MISSION ANALYSIS TOOL FOR CRITICAL VALIDATION OF CUBESAT DESIGN AND MISSION SUPPORT

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ABSTRACT

In the frame of the ever-increasing CubeSat sector, accommodating CubeSat philosophy and benefits with requirements inherent to space missions remains a challenge. CubeSats often face the problem of orbit uncertainties, which can impact the mission and the design. The Centre Spatial Universitaire de Montpellier (CSUM) developed an advanced mission analysis methodology to overcome these limitations in the context of its 3U CubeSat ROBUSTA-3A. It focuses on successive yet correlated blocks, each being an in-depth simulation of a subsystem. This process can be tailored for use in any phase of a small satellite project facing cross-impacts of complex dynamics. It yields precise and correlated results from each simulated subsystem. Using this methodology on ROBUSTA-3A allowed concluding about the compliancy of several orbits to mission requirements and spacecraft final design, review some subsystem activation strategy, or update mission profile and operation plans. Additionally, verification of outputs permits cross-checking results and avoiding simulation anomalies.

1 INTRODUCTION

Since the creation of the CubeSat standard in 1999, the number of small satellites launched has increased exponentially. With only 11 launched in 2000, 705 nanosatellites are expected to be sent into orbit in 2022 [1]. The success rate of CubeSats has also increased through the years to stabilize at around 75% [2]. In particular, University-led projects, which represent approximately 30% of all CubeSats, often overlook some aspects of CubeSat engineering, leading to higher chances of failure. Among these aspects resides mission analysis [3]. It is then recommended to update the mission analysis all along the development cycle of the CubeSat.

The Centre Spatial Universitaire de Montpellier (CSUM) has successfully launched and operated 1U CubeSats entirely designed in-house. Most notably, ROBUSTA-1B is still operational after almost five years. The CSUM now aims at developing an in-house 3U CubeSat named ROBUSTA-3A, which is expected to launch in 2023. It will provide far better performances to collect environmental data and perform various technology demonstrations. As presented in a previous paper [4], the primary goal of this nanosatellite is to improve the weather forecast in the French Mediterranean coastal region, to detect heavy rain episodes called "épisodes cévenols". As a secondary payload, the CubeSat will demonstrate the capabilities of the I2T5 propulsion system from ThrustMe, an iodine cold gas thruster. This step-up comes with many new challenges that we must answer at project level and for future missions at CSUM. Some of them were faced during the critical design phase, when we needed to study the impacts of orbit uncertainties on the mission, validate the design, and provide operational planning and mission support. In particular, the uncertainty regarding the orbit the satellite will be released onto is probably the most significant constraint. This constraint is inherent to CubeSat missions and even more for ROBUSTA-3A, which aims at being the basis of a 3U platform that will potentially be operated on a broad range of orbits.

Several tools have been developed for CubeSats or larger satellites to provide mission analysis/profile support. However, they are either focused on specific aspects of the mission or used for preliminary design with limited precision. For example, National Aeronautics and Space Administration's (NASA) Global Mission Analysis Tool is useful for trajectory optimization and maneuvers planning [5]. However, it will not analyze the power or thermal behavior. Many tools are under development to support preliminary design of satellites in the frame of Concurrent Design Engineering (CDE) whether from space agencies, academics, or private companies [6]. For its part, the French Centre National d'Etudes Spatiales (CNES) developed the IDM-CIC tool to set up a technical reference for the CDE process [7]. It can build a database that interacts with engineering modules performing specific simulations (electric, thermal, communication, data handling). It is generally used in pair with SIMU-CIC, which generates satellite orbit and attitude files compliant with the Centre d'Ingénierie Concourante (CIC) protocol [8] in the Scilab-CelestLab environment. These tools are at the center of the concurrent engineering process and help establish system technical budgets. Yet, they fail short when validating mission profiles considering the system correlated dynamics. CEntre pour les Nanosatellites en Sciences de l'UniverS (CENSUS), the space pole of Paris Sciences & Lettres (PSL) University, develops an open-source software suite for space mission profiles called DOCKS [9]. This suite focuses on computing mission profiles in the initial design phases of scientific nanosatellite missions by providing a set of Python modules still under development (three of them are already developed). Although the open-source suite of plugins idea is very appealing, it lacks the level of accuracy and specificity required. Some tools are developed to increase the reliability of the simulations by linking subsystems. Recent work aims to give more realistic battery behavior in CubeSats thanks to a thermal-electrical model [10]. The simulation is then more precise, but in this case, the thermal simulation is still limited and employed only for preliminary analysis. Another work links orbit, attitude, and radiation source model to have a precise irradiance value, which can be used for thermal simulations or solar panel power input determination [11]. This work only accounts for specific attitude laws like Sun pointing rather than considering an entire attitude dynamic.

Given ROBUSTA-3A situation, the CSUM developed an advanced mission analysis methodology to apply to all current and future projects. It comprises several simulations linked together, namely mission, Attitude Determination and Control System (ADCS), Thermal and Electrical Power System (EPS). The aim of the direct interactions between the simulations is to have a realistic space environment and precise simulation results that can be used at every stage of the design of CubeSats, from early phases to mission planning. While initially developed for CSUM projects, the methodology can be applied to any small satellite project to create meaningful mission analysis and reduce failure chances.

