase of the ΔV needs (or propellant mass) wrt. the corresponding high thrust strategy but the duration of the transfer could be considered as prohibitive.

Second studies were based on the integration of the super GTO strategies into a thrust arcs strategy. The results were that the duration of the transfer could be decreased with burns around apogee and burns around perigee. The increase of the ΔV needed for achieving the orbit transfer were more significant.

Finally the continuous thrust strategy has been discovered and disclosed in the Koppel patents [**10**] (dealing with orbit transfer starting from an elliptical initial orbit that differs substantially from the target orbit, and in particular that has eccentricity that is different from that of the target orbit...) in order to decrease at a maximum the duration of the orbit transfer without taking care of the slight increase of propellant mass used during the orbit transfer manoeuvre because when using High Specific Impulse Thrusters the mass penalty due to higher ΔV is not really significant. Heavy optimization techniques, mainly ignoring possible service interruptions, conducted by S. Geffroy[**8**] have shown similar results as the proposed strategy. This strategy has been compared with the strategy given by Spitzer[**9**]. Lots of practical advantages have been found in favour of the so called continuous thrust strategy [**10**].

This simple historical shows that the duration of the orbit transfer between GTO ant GEO could be reduced by more than 60 % (with the same thrust level). This is naturally the counterpart of the loss of the manoeuvre efficiency. One should note also that the total number of orbits needed for the transfer has also been reduced by more than a factor 3. This is a very important result, because the radiations within the Van Allen belts can be minimised when the number of orbits crossing the proton belts are minimised. This number can be considered as directly in relation with the total number of orbits.

B. STRATEGIES FROM LEO TO GEO

Spiral strategies allow to perform the transfer without the need of any optimization tool. The well known Edelbaum equation (coming from optimization considerations) provides the ΔV needed between two different circular orbits at different inclination when ignoring possible service interruptions.

However, when the power on board is not fully available for the thrusters (during parts of eclipses for example), one cannot ignore anymore those possible service interruptions: the thrust has to be switched off during those service interruptions and finally only part of the orbit can be used for the orbit transfer. The major effect of those service interruptions in the orbit transfer degraded by the eclipses, even partially, is to increase the orbit eccentricity of the intermediate orbits. Thus the general problem becomes as pointed out in part A above to find the optimal thrust orientation for minimizing the transfer duration when starting from an intermediate elliptical orbit for reaching the circular GEO orbit. This goal falls also into the Koppel patents [**10**] claims.

C. OPTIMISER FOR ORBIT TRANSFER

Finally whatever the starting orbit is, in operation it is needed to find an optimal strategy for reaching the final orbit GEO. In addition to the possible service interruptions, for example caused by the power unavailability at the end of long Sun's eclipses or other thrust switch-off reasons like visibility constraint by ground station (even if we know since SMART-1 in operation in flight [**14**] that the visibility is not a real problem and that operators can safely "sleep" when the electric propulsion is switched on because in any case the accumulated delta V off visibility is low enough for recovering the location of the spacecraft), the orbit transfer may be degraded by the presence of many possible perturbations, among them, the Earth flatness effect (so called J2), the Moon and Sun gravitational potential perturbation, the Sun pressure on the large areas of the satellite.

A tool that optimise the orbit transfer and take into account in the optimization problem all the above mentioned perturbations and service interruptions is not available in the public domain (and maybe because of its large complexity, the optimization problem is not suited for fast solutions and may not be very robust).

However a robust very fast tool derived from S. Geffroy[**8**] thesis, "Program Mipelec" is freely available from CNES website in [**11**].

Hence the logic used in the present work is to follow the Bellman principle [**1**], that is to optimise the "time to go" from every starting point with such optimiser that do not take any constrains or perturbations. The integration of such optimiser is needed into a full perturbation and service interruption orbit propagator for providing the right thrust direction via the attitude control.

