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Concurrent design of miniaturised spacecraft: tools for supporting the system definition and sizing

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Acknowledgment

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Abstract

This work is framed within the Systems Engineering domain, and in particular in the area of approaches and methodologies for the early design stages of space systems and missions.

This thesis aims at defining a set of tools for enabling the design and sizing of space missions developed by nanosatellites. The tools will support the design from phase 0 through phase B of the life cycle, making use of the MBSE (Model Based System Engineering) and Concurrent Design approaches.
The Model-Based Systems Engineering (MBSE) is an approach currently used in the industry to improve the efficiency and effectiveness of the design and development process. The implementation of MBSE in the Concurrent Design concept allows to have a rapid and efficient development of conceptual design.

To understand what potential benefits or challenges could arise from this approach, it was first necessary to review the current state of the art. While several facilities, mainly located at space agencies and large companies, already exist for supporting the early design of "traditional" space missions, very few examples are available for small missions and systems.

The idea at the basis of the present work is to develop some tools useful for the implementation of the concurrent design approach to small-scale missions and systems. In particular, two main elements have been developed:

- A database of CubeSat-like technology. Data on CubeSat components were grouped together in a single Excel® document, some coming from the literature, others from ESA's and NASA's State-of-the-Art, and other data already available in the research team from past projects.
- A set of spreadsheets to carry out the conceptual to preliminary sizing of the system and subsystems. The spreadsheets guide the designer through the development of the design solution and allow the generation of various systems budget, such as Power Budget, Energy Budget, Mass budget and Link budget of the satellite to be sized.

The tools were validated through application in the SPEISAT (Spei Satelles) project, a telecommunications mission with two main objectives:

- The primary mission is to bring into orbit a "Nanobook", a miniaturized chip encoded in binary code that contains a message of hope by Pope Francis, first shared on March 27, 2020, during the COVID pandemic and known as Statio Orbis.
- The secondary mission is to collect data to characterize the behaviour of the spacecraft and of the space environment, using a sensing suite equipped with an inertial measurement unit, magnetometers, and temperature sensors.

The developed tools are compliant with respect to the ESA's Concurrent Design Facility (CDF), and they could be integrated within it without major modification. Most important, these tools are part of the upgrade of the CubeSat Concurrent Engineering System (CES), a design facility that is used at PoliTO for supporting both research and educational activities.

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Abbreviations

3SD	Small Space Systems Design
ACS	Attitude Control System
ADCS	Attitude Determination & Control System
API	Application Programming Interface
ARP	Average Required Power
ASI	Agenzia Spaziale Italiana
BER	Bit Error Rate
C&DH	Command & Data Handling
CDF	Concurrent Design Facility
ComSys	Communication System
ConOps	Concept of Operations
COTS	Off-The-Shelf Component
DoD	Depth of Discharge
ECSS	European Cooperation for Space Standardization
EIRP	Effective Isotropic Radiated Power
EPS	Electric Power System
ESA	European Space Agency
f	frequency
F	Noise figure
G	Gain
GPS	Global Positioning System
GS	Ground Station
IMU	Inertial Measurement Unit
IoT	Internet of Things
IRL	Isotropic Receive Level
JPL	Jet Propulsion Laboratory
KSAT	Kongsberg Satellite Service
L	Loss
LEO	Low Earth Orbit
LEOP	Launch and Early Operations Phase
LVLH	Local Vertical Local Horizontal
M	Method
max	maximum
MB	Model-Based
MBSE	Model-Based Systems Engineering
MCC	Mission Control Centre
NASA	National Aeronautics and Space Administration
OAB	Operational Architecture Blank
OAIB	Operational Activity Interaction Blank
P	Power
PS	Propulsion System
RF	Radio Frequency
RPG	Required Power Generation
RW	Reaction Wheel
SoA	State-of-the-Art

SPEISAT	Spei Satelles
SSO	Sun Synchronous Orbit
SSoT	Single Source of Truth
STK	Systems Tool Kit
T	Temperature
T	Tool
TBD	To be determined
TCS	Thermal Control System
TT&C	Telemetry, Tracking, and Command

1 Introduction

1.1 Context and objectives of the research project

The thesis is focused on design methodologies in the early phases of the mission lifecycle in the Systems Engineering domain. How Model-Based Systems Engineering (MBSE) tools and Concurrent Design (CD) are the most effective state-of-the-art method for space mission design during the early phases of a space mission.

As a reference project was considered Spei Satelles (SPEISAT) Mission, a telecommunications mission funded with the cooperation between Politecnico di Torino, Agenzia Spaziale Italiana (ASI) and Italian National Council of Researches (Consiglio Nazionale delle Ricerche - CNR) with two main objectives:

- The primary mission is to bring into orbit a "Nanobook", a miniaturized chip encoded in binary code that contains a message of hope by Pope Francis, first shared on March 27, 2020, during the COVID pandemic and known as Statio Orbis.
- The secondary mission is to collect data to characterize the behaviour of the space environment, using a sensing suite equipped with an inertial measurement unit, magnetometers, and temperature sensors.

The thesis tries to achieve this through five chapters.

The first chapter focuses on providing the reader with pieces of information relating to the State-of-the-art in which the thesis will be located, CubeSats, Space Mission taking as reference Spei Satelles missions, Concurrent Design, and Concurrent Design Facility.

The second chapter shows an overview of Model-Based Systems Engineering with the main tools that support it, analysing which could be the potential benefits or challenges that might come from this approach.

The third chapter takes on the role of a user-friendly manual for the tool 3SD. The goal here is to break down the tool's operation in a way that is easy for users to grasp. The chapter aims to guide users through the functionality of 3SD, making it simpler for them to get a handle on how it is meant to operate.

The fourth chapter is where we test 3SD. Users input data from Spei Satelles mission case study and check how well the tool's outputs match the real data.

The concluding chapter will concern the conclusions that will be drawn from the work carried out.

1.2 CubeSat

The history of “CubeSats” started in 1999 when professor Jordi Puig-Suari of California Polytechnic State University at San Louis Obispo, and Professor Bob Twiggs of Stanford university proposed this new type of satellite to enable the students in the university to design, build, test, and operate satellites during the Graduate degree program with financial constraints.

As reported in CubeSat Design Specification Rev14.1 [1] a CubeSat is a class of satellites that adopt a standard size and form factor, which unit is defined as ‘U’. The "CubeSat" is a type of miniaturized satellite for low earth orbit (LEO) space research and applications. The dimension of a single cubic unit called ‘1U’ is 10x10x11.35 centimetres and each unit have a mass of no more than 1.33 kilograms. Besides being light and small, designers often use commercial off-the-shelf (COTS) components for electronic and structural parts this allows to reduce the cost.

Generally, CubeSat is widely used for different applications mostly involving miniaturized experiments that provide Earth observation like ESA space mission Picasso (3U) or Simba (3U) and amateur radio applications. Furthermore, some are used as technology or as feasibility demonstrators of a spacecraft that can help to justify the cost and feasibility of a future satellite.

In some cases, they may be used for low-cost scientific experiments and investigations like the mission Milani (6U) and other future space missions to the Moon and beyond are in the planning stages.

All this has been useful to introduce the complexity of these nanosatellites, and since are involved several subsystems and payloads in small spaces, the need to greatly limit consumption and the low budget make the system engineer role important, through the "Model-Based" and the cooperation through the "Concurrent design" sessions can be of considerable importance for the development of future missions.

1.3 Space Missions

Why is a space mission important? And how it works?

Exploring space helps answer fundamental questions about our place in the universe and the solar system’s history.

A space mission generally comprises three segments designed, interfaced, and managed to meet the mission’s objectives. During the design of the space mission and, during the definition of the mission segments, you can encounter different dependencies on each other, this is the greatest challenge for the development and effective execution of space missions.

- The **Space Segment** includes the spacecraft with its payload in orbit.
- The **Transfer Segment** includes the transport of the spacecraft and its payload from the launch station to the operational orbit carried out by a launcher (typically a rocket).
- The **Ground Segment** has the goal of monitoring and controlling the spacecraft and its payload and after that, it analysed and shares the collected data.

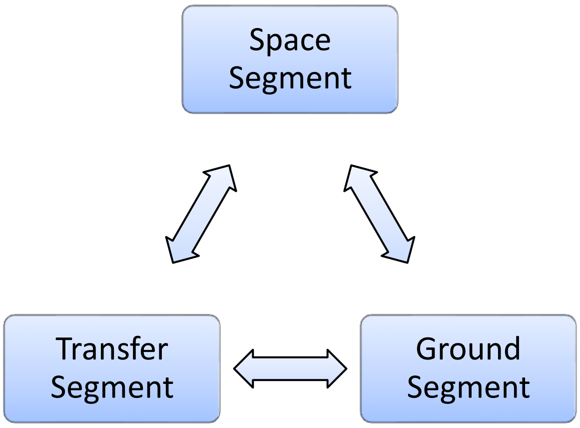


Figure 1: Mission segments

The design of the Ground and Transfer segments includes different drivers about the functions and the physical parameters of the spacecraft, which depend essentially on the mission objective and the mission duration.

Moreover, the three cited mission segments can be further subdivided into the so-called system elements:

Mission subject	**Spacecraft Bus**	**Payload**
Launch Segment	**Launch site**	**Orbit**
Ground Station and Networks	**Mission Operations**	**Mission Products**

Command, Control, and Communications Architecture

Throughout the history of space flight, all the tasks and processes necessary for the development of space programs have been carefully processed.

Nowadays the space industry can rely on the consolidated experience over the years, this is documented in different international and industrial standards.
We must pay particular attention to how in the past space missions have had an orientation along the technological path and performance values, Instead, currently, the gain is increasingly measured by profit considerations and value for money.

In this regard, it is clear that the expectations of a space mission are only measured by the satisfaction of technical and scientific needs.

Due to limited budgets imposed by institutions, public authorities, consumers, and agencies, an essential driver of a space program is the achievement of project goals within the required time and budget.

To summarize, it is noted that in the space sector programs are characterized as follows:

- Uniqueness of the approaches implementation.
- Time limitations.
- Limited resources.
- Political goals.
- Risky processes.
- Intercultural and multicultural cooperation.
- Interdisciplinary challenges.
- Overly complex requirements and tasks.

A good space program must have different criteria for success to be among these serves planning, cost, and quality, which are influenced by the tasks to be performed, and the size and complexity of the space mission.

During the development of a project, we often have to solve the discrepancy due to the need to "plan in detail" and "adapt to the needs" to do this, it is necessary to apply systematic methods according to the project and the nature of the same. Typically, a project (from the working point of view) is planned with a top-down approach for the entire life cycle of the mission.

1.4 Concurrent Engineering

What is Concurrent Engineering?

"*Concurrent Engineering (CE) is a comprehensive, systematic approach to the integrated, concurrent design and development of complex products and their related processes, including marketing, manufacturing, logistics, sales, customer support, and disposal*" [2].

