INTEGRATED TRAJECTORY AND ENERGY MANAGEMENT SIMULATOR FOR ELECTRIC PROPULSION SPACECRAFT

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ABSTRACT

We present a new spacecraft simulator intended to allow a realistic assessment of the behaviour of the main spacecraft subsystems in missions with electric propulsion. Built around a dedicated low thrust trajectory propagator, the simulator takes into account at each time step the exchanges of energy among the different subsystems and the instantaneous power production as a function of orbital position and spacecraft attitude. By such direct simulation approach, the mission designer is able to catch the full interplay of spacecraft dynamics, onboard energy flows and propulsive thrusting.

INTRODUCTION

Energy management is a key issue in spacecraft equipped with electric propulsion systems. Such high specific impulse thrusters are normally operated for long durations, ranging from a few hours to several months, to impart a small but persistent acceleration to a space vehicle. Substantial delta-V may be produced in this way, resulting in large modifications to the spacecraft trajectory, using a lower propellant mass than for chemical thrusters. However, for the whole duration of thruster operation the propulsion system must be supplied with electrical power, either from the solar arrays (or other onboard generators) or from batteries. At typical power-to-thrust ratios ranging from 15 to 50 W/mN, the drain on the onboard energy reserve can be quite severe and the instantaneous power demand will have to be carefully weighed against that of the other onboard systems and, of course, of the payload. Therefore, contrary to the traditional case of impulsive chemical thrust (firing at high thrust for short duration, with negligible onboard power drain), the use of electric propulsion has a profound impact on the day-to-day management of the onboard resources.

Spacecraft dynamics under continuous electrical thrust and energy management are closely coupled: in many cases, orbital and attitude dynamics dictate the conditions for exposure to sunlight of the solar arrays (eclipse periods, angle of view, etc.) and power and energy availability govern the possibility to switch on the electric thruster, which in turn affects the dynamics, etc. In power-limited or energy-limited spacecraft, “a priori” determination of the availability of enough energy to operate the thruster (or any other power hungry subsystem) at a given moment during a mission is not trivial. Therefore, mission design with electric propulsion is normally carried out by adopting a conservative approach towards the use of onboard power; typical choices are, for example, to oversize the power system so to allow simultaneous operation of the thruster and the payload at any time; or, conversely, to restrict thruster operation to periods of payload inactivity, and vice-versa.

The mission simulator we present in this paper has been devolped to overcome the limitations of such generic approach and gain direct insight into the resulting effects of spacecraft subsystems influencing each other dynamically while competing for available energy. The simulator features great flexibility in the definition of the spacecraft architecture and of the thrusting strategies and is therefore suited to a large variety of different operational scenarios.

SOFTWARE STRUCTURE

The simulator (**SATSLab** - **S**pacecraft **A**ttitude, **T**rajectory and **S**ubsystems **Lab**oratory) has been developed during the last few years as a suite of software modules built around the D-Orbit core. D-Orbit is Alta’s proprietary high-accuracy low thrust orbital propagator [1], featuring full perturbations, the possibility to simulate interplanetary trajectories with a wide variety of main bodies, and data export for visualization in Celestia. The SATSLab modules include attitude dynamics and control, solar array and battery simulation, thruster and payload simulation. The user can describe the spacecraft geometry as a combination of pre-defined solids or import a geometry file from a commercial 3D modeller, so that shape-dependent attitude and orbital perturbations, such as those due to solar radiation pressure or to atmospheric drag, can be computed to high accuracy. SATSLab can implement a variety of in-plane and out-of-plane thrusting strategies, including complex strategies based on real-time evaluation of the onboard resources, through an user-friendly GUI or by external text-files and can be extended to any custom-tailored propulsion strategy to accommodate for specific mission needs. With the computational modules written in MATLAB™ and the GUI in Java™, SATSLab is completely platform-independent, providing the same functionality and user experience in the Windows, Mac OS X and Linux environments.

