Joint Trajectory and Energy Management Simulation of Low Thrust Missions

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Spacecraft equipped with electric propulsion systems need an accurate monitoring of on-board available energy. The high power-to-thrust ratios typical of these propulsive systems and their long thrusting periods cause a major demand of electrical power, so that the use of electric propulsion strongly influence the management of on-board resources. The strong interaction among power generation, energy storage and propulsion is evident considering that both the energy availability and the power required by the main subsystems affect the spacecraft thrusting capabilities. Thus, it is clear that these aspects must be considered jointly even in preliminary mission analysis. The integrated simulator here presented, SATSLab, is conceived to support preliminary mission analysis considering the coupling of on-board available energy and attitude-orbital dynamics in electric propulsion equipped missions. In this paper a brief overview of the STASLab software package is given. Examples of relevant mission scenarios are presented, highlighting the simulator capability to reveal non-trivial features of the energy-trajectory interplay.

I. Introduction

ENERGY management is a key issue in spacecraft equipped with Electric Propulsion (EP) systems, which must be supplied with electrical power, either from solar arrays (or other onboard generators) or from batteries, for the whole duration of thruster operation. At typical power-to-thrust ratios ranging from 15 to 50 W/mN [1], the drain on the onboard energy reserve can be quite severe and the instantaneous power demand have to be carefully weighed against that of the other onboard systems and, of course, of the payload. Spacecraft dynamics under continuous electrical thrust and onboard 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 EP system, which in turn affects the dynamics, etc.

In general, “a priori” determination of the availability of enough energy to operate thrusters (or other power-hungry subsystems) at a given moment during a mission is not trivial. Therefore, preliminary spacecraft and mission design with EP is normally carried out adopting a conservative approach towards the use of onboard power. Typical choices are, for instance, to oversize the power and energy storage 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[2].

For 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[3]. This quite simple strategy is not particularly demanding for the spacecraft on

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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.

Direct assessment of the actual energy available onboard, as in SATSLab's simulations[4], is a more effective approach. SATSLab mission simulator was developed at Alta to overcome the limitations of the above mentioned generic approach and gain direct insight into the effects on spacecraft trajectory of spacecraft subsystems 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[5]. The simulator (SATSLab - Spacecraft Attitude, Trajectory and Subsystems Laboratory) was 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[6], featuring full perturbations, the possibility to simulate interplanetary trajectories with a wide variety of main bodies, and data export for visualization in Celestia[4]. Figure 1 shows SATSLab main Graphical User Interface (GUI) with the Simulation Tree in the magenta square, the live plot and post-processing panel in the red square and the main commands in the green ones. The blue box highlights the user log where each action is registered and where user receives any relevant notice or warning.

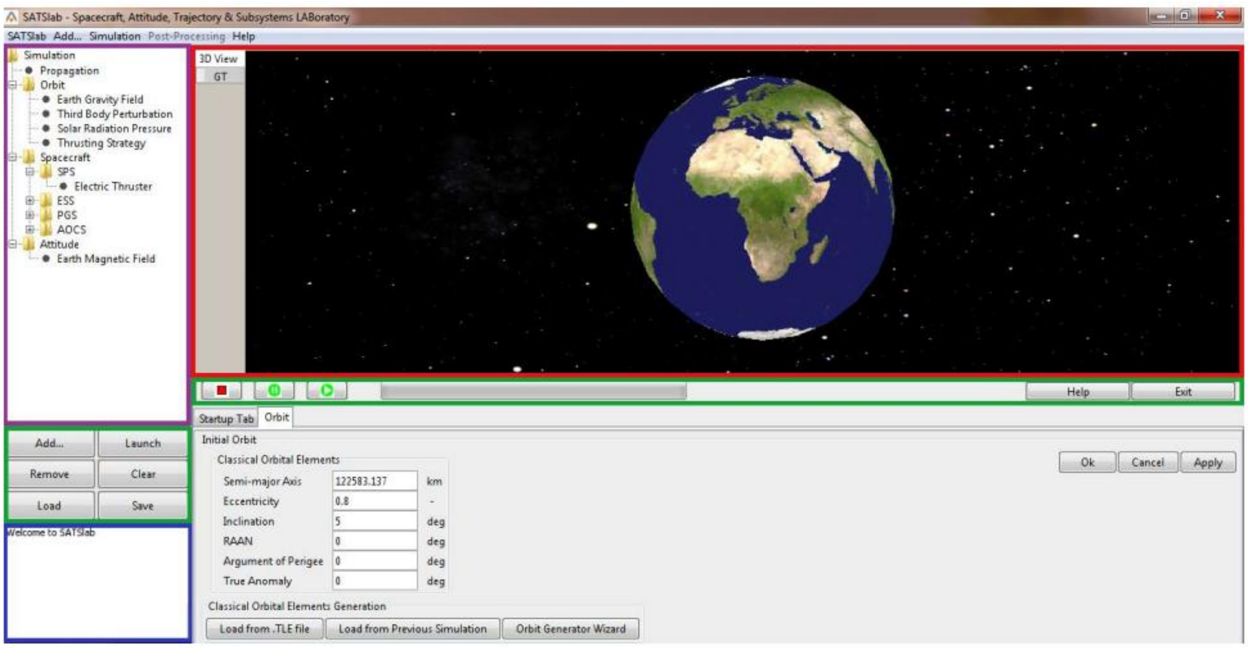

Figure 1. SATSLab GUI, its main sections and the Orbit panel.

The SATSLab modules include orbit and attitude dynamics propagation, power generation and energy storage subsystems control, thruster and payload simulation. The user can describe spacecraft geometry as a combination of pre-defined solids or import a geometry file from a commercial 3D modeler, so that shape-dependent attitude and orbital perturbations 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™, the simulator is completely platform-independent, providing the same functionality and user experience regardless of the operating system of the computer platform.