The CE's goals are higher productivity and lower costs through improved development time and shorter time to market. All participants in the concurrent engineering session are obliged to always consider all the elements of the product life cycle, from the design of the same to disposal, including costs, quality, and time.

With Concurrent Engineering it is possible to parallel and thus overlap the development of the different activities, in this way, the aim is to stimulate a continuous exchange of information between the different work teams in order to shorten the time needed to carry out the entire project plan.

For the implementation of this strategy, certain requirements such as:

- The use of widespread skills.
- Overlapping of project activities.
- Two-way communication.
- Gradual release of information as these are defined.
- Integration between different business functions.

CE as a long-term business strategy, promises and provides long-term benefits to businesses if properly implemented. It allows you to form an agile and flexible organization with the aim of obtaining a great competitive advantage that lasts over time.

CE is neither a method nor a tool, but a concept, a way of thinking, which requires many methods and tools for its realization.

Although the original term coined in the distant 1980s has long been used, it has been replaced over time by many other terms that indicate collaboration and the exchange of information between various disciplines, functions, and cultures. in fact, CE requires a socio-technical approach in which the social environment is considered in which the CE product and process development process takes place. There is a massive interaction between this social environment and the CE process.

For its implementation, the CE turns out to be a long-lasting process because it demands at the same time a lot of organizational and technical abilities which turn out difficult to acquire in brief time.
In fact, from the point of view of the organization, there is a gradual transition from work in a sequential way to work in parallel, which, as previously mentioned, requires greater interaction and exchange of information between people from different departments or companies. But the culture of information sharing, and collaboration is often not present in people’s minds and must be gradually instilled.

The CE, in recent decades thanks to an active community such as the "International Society for Productivity Enhancement, Inc." (ISPE), which has been extensively researched and developed by numerous researchers globally, is the subject of investigation. Among these in 1994, ISPE introduced the annual international conferences on Concurrent Engineering, which became training meetings for a community of people from many countries around the world. Researchers and senior experts from this community meet every year to share their experiences and discuss current issues on concurrent engineering, including applications developments and challenges.

1.5 Concurrent Design Facility

What is Concurrent Design Facility?

"The Concurrent Design Facility (CDF) is defined as a working environment in which engineers specializing in different areas of expertise meet to carry out the conceptual design of a project."

In the specific case CDF is designed for the rapid and efficient conceptual design of space systems to ensure in the shortest possible time consistent and high-quality results for the pre-phase A or Level-0 assessment studies. In particular, it can provide as follows:

- New type of evaluation of the mission concept
- Evaluation of options and trade-offs of a space system
- Validation of innovative technologies at the system/mission level
- Payload instrument conceptual design
- Reviews of industrial phase A studies
- Scientific requirements definition and consolidation
- Education and training

Which are the elements of a Concurrent Design Facility?

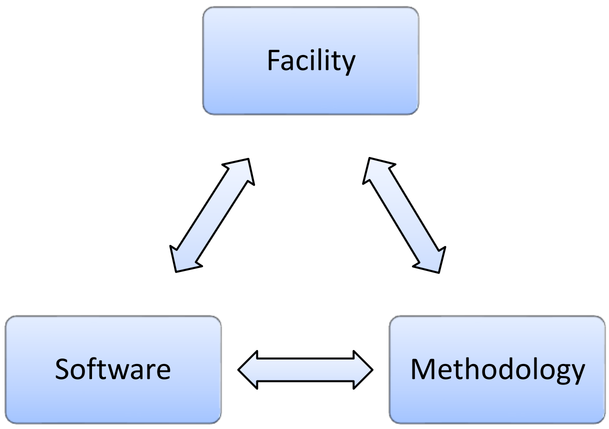


Figure 2: CDF Elements

The three elements in the diagram in Figure 2 can be further described as follows:

- **Facility**: Including all those environments, equipment, and hardware necessary for the performance of activities in the Concurrent Design Facility
- **Software**: It consists of a design database that allows to automatically link the design of the individual elements of a space mission to have as the result a space mission in a "coherent" system (e.g., Valispace, COMET, MS Excel, etc…)
- **Methodology**: Defined as the study of the method on which a given science or discipline is based and in the specific case is the process necessary to efficiently coordinate the design activities of engineers in a concurrent design environment

Currently the CDF is applied in several Space Agencies among these we can find:

- ESA: The European Space Agency has its Concurrent Design Facility in Noordwyk, Netherlands at the European Space Research and Technology Centre (ESTEC)
- NASA: The National Aeronautics and Space Administration has its Concurrent Mission and System Design in Cleveland, Ohio at the Glenn Research Centre (GRC)
- The Italian Space Agency (ASI) has developed its own Concurrent Engineering Facility
- Centre National d'Etudes Spatiales (CNES)
- JAXA with its Mission Design Centre
- German Aerospace Centre (DLR)

Focusing on the ESA CDF it is operating for more than 20 years, undergoing changes, and improving more and more beyond having influenced the agencies as can be seen in Figure 3 below.

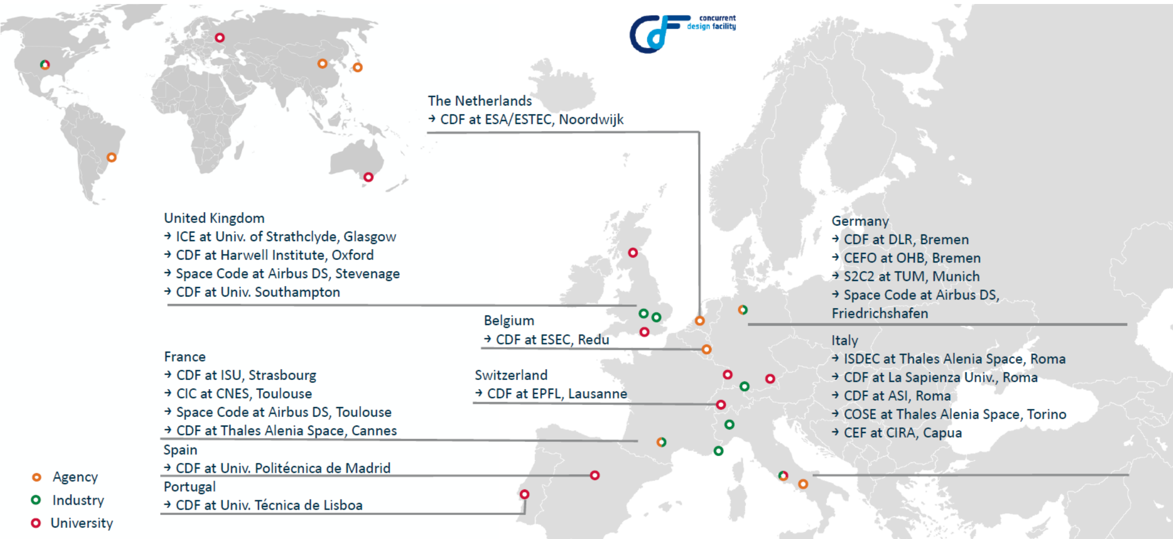


Figure 3: CDF in Europe

In addition to having an influence on member states, information from each EC session is centralized in a central repository that is accessible to all participants in the concurrent engineering session, to do this ESA over the years has used several tools, including:

- Integrated Design Model (IDM) in MS Excel: that was the first design tool of ESA CDF
- Open Concurrent Design Tool (OCDT) used until the end of 2021.
- Concurrent Model-based Engineering Tool (COMET) replaces OCDT in January 2022

These tools and others not related to the ESA CDF will be discussed in the next chapter deepening the characteristics in addition to the positive and negative aspects.

2 Model-Based Systems Engineering

What is it the Model Based Systems Engineering?

Model-Based Systems Engineering (MBSE) is an engineering approach that uses computational models to design and manage complex systems. This method has roots in Model-Based Design (MBD) and Computer-Aided Design (CAD). The fundamental idea behind MBSE is to use accurate digital models of a system to understand its behaviour, interactions, and performance in a comprehensive and integrated way.

The use of digital models in system design dates to the 1960s and 1970s, when the first computer simulation tools were introduced in the aerospace and automotive industries. However, the MBSE as a separate discipline emerged more clearly in the late 1990s and early 2000s.

MBSE is currently used in a wide range of industries and industries to address complex projects and improve the efficiency and effectiveness of the design and development process. These are some of its current uses:

- **Aerospace and Defence**
  In the aerospace and defence industry, MBSE is used to design and develop complex systems such as aircraft, spacecraft, missile systems, and other advanced technologies. MBSE models allow for a deep understanding of the system, facilitating simulation and design optimization. Requirement traceability is particularly critical in this sector, and MBSE ensures that each requirement is met.
- **Automotive**
  In the automotive industry, MBSE is used to design complex vehicles and autonomous driving systems. MBSE models enable simulating vehicle behaviour in various road scenarios, enhancing safety and efficiency. Model-based design also helps resolve interoperability issues among various electronic and electrical vehicle components.
- **Electronics and Devices**
  In the electronics industry, MBSE is employed to design intricate devices such as smartphones, electronic computers, and other IoT devices. This allows for optimizing circuit design and evaluating system performance under real-world conditions.
- **Energy**
  In the energy sector, MBSE is used to design smart grids, power plants, and distribution systems. MBSE models simulate energy flow, optimize distribution, and identify areas of inefficiency.

- **Healthcare**
  In healthcare, MBSE is used to design complex medical equipment, such as imaging devices and diagnostic systems. These models help simulate interaction with the human body and enhance the accuracy of diagnoses.
- **Manufacturing and Logistics**
  MBSE is used to optimize manufacturing and logistics processes, aiding in the design of more efficient supply chains, and reducing operational costs. MBSE models simulate and analyse workflows, identifying areas for improvement.
- **Complex systems and Integrated systems**
  MBSE is widely utilized to design complex systems and integrated systems, such as public transportation systems, urban traffic management systems, and integrated communication networks. These models assist in coordinating the interaction among various components and systems to ensure seamless operation.

Focusing on the Aerospace and defence sector which is the field of application of the thesis we find an additional subdivision into several sectors as shown below.

- **Aircraft Design:**
  In the aerospace sector, MBSE is instrumental in aircraft design. Engineers create detailed models that encompass every aspect of an aircraft, from its aerodynamics and avionics to its structural components. These models enable simulation and analysis of the aircraft's behaviour under various conditions, leading to optimized designs for performance, fuel efficiency, and safety.
- **Spacecraft Development:**
  For spacecraft, MBSE plays a critical role in ensuring the functionality and safety of space missions. Engineers create models that simulate the spacecraft's interactions with external factors such as gravity, radiation, and vacuum. This aids in the design of robust systems, including propulsion, life support, and communication systems, ensuring they can withstand the extreme conditions of space.
- **Missile Systems:**
  In the defence sector, MBSE is used to design missile systems. Engineers model various components, including guidance systems, propulsion, and warheads. By simulating different scenarios, such as target tracking and interception trajectories, MBSE helps optimize missile designs for accuracy and effectiveness.
- **Requirement Management:**
  One of the key aspects of MBSE in aerospace and defence is rigorous requirement management. Every component and system in an aircraft or defence system must meet specific requirements. MBSE tools allow for the meticulous tracing of requirements throughout the entire design and development process. This ensures that each design decision aligns with the established requirements, leading to a coherent and functional end product.