D. SHORT SYNTHESIS OF THE ORBIT TRANSFER OPTIMISER "MIPELEC"

From [**12**] the equations of motion (6 orbit variables and equations for perigee altitude, apogee altitude, inclination, perigee argument, right ascension of the ascending node (*RAAN*) and true anomaly) with the real mass (7th variable and equation linked to the propulsion mass consumption) are normalized introducing a small non-dimensional parameter (thus valid for low thrust propulsion only) with "*Sma*" standing for "semi major axis length" and μ_{Earth} being the Earth gravitation, the small parameter ε is:

$$\varepsilon = \frac{Thrust_{\max} \cdot Sma_{final}^{2}}{Mass_{initial} \cdot \mu_{Earth}} \qquad (1)$$

The full problem is reduced to a first order problem in ε for the argument of true longitude (angle better suited when dealing with circular and low inclination orbits, similar to the true anomaly angle from perigee but with the addition of the perigee argument and the RAAN). Hence, the true longitude becomes the independent variable instead of the time. Further a transformation, with an additional independant variable such as the initial condition is set to 0 for this new independant variable and final condition is set to 1 for this new independant variable, is performed in order to rearrange the problem into a classical *ODE* two point boundary value fixed problem.

The optimisation problem of minimum final time is then reformulated by adding the constrains differential equations multiplied with their Lagrange parameters into the augmented performance index (thus introducing an Hamiltonian and doubling the number of variables) and the minimisation of the Hamiltonian provides the optimal thrust and thrust direction. Hence the optimised problem is reduced to a two point boundary value problem with 14 differential equations.

Finally the equations are averaged with respect to the fast rotating variable (the argument of true longitude, so very similar to the orbital true anomaly) but keeping the averaged command (thrust direction) depending explicitely on that rapid movement. This is finally the problem that is solved as a two point boundary value problem.

The drawback of such approach involving averaging technique is that the initial conditions in terms of orbital true anomaly (which is the fast rotating variable) cannot be specified, that means that the problem is solved for always starting at the perigee (with an orbital true anomaly=0). Hence some specific actions into the orbit propagator must take care of that drawback.

E. IMPLEMENTATION OF ORBIT TRANSFER OPTIMISER "MIPELEC"

The program was written end of the 90s in Fortran 77 for Sun stations. A short time later it become available as an open source [**11**]. A complete review of the source code was needed in order to be able to be compatible with Windows on PC. On such Windows platform, the program didn't have any graphical interface, making the checks and verifications quite difficult. But integration of the program Mipelec within Microsoft Excel (using Excel macro commands) make the tool quite well user oriented and good outputs could be performed automatically. Intensive use of the tool was performed for some specific applications of GTO to GEO transfers and comparisons with other tools (like TriaXOrbitaL from KopooS[**13**]) were performed showing advantages up to about few % in duration of transfer and also because it is a full continuous thrust orbit transfer in terms of mass consumption in favour of Mipelec.

3. INTEGRATION OF THE OPTIMISER FOR ORBIT TRANSFER WITH ESPSS ORBIT PROPAGATOR

The Satellite library of ESPSS includes the equations of the orbit propagator in the *Frame* component. The *Frame* component is featured with one input port called *Forces* (for connecting there all component providing thrusts and force perturbation, angular momentum) and output several results to a port called *State* (with the status of the orbital and attitude variables, and also the bodies Sun, Moon and all other planets vectors).

According to [**2**], a first new component called *Sensor* has been defined for mainly capturing the value of the true anomaly from the *State* port of the *Frame* and outputting, thanks to the optimiser results, the command to a *PID* for driving the reaction wheels.

A new major component *OT* has been defined for the orbit transfer optimization. Its output (toward the previous first new component) are the current optimal thrust direction and the current true anomaly provided by the Optimiser .