We present the simulator's architecture and workflow arrangement in Sec II. In Sec. III and IV, the code core implementing a set of predefined or used-defined thrusting strategies and the coupling with the power management are presented. A representative mission example is shown in Sec. V, including simulation of Low Earth Orbit (LEO) with complex, and demanding for the spacecraft, illumination conditions. This specific application, in particular, shows that direct simulations may result in greater, unexpected insight into the mission features, ultimately leading to better understanding of the mission operational constraints and enhanced overall performance.

II. SATSLab Overview

A. Software Architecture

SATSLab is conceived as modular software where several tools come into play upon user request. The core of the code is the propagation tool that allows simulating purely keplerian orbits (around one of the multiple central bodies available). Additionally, orbital perturbations can be considered and their influence on the spacecraft position and velocity modeled along a given time frame. In particular, the code allows computing atmospheric drag and solar radiation pressure according with the user defined geometry, a number of predefined (and editable for experienced users) relevant parameters and automatically computed Earth/spacecraft and Sun/spacecraft relative positions. If spacecraft attitude is required, the code propagates simultaneously the whole state vector composed by position and velocity, spacecraft attitude, and the status of the onboard subsystems; if also the power management is required to be simulated, the state vector is expanded to include also the instantaneous values of power provided by the solar arrays, the charge level of the batteries, the power consumption of the various subsystems and the payload, the magnitude and orientation of thrust, etc. At each time step, the onboard available energy is computed considering the power generated by solar arrays (accounting also for solar cell efficiency degradation mechanisms) and the power requirements of all simulated subsystems.

The code allows a full custom definition of the spacecraft bus in terms of payload (mass, power and operating ranges), bus, AOCS and propulsion system. As an optional add-on, the heliocentric module is available to simulate low-thrust interplanetary transfers, under realistic illumination conditions (ephemeris are automatically loaded) and under the influence of multiple primary bodies.

The typical simulation workflow is shown in Fig. 2. User's experience starts from entering in SATSLab GUI all the elements relevant for the approached scenario. These elements populate the Simulation Tree (yellow box of Fig. 2) and each of them enables the user to define a whole set of relevant parameters to describe, also in detail, spacecraft subsystems and mission scenario. At the end of each simulation, the GUI enables access to a thorough set of post-processing options such as standard and user-defined plots or data export to Celestia, worksheet or text file.

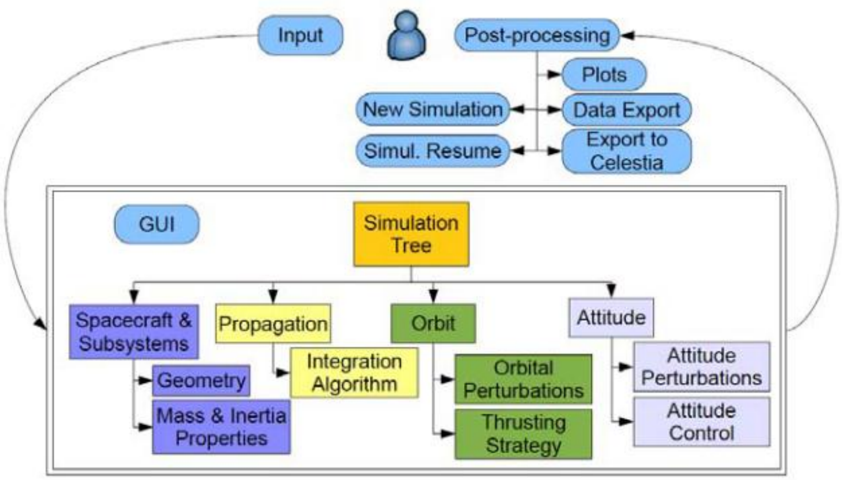

Figure 2. Typical SATSLab simulation workflow.

B. SATSLab Specific Features

SATSLab differs from the many (non-spacecraft specific) mission analysis packages available (e.g. AGI's STK, ESA's STA, AI Solution's FreeFlyer, etc.) essentially for two specific characteristics:

- the unique capability to assess jointly the trajectory propagation and the subsystem status aspects of the mission. This is specially important in missions with limited power or mass budget and complex trajectories.
- the ability to simulate low-thrust trajectories requiring just a limited number of standard input parameters by the user. This allows for quick assessment of complex missions also by non-specialists. Advanced options, like the specific thrusting strategy to be adopted, can be selected by experienced users.

In the following two sections, particular attention is deserved to these two aspects with the basic ideas used for their implementation and some exemplificative applications.

III. Low-thrust Strategies

C. Thrusting Strategies

Besides the general propagation options and spacecraft components specifications, one of the more remarkable features of SATSLab is the inclusion of a dedicated "Thrusting Strategy" panel. Thanks to the user-friendly interface here implemented, also non-expert users, starting from SATSLab Simulation Tree, can enter in one single panel all the inputs required for the simulation. Figure 3 shows a close-up of SATSLab user interface and, in particular, a "Simulation Tree" with some nodes (left) and a detail of the "Thrusting Strategy" panel (right).