- **Risk Mitigation:**
  Aerospace and defence projects often involve substantial risks, including technical challenges, tight schedules, and stringent safety standards. MBSE enables engineers to simulate potential issues and assess risks comprehensively. By identifying and addressing risks early in the design phase through simulations, costly errors are minimized, and the overall project risk is significantly reduced.
- **Interdisciplinary Collaboration:**
  In complex aerospace and defence projects, various engineering disciplines must collaborate seamlessly. MBSE provides a common platform where mechanical, electrical, avionic, and software engineers can work together. These interdisciplinary collaborations are essential for ensuring that all components integrate seamlessly, allowing for the development of sophisticated aircraft and defence systems.
- **Maintenance and Lifecycle Management:**
  MBSE is not only crucial during the design phase but also throughout the entire lifecycle of aerospace and defence systems. Models created during design can be utilized for maintenance and upgrades. By understanding the system comprehensively through the model, engineers can efficiently plan maintenance activities and implement upgrades, ensuring the systems remain operational and up to date with evolving requirements and technologies.

Among all these applications in the field of Aerospace & Defence, the thesis will be applied specifically to the Spacecraft Development sector which has the following applications of MBSE:

- **Conceptual Design:**
  In the early stages of spacecraft development, engineers use MBSE for conceptual design. Models are created to represent different ideas and concepts. These models help engineers assess the performance, efficiency, and feasibility of various concepts, allowing the selection of the best design approach.
- **Mission Simulation:**
  MBSE is used to simulate space missions. This includes simulating different phases of a mission such as launch, orbit insertion, orbital manoeuvres, and landing. Simulating these phases helps engineers optimize propulsion systems, establish optimal orbital trajectories, and ensure the overall success of the mission.
- **Subsystem Integration:**
  A spacecraft consists of numerous subsystems, including propulsion systems, navigation systems, communication systems, and life support systems. MBSE is used to model and integrate these subsystems. Models enable engineers to identify interactions between various subsystems and ensure they work synergistically without interference.

- **Thermal and Structural Analysis:**
  Engineers use thermal and structural models in MBSE to conduct complex thermal and structural analyses. Thermal simulations are crucial to ensure that the spacecraft can withstand extreme temperature variations in space. Similarly, structural analyses are vital to ensure that the spacecraft's structure is robust and safe during launch and in orbit.
- **Resource Management:**
  In spacecraft design, efficient management of resources such as power, fuel, and oxygen is essential. MBSE helps model the consumption of resources during different mission phases. These models are fundamental for planning refuelling, storage, and efficient utilization of resources onboard the spacecraft.
- **Safety and Redundancy:**
  Safety is a top priority in spacecraft development. MBSE enables the modelling of safety systems and redundancy. Engineers can simulate failure scenarios and ensure that backup systems and safety procedures can intervene in emergencies, ensuring astronaut safety and mission success.
- **Maintenance and Upgrades:**
  After launch, MBSE continues to play a significant role in spacecraft maintenance and upgrades. Detailed models of the spacecraft are used to plan maintenance operations, assess component wear, and implement technological upgrades to extend the operational life of the spacecraft.

In particular, the following thesis in the following chapters will describe a tool created using Microsoft Excel, which will be the union between Conceptual Design and Subsystem Integration. to get an idea of the feasibility of the mission according to the type of mission and type of satellite you want to use.

2.1 Main Tools

There are several tools available for implementing Model-Based Systems Engineering (MBSE). The choice of a tool depends on the specific project requirements and team preferences. These are some of the most widely used tools in the literature for the MBSE:

- IBM Engineering Lifecycle Management (ELM).
- Siemens Teamcenter.
- No Magic MagicDraw.
- Dassault Systèmes CATIA.
- Sparx Systems Enterprise Architect.
- PTC Integrity Modeler.
- Capella.
- SysML Plugin for Enterprise Architect.
- OpenModelica.

In addition to the tools mentioned above we will talk separately about three additional tools, namely:

- Open Concurrent Design Tool (OCDT)
- Concurrent Model-based Engineering Tool (COMET)
- Valispace

2.1.1 Open Concurrent Design Tool (OCDT)

The Open Concurrent Design Tool features a client/server type architecture that involves a database management system to improve data sharing and design interoperability. OCDT implements the conceptual data model defined in [3] called "Technical Memorandum, titled System Engineering - Engineering Design Model Data Exchange (CDF)", this allows to create a standardized and interoperable environment.

OCDT based on the MBSE approach involves user capabilities to allow team members to create, modify, and eliminate a parametric engineering model of a space mission.

OCDT has a service-oriented architecture divided into three layers composed of a set of specific software modules that perform a specific set of functions enabled in the tool.

The levels represented in Figure 4 are:

1. A permanent design database developed in PostgreSQL.
2. ConCORDE (Concurrent Concepts, Options, Requirements and De-sign Editor), which represents the fully integrated graphical user interface in Excel which provides the following functionality with respect to the end user:
   - For concurrent design team members: The process involves creating, modifying, or deleting requirements; implementing parameterized design concepts;

establishing reference units of measurement; and making overall design decisions that involve data, options, and compromises.
- For model managers: Participant Setup, Management, Permissions, and Model Organization.
- For site administrators: User account management, permissions and roles, backup and restore, server configuration.

3. Web services layer based on NodeJS®

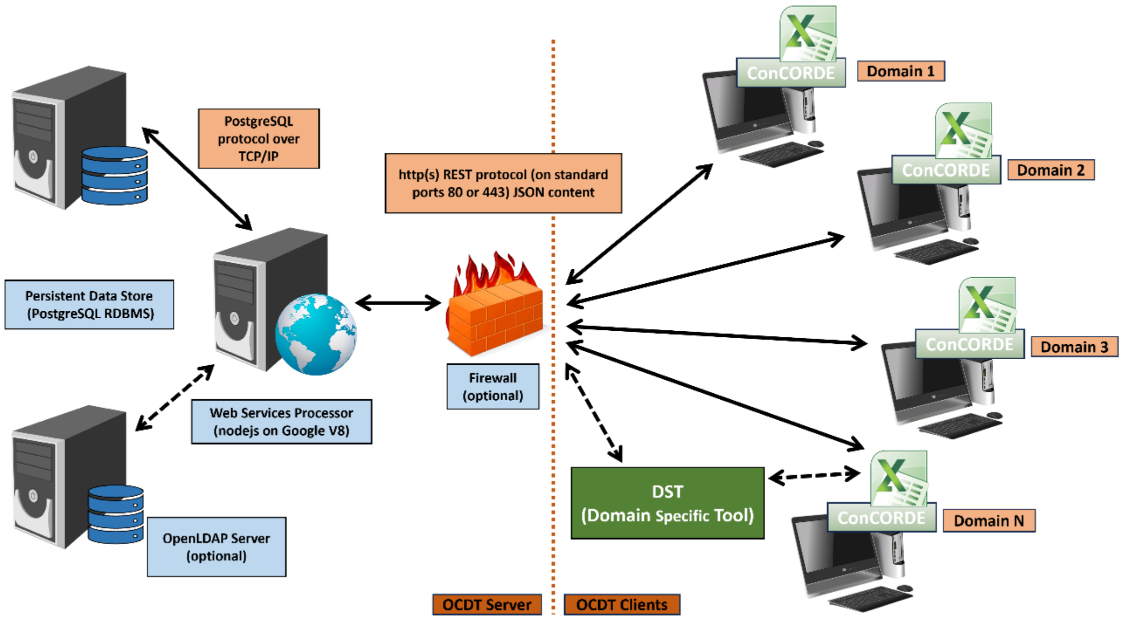


Figure 4: Schematic Overview of the OCDT architecture

This tool after 150 application cases in just over 8 years in January 2022 was completely replaced in the ESA CDF by Concurrent Model-based Engineering Tool (COMET).

2.1.2 Concurrent Model-based Engineering Tool (COMET)

The ESA Facility since January 2022 is adopting a new tool for concurrent Engineering or COMET (Concurrent Model-based Engineering Tool) [4], as its predecessor is an Open-Source tool therefore it is freely available outside the ESA Member States, so it manages to facilitate cooperation between space agencies, research institutes or larger companies.
This tool, in addition to having a renewed user interface ensuring a certain contemporaneity, also has an improvement in overall performance such as:

- A new methodology for the generation of reports, including the mass and power budgets for the design missions.
- Complete backward compatibility with OCDT, thus ensuring the re-use of models created in the past.