The simulator propagates the spacecraft state vector through time by computing, at each time step, position and velocity, the spacecraft attitude, and the status of the onboard subsystems. The state vector is a variable size array that can accommodate up to 14 elements according to the user's choices; it includes such items as the instantaneous power provided by the solar arrays, the level of charge of the batteries, the power consumption of the various subsystems and the payload, the magnitude and orientation of the thrust vector, etc. (Fig. 1). Most of the state vector components are strongly coupled. The structure of the software is presented schematically in Fig. 2.

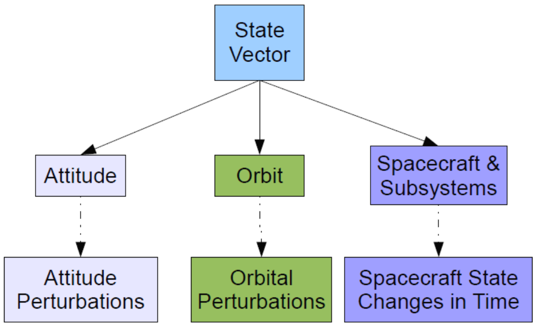

Fig. 1 - The state vector.

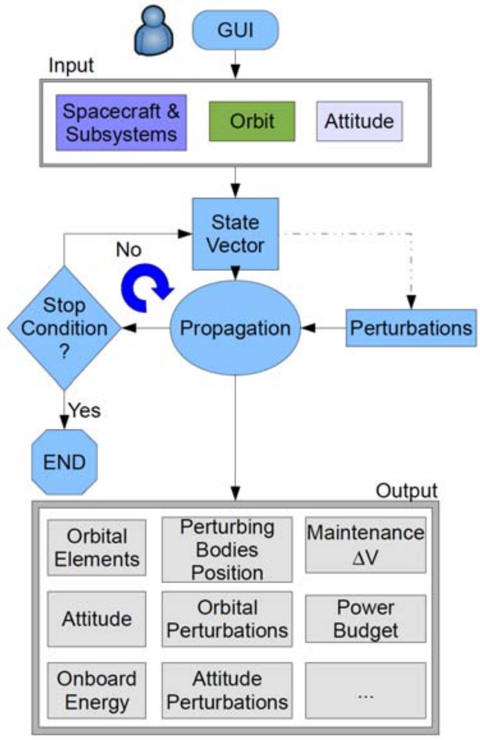

Fig. 2 - SATSLab Structure.

Fig. 3 shows that almost every perturbative effect accounted for interacts with a large number of different components of the state vector. As an example, the link between the attitude control torque and the state vector components is mainly due to the position of the spacecraft, its instantaneous attitude with respect to the one desired and the needed power with respect to the onboard available energy.