Thus the component *OT* include the Mipelec program transformed as a simple Fortran subroutine that from input parameter (defined in the data of the component *OT*) of the initial and final orbit, thrust, mass and *Isp* provides an array for the optimal thrust direction versus the time. Interpolations are performed for delivering the current values for thrust direction and *OT* true anomaly. An automatic feature is included into that component *OT* for allowing new optimizations each time any one of the data is changed while waiting the time where the true anomaly is zero or near zero for effectively performing it.

The Sun's eclipses are already computed in the solar arrays component, and it is again directly computed at system level. When eclipses occur, the propulsion system is supposedly fed by the electrical power coming from the batteries for a limited period of time (up to 72 minutes for a GTO to GEO transfer) after what the thrusters are authoritatively switched off. The end of eclipses automatically switches on the thrusters again.

As the cumulated time of the Off-thrust period can become significant, for the right synchronization of the perigee times between Optimiser and Frame, an input of the component *OT* is a time shift. This time shift is detected by the component *Sensor* once both Optimiser *OT* and *Frame* have reached their perigee. In addition the component *Sensor* computes the quaternion error between the current attitude quaternion of the satellite and the optimal one given by the optimal thrust direction. The quaternion error drive through the *PID* each of the three reaction wheels of the system for orienting the optimal direction of the thrust.

Finally the system model is shown in Figure 1. All components are symbolised by independent objects with links to the ports.

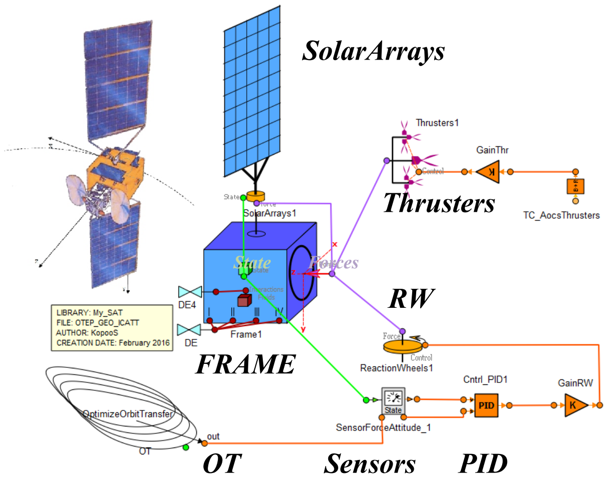

Figure 1. System model under EcosimPro ESPSS

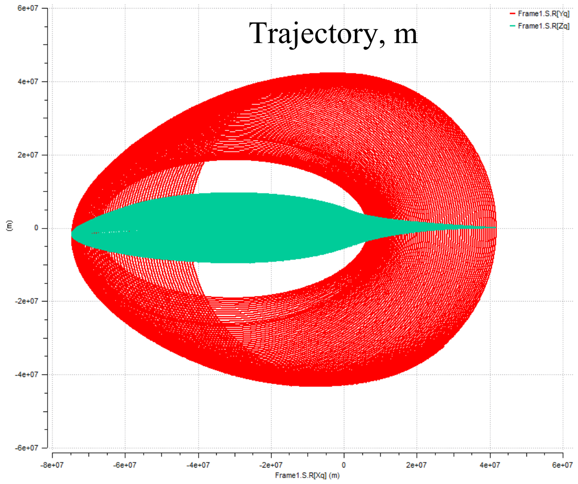

Figure 2. Orbit transfer optimised in operations

4. OPERATIONAL TEST CASE: SUPER-GTO TRANSFER TO GEO

Model Figure 1 is driven by a set of commands called in EcosimPro® *Experiment* that can update some of the characteristics (data) of the model if needed and provides the sequence of commands or loops of commands.

The case of interest here is a full continuous Electric Propulsion super-GTO transfer to GEO with all the possible perturbations: Earth flatness J2, Moon/Sun perturbations, Solar pressure (when not in eclipse) and eclipses. In order to reduce a bit more the number of passages into the Van Allen belts, it is foreseen to use two thrust levels: a higher thrust level in a first part followed by a lower thrust with a higher specific impulse for having less mass consumption.