This paper will present the benefits of using the advanced mission analysis methodology developed by the CSUM and how small projects can employ it at different satellite development stages. Then comes the description of the generic process itself. Finally, the paper puts the methodology into practice through the design validation of ROBUSTA-3A.

2 OBJECTIVES AND USES

The CSUM developed a process that allows complex mission analysis using detailed mission, attitude, thermal, and power simulations. The need to develop such a process comes from several challenges and historic difficulties encountered during the conception and development of CubeSat missions. Mission analysis and more generally mission definition such as orbit selection, orbit injection, or period of injection have a significant impact on the design of the spacecraft and the validation of the system. In the frame of the New Space sector, and even more in university CubeSat projects, these launch conditions are generally unknown until a few months before the actual launch date. Indeed, projects are sometimes very flexible due to several launch opportunities. In addition, CubeSats are most often secondary payloads or piggy-backed payloads for launch vehicles, making them subject to undesired orbit modifications coming from the primary payload. Therefore, having a fast and straightforward method for studying changes in orbit is required. The methodology presented in this paper aims, with standard inputs for this kind of analysis, to generate a significant number of required data outputs at any stage of the project.

Depending on the project phases, the uses of this process should evolve to provide users with the desired data and possibly impact the design of the spacecraft or the system. Table 1 shows examples of possible outputs obtainable through this process.

Table 1: Overview of proposed uses and outputs for mission analysis process depending on project phases

Project Phase	Uses	Possible Outputs
Phase 0 / A	- Overview of missions' scenarios - Orbits selection trade-off regarding mission specifications - Processing of first technical values for mission feasibility verification	- Intervisibility durations and periodicity - ADCS specification
Phase B	- Preliminary technical budgets - Preliminary spacecraft and system design validation: • Trade-off for physical configuration, sensors or antennas orientation and positioning • Number and characteristics of ground segment(s)	- Harvested energy, Depth of discharge and consumed power - Pointing error, maneuvers duration - Intervisibility durations and periodicity - Temperatures estimations
Phase C	- Detailed technical budgets - Updated mission analysis including system failures and discrepancies studies	- Harvested energy, Depth of discharge and consumed power - Pointing error, maneuvers duration - Intervisibility durations and periodicity - Temperatures mapping and dynamics
Phase D	- System design and mission profile validation - Performances modeling - Final spacecraft design simulation updated with tested values	- Final technical budgets models - Technical budgets including failure cases (i.e., appendixes failures) - Operational Plan
Phase E	- Mission planning, task plan and operations support: - Simulations blocks correlation using real in-orbit data	- Operations timelines - Mission task plans

Still, those outputs of the process should be mission-specific and rely on the level of detail of each simulation block's content. An example is given in the last section of this paper as a case study for ROBUSTA-3A system.

Inputs to be considered initially for this process are usually data and parameters defined and estimated in early phases. We can list:

- orbital parameters,
- ground segment location and characteristics,
- mission scenarios and timelines,
- space segment power modes and consumption,
- space segment design and configuration,
- spacecraft attitude targets.

The idea is that, with this limited set of information and by interfacing dedicated and specific numerical models, a large amount of data summarizing system and satellite-level characteristics is generated. A case-by-case comparison thus becomes possible by modifying the values of input parameters.

Although inputs and outputs listed above are dependent on the project's development stage, the methodology shall allow for any level of detail inside simulation units. Therefore, it can be used at any stage of the development, with outcomes evolution as a function of project phases.

However, the assets and uses of this methodology are various and not limited to orbit selection impacts and mission analysis. By taking advantage of the interdependence of the simulation blocks, the process should provide much more detailed outputs for the modeled subsystem than with a standalone simulation. As described in the following sections, each interface between simulation blocks brings an additional level of detail and representativeness of flight conditions and environment. Indeed, they convey the correlation between subsystem models. For example, the impact of thermal behavior and attitude uncertainty on harvested energy could be observed. Another example is the impact of pointing errors on communication times with ground segments. Also, the process described in this paper should allow a fast verification method by analysis of the design and a cross-validation and relevancy study of the numerical models. Tests are sometimes impossible, or at least strongly time and resources consuming, like attitude or thermal control. Therefore, the fine-tuning of these models, which can occur iteratively during the system's development cycle, is a valuable asset.

3 METHODOLOGY FOR ADVANCED MISSION ANALYSIS

The first version of this mission analysis methodology was presented in previous work [4]. The current paper shows further development of this methodology, depicted in Figure 1. Each block represents a major step, from the creation and simulation of the mission profile to the visualization of the relevant data. The configuration presented in this work is not frozen, and additional blocks could be added upon project requests. Because the underlying aim is to build a polyvalent procedure, this section of the paper focuses on the logic rather than the simulations themselves. The level of detail/precision of each simulation unit is left at the project team's discretion based on its objective and at which stage of the project it is run. Similarly, they can rely on any software/language as long as they can read/write files in the format presented hereafter. Our simulation setup can be found in more detail in section 4.3.