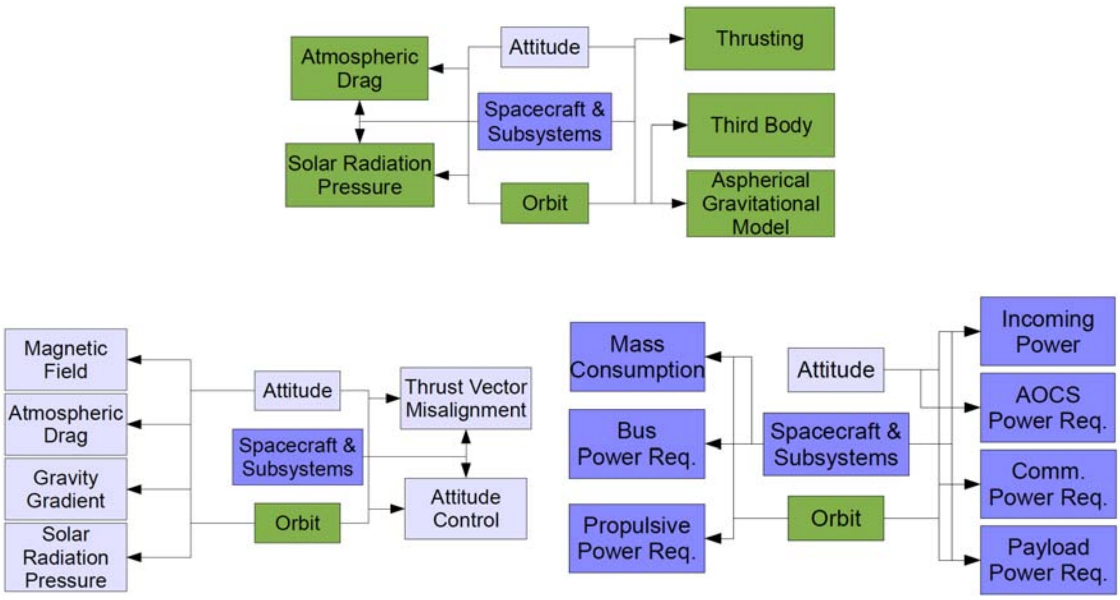

Fig. 3 - Interconnections among state vector components. Top: orbital dynamics; bottom left: attitude dynamics; bottom right: subsystems energy.

Onboard available energy is computed during the simulation considering the power generated by the solar arrays (including efficiency degradation with aging) and the power requirements of each simulated subsystem. The user can define custom power consumption laws for the payload, the spacecraft bus, the AOCS and the propulsion subsystem. A simple choice, yet realistic enough for preliminary analyses, is to allocate a certain constant power consumption to the S/C bus and to switch on the payload at pre-defined orbital intervals.

SPACECRAFT DYNAMICS

Orbital propagation is based upon the classical formulation by Cowell:

$$\ddot{r} = -\frac{\mu}{r^3}\vec{r} + \vec{a}_p \tag{1}$$

where the term $\vec{a}_P$ represents all the perturbations linearly summed. The orbital propagation options allow the user to simulate the orbital evolution in the standard Cartesian reference frame or using modified equinoctial orbital elements [2]. The trajectory may also be computed neglecting the orbital perturbation and considering a simple two body, unperturbed keplerian model. In this case the simulation is focused on the attitude and subsystem energy evolution, neglecting the impact of orbital perturbations on the trajectory, to get a quicker first glance at mission feasibility. The software provides a wide range of selections for the central body of the spacecraft trajectory featuring a full set of perturbations for geocentric and interplanetary trajectories.

SATSLab is designed to compute the intensity of atmospheric drag and solar radiation pressure (SRP) perturbations taking into account spacecraft mass, inertia properties and geometry, Earth/spacecraft and Sun/spacecraft relative positions and a number of other influencing parameters. In particular, spacecraft mass and principal moments of inertia govern the connection between the perturbation forces and torques, and orbital and attitude dynamics, respectively. The applied torques are computed by the software considering the pertubative effects (solar radiation pressure, atmospheric drag, magnetic torque, thrust misalignment, etc.) and the attitude control torque provided by the Attitude Control Subsystem. The control torque is modeled as provided by means of reaction wheels and/or torque rods, with an impact of the onboard available energy and affecting the rest of subsystems, as well as the spacecraft trajectory, in various different ways.

For the computation of atmospheric drag and SRP, spacecraft geometry is the major influencing parameter. SATSLab spacecraft geometry definition module allows the user to pick a detailed 3D CAD model of the spacecraft, a simple solid shape or a preset geometry to describe the attitude-dependent exposed area and the location of the center of pressure (for either solar radiation or atmospheric drag). The information provided by the user is then analyzed to set up four data tables containing a discretized description of the spacecraft geometry. Indeed, the values of the exposed cross section (A_S and A_D) and of the vector of the center of pressure offset with respect to the spacecraft center of mass ($\vec{P}_S$ and $\vec{P}_D$) for each pair of azimuth-elevation angles (θ,α) are sufficient to describe the spacecraft to the end of computation of SRP and air drag. At each timestep during the propagation, the orbital and attitude perturbations due to SRP and atmospheric drag are computed by evaluating the solar view angle and the orbital velocity vector angle with respect to instantaneous attitude and extracting the A and $\vec{P}$ values via interpolation from the spacecraft geometry tables. Torque is given by the expressions:

$$\begin{aligned} \vec{T}_D &= \vec{P}_D(\theta,\alpha) \times A_S(\theta,\alpha)\left(-\frac{1}{2}C_D\,\rho\,\vec{v}_{rel}\,|\vec{v}_{rel}|\right) \\ \vec{T}_S &= \vec{P}_S(\theta,\alpha) \times A_D(\theta,\alpha)\left(-p_{SR}\,\xi\,\frac{\vec{r}_{Sun-SC}}{|\vec{r}_{Sun-SC}|}\right) \end{aligned} \tag{2}$$

where C_D is the drag coefficient, ρ is atmospheric density, $\vec{v}_{rel}$ is the spacecraft orbital velocity, p_{SR} is the epoch-dependent solar irradiation, ξ is the average reflectivity of the spacecraft surface, and $\vec{r}_{Sun-SC}$ is the Sun/spacecraft vector. Fig. 4 presents a flowchart for the determination of SRP and atmospheric drag perturbation, and the definition of azimuth and elevation in the body principal reference frame.

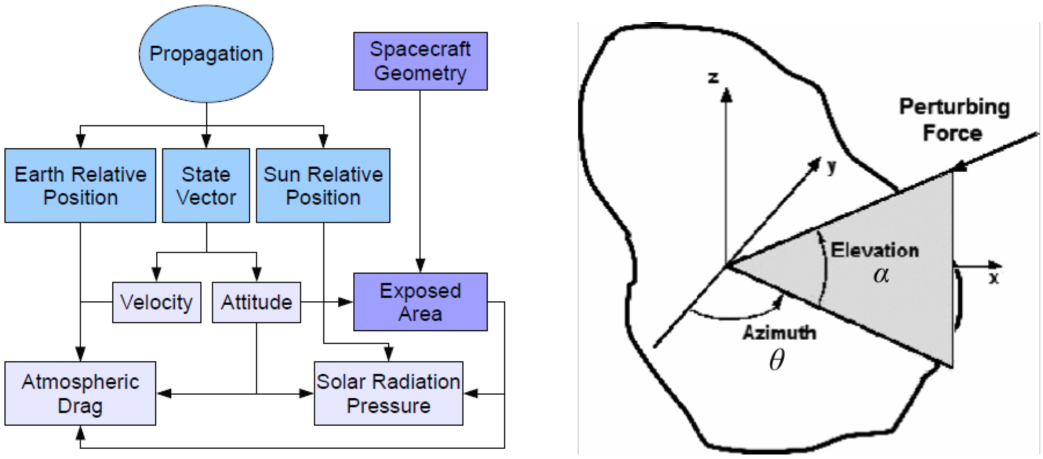

Fig. 4 - Left: solar radiation pressure and drag perturbation determination flowchart;
right: relative position of perturbing force and orbiting body.

THRUSTING STRATEGY AND COUPLING WITH ENERGY MANAGEMENT

SATSLab offers great flexibility in the implementation of complex thrusting strategy, usually associated to real-time mission operations and to the implementation of a high degree of spacecraft autonomy. The capability of SATSLab to perform fully coupled simulations with adaptive thrusting strategies allows for very realistic, sophisticated simulations of low thrust missions.

SATSLab allows the user to define the desired thrusting strategies accounting for the spacecraft position, the mission time or the Julian Day, the onboard available energy, the eclipse condition. For a more complete strategy definition, different thrusting strategies can be combined and used in different phases of the simulation according to spacecraft position and mission time. The simplest thrusting strategy available in SATSLab (indicated in Fig. 5 as "Predefined") consists of a time constant strategy where the thrusting conditions are only determined by the Spacecraft Propulsion Subsystem (SPS). A more general strategy can be set by the user specifying several restrictions on the SPS functioning. Indeed, the thruster operations can be adjusted during the integration considering the spacecraft position, attitude, and the onboard available energy. Depending on the mission purposes, position-dependent strategies may be defined in order to modify a given orbital parameter or a set of them.