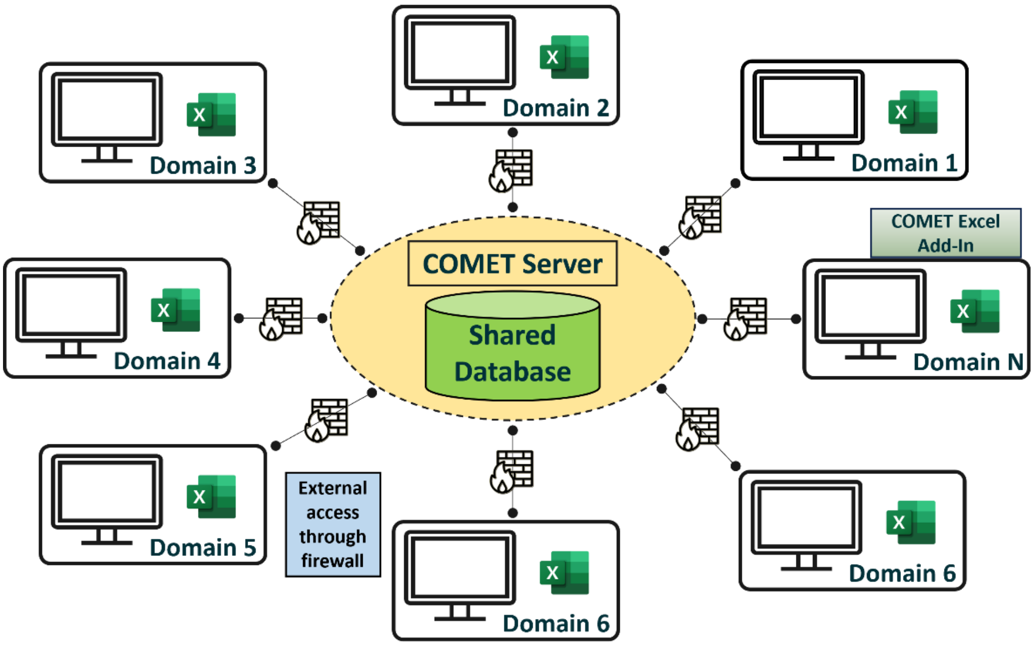


Figure 5: COMET architecture

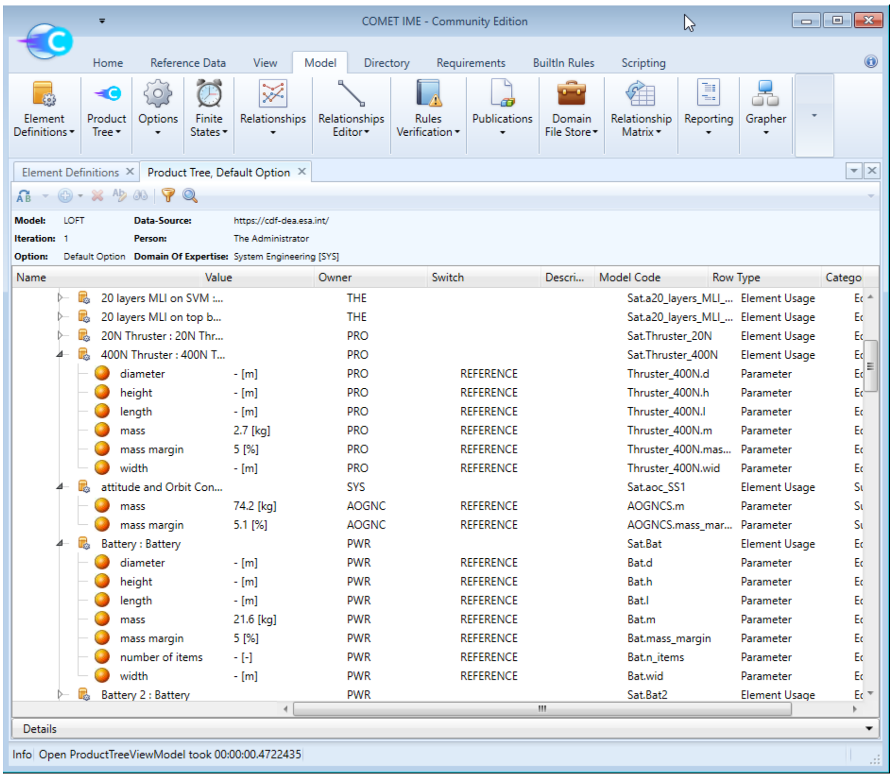


Figure 6: COMET's Interface

This "new" tool over the years It will be used increasingly by ESA as demonstrated by the uses in the "ESA Academy's CubeSat Concurrent Engineering Workshop 2023" organized from 14 to 17 February 2023 at the ESA Academy's Training and Learning Facility in ESEC-Galaxia, Belgium.

2.1.3 Valispace

As an alternative to all the tools seen so far, we also find another tool that is not open source: Valispace.

Valispace is a web-based engineering platform designed to be used for different purposes such as:

- Advanced requirements management,
- Design,
- Simulation,
- Collaboration in complex engineering projects.

This tool is particularly valuable for projects that involve the design and evaluation of intricate systems, such as in the aerospace, automotive, electronic, and other high-tech industries. Valispace allows users to define, track, and manage project requirements by creating a hierarchy of requirements and associating relevant documentation. Engineers can create models and simulations directly within the platform, evaluate system performance, and conduct sensitivity analysis and optimization.

The platform promotes collaboration among team members, enabling simultaneous work on models and facilitating clear communication. A fundamental aspect of Valispace is its data integration, enabling users to synchronize information from various sources and tools such as CAD models, spreadsheets, and simulation software. The platform keeps track of changes made to requirements and models over time, providing a clear record of modifications made by team members. Furthermore, Valispace simplifies the creation of detailed documentation and reports, allowing users to extract and format data to generate project documents and evaluation reports. In summary, Valispace offers a centralized environment where requirements, models, and analyses can be efficiently managed, enabling faster, collaborative, and informed design processes.

After mentioning all these tools, it is also important to say that it is not a better tool than the other, but the choice must be based on three different factors, namely:

- Project requirements
- Budget available
- Ease of learning to use the tool
- Familiarity of the team with the tool

It is only based on these factors that you can choose which tool will perform best.

3 Introduction to 3SD

The tool called Small Space Systems Design (3SD) was created with the aim of speeding up the preliminary design phase for a space mission by drastically reducing its timing, to do this different implementation options were evaluated including:

- MatLab App
- Python App
- Excel Workbook

The first two options, although they seem the most suitable, were more complex to carry on given the vastness of the database used. Therefore, the development decision fell on Microsoft Excel.

For the implementation of the tool, it was first necessary to carry out a thorough study of the thesis work carried out in the past by several colleagues. Specifically, the primary purpose of 3SD was from the beginning to unite all the subsystems in a single source then create a "Single source of truth" (SSoT) that you can define as: "*The practice of aggregating the data from many systems within an organization to a single location*" [5].

At present this tool has been created with the intention of allowing the user to perform the following functions:

- Select the type of Satellite (from the smallest to the largest) from the following:
  - Pico-Satellite
  - Nanosatellite
  - Micro-Satellite
  - Small-Satellite
  - Mini-Satellite
  - Small to medium Satellite
  - Medium Satellite
  - Large-Satellite
  - Very Large-Satellite

- Select the type of mission from the following:
  - <u>Earth Observation</u>: Earth observation space missions are designed to study Earth's natural processes, human activities, and their impact on the environment. They provide valuable data to understand climate change, monitor natural disasters (such as hurricanes, fires, and earthquakes), assess the health of the environment, and manage Earth's resources.
  - <u>Communication</u>: Communication space missions are primarily designed to establish reliable and efficient communication links. They enable voice, data, video, and internet transmissions, connecting remote or inaccessible regions, ships at sea, aircraft in flight, and military operations.

Communication satellites also serve as key components in international telecommunication networks.

- Technology Demonstration: The primary purpose of technology demonstration space missions is to assess the performance, reliability, and functionality of recent technologies in space conditions. These missions help scientists, engineers, and space agencies understand how innovative concepts behave in the harsh environment of space. Successful demonstrations can lead to the adoption of these technologies in future space missions, improving spacecraft efficiency, safety, and scientific capabilities.
- Scientific Research: Scientific research space missions aim to investigate fundamental scientific questions, validate theories, and explore the behaviour of matter and energy in the unique environment of space. Conducting experiments in microgravity or observing celestial objects without atmospheric interference can lead to discoveries that are impossible to achieve on Earth.
- Educational Outreach: The primary purpose of educational outreach space missions is to provide educational opportunities, inspire curiosity, and enhance STEM education. These missions aim to capture the imagination of students, encouraging them to pursue careers in science and technology while promoting scientific literacy and innovation.

- Select the format of the CubeSat from those available below:
  - 1U
  - 2U
  - 3U
  - 6U
  - 12U
  - 16U

  According to CDS [1]

- Mission duration

- Orbit information
  - Orbit inclination
  - Perigee Altitude

- Components selected from a database based on different sources such a NASA SoA [6] and datasheets of manufacturers for each of the following Subsystem:
  - Communication system (ComSys)
  - Thermal Control System (TCS)
  - Electrical Power System (EPS)
  - Propulsion System (PS)
  - Attitude & Determination Control System (ADCS)

  - Payload system
  - Command & Data handling System (C&DH)
- Budget generation
  - Power Budget
  - Energy Budget
  - Mass Budget
  - Link Budget

After providing an overview of the tool's contents, it is essential to detail its structure by outlining the various worksheets included. Thus, the tool concludes with the following worksheets:

- Info
- Mission Choice
- Components
- Budgets
- Mission Database
- EPS Database
- Propulsion Database
- ADCS Database
- C&DH Database
- COMSYS Database
- Payload Database
- TCS Database

In the next chapters will be treated each aspect of the tool describing in detail each worksheet

3.1 Info Worksheet

The worksheet "Info" turns out to be a sheet used as index for the tool, in fact inside as you can see in the figures below there is a brief description of the content of the sheets below.

Specifically, you can split worksheets into three macro groups:

- The first group Table 1 is the one in which all the calculations are performed, in fact this group brings together the sheets "Mission Choice", "Components" and "Budgets".

Worksheet Title	Worksheet Description
Mission Choice	In this worksheet the user must choose the mission that he wants to develop to do this he must select: • Type of satellite • Type of mission • Type of CubeSat • Propulsion system (yes/no) • Mission Duration • Orbit Inclination • Altitude of perigee After selecting all the above parameters, all the choices made in specific tables will appear in real time. The data that will appear in the tables are of a statistical type and derive from research carried out on different papers. In the following sheets it will be possible to modify them where necessary. Finally, the user will have to compile the mission architecture table with the fields indicated, as shown in the note next to the table.
Components	Choice of satellite components. In this worksheet the user must select a set of components that are used for the preliminary design for each of the following subsystems: • Telecommunication System • Thermal Control System • Electrical Power System • Propulsion System • Attitude & Determination Control System • Payload System • Command & Data Handling System These data are part of a database chosen ad-hoc therefore where required it will be possible to customize some data entered
Budgets	This worksheet includes everything you need to evaluate: • Power budget • Duty cycle • Energy budget • Mass Budget • Link budget (for uplink and downlink) The input of this worksheet comes from the worksheets "Mission Choice" and "Components" but there are also Input that the user can enter manually.

Table 1: Mission choice, Components and Budgets worksheet description

- The second group Table 2 includes the high level database generated by taking statistical data of different missions or referring to technical books [6] [7] [8]

Mission Database	This worksheet contains a series of Databases taken from literature or past space missions involving cubesat. Specifically there will be data interenti to: • Power Distribution ranges • Mass Distribution ranges • Type of satellites • Cubesat sizes

Table 2: Mission Database worksheet description

- Finally, the third group made up of Table 3 and Table 4 includes a database of components for each of the subsystems of a satellite.

EPS Database	This worksheet contains a series of Database on the Electric Power System taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA Specifically there will be databases that will involve the following components: • Solar Cells • Solar Arrays/panels • Battery pack • Power Management and Distribution
Propulsion Database	This worksheet contains a series of Propulsion System Databases taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA Specifically there will be databases that will involve the following components: • Hydrazine Chemical Propulsor • Alternative Monopropellant and Bipropellant Propulsor • Hybrid Chemical Propulsor • Cold and Warm Gas Propulsor • Solid Motor Chemical Propulsor • Electrothermal Electric Propulsor • Electrospray Electric Propulsor • Gridded-Ion Electric Propulsor • Hall-Effect Electric Propulsor • Pulsed Plasma and Vacuum Arc Electric Propulsor
ADCS Database	This worksheet contains a series of Attitude and Determination Control System Databases taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA Specifically there will be databases that will involve the following components: • Reaction Wheels • Star Trackers • Magnetic Torquers • Magnetometers • GPS Receiver • Gyros • Sun Sensors • Etc...