The Electric propulsion used on-board is a maximum thrust of 1.239 N with an Isp of 1457 s, the specific power to thrust ratio is 15 kW/N, so the power needed for the propulsion is 18.6 kW. The second level of thrust is reduced to 929 mN with an Isp of 1942 s using the same total power.

The experiment includes 3 updates of the Optimiser *OT* after the first initialization.

A general view of the operational orbit transfer is shown in Figure 2. The two components of the position vector R_y and R_z are plotted versus the component R_x aligned with the semi-major axis of the initial orbit. The initial orbit is a super-GTO 200 x 61000 km inclined at 27° and the final orbit is the GEO. The orbital parameters of RAAN and perigee arguments are both set to zero so that the starting date of the operations at spring equinox (20 March) is a kind of worst case in order to maximize the eclipse's durations occurring at the apogee of the firsts orbits (of course, a choice of perigee argument of 180° instead of 0° could avoid this worst case for this date). The long eclipses can be seen in Figure 3 where the thrust vector component (in satellite axis) exhibits drops to zero when battery power can no more be used during long eclipses. The small perturbing forces (from Sun pressure, etc.) are included in the thrust as one can see as a large zoom for the components along X, Y. The two levels of the main thrust force (along the direction Z satellite) are clearly apparent on Figure 3 as well as in Figure 6 for the mass versus the time where higher thrust slope is much stronger than after the reduction of thrust.

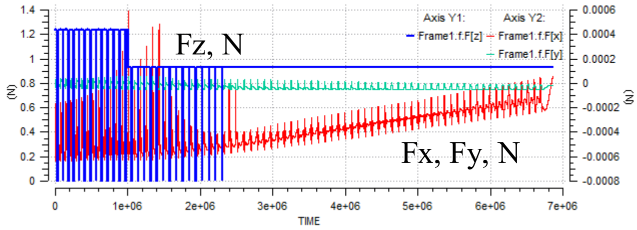

Figure 3. Thrust level (drop to zero in long eclipses)

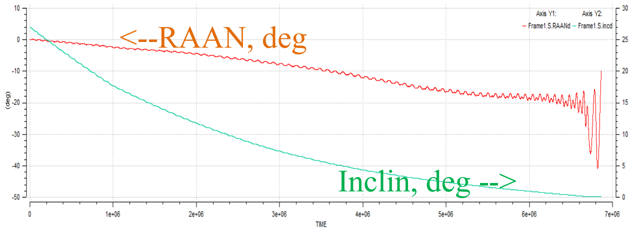

Figure 4. RAAN evolution and inclination down to 0°

The orbit transfer is well described by the evolution of the orbital parameters: in Figure 4 the inclination changes from 27° to almost 0° at the end of the orbit transfer. The evolutions of the altitudes of apogee and perigee and the altitude versus the time are plotted in Figure 5. One can notice first that together, Figure 4 and Figure 5 are in line with the claims of the patents [10]. For the case studied, the total number of orbit is 77. In addition that last interesting plot shows also (with the time independent data of the Optimiser which have been changed into the *experiment* loop: apogee and perigee altitudes of *OT*) the time at which new optimizations have been performed: the first one at initialization, the second when the thrust level has been reduced and two other times at 33% and 66% of the total transfer duration. This plot shows also that the final parameters of the orbit apogee and perigee altitudes converge strictly toward to the optimiser specified goal for the final GEO orbit.