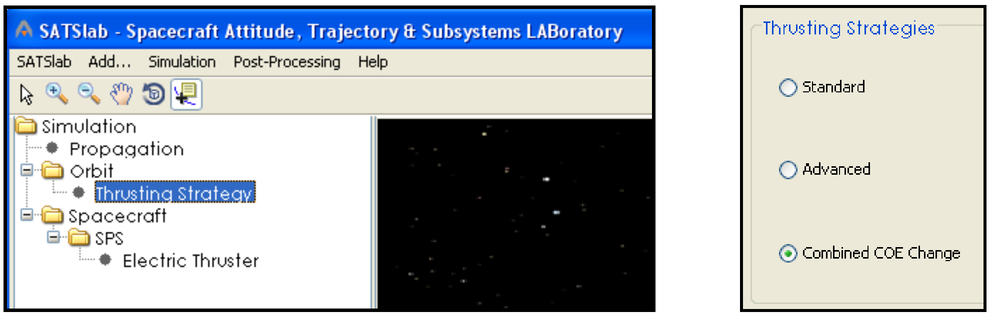

Figure 3. Close-up of the current status of SATSLab user interface (left) and detail of the "Thrusting Strategy" panel (right).

The "Thrusting Strategy" node, highlighted in Fig. 3 (left), is the one where the specific operation mode of the electric thruster can be chosen. Figure 3 (right) shows the definition of the thrusting strategies: the thrusting scheme selection. Three different thrusting scheme options are available for user selection:

- *Standard Strategies*: this option allows the user to choose among a preset thrusting strategy (see Figure 4, fourth box) for a part or for the whole duration of the simulation. In particular, these standard strategies allow the user to change a specific orbital element, to raise the orbit altitude or to perform drag compensation maneuvers within a user-defined box. The user can command the switch from one strategy to the other selecting an orbital or physical parameter (in the leftmost list) and a given threshold. Most of the strategies also allow the user to define an effectiveness parameter (see Figure 4, rightmost box), in order to operate the thruster only in those parts of the orbit where the maneuver turns out to be more convenient.

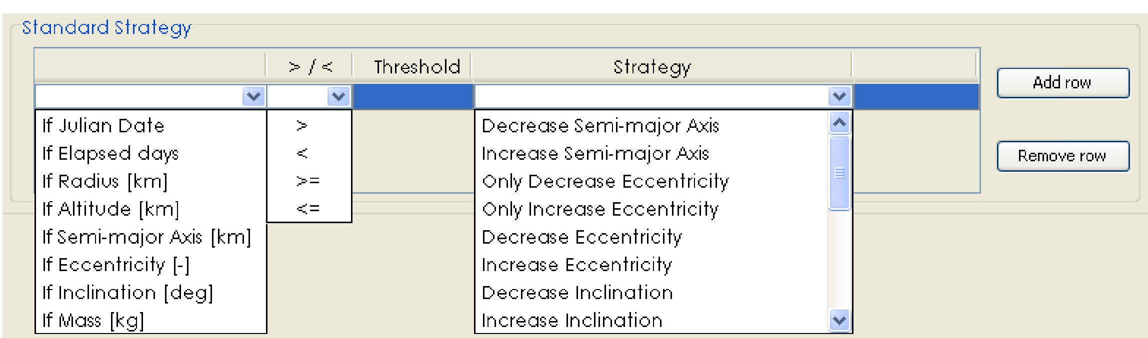

Figure 4. Standard Strategy panel: the first three boxes allow to define a thrusting strategy switch threshold with respect to physical or orbital parameters; the last two boxes contain the desired effect on the orbit and the effectiveness parameter.

- *Advanced Strategies*: this more advanced scheme allows the user to set both a thrusting arc (first two boxes of table in Fig. 5) with respect to a physical or orbital parameter (see leftmost list in Figure 5) and the thrusting angles along this (the last two boxes of the table in Figure 5). This option is actually more suitable for experienced users who may want to test a thrusting strategy already identified by external means. The in-plane and out-of-plane thrusting angles can be expressed with respect to four different reference frames (third box of the table in Figure 5): Earth-Centered Inertial Reference Frame (IJK), Perifocal Reference Frame (PQW), Radial-Circumferential-Normal Reference Frame (RCN) and Tangential-Normal Reference Frame (TNH)[7].

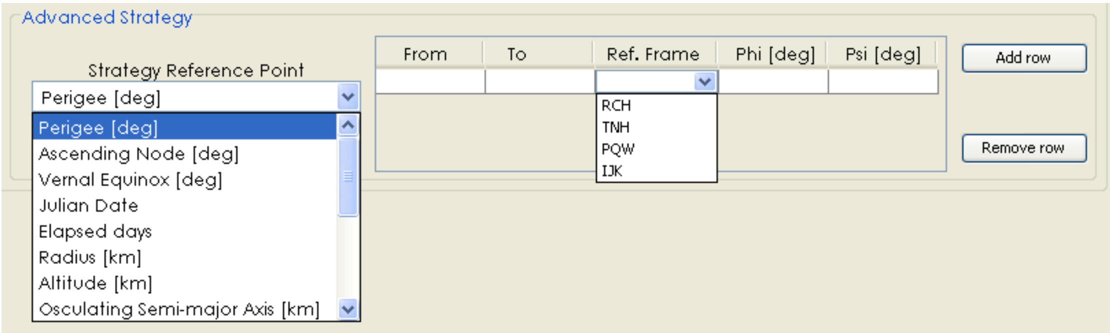

Figure 5. Advanced Strategy panel: the leftmost list allows to choose a physical or orbital parameter in order to define a thrusting arc (first two boxes of the table). The third box identifies a reference frame for the thrusting angles (last two boxes of the table).

- *Combined Orbital Element Change*: this more sophisticated option enables the user to define a set of target orbital elements and two additional parameters: tolerance and effectiveness[8]. These two parameters represent respectively the difference between the final value of the orbital element and the desired one, and the ratio between the instantaneous rate of change of a specific element and the maximum obtainable element variation, considering the osculating orbital elements. This last option, in particular, turns out to be particularly helpful in those cases in which the user wants to design a low-thrust trajectory from a given initial orbit to a target one.