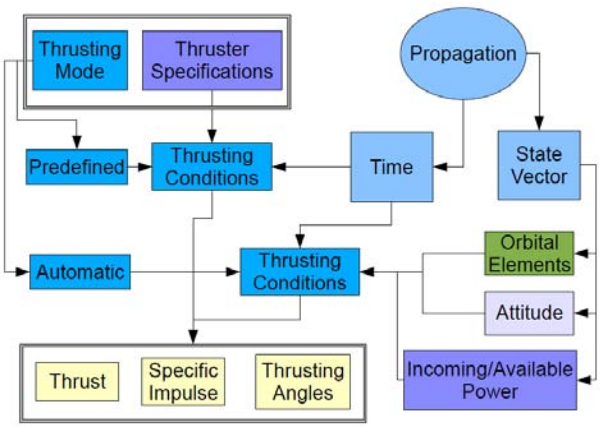

Fig. 5 - Thrust conditions determination.

In orbit raising maneuvers, the optimal rate of change of semi-major axis is generally obtained with tangential thrusting strategy maintained for the entire orbit. The same thrusting strategy applied in an angular region around the perigee or the apogee can raise the orbit apogee or decrease the orbit perigee. Different regions can similarly allow the user to obtain the desired change of a given orbital parameter or of a combination of them. More sophisticated strategies can be implemented defining a particular thrust vector for the entire trajectory or for a part of it, considering both the in-orbital plane component and the out of plane component of the thrust vector. These strategies can also be imported by the user from external text files. Different thrusting strategies can also be combined in a multi-strategy approach, with the software switching to different thrust laws when certain user-defined conditions on components of the state vector, or on functions of its components, are met.

By way of example, the thrusting conditions or the thrusting strategy may depend on the spacecraft position along its orbit so that the thruster is operating continuously for a given period only, switching to a phased thrusting strategy upon the attainment of a given condition (such as, e.g., when the battery charge drops below a certain level). A typical orbital maintenance strategy consists of maintaining the spacecraft within predefined altitude boundaries alternating ballistic and thrusting phases. This quite simple strategy is not particularly demanding for the spacecraft on condition that, along the thrusting arcs, enough electrical power is available. This may not be always the case, as for instance during natural eclipses. A convenient way to avoid such eventuality, and one easily modelled in mathematical terms for mission analysis, is to turn off the thruster during the eclipses; however, this solution could turn out to be too conservative and to result in an undesired increase of the transfer time. This can be avoided by direct assessment of the actual energy available onboard, as in SATSLab's simulations.

Given the position of the thruster with respect to the body centered principal reference frame, the thrusting direction is completely defined once the position of the spacecraft in the inertial reference frame is provided by the attitude propagation module. The determination of the power requirements of the attitude control system, as well as a detailed knowledge of the attitude perturbation torques, are fundamental to obtain both the actual attitude, which also may constrain (in the more advanced options) the thrusting direction, and the overall subsystem power requirements. The thrusting vector can be kept constant with respect to a preset reference frame for the entire duration of the simulation or can be related to the estimated spacecraft attitude.

SIMULATOR OPERATION

SATSLab's Graphical User Interface (GUI) is designed to provide the user with a constant and complete control of the propagation inputs and parameters before and during the simulation process. Fig. 6 shows the main GUI window with the Orbit Definition tab opened in the bottom part of the window; different areas are highlighted in colors.