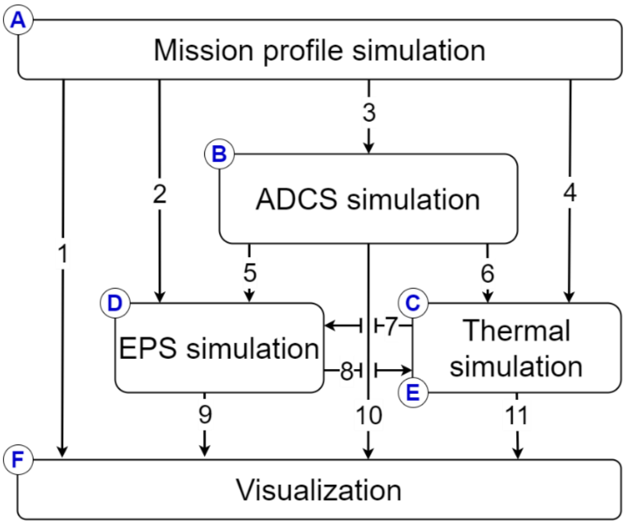


Figure 1. Mission analysis process. Each step/block is associated with a letter, and each connection between blocks is associated with a number.

Exchanging information between the simulation blocks depicted in Figure 1 may seem problematic considering the variety of software-dependent inputs/outputs. Hopefully, this problem has arisen before for space missions and has led to the introduction of data exchange standards. In the present work, the communication process between these blocks is the CIC data exchange protocol from CNES [8], largely inspired by the Consultative Committee for Space Data Systems (CCSDS) reference format [12][13]. Based on this protocol, every arrow in Figure 1 can be made of position and velocity data (OEM files), attitude data (AEM files), or complementary data (MEM files). Complementary data is anything that does not fit in the first two categories (geometrical, thermal, electrical, etc.). All that is left is to create parsing scripts between the CIC data exchange protocol and every simulation block. In the following list, we go through the stages of the process.

A. The mission profile simulation serves two purposes: it creates a mission profile with the relevant time-tagged information, in the same way as for mission operation, and it simulates the spacecraft trajectory. These outputs may be meaningful and visualized as they are but also mandatory to downstream blocks. The more detailed the mission profile and corresponding satellite state are, the more realistic the following simulations can be. For example, one might need to validate that a satellite can communicate with a ground station. Hence, the mission profile simulation must identify passes over the ground station that provide long enough communication periods during the scenario and plan satellite modes and target attitudes accordingly.

B. Simulating the actual attitude of a spacecraft is essential because the behavior of several subsystems stems from it. Indeed, the energy harvested by solar panels is a direct function of the angle between the normal to the solar panels and the Sun direction, also known as the Sun aspect angle. The same could be said about the Telemetry Tracking and Command (TT&C) subsystem and the spacecraft's thermal behavior. Therefore, it is common to investigate the spacecraft's performance for all its expected attitudes when designing a mission. Yet, without a proper ADCS simulation, all one can do is consider target attitudes, which is equivalent to considering an ideal attitude control. Although this approach is valid in the early stages, the final design and validation require the introduction of ADCS dynamics. It is especially true for CubeSats, where limited performance in terms of attitude control and perturbative phenomena result in relatively long maneuvers and sometimes poor accuracy [14]. From mission profile simulation outputs (mainly the spacecraft trajectory and the target attitude), the ADCS block simulates the attitude dynamics and kinematics of the spacecraft and transmits the resulting attitude (arrows 5, 6). Depending on the expected precision of the outcome, it is possible, for example, to simulate actuators and sensors, test onboard algorithms and their response to mission scenarios, or consider various sources of perturbations.

C. In this process, we propose to perform two thermal simulations. The first one is focused on the solar panels to acquire their temperature now that the position (arrow 4) and orientation of the spacecraft (arrow 6) are known. This information is given to the EPS block (arrow 7) to compute the power generated as a function of the temperature of the solar cells. Although solar cells temperatures significantly impact their efficiency, one could skip this simulation based on the project's needs, especially in the early phases.

D. Fed by all upstream blocks, the EPS simulation calculates the power harvested as well as the power dissipated (arrows 2, 5, 7). Hence, it requires at least the maximum power consumption of each subsystem. However, it can be improved if the evolution of several pieces of equipment consumption during the scenario is known. The resulting Depth of Discharge (DoD) of the batteries is mandatory to validate that the spacecraft design is compatible with critical moments of the mission.

E. Going back to the thermal block with the power dissipated by each piece of equipment, a global simulation is now run. It estimates temperatures at every relevant spot of the spacecraft and checks that the satellite's thermal behavior is compatible with its design.

F. Output data are analyzed in the most meaningful ways for each project, from plotting graphics with the language of its liking to 3D visualization using tools such as Visualization Tool for Space Data (VTS). We also recommend using a flag system to raise warnings when critical values leave their design range. Thus, the results can be analyzed in greater detail to investigate why a warning was raised.

Connections between blocks depend on the expected outcomes of the mission analysis process. In Table 2, we list the minimal information they should carry for the methodology that we propose to be relevant.

Table 2. Minimal recommended data exchange between mission analysis blocks.