Table 3: EPS, Propulsion and ADCS Database worksheets description

C&DH Database	**This worksheet contains a series of Command and Data Handling System Databases taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA** **Specifically there will be databases that will involve the following components:** **• On Board Computer** **• Type of Memory**
COMSYS Database	**This worksheet contains a series of Communication System Databases taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA** **Specifically there will be databases that will involve the following components:** **• Antenna** **• Radio**
Payload Database	**This worksheet contains a series of Payload taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA**
TCS Database	**This worksheet contains a series of Thermal control solutions taken from literature, past space missions involving cubesat and State-of-the-Art published in January 2023 by NASA** **Specifically there will be databases that will involve the following components:** **• Heater** **• Cryocooler** **• Thermal Straps**

Table 4: C&DH, COMSYS, Payload and TCS Database worksheets description

In the following chapters the groups will be unpacked describing separately how they were created and what their actual use is.

3.2 *Database Worksheets*

The worksheets called "Database" are the heart of the tool, in fact it is from the generation of these that the worksheets of Table 1 can operate. To do this initially it was necessary to reflect on what were the main needs of the user and so I asked myself the following question:

What kind of satellite and mission do you want to design?

To answer this question, an extensive study has commenced on contemporary space missions' type and the corresponding satellite classifications (including their mass and power ranges) that can perform them Table 5.

Satellite Type	Mass Range	Power Range [W]
Pico-satellite	< 0.1 kg	1W - 10W
Nanosatellite (CubeSat)	1 kg - 20 kg	1W -100W
Micro-satellite	10 kg - 100 kg	10W - 500W
Small satellite	< 100 kg	1W - 500W
Mini satellite	100 kg - 500 kg	100W - 1kW
Small to Medium Satellite	100 kg - 1000 kg	100W - 5kW
Medium-Satellite	1000 kg - 10000 kg	1kW - 7kW
Large-Satellite	> 10000 kg	2kW - 50kW
Very Large-Satellite	> 100000 kg	50kW - 1MW

Table 5: Type of Satellites

After this initial exploration of satellite types, and considering the vast array of satellite missions, I have decided to focus my attention on nanosatellites, also known as CubeSats. A new study has commenced to examine various CubeSat formats Table 6 and their potential applications in according to [1]. The study will also consider the mass and power ranges for each subsystem included.

Size [U]	Volume [cm^3]	Mass [Kg]	Power [W]		Volume [m^2]
			Min	Max	
1U	1000	1,33	1	3	0,06
2U	2000	2,66	3	5	0,1
3U	3000	3,99	5	10	0,14
6U	6000	7,98	10	20	0,22
12U	12000	15,96	20	40	0,32
16U	16000	21,28	40	60	0,4

Table 6: CubeSat sizes

The Table 7 and Table 8 below show the approximate mass and power ranges for each subsystem for different mission types. This statistical information will serve as a comparison point in subsequent worksheets to roughly estimate initial performance.

CubeSat Mission Type	Telecommunication Subsystem (%)		Thermal Control System (%)		Electrical Power System (%)		Propulsion System (%)		Attitude & Determination Control System (%)		Payload System (%)		Data Handling System (%)	
Earth Observation	25	35	10	20	10	20	0	5	10	20	25	35	5	10
Communication	40	50	10	20	10	20	0	5	10	20	N/A	N/A	10	20
Technology Demonstration	15	25	10	20	10	20	0	5	10	20	20	30	10	20
Scientific Research	15	25	10	20	10	20	0	5	10	20	25	35	10	20
Educational Outreach	20	30	10	20	10	20	0	5	10	20	25	35	10	20

Table 7: Power Distribution

CubeSat Mission Type	Telecommunication Subsystem (%)		Thermal Control System (%)		Electrical Power System (%)		Propulsion System (%)		Attitude & Determination Control System (%)		Payload System (%)		Data Handling System (%)	
Earth Observation	5	10	5	15	10	20	0	5	5	15	25	35	10	20
Communication	10	20	5	15	10	20	0	5	5	15	N/A	N/A	15	25
Technology Demonstration	5	10	5	15	10	20	0	5	5	15	15	25	15	25
Scientific Research	5	10	5	15	10	20	0	5	5	15	20	30	15	25
Educational Outreach	5	10	5	15	10	20	0	5	5	15	20	30	15	25

Table 8: Mass Distribution

Instead, components for the database of each subsystem were selected from Commercial Off-the-Shelf (COTS) products, with information taken directly from manufacturer datasheets, as well as the NASA State-of-the-Art [6] and online databases [9] [10]. This method ensured the inclusion of the widest range of components possible.

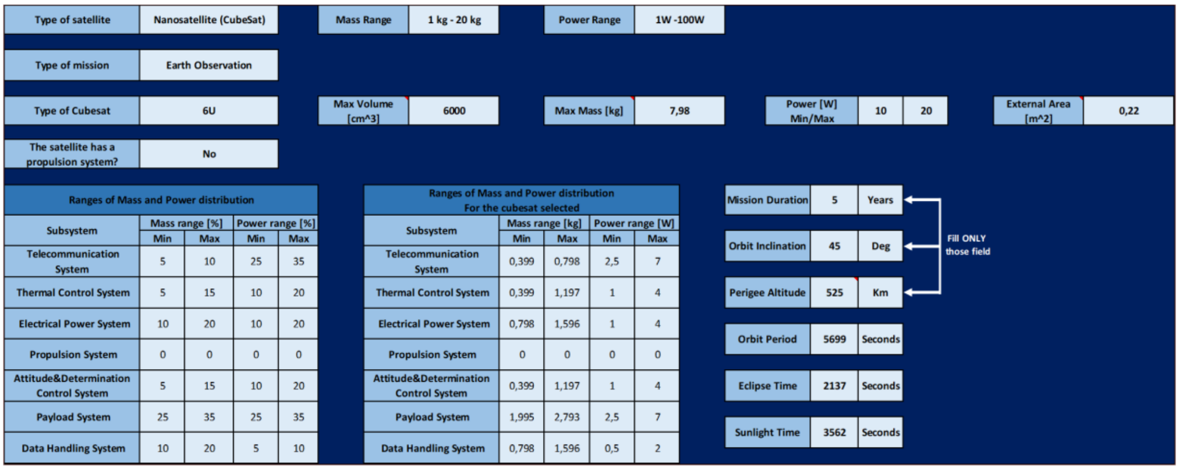
This is the breakdown of the components contained within the database of each subsystem:

- Communication system (ComSys)
  - Antenna
  - Radio
- Thermal Control System (TCS)
  - Heater
  - Cryocooler
  - Thermal Straps
- Electrical Power System (EPS)
  - Solar Cells
  - Solar Arrays/panels
  - Battery pack
  - Power Management and Distribution
- Propulsion System (PS)
  - Hydrazine Chemical Propulsor
  - Alternative Monopropellant and Bipropellant Propulsor
  - Hybrid Chemical Propulsor
  - Cold and Warm Gas Propulsor
  - Solid Motor Chemical Propulsor
  - Electrothermal Electric Propulsor
  - Electrospray Electric Propulsor
  - Gridded-Ion Electric Propulsor
  - Hall-Effect Electric Propulsor
  - Pulsed Plasma and Vacuum Arc Electric Propulsor
- Attitude & Determination Control System (ADCS)
  - Reaction Wheels
  - Star Trackers
  - Magnetic Torquers
  - Magnetometers
  - GPS Receiver
  - Gyros
  - Sun Sensors
- Payload system
- Command & Data handling System (C&DH)
  - On Board Computer
  - Type of Memory

In the upcoming sections, we will address the computational aspect of 3SD while showcasing the user interface.

3.3 Mission Choice Worksheet

This section outlines the intent of the "Mission Choice" worksheet, which is to furnish the user with an overview of the mission being designed. Thus, the sheet presents initial decisions concerning the mission type, followed by those concerning satellite type and operational orbit. Figure 7 shows the user interface that the user will be interacting with, while Figure 8 shows a flow chart that details the steps to be taken to insert information into the worksheet.



Type of satellite	Nanosatellite (CubeSat)	Mass Range	1 kg - 20 kg	Power Range	1W -100W
Type of mission	Earth Observation				
Type of Cubesat	6U	Max Volume [cm^3]	6000	Max Mass [kg]	7,98
The satellite has a propulsion system?	No				

Power [W] Min/Max	10	20	
External Area [m^2]	0,22		

Ranges of Mass and Power distribution				
Subsystem	Mass range [%]		Power range [%]	
	Min	Max	Min	Max
Telecommunication System	5	10	25	35
Thermal Control System	5	15	10	20
Electrical Power System	10	20	10	20
Propulsion System	0	0	0	0
Attitude&Determination Control System	5	15	10	20
Payload System	25	35	25	35
Data Handling System	10	20	5	10

Ranges of Mass and Power distribution For the cubesat selected				
Subsystem	Mass range [kg]		Power range [W]	
	Min	Max	Min	Max
Telecommunication System	0,399	0,798	2,5	7
Thermal Control System	0,399	1,197	1	4
Electrical Power System	0,798	1,596	1	4
Propulsion System	0	0	0	0
Attitude&Determination Control System	0,399	1,197	1	4
Payload System	1,995	2,793	2,5	7
Data Handling System	0,798	1,596	0,5	2

Mission Duration	5	Years
Orbit Inclination	45	Deg
Perigee Altitude	525	Km
Orbit Period	5699	Seconds
Eclipse Time	2137	Seconds
Sunlight Time	3562	Seconds

Figure 7: "Mission Choice" user interface

As outlined in Section 3.2, all initial inputs for this worksheet are sourced from the "Mission Database". The subsequent step towards selecting a satellite type, CubeSat format, and mission type requires deciding whether to incorporate a propulsion system onboard the satellite.

This choice holds significance for two distinct factors:

- The limited space within a CubeSat poses a risk of overfilling if a propulsion system is onboard, as this would require space for a tank.
- Selecting an electric powertrain solution involves weighing the pros and cons. While the size of the solution would likely be smaller compared to chemical propulsion, there is a substantial demand for power supply, which may be a drawback.