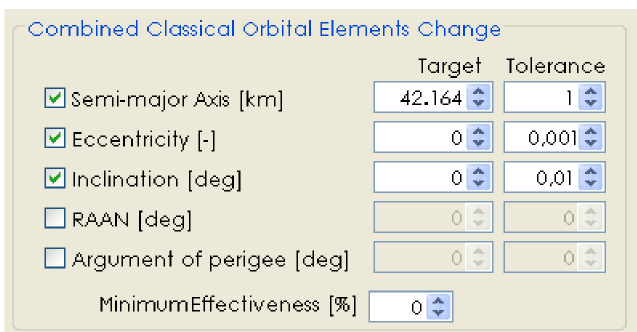

Figure 6. Combined Orbital Element Change panel: for each orbital element, if selected, a target value, a tolerance and an effectiveness threshold can be selected.

D. Simulation Example

To give an idea of how such pre-set strategies can be used, we present here the simple case of a standard GTO to GEO transfer. It should be remembered that the code doesn't perform any optimization, so that the implemented strategies represent just a fast way for preliminary assessment of a transfer strategy.

The initial spacecraft mass is set equal to 1132 kg, the upper limit of the PSLV-XL[9] payload into a GTO orbit. The electric propulsion system is assumed to be based on two SNECMA PPS-1350 thrusters[10]. No orbital perturbation is considered, apart from the acceleration imparted by the thrusters to the spacecraft during sunlit phases. Simulation data are summarized in Tab. 1.

Initial Orbit				
Semi-major axis	**Eccentricity**	**Inclination**	**RAAN**	**Arg. of Perigee**
24361.137 *km*	0.730795	17.8 *deg*	0 *deg*	0 *deg*
Target Orbit				
Semi-major axis	**Eccentricity**	**Inclination**	**RAAN**	**Arg. of Perigee**
42164 *km*	0	0 *deg*	N/A	N/A
Spacecraft & Thruster Characteristics				
Spacecraft Initial Mass	**Thrust**	**Specific Impulse**	**Power**	
1132 kg	81.5 ± 1.5 *mN*	1520 ± 40 *s*	1.5 *kW*	
SATSLab Simulation Settings				
Integration Algorithm	**Absolute Tolerance**	**Relative Tolerance**	**Starting date**	
Runge-Kutta (4,5)	1e-7	1e-7	01/01/2019	

Table 1. Simulation data used. No orbital perturbations are considered; the thruster is switched off during the eclipse phases.

SATSLab computes the required transfer in less than 6 minutes on a standard PC (CPU AMD Athlon 64 X2 @ 2.6 GHz, 2 GB RAM). Results are shown in Fig. 7 and listed in Tab. 2. The last two columns of Tab. 2 also show a comparison between the results provided by SATSLab and an optimized solution for the same transfer case obtained by Schäff *et al.*[9] combining different optimization techniques.

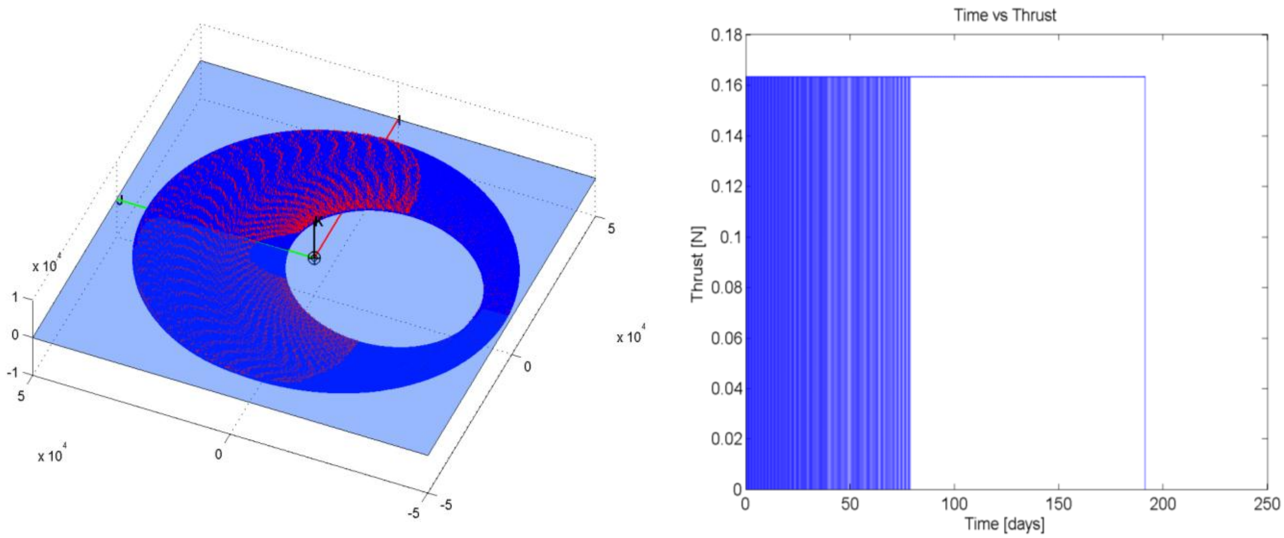

Figure 7. 3D View of the GTO-GEO transfer trajectory (left) and propellant mass consumption (right).

	SATSLab Output	***Absolute difference w.r.t optimized solutions***	***Relative difference w.r.t optimized solutions***
Duration	191.1 *days*	12.1 *days*	+6.7%
Propellant Consumption	178.7 *kg*	13.3 *kg*	+8%
Eclipse Arcs	303	117	+62.9%

Table 2. Results provided by SATSLab for the low thrust GTO to GEO transfer; the third and fourth columns show the difference between SATSLab results and the optimized solution of Schäff *et al.*

Figure 8 show some of the standard plots produced by SATSLab after the runs; in particular, it is shown how the relevant orbital parameters change from their initial GTO values to the target GTO ones.