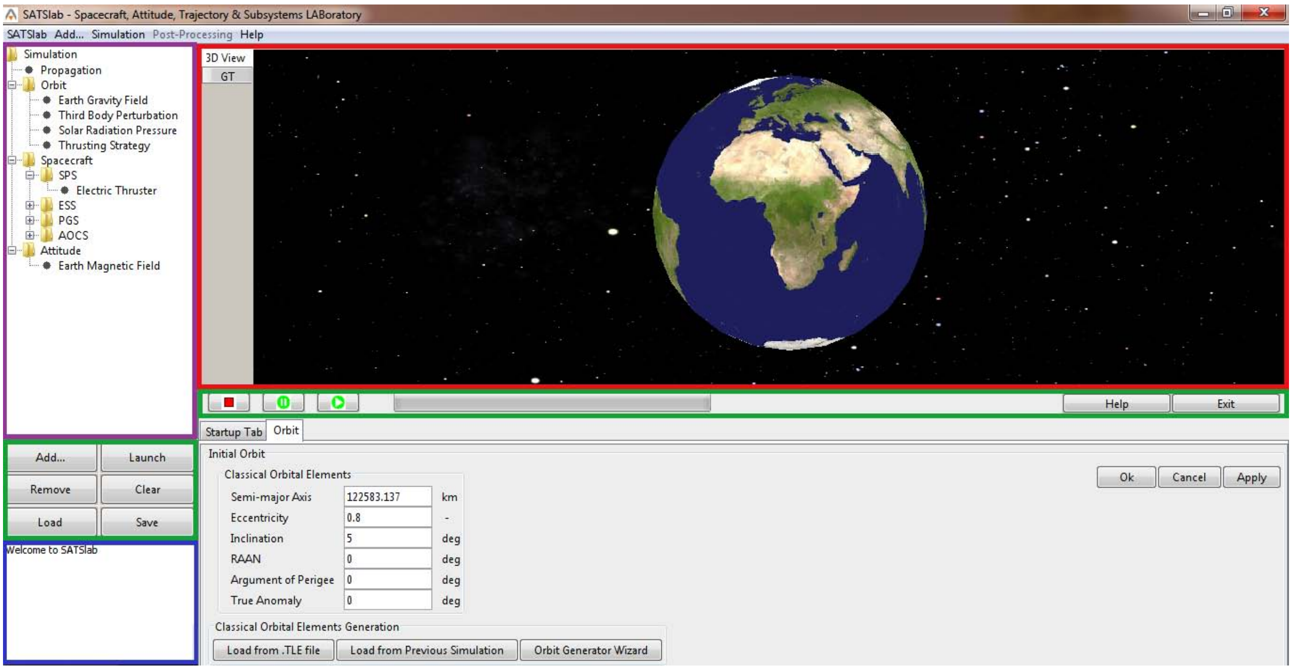

Fig. 6 - SATSLab main GUI window.

The red box identifies the visualization and post-processing area. The green box contains the control buttons and the progress bar. In the bottom left part, the blue boxs highlights the communication panel. In the left part, inside the purple box, there is the simulation tree, stemming from the principal node (aptly named *Simulation*). The user can add four "children" nodes: *Spacecraft*, *Orbit*, *Attitude* and *Propagation*. Further children nodes can be added to each one of these to include specific options or preferences to each module.

The typical user's workflow through the simulation process (Fig. 7) can be summarized in the following steps:

- Create and populate the simulation tree
- Assign simulation parameters

- Create an initial orbital state
- Create an initial attitude state (optional)

- Select an integrator (mandatory for simulations involving perturbed keplerian dynamics)
- Launch the integration
- Graph or export the simulation results

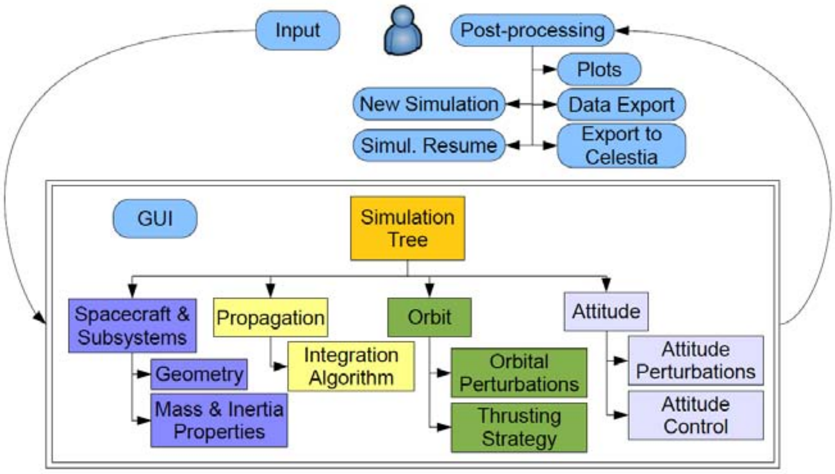

Fig. 7 - SATSLab User Workflow.