Connection #	Minimal content
1	Satellite trajectory
2	Satellite trajectory, power modes, Sun visibility
3	Satellite trajectory, attitude mode/law
4	Satellite trajectory
5	Satellite attitude
6	Satellite attitude
7	Solar panels temperature
8	Equipment consumption
9	Depth of discharge
10	Pointing error
11	Temperatures of critical equipment

4 STUDY CASE

4.1 Presentation of the ROBUSTA-3A mission

The ROBUSTA-3A project began in 2013 with the identification of the need for CSUM to have an in-house designed three-axis stabilized platform, which would allow higher science value and education returns [4]. This first 3U CubeSat project aims to predict violent rainy events in the south of France. In addition, it serves as an educational platform, as 157 students have worked on it over the years. Finally, it will fly various payloads from partners to demonstrate them in flight.

The scientific objective of ROBUSTA-3A is to allow for retrieving the Integrated Water Vapor (IWV) from Ship Based Terminals (SBT) and forwarding the data to Météo France in a short time to be used in meteorological models. The IWV has been employed for decades for weather forecasting, and it can be retrieved from the propagation delay estimated in localization techniques based on the Global Navigation Satellite System (GNSS). As a matter of fact, GNSS techniques require an estimate of the propagation delay of the signal going through the atmosphere, primarily due to water vapors, to provide accurate positioning. However, most stations used for this purpose are on land. A recent study shows that using shipborne IWV analysis would be valuable [15][16]. ROBUSTA-3A would then permit such an analysis.

In addition to scientific objectives, the 3U-CubeSat hosts five technological in orbit demonstrations:

- Hold Down and Release Mechanisms (HDRM) for solar panels by NIMESIS.
- Deployment hinges for solar panels by CLIX industries.
- Airplane-proven harness technologies applied to satellites, co-developed by the CSUM and Latécoère Interconnection System.
- An Ultra High Frequency (UHF) radio developed by the CSUM which can emit up to 3 W and hosted on a credit card size hardware.
- The 0.5U I2T5 cold gas iodine thruster from ThrustMe. In this case, an off-axis thrust nozzle was designed to allow the positioning of the propulsion system in an uncommon location [4].

Finally, providing three-axis attitude control during orbit control maneuvers is considered a milestone in the CSUM development. Indeed, the thruster operation is a real challenge as it will inherently disturb the satellite's attitude. This perturbation comes from the misalignment of the thrust vector with the center of mass of the satellite, which causes an undesired torque.

4.2 Simulation Configuration

ROBUSTA-3A is expected to fly on a Sun Synchronous Orbit, although the precise orbit is unknown. Considering the mission constraint and the French Space Operation Act (FSOA), a Sun-Synchronous Orbit (SSO) with an altitude between 510 km and 590 km should be chosen. The other parameters are unknown as until a launch is booked, it is hard for a CubeSat to know the exact orbit it will be released onto. As a result, it was decided to analyze a range of orbits to validate the design of the satellite. Hence, this process may show that the satellite is not adapted to some orbits. In this case, the range of valid orbits will be adjusted.

The analysis is repeated for three scenarios:

- “Deployment”: the few orbits following the satellite ejection from the launcher. Directly after the ejection, ROBUSTA-3A is supposed to wait several minutes before deploying its solar panels in pairs, followed by the UHF antenna. At this point, the satellite can initiate the detumbling phase to mitigate the initial angular velocity given by the ejection. Once it is stabilized enough, it goes back to Sun-pointing.
- “Mission 1”: refers to the reception of data from the SBT in UHF and its transmission to the ground station via the S-Band antenna. First, the satellite starts tracking the ground station in advance to have time to perform the initial slew maneuver. Considering our ADCS design, changing the attitude target 10 minutes prior to the communications is sufficient. ROBUSTA-3A then sends pings to initiate communication with the SBT, allowing for data upload, followed by the downlink of the data to the ground station in S-Band. When visibility is lost between the two entities, the CubeSat points its solar panels towards the Sun.
- “Mission 2”: refers to the demonstration of the propulsion system from ThrustMe. In this scenario, a first orbit in Sun pointing is simulated. A slew maneuver is then performed to align the thrust vector with the velocity vector to lower the orbit. The thruster is then operated in three distinct phases: warm-up, steady-state firing, and cooling. At the end of the scenario, the satellite goes back to Sun-pointing.

The simulation choice is driven towards worst-case orbits like hot case, cold case, and worst case for power management. In addition, an “expected orbit” case is also studied. The time of the year and the Local Time of the Ascending Node (LTAN) are chosen to create the hot case, the cold case, which is also the worst case for EPS, and the expected orbit. The time of the year for Mission 1 scenarios is an exception as it will take place only in fall or spring. A simulation date around September 2023 was chosen as it is most likely the first time Mission 1 will happen, considering the nanosatellite is expected to launch in summer or fall 2023. For the simulation, a date around March is not studied as it is not expected to change the results much. The altitudes taken for the simulation can be below 510 km as it considers the natural decay of the orbit. Mission 1 happens during the first operational year, while Mission 2 happens during the second year. The simulation altitudes are used only for worst-case study purposes and are not necessarily consistent with a possible launch date. A summary of the different cases studied is shown in Table 3.