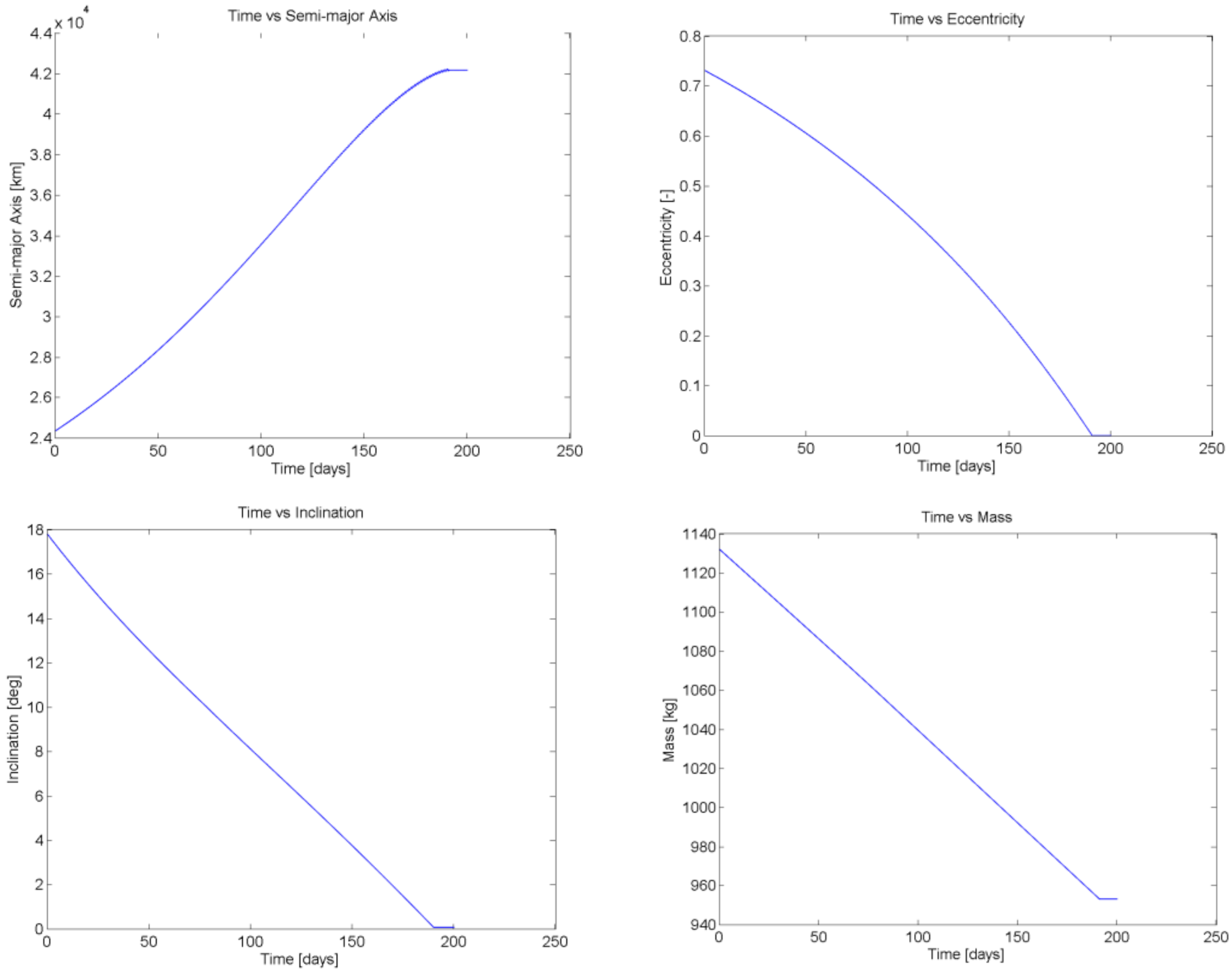

Figure 8. Time evolution of orbit semi-major axis (top left), eccentricity (top right), inclination (bottom left) and mass (bottom right).

The SATSLab simulation is fairly accurate in terms of maneuver duration and propellant consumption, being well within a 10% margin from the results of the more complex optimization here taken as a reference. On the other hand, the gross overestimation of the number of eclipse arcs is probably less important during preliminary mission definition phases. Such accuracy is deemed to be adequate for much of the preliminary work, considering that the results are obtained very quickly.

IV. Energy Management

SATSLab is much more than an orbital propagator, featuring the ability to determine, if required, the spacecraft instantaneous power demand and accordingly constraining the thrust strategy, if necessary. In particular, thrusting conditions or thrusting strategies most likely depend on the spacecraft position along its orbit, with onboard available energy changing along the trajectory due to spacecraft power consumption and its position and attitude relative to the sun. Therefore, it may happen that the thruster can be operated continuously only for a given period and, upon the attainment of a given condition (such as the reaching of a preset battery Depth Of Discharge - DOD), it must switch to a non-continuous thrusting strategy. **Figure 9** shows the schematic orbit-attitude-onboard subsystems interplay, according to the philosophy used for the SATSLab implementation.