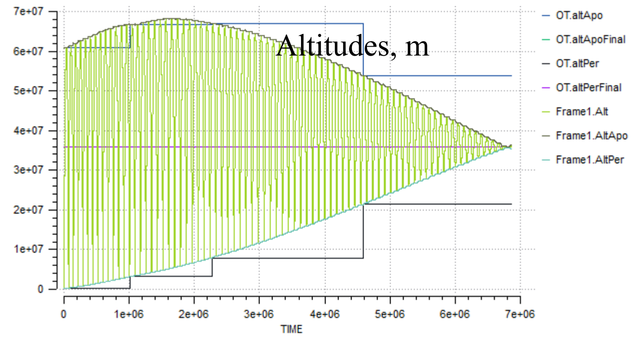

Figure 5. Apogee, Perigee altitudes and Optimiser data

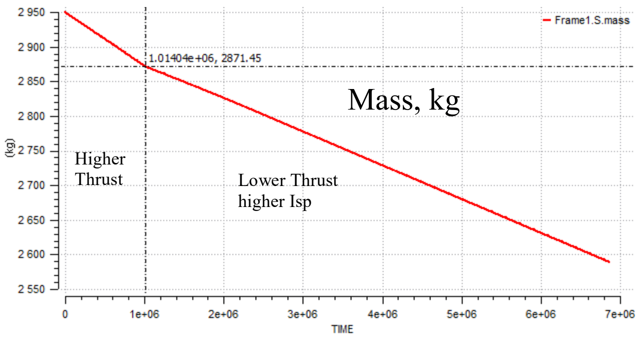

Figure 6. Total satellite mass evolution

The plot shown in Figure 7 is for information about the attitude quaternions wrt Earth centred inertial (ECI). The quaternion components are Q_1 the real part and Q_2 to Q_4 the imaginary part. It is interesting to note that the last quaternion component is always null which is in line with the fact that the thrust is aligned along the Z axis of the satellite, so any orientation around that axis has no effect and thus is not needed (unless this unused degree of freedom for propulsion can be used, like for SMART-1, for performing an orientation around that axis to allow to orient the solar arrays at best with respect to the Sun). The "automatic" change of the thrust orientation strategy at 1.5 millions of seconds is well highlighted in this plot while the plot in Figure 8 showing the thrust orientation unit vector components wrt to the Earth centred inertial frame is much less obvious due to the unit vectors cross coupling effects between components.

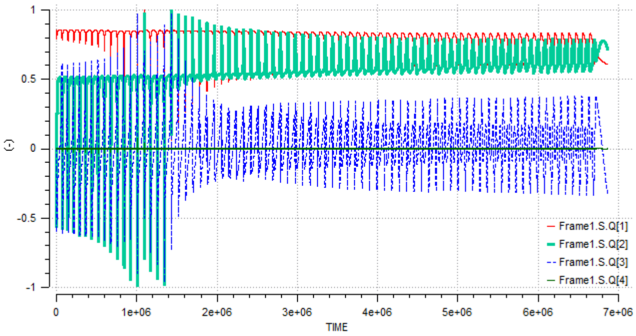

Figure 7. Quaternion of satellite attitude wrt ECI

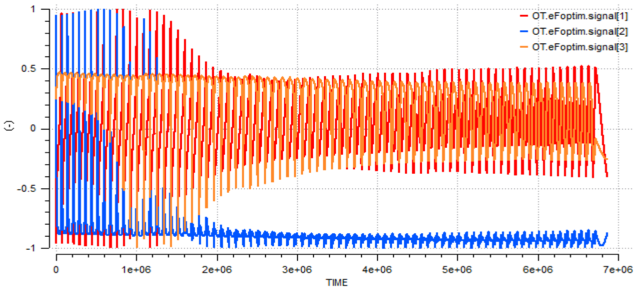

Figure 8. Thrust orientation evolution wrt ECI

Finally it is important to note that most of the difficulty of the integration of the Optimiser into ESPSS was lying in the synchronisation problem. The plot shown in Figure 9 describes two aspects: one dealing with the quite large change in the optimised final time (after accounting for the significant thrust-off periods during service interruptions i.e. during parts of eclipses where the thrust is turned off, and the consequences of the thrust level reduction) the total transfer duration increases by about 2 millions of seconds (on the left side scale), the second part of the plot (at right side scale) is dealing with the so called time shift *Tshift* for synchronising the respective time at perigee of the orbit propagator in ESPSS and the one given by the optimiser *OT*. This synchronisation shift is, at the end of the transfer, reaching about 10 hours, meaning that the results of the Optimiser given for 10 hours later than the current time of the ESPSS are taken into account for the right optimised orientation of the thrust into the ESPSS simulation.