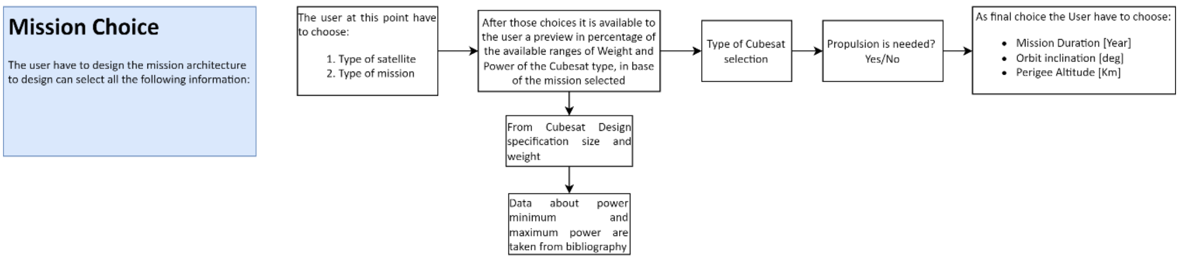


Figure 8: Mission Choice worksheet flow graph

These two aspects should be considered when making a choice. The last mission choices to be made are the total duration of the mission in years, inclination of the orbit in degrees and altitude of the perigee in km (since the Earth is considered as the main body in the whole tool)

These choices determine the orbital period of the satellite in question, thereby defining the duration of both eclipse and sunlight periods as follows:

$$Orbit\ Period = 2\pi\sqrt{\frac{(Perigee\ Altitude + R_{Earth})^3}{\mu_{Earth}}} \quad (1)$$

$$where\ \mu_{Earth} = 398600\ \frac{km^3}{s^2}\ and\ R_{Earth} = 6371\ km$$

$$Eclipse\ time = \left(\frac{Orbit\ Period}{\pi}\right) * arccos\left[\frac{\sqrt{Perigee\ Altitude^2 + (2 * R_{Earth} * Perigee\ Altitude)}}{\cos(\beta)}\right] \quad (2)$$

$$Sunlight\ time = Orbit\ Period - Eclipse\ time \quad (3)$$

Finally, to conclude the use of the worksheet is required the user to fill in the table with the mission architecture [8] data that includes:

- **Subject**: Passive/Active subject.
- **Payload**: Spacecraft hardware and software that observe or interact with the subject.
- **Spacecraft Bus**: The other spacecraft subsystems needed to support the payload.
- **Ground Segment**: The communication equipment and facilities that communicate with and control spacecraft.
- **Mission Operations**: The individuals and programs responsible for the day-to-day operations of the space mission.
- **Command, Control and Communications architecture**: How all the parts of the space mission communicate with each other
- **Orbit**: The path of the spacecraft during its operational mission. Single Satellite/Constellation
- **Launch Segment**: How the spacecraft gets into orbit; may include upper stages or integral propulsion

At this point, the user has an idea of the type of mission he must design and the type of spacecraft to be dimensioned that will be explained in detail in the following sections.

3.4 Components Worksheet

In this worksheet the user can select a set of components from those contained in the Subsystem Database mentioned in section 3.2, to make this choice has been assigned to each subsystem a table. To make the choice of the component and eventually compare it with further solutions the user will have to click in the cell under the writing Model or Product, at this point a drop-down menu will open with all the different options in the database as shown in Figure 9 below.

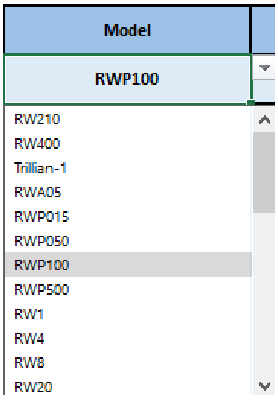


Figure 9: Drop down menu example.

In Figure 10 it is possible to see the aspect of a portion of table for the Attitude and Determination Control System (ADCS) and as it is structured the same, the structure of the tables is the same also for all the other subsystems. Specifically, it is possible identify a table model divided by family of components, which have in the columns in order from left to right:

- Product name
- Manufacturer
- Technical data of the component selected.

Attitude & Determination Control System						
Reaction Wheel Selection						
Model	Manufacturer	Mass [kg]	Peak Power [W]	Peak Torque[Nm]	Momentum Capacity [Nms]	
RWP100	Berlin Space Technologies -4	0,33	1	0,007	0,1	ON
RWP100	Berlin Space Technologies -4	0,33	1	0,007	0,1	ON
RWP100	Berlin Space Technologies -4	0,33	1	0,007	0,1	ON
RW4	Berlin Space Technologies -7	3,2	10	0,25	4	OFF
Trillian-1	AAC Clyde Space -3	1,5	24	47,1	1,2	OFF

Star Tracker Selection							
Model	Manufacturer	Mass [kg]	Power [W]	FOV	Cross axis accuracy (3s)	Twist accuracy (3s)	
T1	Terma -1	0,76	0,8	20° circular	2,2"	9"	ON
Twinkle	Arcsec -2	0,04	0,6	10,4°	30	180	ON
STNS	Solar MEMS Technologies	0,14	1	12°	40"	70"	ON
Sagitta	Arcsec -1	0,275	1,4	25,4°	6	30	OFF
Spacestar	Leonardo	1,6	6	20° x 20°	7,7"	10,6"	OFF

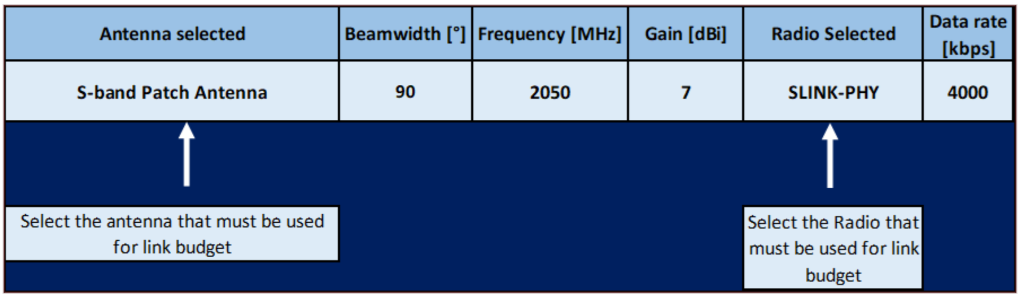
Figure 10: Example of components selection

After selecting the components of each family and subsystem, the user must enable them using the ON/OFF column on the right of each table. It is important to specify that only the enabled components (ON) will be used by the tool for the preliminary calculation of budgets while those disabled (OFF) will be ignored.

For each table, the summary of the above subsystem is presented and listed:

- Total Power of each component's family [W]
- Total Mass of each component's family [kg]
- Subsystem total power required [W]
- Subsystem total mass [kg]

Only the Communication system has more information, in fact the user will have to enter in the fields (one at a time if he has selected more than one) the selected antenna and the radio used which will serve as input for the part of link budget as shown in Figure 11.



Antenna selected	Beamwidth [°]	Frequency [MHz]	Gain [dBi]	Radio Selected	Data rate [kbps]
S-band Patch Antenna	90	2050	7	SLINK-PHY	4000

Figure 11: Antenna and Radio input for Link budget

In the Figure 12 below, the flow diagram for the relevant worksheet displays all potential component families to be utilized.

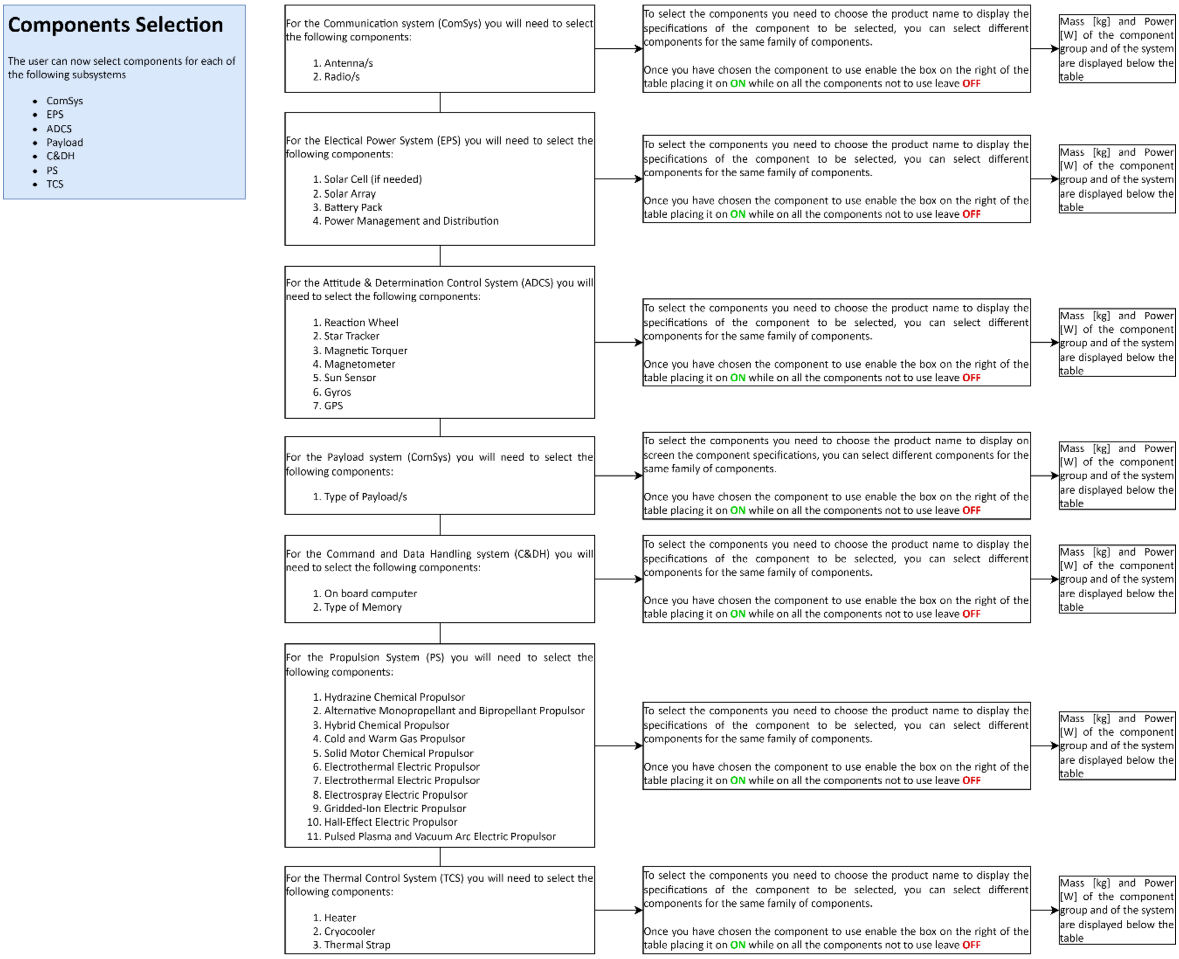


Figure 12: Components worksheet flow diagram

In the following section all the inputs considered in section 3.3 and 3.4 will be merged to generate preliminary budgets.

3.5 Budgets Worksheet

In the worksheet called "Budgets" all calculations are made using the input from the other sheets based on the user's choices, for the generation of the following budgets:

- Power Budget
- Duty Cycle
- Energy Budget
- Mass Budget
- Link Budget

In Figure 13 below you can see the flowchart below for the generation of each of the budgets that will be described later.