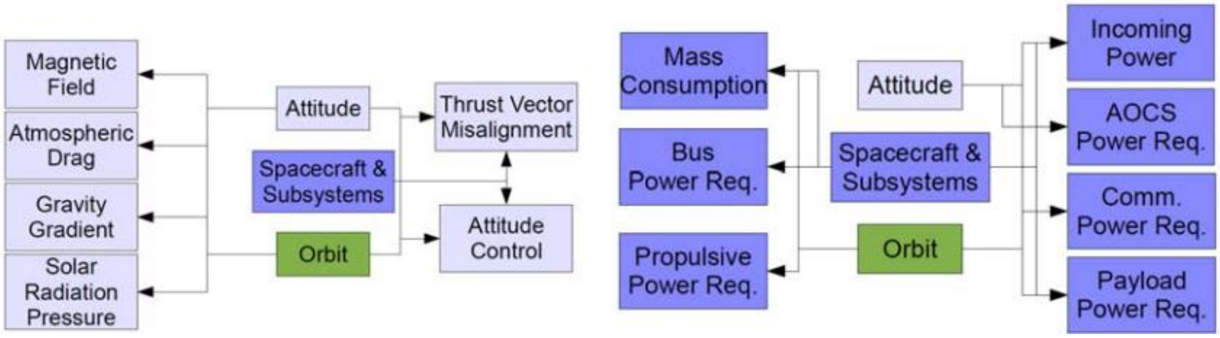

Figure 9. Schematic of orbit, attitude and spacecraft subsystems interplay.

By way of example, we enter into the SATSLab Simulation Tree some more details of the spacecraft considered in the mission scenario described in Sec. III, in order to assess the behavior of the Power Generation Subsystem (PGS) and the Energy Storage Subsystem (ESS). The relevant parameters assumed for these subsystems are listed in Tab. 3.

Parameter	***Value***
Incoming Power	3.5 kW (constant during sunlight phases)
Total Batteries Capacity	2 kWh
Base Power Consumption	200 W (constant during the whole mission)
Communication Subsystem	50 W (arc centered around ground stations longitude)
Payload & Other Subsystems	100 W (90° arc centered around pericenter)

Table 3. Relevant PGS and ESS parameters.

Figure 10 shows the difference between incoming and outgoing power, with a close-up on the first day, and the battery DOD during the whole transfer. The top-left plot of Fig. 10 clearly shows that during the transfer the highest value of the incoming power is 300 W (no eclipse and 2 thrusters operating) while during eclipse phases the outgoing power value grows up to 350 W.

The direct simulation implemented in SATSLab allows to find out that the batteries reach a maximum DOD level of 67.2%; this value can be used as an input to the design of the spacecraft and, in particular, of the ESS subsystem. It is worth noting that no eclipse phases occur from day 82 till the end of orbital maneuver, then batteries charge level is always 100%.

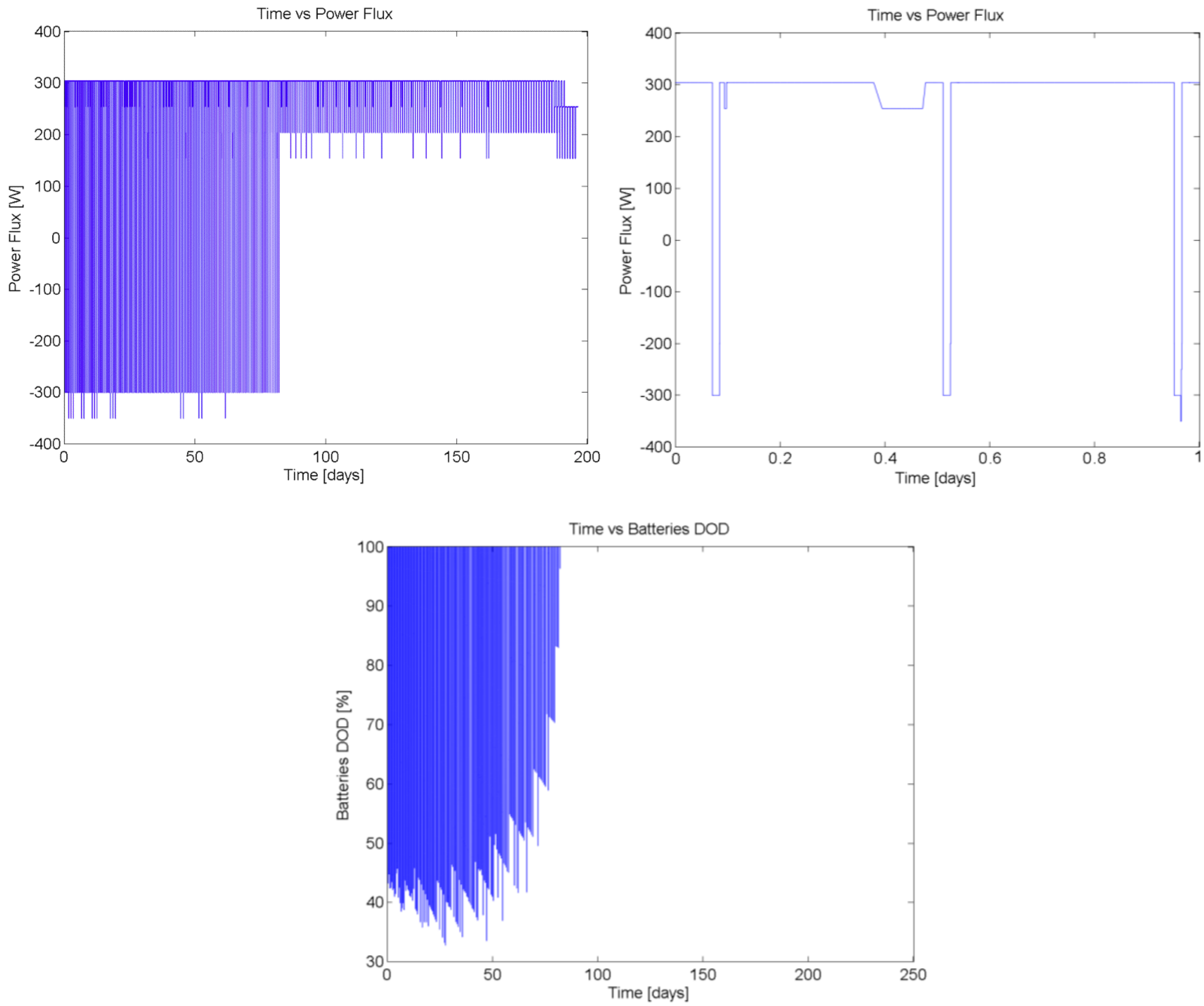

Figure 10. Top left: difference between incoming and outgoing power; top right: close-up of the first day of the transfer; bottom: battery DOD.