Table 3. Cases selected for the mission analysis of ROBUSTA-3A

N°	Scenario	Time of the year	Injection altitude (km)	Simulation altitude (km)	LTAN (hour)	Case type
1	Mission 1	September	590	590	22.5	Expected
2	Mission 1	September	510	475	12	Cold/worst for EPS
3	Mission 1	September	590	590	18	Hot
4	Mission 2	January	590	585	22.5	Expected
5	Mission 2	June	510	425	12	Cold
6	Mission 2	January	590	585	18	Hot
7	Deployment	January	590	590	22.5	Expected
8	Deployment	June	510	510	12	Cold/worst for EPS
9	Deployment	January	590	590	18	Hot

To illustrate how the methodology presented in this paper is employed, case number 1 is investigated. The expected orbit for Mission 1 scenario is the one that is supposed to be beneficial for ROBUSTA-3A as communication time with the ground station and SBT are longer. The higher value of the initial altitude is then chosen. For the LTAN, 22h30 was chosen as it is a typical value for SSO [17]. Figure 2 shows a classic timeline of Mission 1, with the events on top and duration below. The events without duration have their timespan determined by the mission profile simulation.

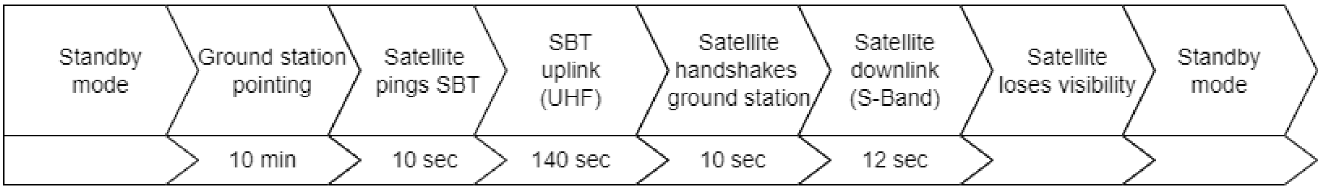


Figure 2. Mission 1 timeline

Although the SBT gathers data continuously, not all the information can serve meteorology. An area has been defined in the Mediterranean Sea, south of France, where the data points are helpful for the detection of "épisodes cévenols". In addition, because this knowledge is exploited for weather forecasting, it needs to be relatively recent. As a result, the satellite shall be able to downlink SBT data during the same pass as the uplink. From these requirements, one can see that not all the satellite passes above the ground station and the SBT are useful for Mission 1, as displayed in the mission analysis results in section 4.4.

4.3 Methodology Application

The simulations use Scilab/Celestlab Toolbox, MATLAB/Simulink and Thermica (courtesy of Airbus Defence and Space). In addition, VTS (courtesy of CNES) is used to visualize the results.

Mission Profile Simulation

The mission profile simulation gives a detailed plan of events that the other simulations will use. The time, orbital parameters, and scenarios are inputs of the simulation. First, a sequence is determined, which is a timeline of events that includes attitude mode and law, satellite mode, power mode of equipment, and the solar panels' deployment status. It represents the satellite's state with the target to point at, but the exact sequence timing depends on the position of the CubeSat. Then, the mission profile simulation, coded on Scilab with the help of Celestlab toolbox, is employed to determine orbital parameters and decide when to activate the sequence of events based on parameters like ground station visibility. The tool will generate a detailed timeline with ephemerides of the satellite, Sun visibility, and the sequence parameters mentioned. These can later be transferred to the EPS simulation (arrow 2) for assessment of power consumption and DoD of the batteries, ADCS simulation (arrow 3) for attitude calculation, and thermal simulation (arrow 4) for temperature assessment of the satellite's equipment. For Mission 1 scenario, the visibility duration with the SBT is also accounted for. This scenario is simulated over one day with a time step of one second. The simulation is also used on larger time scales to determine communication time statistics and time between valid passes based on the ship's trajectory.

ADCS simulation

At CSUM, we developed an in-house simulation environment in MATLAB/Simulink to develop and test filters and control algorithms that will process sensor data and command actuators.

Spacecraft's attitude, represented using the quaternion convention, is propagated through classic equations of motion, namely kinematic and dynamic. Sensors and actuators are simulated given their expected configuration in the spacecraft. External disturbances, which influence the attitude, are simulated thanks to various models (atmospheric, geomagnetic, etc.). This tool also considers internal disturbances relative to uncertainties in the spacecraft inertia matrix and the use of a propulsion system, as is the case for ROBUSTA-3A. Indeed, during propulsive maneuvers, a significant aspect is the inherent disturbance torque resulting from the misalignment of the thrust axis with the center of mass of the spacecraft [14]. It is not relevant for the study of Mission 1.

In the frame of our advanced mission analysis methodology, the ADCS simulation is fed with various ephemeris files representative of a given scenario of operation (trajectory, modes, target attitude, etc.). As a result, it can output any attitude-relative information required by downstream simulations. In addition, actuators' consumption is transmitted to both the EPS block and the Thermal block to refine their calculations.