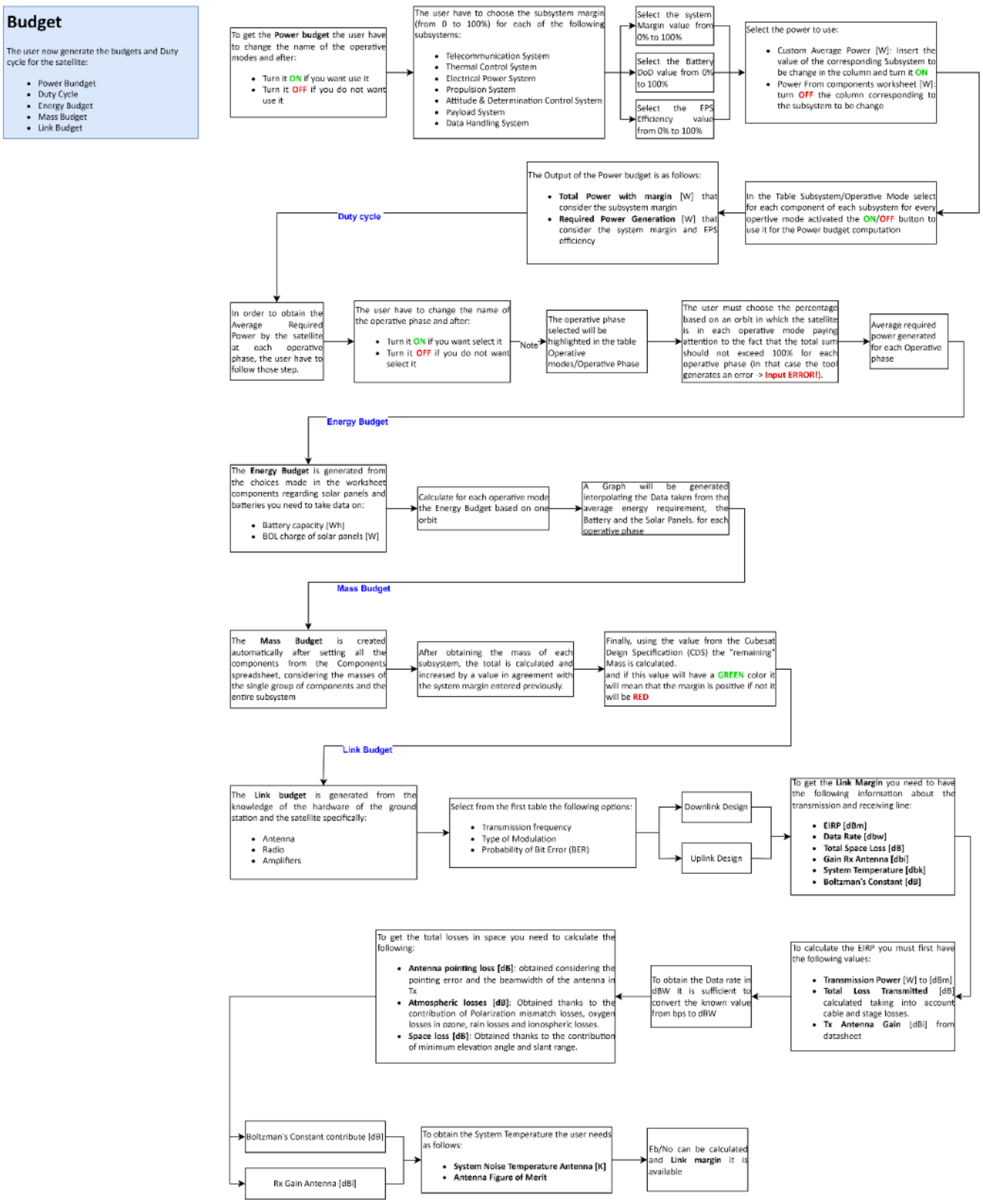


Figure 13: Budgets worksheet flow diagram

3.5.1 Power Budget

What is it the Power Budget? And why is it needed?

The power budget is a critical aspect of its design and operation, ensuring that all systems receive an adequate and stable supply of power throughout the mission. The power budget refers to the allocation and management of the electrical power to various spacecraft components and instruments. The power budgeting process begins with the calculation of the spacecraft's total power requirements. This includes the power needed to operate communication systems, scientific instruments, propulsion systems, computers, and other equipment on board. Engineers must account for different operative modes, such as normal operation, standby, and high-power usage during specific tasks.

Having defined what, it is and why it is needed, let us see how it has been implemented in 3SD, starting with the inputs. In fact, as shown in the figures below, the user will have to make a few specific choices before proceeding to generate the power budget:

- Select the name of the operative mode with its activation (ON/OFF) as shown in Figure 14.

Operative Mode	ON/OFF
Operative Mode 1	ON
Operative Mode 2	ON
Operative Mode 3	ON
Operative Mode 4	ON
Operative Mode 5	OFF
Operative Mode 6	OFF
Operative Mode 7	ON
Operative Mode 8	OFF

Figure 14: Operative Mode selection

- Selecting the subsystem margins as shown in Figure 15.

Subsystem	Subsystem Margin
Telecommunication System	20,00%
Thermal Control System	20,00%
Electrical Power System	20,00%
Propulsion System	20,00%
Attitude&Determination Control System	20,00%
Payload System	20,00%
Data Handling System	20,00%

Figure 15: Subsystem Margins

- System margin DoD and EPS efficiency selection as shown in Figure 16.

System Margin	DoD	EPS Efficiency
10,00%	10%	95,00%

Figure 16: Satellite input

Before effectively proceeding to the calculation of the power budget, which will have as output the Required Power Generation (RPG) relative to the operative mode, it is necessary to select the inputs of Figure 17. However, to do this the user first need to understand how the table is structured in the tool and what each column represents:

- **Power Range**: Represents the maximum and minimum values taken from the statistical data, are indicative values to be compared only with the values in the adjacent columns.
- **Power Selected**: This column contains values from:
  - Summary of each subsystem of the worksheet "Components" if the custom value is set to OFF.
  - Custom value if in the right column the "Custom Average Power" is set to ON.
- **Custom Average Power**: The last column is the one where the user, if he does not have a precise idea of the peak value of the subsystem, can set the power manually, having the foresight to enable it correctly turned ON if he wants to use it.

Subsystem	Power range [W]		Power Selected [W]	Custom Average Power [W]	
	Min	Max			
Telecommunication System	2,5	7	17,25	17,25	ON
Thermal Control System	1	4	2,76	3,75	OFF
Electrical Power System	1	4	1,9	1,9	ON
Propulsion System	0	0	20	20	ON
Attitude&Determination Control System	1	4	11,1	11,1	ON
Payload System	2,5	7	1,8	11,2	OFF
Data Handling System	0,5	2	10,8	0,7	OFF

Figure 17: Maximum Power input

At this point it is possible to go to the modification of the table in Figure 18, selecting for each of the selected operative modes the component "ON" and "OFF". After this operation the changes can be observed in real time in the tables of Figure 19 and Figure 20, representing respectively the percentage of use of the subsystem in a given operative mode and its consumption in watts taking into account the margin of the subsystem.

Subsystem	Component	Operative Mode 1	Operative Mode 2	Operative Mode 3	Operative Mode 4	NULL	NULL	Operative Mode 7	NULL
ComSys	Radio	ON	ON	ON	ON	ON	ON	ON	ON
TCS	TCS	ON	ON	ON	ON	ON	ON	ON	ON
EPS	Solar cell	ON	ON	ON	ON	ON	ON	ON	ON
	Solar Array	ON	ON	ON	ON	ON	ON	ON	ON
	Battery pack	ON	ON	ON	ON	ON	ON	ON	ON
	Power Management	ON	ON	ON	ON	ON	ON	ON	ON
PS	Propulsor	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON
ADCS	Reaction Wheel	OFF	OFF	ON	OFF	ON	OFF	OFF	ON
	Star Tracker	OFF	ON	ON	ON	OFF	OFF	OFF	ON
	Magnetic Torquer	OFF	ON	ON	ON	OFF	OFF	OFF	ON
	Magnetometer	OFF	OFF	ON	OFF	OFF	OFF	ON	ON
	Sun Sensor	OFF	OFF	ON	OFF	OFF	OFF	OFF	ON
	Gyros	OFF	OFF	ON	OFF	OFF	OFF	OFF	ON
	GPS	ON	OFF	ON	ON	OFF	OFF	ON	ON
C&DH	OBC	ON	ON	ON	ON	ON	ON	ON	ON
Payload	Payload	OFF	ON	OFF	ON	ON	OFF	OFF	OFF

Figure 18: Components ON/OFF for each Operative Mode

Subsystem	Operative Mode 1	Operative Mode 2	Operative Mode 3	Operative Mode 4	NULL	NULL	Operative Mode 7	NULL
ComSys	5,80%	5,80%	5,80%	5,80%			5,80%	
TCS	100,00%	100,00%	100,00%	100,00%			100,00%	
EPS	4,74%	4,74%	4,74%	4,74%			4,74%	
PS	0,00%	0,00%	0,00%	0,00%			0,00%	
ADCS	0,90%	27,57%	61,80%	28,47%			1,17%	
Payload	0,00%	100,00%	0,00%	100,00%			0,00%	
C&DH	100,00%	100,00%	100,00%	100,00%			100,00%	

Figure 19: Power usage in percentage for each subsystem

In order to obtain the values in percentage of use of every subsystem in every operative way the tool has been used the following equation:

$$\%_{subsystem} = \frac{\sum Power_{Component\ ON}}{Power_{Subsystem}} \% \qquad (4)$$

Subsystem	Operative Mode 1	Operative Mode 2	Operative Mode 3	Operative Mode 4	NULL	NULL	Operative Mode 7	NULL
ComSys	1,2	1,2	1,2	1,2			1,2	
TCS	3,312	3,312	3,312	3,312			3,312	
EPS	0,108	0,108	0,108	0,108			0,108	
PS	0	0	0	0			0	
ADCS	0,12	3,672	8,232	3,792			0,156	
Payload	0	2,16	0	2,16			0	
C&DH	12,96	12,96	12,96	12,96			12,96	

Figure 20: Power usage in Watt for each Subsystem

The final output of the power budget is the Required Power Generation (RPG) This value was obtained for each mode of operation by summing the contribution of each subsystem, also contributing to the calculation the contribution of the efficiency of the EPS and the system and subsystem margins selected, as shown in the equations below:

$$Power_{Subsystem_{with\ margin}} = \%_{Subsystem} * \left[Power_{Subsystem} + \left(Power_{Subsystem} * Margin_{Subsystem}\right)\right] \quad (5)$$

$$Total\ Power_{with\ margin}\ _{Op\ Mode} = \sum Power_{Subsystem_{with\ margin}} \quad (6)$$

$$RPG_{Op\ Mode} = Total\ Power_{with\ margin}\ _{Op\ Mode} * \left(1 - EPS_{efficiency}\right) * \left(1 + Margin_{System}\right) \quad (7)$$

In the next section the duty cycle in every operative phase will be analysed on the base of the outputs of the power budget

3.5.2 Duty Cycle

Why is the duty cycle necessary?