SIMULATION EXAMPLE

As an example of a simple situation where the coupled simulation leads to unexpected insight into the mission feasibility, let's consider a 1 m cross section remote sensing spacecraft in a polar, non- sun-synchronous circular LEO at 300 km altitude. It is required to maintain the spacecraft altitude within a 50 m range; to this end, atmospheric drag is compensated by periodic firing of a HT-100 Hall thruster [3, 4]. At 8 mN thrust, the HT-100 runs at 25% efficiency with a specific impulse of 1200 s, requiring 188 W of electrical power input. The spacecraft has a continuous power consumption of 25 W for housekeeping tasks during all of the mission. At each orbit, a 100 W payload is switched on for half the orbital period.

We assume a onboard power generation capability of 150 W maximum from the solar arrays, consistent with a small, unexpensive satellite. A preliminary analysis shows immediately that the power required is as high as 313 W during the combined operation of the thruster and the payload, a condition that can actually occur very often. This power requirement exceeds by far the maximum output from the solar panels; to make the matter worse, the payload might need to be switched on during night (for example, to operate a small SAR or other active imagers). Therefore, it would appear that the mission is impossible unless some of the constraints are relaxed: e.g., one could choose a higher orbital altitude to lower the atmospheric drag, which would however result in reduced remote sensing performance. Similarly, any other adjustment to the mission parameters would result in reduced performance or increased mission cost.

Direct simulation of the mission with SATSLab gives a quite different picture. The mission turns out to be feasible by adding a 150 Wh battery, at the expense of just about 1 kg additional mass with present day cell technology. The simulator takes care of switching on the thruster to perform drag compensation only when available energy is enough to guarantee correct operation of the payload, as an onboard autonomous controller would do. Fig. 8 shows the computed orbital altitude as a function of time during one day; Fig. 9 shows the charge left in the battery at each moment during the same period: the depth of discharge stays safely below 20% at all times.

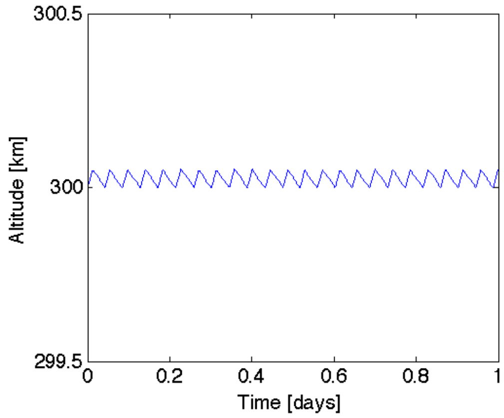

Fig. 8 - Orbital altitude

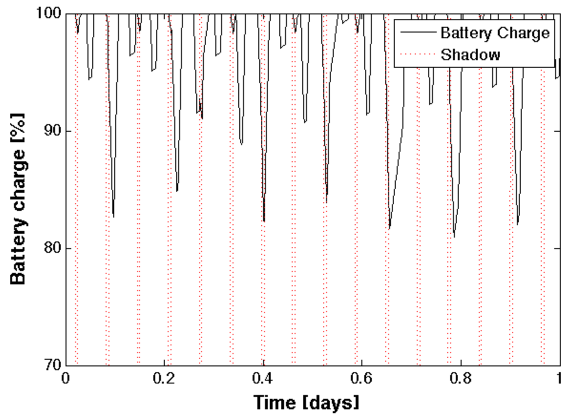

Fig. 9 - Battery charge status

CONCLUSIONS

The SATSLab simulator is best suited for analysis of missions with electric propulsion or for those cases in which energy availability onboard has a strong impact on mission profile. Direct simulation enables realistic assessment of mission operations with limited onboard resources, allowing for better understanding of the mission operational constraints and enhanced overall performance. The simulator is constantly updated with additional modules, such as a thermal control module presently under development, to provide a flexible tool for realistic mission assessment.

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