Thermal simulation

The main software used for thermal simulation is Thermica, a plug-in application of the Systema environment. It consists in interactive modules such as geometry design, trajectory definition and result post-processing. A Thermica 3D model is built based on a simplified Solidworks model of ROBUSTA-3A. In this model, the mesh allows discretizing the model in many nodes depending on accuracy and simulation time needs. The current spacecraft thermal model has around 3000 nodes. Systema easily reads the position and velocity of a satellite from files with different types of data, including the CIC format, our main interest. OEM and AEM files from the ADCS simulation are implemented, then they are linked by the user in Systema in the mission module. At this point, the geometrical model of ROBUSTA 3A, trajectory, and kinematics data from a particular case is coupled, allowing for the first thermal simulation, computing the temperature of the solar panels.

For the second simulation, additional input is the power dissipation of the equipment. The CIC file cannot be directly imported to Systema. A MATLAB script was created to avoid the unnecessary burden of manually writing the values for the nodes. It automates the process and reduces human error possibilities. The script transforms the CIC data into Mortran, a thermal-oriented language based on Fortran 77, which Thermica uses for these data types. The second advantage of the script is to reduce the number of user tasks, reducing human errors and, thus, the number of simulation failures.

Each time the first or second simulation is completed, the results are extracted in CIC format, in accordance with the advanced mission analysis methodology philosophy. The thermal simulation process is shown in Figure 3.

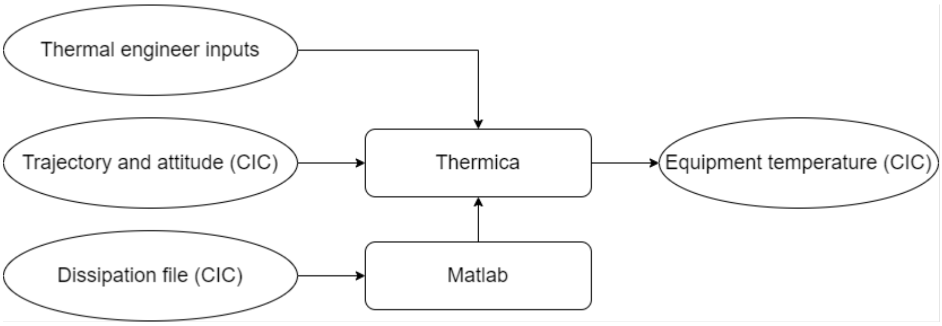


Figure 3. Thermal simulation process

EPS Simulation

To calculate the satellite energy behavior, we use a model integrating a set of equations that model the solar panels, the battery, and the satellite's load. The inputs of this complete model are the results obtained from the ADCS, the mission profile, and the thermal simulations.

The electrical model first calculates the satellite currents. They are mainly composed of solar panel current, load current, and battery current. First, the current of the solar panels is calculated depending on the temperature and their position with respect to the Sun. Next, the satellite consumption current is calculated depending on the satellite's modes, given by the mission profile simulation. Finally, the battery current is calculated with the difference between the first two currents. Knowing the battery's current, we can calculate the DoD of the batteries. That, as previously expressed, is fundamental data for the verification of the mission.

Finally, equipment maximum power is modeled, and the subsystem consumption of each satellite's modes is defined. The electrical model estimates each satellite subsystem's consumption at each instant of the mission profile. These results are one of the thermal simulation inputs for calculating the temperature work ranges of each subsystem.

Data Visualization

Finally, the simulations data is studied with VTS, and graphs are plotted using MATLAB or Scilab. VTS allows the visualization of the timeline of events, like Sun visibility or attitude law, while graphs are more adapted to analyze parameters that take a lot of different values. Flag files are created in each simulation, giving binary information of the success criteria of a parameter (success/failure). For example, the temperature of equipment should stay in a defined range of values, in which case it is a success. These flags can be easily plotted in VTS to quickly determine if the satellite encountered a problem during the scenario. Compared to verifying values one by one, it is a non-negligible timesaver.

4.4 Mission Analysis Results

The chosen case study with the methodology and simulations presented in the previous sections yields precise results. Figure 4 shows the visibility of the SBT and the ground station from the satellite. It is one of the results of the mission profile simulation. With the SBT antennas being omnidirectional, the margin for the link budget with this terminal is smaller than with the ground station. Thus, a greater minimum elevation angle is considered, resulting in lower visibility duration. Every time both the ground station and the SBT are visible is a valid path to perform our scientific objective as required by mission specification. Hence, this graph can be used to plan required maneuvers for Mission 1.

One of the most important metrics that the ADCS simulation can yield is the pointing error. It can be compared to the requirements for each pointing and allows to determine if the time given to maneuver is sufficient. As shown in Figure 4, the pointing error is within requirements for both inertial pointing and ground station tracking. The two large spikes are caused by the target change from the Sun to the ground station (and vice versa). These slew maneuvers durations are consistent with their allocated times.