V. Case Study

To look more in detail into the advantages offered by the coupled simulation of trajectory and onboard energy and power fluxes, let us consider an orbit maintenance maneuver performed by a small platform in a 350 km non-Sun-synchronous circular orbit. This maneuver, as described in Sec. I, consists of alternating ballistic and thrusting phases to keep the spacecraft within a predefined orbital altitude band. In particular, an altitude tolerance of 100 m has been chosen to provide a good compromise between number and duration of the thrusting phases. Thus the thruster starts operating when an altitude of 350 km is reached and it stops when the platform reaches 350.1 km. In order to obtain a more realistic simulations, besides the atmospheric drag (computed according to the "US Standard Atmosphere 1976" atmospheric model[7]), the Earth oblateness perturbation terms J_2-J_6 are also taken into account in the orbital propagator.

The platform considered is a 350 kg Earth observation satellite with an attitude control system that keeps the spacecraft with one body axis constantly aligned with orbital position vector. A 1 m^2 solar array, providing 300 W of power, is mounted on the top side of spacecraft, aligned with the orbit angular momentum vector. One of the spacecraft lateral surfaces experiences atmospheric drag over a surface of 1.4 m^2 during the whole mission, while the EP system is mounted on the opposite side of the spacecraft. The EP system is based on Alta's HT-100 Hall effect thruster[11], with a maximum power consumption of 175 W.

The evaluation of the impact of an electric thruster on such a small satellite is not straightforward because the instantaneous power budget has to be taken into account. It may happen that in a mission phase when the propulsion system is expected to operate, the satellite could experience eclipse conditions and the available energy (considering constant power consumption by the platform, a possible additional payload, and the thruster and accounting for a realistic battery DOD) could be insufficient for actual thruster switch on. In this SATSLab simulation, the EP subsystem is envisaged to operate also during eclipses but a 75% threshold on battery charge level is introduced in order to avoid negative effects on the battery life. Simulation parameters are summarized in Tab. 4.

Orbit				
Initial Orbit: Non-Sun-synchronous circular, 350 km of Altitude			**Altitude Tolerance:** 100 m	
Spacecraft Characteristics				
Spacecraft Initial Mass	**Drag-exposed Area**	**Generated Power**	**Battery Capacity**	
350 kg	1.4 m^2	300 W	500 Wh	
Thruster Characteristics				
Thrust	**Specific Impulse**		**Power Consumption**	
8 *mN*	1100 *s*		175 *W*	
Power Consumption				
Spacecraft	**Communication Subsystem**		**Payload & Other Subsystems**	
100 W (constant)	25 W (10° around ground stations longitude)		65 W (half of the orbit)	
SATSLab Simulation Settings				
Integration Algorithm	**Absolute Tolerance**	**Relative Tolerance**	**Starting date**	**Simulation Duration**
Runge-Kutta (4,5)	1e-7	1e-7	01/01/2019	30 days

Table 4. Relevant spacecraft data and settings used for the small Earth observation orbit maintenance simulation scenario.