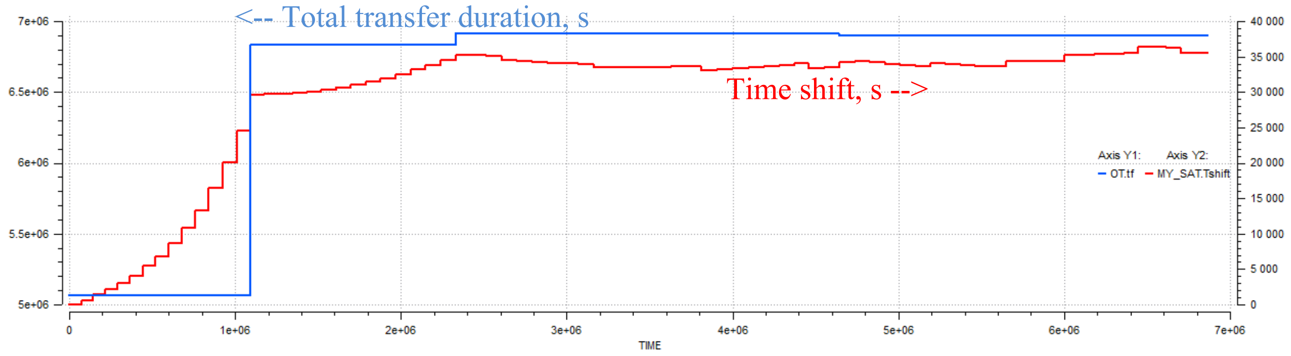

Figure 9. Total transfer duration at each time the Optimiser is called; Time shift synchronization at perigee

No attempts were made to make more than 3 updates of the optimiser performance because only very slight changes in the final outputs would result. But of course, taking into account the fact that the optimiser routine run time is quasi nil, this could be performed for each orbit as well.

The main outputs of the transfer are:

Total duration of the super-GTO to GEO transfer (with two levels of thrust and off thrust periods): 2.6 months

Total ΔV : 2327 m/s while the optimised ΔV for a full continuous constant thrust orbit transfer (without any perturbations, without thrust off periods and without changes in the thrust level) would be 2306 m/s. Hence the quite "real" Total ΔV represents an increase of less than 1 % wrt the optimised ΔV (in previous rough results [**15**], the cost of the real transfer was slightly higher, but in the present paper the number of points used for the Optimiser has been slightly increased to 2000 points for a better description and accuracy of the thrust orientation during the whole orbit transfer).

5. CONCLUSION

A successful low thrust orbit transfer optimiser integration within a new feature of the propulsion library *ESPSS* i.e. the Satellite library, has been performed. The effects of the orbital perturbations, of the operational constrains and service interruption composed of off-thrust periods can be taken into account while keeping the optimised process according to Bellman principle.

The understanding of the optimiser drawbacks was needed for managing properly the optimised thrust orientation during an orbit transfer into the orbit and attitude propagator tool of *ESPSS* Satellite library [**16**]. The main result of the study shows that only few updates of the optimised thrust orientation are needed in order to finally reach the final goal at GEO. But those few updates are of course mandatory to be performed. The losses in term of delta V are very low (<1%) while the main effect is on the real duration (+ 2 days) which includes the off-thrust periods during parts of the long Sun's eclipses.

6. ACKNOWLEDGMENTS

KopooS thanks the French space agency CNES for the distribution of the program source of Mipelec freely on the web.

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