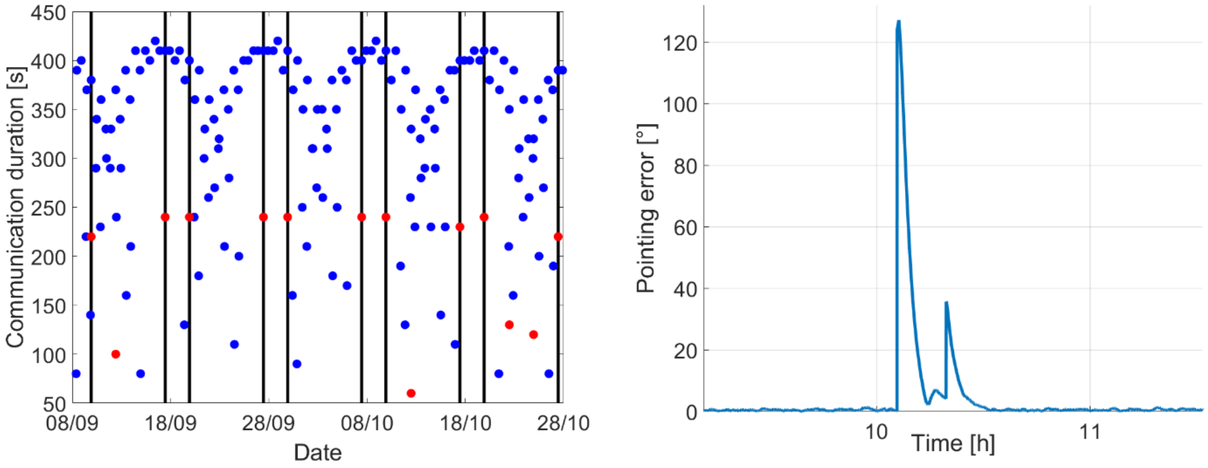


Figure 4. Communication duration with ROBUSTA-3A depending on the date (left). Ground station communications are blue, SBT are red, and vertical black lines represent valid passes. Pointing error depending on the simulation time (right).

For ROBUSTA-3A, one of the mission analysis aims is to verify that the DoD is kept under 20%, although a 40% limit is accepted for specific maneuvers such as detumbling after the launch. For this scenario, Figure 5 shows that this requirement is satisfied with a safe margin. After the tenth hour of the simulation, a step can be observed on the power consumed, followed by a spike. The step corresponds to the satellite maneuvering and communications in UHF, while the spike occurs with the usage of the S-Band in transmission mode. In addition, it is interesting to note the higher-power input at the end of eclipses thanks to lower temperatures of the solar panels.

During the communication event, the temperature of the S-Band module increases drastically, as can be seen in Figure 5, although staying in its operational range. The cycling due to the eclipse is dented for the reaction wheels and battery compared to the S-Band. It is due to the heaters' action that keeps the wheels in their operating range. Much other equipment is studied but not shown here for clarity.

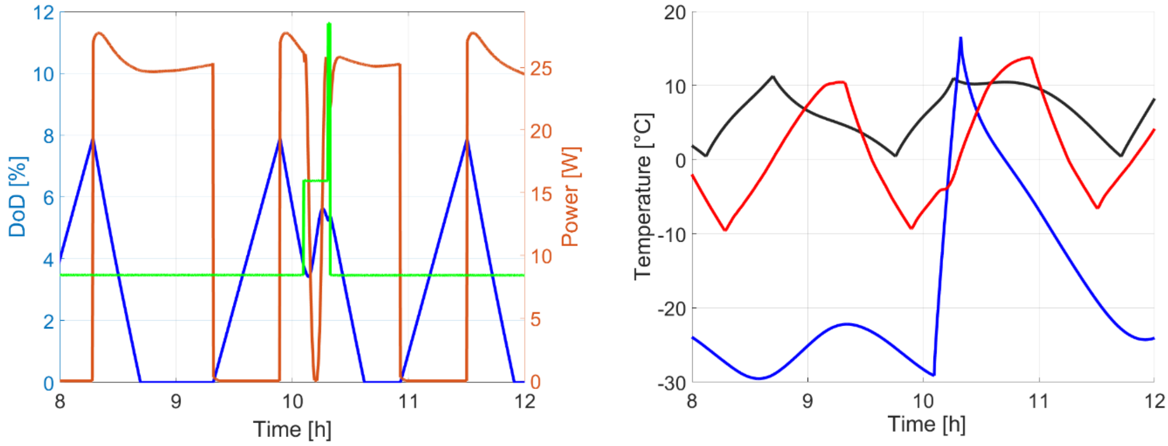
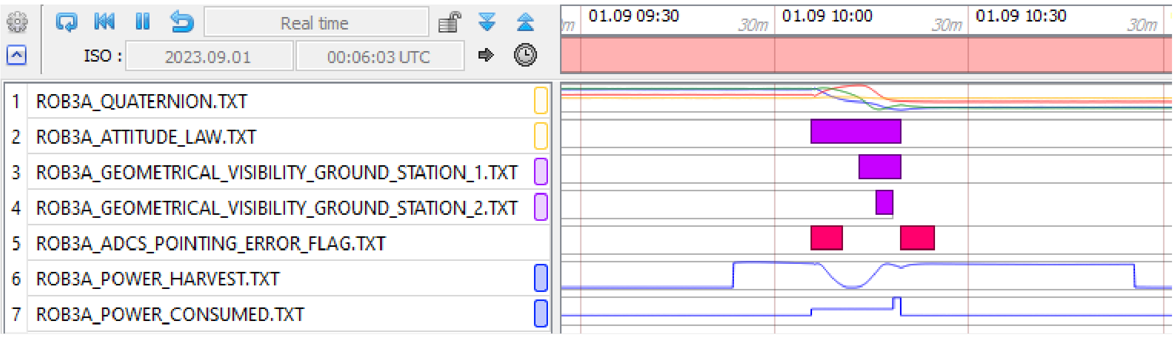


Figure 5. DoD (blue), power input (orange), and power output (green) depending on the simulation time (left). S-Band (blue), reaction wheel (black), and battery (red) temperatures depending on the simulation time (right).