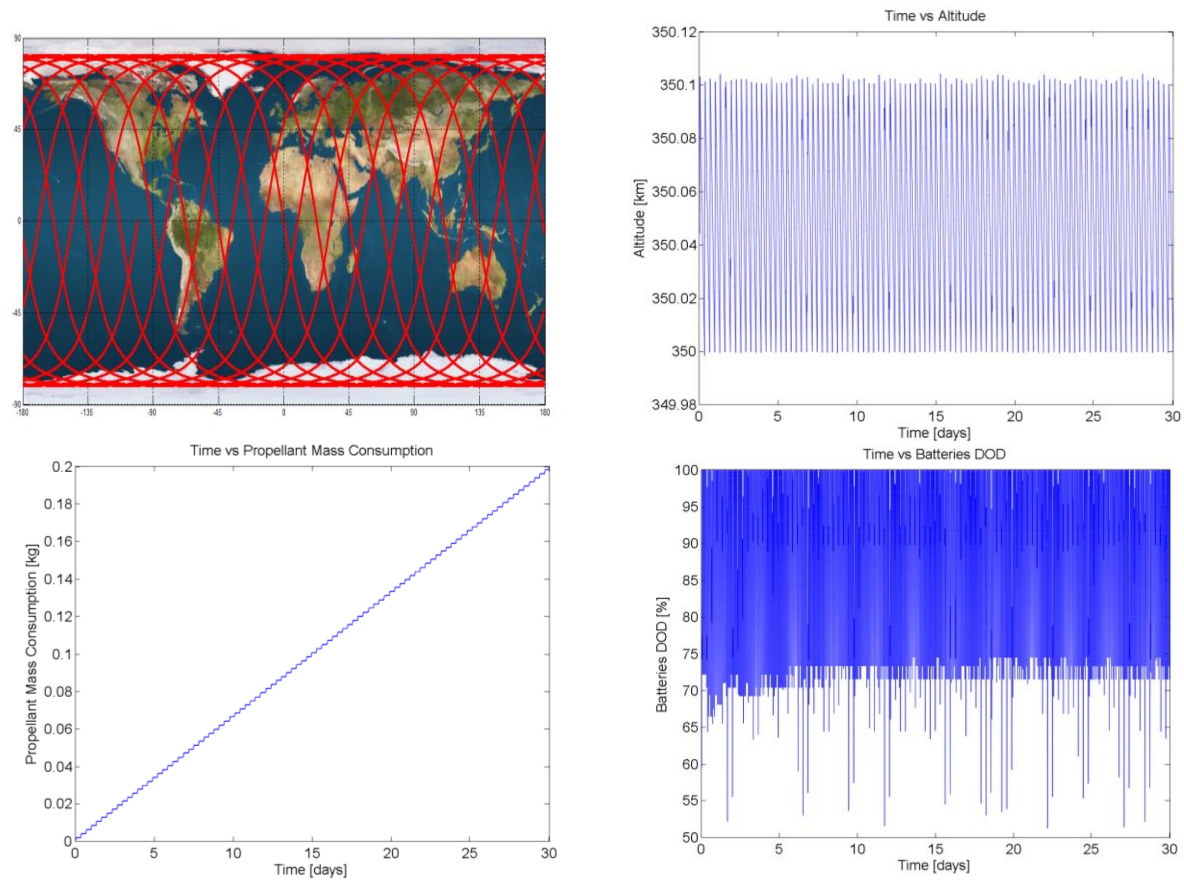

Figure 11. From the upper left corner: ground track, orbital altitude, propellant mass consumption and battery charge level.

The simulation results show that approximately 6.67 g/day of propellant are required to compensate the atmospheric drag with a daily delta-V of about 0.2 m/s. Figure 11 shows some of the typical SATSLab outputs: the ground track, the orbital altitude evolution, the propellant mass consumption and the instantaneous battery depth of discharge superimposed to the eclipse periods over one day.

The last plot of Figure 11 shows that the maximum DOD reached by spacecraft batteries is 48.7% and this happens only three times during the whole simulation. As a matter of fact, since the EP system is turned off as soon as batteries charge level is below 75% these DOD peaks are due to spacecraft base power consumption, payload, communication and other subsystems. The power consumption of these subsystem, less severe with respect to that of the EP system, have not been turned off according to batter charge level since they have been considered essential for spacecraft functioning.

Figure 12 shows the difference between incoming and outgoing power (left) and batteries level of charge during the first day of the transfer.

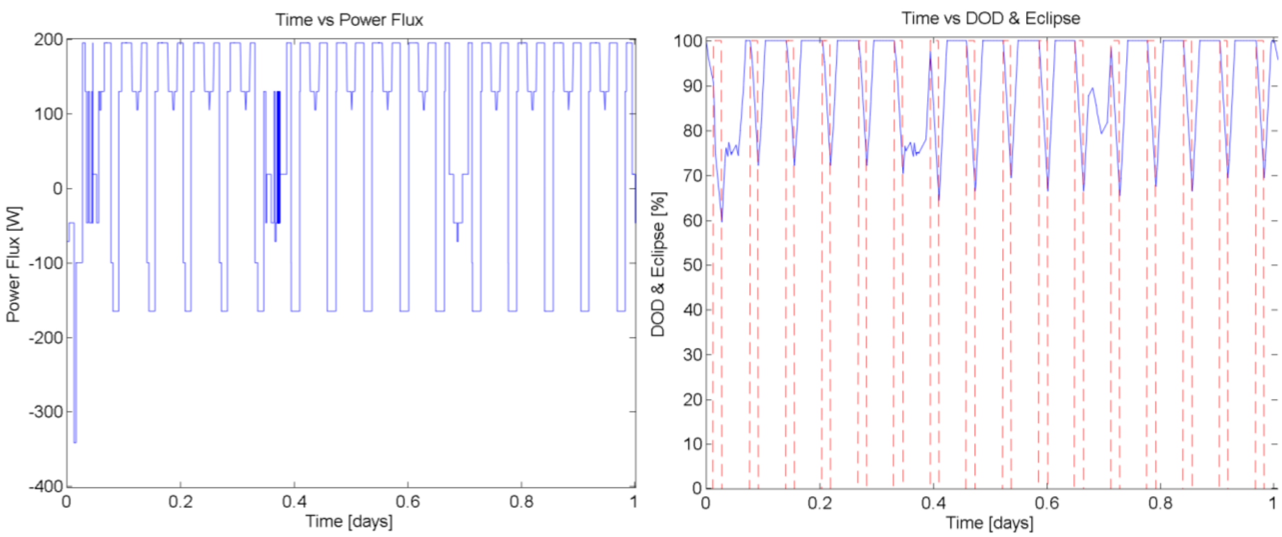

Figure 12. Left: difference between incoming and outgoing power; right: battery charge level and eclipse periods (red dashed line).

The power flux, shown in the left plot of Figure 12, shows that up to 365 W of power can be required by the whole spacecraft also during eclipse phases. The different operational conditions of each subsystem are responsible for a number of different levels of incoming and outgoing power fluxes and, for this reason, the a priori determination of the availability of enough energy to keep the spacecraft operational during the mission is not trivial.

VI. Conclusion

In this paper, we have discussed the importance of a combined estimation of spacecraft trajectory and subsystems energy state and presented the SATSLab software package, able to assess and manage simultaneously spacecraft trajectory and onboard available energy. A few relevant examples have been shown of mission scenarios where direct simulation allows for better understanding of the mission operational constraints. In these cases, the assessment of mission operations with limited onboard resources provided realistic and reliable results enabling a more aware design of mission and spacecraft. Alta's SATSLab simulator is constantly updated with additional modules to provide a flexible tool for realistic mission assessment.

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