Figure 6 shows a screenshot of VTS where the communication event of the satellite is presented. Two pointing error flags are raised because of the attitude target change mentioned earlier and shown in Figure 4. During the visibility of the ground station and the SBT (referred as “Ground station 2” in

Figure 6), no flag is observed, meaning that the pointing error requirement is satisfied during the communications. The first flag lasts less than 10 minutes, validating the choice of the timing for an attitude target change. Flag files are also created for the temperature of critical equipment, although they are not displayed for clarity.


Real time

ISO : 2023.09.01 00:06:03 UTC

1 ROB3A_QUATERNION.TXT
2 ROB3A_ATTITUDE_LAW.TXT
3 ROB3A_GEOMETRICAL_VISIBILITY_GROUND_STATION_1.TXT
4 ROB3A_GEOMETRICAL_VISIBILITY_GROUND_STATION_2.TXT
5 ROB3A_ADCS_POINTING_ERROR_FLAG.TXT
6 ROB3A_POWER_HARVEST.TXT
7 ROB3A_POWER_CONSUMED.TXT

Figure 6. Screenshot of VTS for Mission 1 scenario, case 1

During this mission analysis campaign, we were able to run several of the cases presented in the previous section. Among other things, running our simulation process for ROBUSTA-3A revealed that using the S-Band in several cases was too ambitious regarding energy and power management. Therefore, we decided to turn off the S-Band in satellite modes where it was not essential. Tracing back our hypothesis showed that it came from too optimistic margins taken in our power budget. At the same time, no definite orbit was selected. All of this highlights the need for this global design validation process.

Another outcome of this process was the re-evaluation of a predetermined Thermal Control solution designed in previous project phases. Indeed, the latest results show that battery temperature sometimes falls to non-acceptable negative temperatures. These results take into account, among other things, the S-Band system activation philosophy and computed spacecraft attitude and illumination fluxes. As shown in Figure 6, this can easily be identified through the display of "flags". Therefore, an increase in heaters' power dissipation or inclusion of thermal passive solution should be studied. The new solution will then easily be verified and compared to the previous design and results by running the process in the same configuration.

We witnessed that the expected orbit can change through the project because of launch opportunities and delays in the development. However, thanks to the methodology, the mission analysis can quickly be iterated to retrieve the updated information with the new orbit when changes are made.

5 CONCLUSION

This paper has presented the advanced mission analysis methodology developed at the CSUM. The main aim of this approach is to support complex design validation and orbit evaluation for our CubeSat missions. Although this process was first elaborated with the critical design validation of ROBUSTA-3A in mind, as illustrated in our work, we recommend its adoption during all small satellite projects' phases to increase mission analysis reliability.

Compared to existing CDE-oriented tools, our work focuses on potentially hidden impacts when subsystem dynamics are not carefully investigated. The current methodology comprises four main blocks executed one by one, namely the mission profile, ADCS, thermal, and EPS simulations. Information transmission relies on the CIC protocol.

Although the design validation campaign of ROBUSTA-3A is not fully completed, it was successfully demonstrated that following the advanced mission analysis methodology is relevant. First substantial results have been processed and taken into account for system and satellite design adaptations and tuning. For example, it has been demonstrated through this analysis that the S-Band activation philosophy was underestimated in terms of power consumption over the nominal orbit, which resulted in a non-consistent depth of discharge of the battery. Therefore, the duty cycle for the S-Band system has to be reduced to a minimal value during Mission 1 need. Also, precise thermal results have shown that some equipment like batteries went out of defined ranges for operations, which was not the case on individual thermal simulations. Increasing power dissipation of the heaters or their duty cycle is a satellite design update achieved thanks to this methodology. The paper then shows that the interdependency of the simulations allows cross-verification of the results.

This methodology proves to be very helpful but can still be enhanced. In addition to the proposed simulations in the process, other subsystem blocks could be included depending on the mission needs. For instance, the TT&C subsystem could be added to compute dynamic link budgets. The primary limitation of our advanced mission analysis methodology is that it requires multiple engineers to run the process. Although the CSUM has all the required skills, going through all the simulations can take some time and affect engineers' workload. Developing a fully integrated tool that includes all the simulations could circumvent this aspect and make the process easier to use for a single engineer. However, the development of such a tool would require non-negligible resources. If it is produced, the tool could integrate a software like Stela or DRAMA to compute the satellite's orbital decay, which is often required for mission analysis.

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