A satellite's duty cycle is the planned schedule of active and standby periods for various systems and instruments during the operational phase of a mission. This phase includes the time when the spacecraft is performing its primary scientific, exploration, or communications tasks in space. The duty cycle is carefully designed to optimize power consumption, manage thermal conditions, and ensure the longevity of spacecraft components. During the operational phase, various spacecraft systems and instruments are activated and deactivated based on the mission's scientific objectives and operational requirements. For example, scientific instruments may have specific observation windows during which they are active to collect data from celestial bodies or conduct experiments. Communications systems have scheduled duty cycles for sending data back to Earth or receiving commands from Mission Control. Propulsion systems may be used periodically for trajectory adjustments or orbit manoeuvres, requiring scheduled duty cycles to conserve fuel and power.

Efficient duty cycling is critical for power management, especially when the spacecraft relies on solar panels for power. In addition, duty cycle management helps regulate thermal conditions on the spacecraft, preventing overheating and keeping equipment within specified temperature ranges. In addition, the duty cycle is adaptive and can be adjusted based on mission priorities. For example, during critical scientific observations, certain instruments can have extended active periods, while non-essential systems can be temporarily disabled to provide more power for essential tasks.

Mission Phase	ON/OFF
Phase 1	ON
Phase 2	ON
Phase 3	ON
Phase 4	OFF
Phase 5	OFF
Phase 6	OFF
Phase 7	OFF
Phase 8	OFF
Phase 9	OFF

Figure 21: Mission phase selection

Regarding the duty cycle the user must first act on the table in Figure 21 modifying the name of the operating phase, after choosing the name of the same can enable it through the ON/OFF button, with this action in the table of Figure 22: Duty cycle the columns relative to the enabled operative phase will be enabled. At this point, the user can decide for himself the percentages of use basing them on an orbit of each of the enabled operative modes.

Operative Mode	Phase 1	Phase 2	Phase 3	NULL	NULL	NULL	NULL	NULL	NULL
Operative Mode 1	90,00%								
Operative Mode 2	10,00%	10,00%							
Operative Mode 3		90,00%	100,00%						
Operative Mode 4									
NULL									
NULL									
Operative Mode 7									
NULL									
Average Required Power [W]	19,28	26,98	27,23						

Figure 22: Duty cycle

The generated output will be the Average Required Power (ARP) for every operating phase, which will be one of the inputs of the energy budget.

$$ARP_{Op\ Phase} = \sum Duty\ cycle_{Op\ Mode} * RPG_{Op\ Mode}\ \ in\ W \tag{8}$$

3.5.3 Energy Budget

The energy budget involves planning power generation, storage, and distribution. Solar panels capture sunlight, converted into electricity for various systems. Batteries store excess energy, ensuring stable supply during eclipses or shadow periods. Careful orientation and system management optimize power usage. Thermal control systems, often powered electrically, dissipate excess heat. Effective energy budgeting ensures consistent power supply, critical for satellite functions and mission success.

To perform the energy budget, the tool takes from the "Components" worksheet the data of battery capacity expressed in Wh and the peak power of the solar array at BOL expressed in W. Additional inputs come from the analysis of the power budget and the duty cycle, furthermore to the Depth of Discharge (DoD).

Assumptions were made to optimize the calculation of the energy budget Figure 23:

- Only one orbit was considered.
- The first period of orbit used for the calculation is the eclipse period, in which the equation (9).
- The second orbit period is used for the calculation of the sunlight period, also including battery charge as expressed in equation (10)

	Phase 1	Phase 2	Phase 3	NULL	NULL	NULL	NULL	NULL	NULL
SOC initial [Wh]	99,92	99,92	99,92						
SOC after Eclipse Period	88,47	83,90	83,75						
SOC after Sunlight Period	95,96	87,57	87,30	#VALORE!	#VALORE!	#VALORE!			
[Wh]	99,92	91,25	90,84						

Figure 23: Energy Budget Calculation

$$SOC_{Eclipse} = Battery_{Capacity} - (ARP_{Op\ Phase} * Eclipse_{Period}[hours])\ in\ Wh \quad (9)$$

$$SOC_{Sunlight} = SOC_{Eclipse} + (Solar\ Panel_{BOL} * Sunlight_{Period}) - (ARP_{Op\ Phase} * Sunlight_{Period})\ in\ Wh \quad (10)$$

In Figure 24 we can observe how, based on the different inputs of Average Required Power expressed in W for three different operating phases present in Table 9, different trends are generated in the energy budget chart.

ARP - Phase 1 [W]	ARP - Phase 2 [W]	ARP - Phase 3 [W]
19.28	26.98	27.23

Table 9: ARP Examples

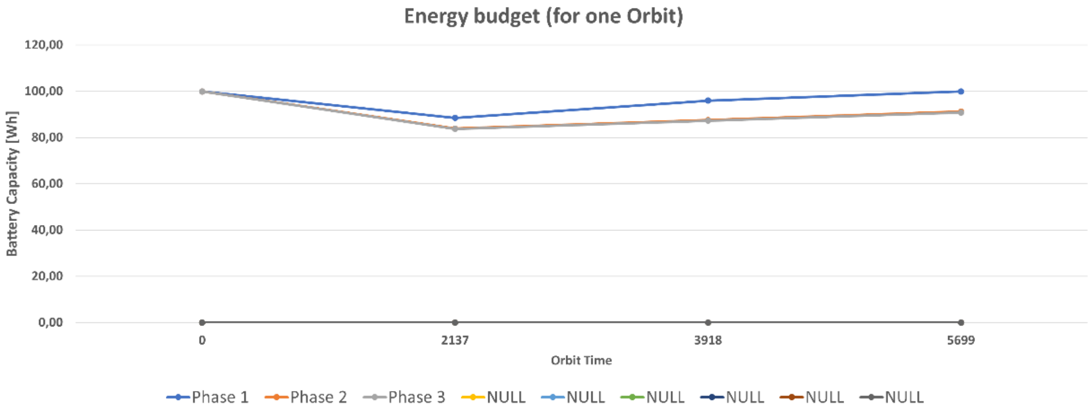


Figure 24: Energy Budget plot

3.5.4 Mass Budget

A satellite's mass budget is a critical roadmap that dictates how weight is distributed among its components. Engineers meticulously allocate weight allowances to the spacecraft's systems and instruments to ensure they match the launch vehicle's payload capacity. Lightweight materials and miniaturization techniques are used to meet strict weight constraints. Balancing structural integrity and functionality, engineers make trade-offs to optimize the satellite's design. Effective mass management is critical to successful deployment, as exceeding the payload capacity can jeopardize the mission's launch. Therefore, the mass budget serves as a critical guideline to ensure that the satellite's components are appropriately sized and weighted for a successful journey into space.

Subsystem	Component	Mass [Kg]	Subsystem Total Mass [Kg]
ComSys	Radio	0,064	0,339
	Antenna	0,275	
TCS	TCS	0,478	0,478
EPS	Battery pack	0,7	1,01
	Power Management	0,31	
PS	Propulsor	1,055	1,055
ADCS	Reaction Wheel	0,99	1,375
	Star Tracker	0,12	
	Magnetic Torquer	0,084	
	Magnetometer	0,036	
	Sun Sensor	0,105	
	Gyros	0,015	
	GPS	0,025	
C&DH	OBC	0,549	0,549
Payload	Payload	0,277	0,277

Figure 25: Satellite Mass Budget

The Mass budget is generated from the selection of components made in the "Components" worksheet, in fact, after the selection of components for each subsystem, the sum for the family of components is automatically made, this mass value is taken and used for the mass budget calculation, this value is used to obtain the total mass of the subsystem (11) as present in the rightmost column of Figure 25 above

$$Mass_{Subsystem} = \sum Mass_{Component_{Subsystem}} \qquad (11)$$

A preview of the mass budget is generated in a pie chart, as shown in Figure TBD below.

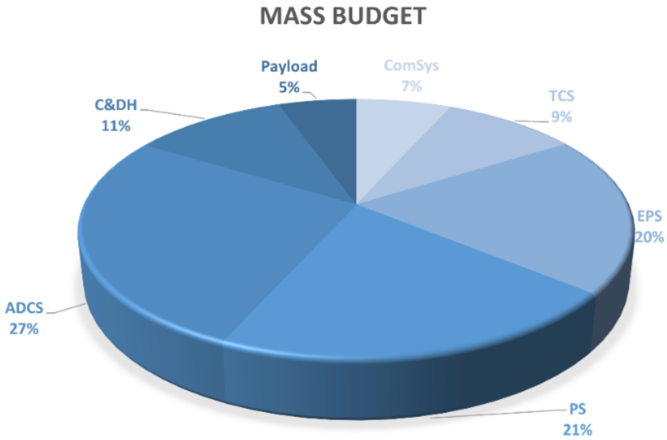


Figure 26: Mass Budget Pie chart

Additionally, equation(12) evaluates the total mass of the satellite by summing and increasing the system margin as expressed in equation(13)

Total Mass [kg]	**5,083**
Total Mass with System Margin [kg]	**5,591**
Total Mass from CDS [kg] for CubeSat format chosen	**7,980**
Remaining mass [kg]	**2,389**

Figure 27: Remaining Mass

$$Mass_{Satellite} = \sum Mass_{Subsystem} \qquad (12)$$

$$Mass_{Satellite_{With\ Margin}} = Mass_{Satellite} + (Mass_{Satellite} * Margin_{System}) \qquad (13)$$

$$Mass_{Remaining} = Mass_{CDS} - Mass_{Satellite_{With\ Margin}} \qquad (14)$$

As a last step, the value obtained in equation (13) is compared with the value obtained from the CubeSat Design Specification for the selected satellite to obtain the remaining usable mass.

3.5.5 Link Budget

The link budget is a critical calculation that determines the performance of the communications system. It evaluates transmit power, propagation losses, antenna gains and receiver sensitivity. This analysis ensures a reliable communications link between the satellite and ground stations. Engineers consider various parameters, such as atmospheric absorption and equipment losses, and build in margins to account for uncertainties, ensuring a robust signal even under adverse conditions. By carefully analysing these factors, the link budget helps optimize the satellite's communications range, data rates and overall reliability. This reliable communication is essential for the transmission of scientific data, commands, and telemetry to ensure the success of the space mission.

In the tool, the user needs some input data to be able to evaluate the budget link and then verify the margin link for both the downlink communication and the uplink communication. In the table in Figure 28, some choices must be made in relation to communication:

- Frequency selection: this is a control parameter; in fact, by setting the correct frequency, you can check that the frequency taken from the "Components" worksheet corresponds to the selected value.
- Modulation
- BER probability

Once these inputs have been made, you can continue with the evaluation of the Downlink Figure 29 and Uplink Figure 30 communication.

Frequency Selected	Min value [GHz]	Max value	Value selected
S-band	2	4	2,05
Wavelength [m]			0,146
Modulation			16QAM
Data Rate [kbps]			4,00E+06
Probability of Bit Error			1,00E-04
Required Eb/No [dB]			12,00

Figure 28: Link budget Input

To obtain the link margin, the process is the same for uplink and downlink, therefore it is treated as a single read, but it is necessary to talk separately about the transmit and receive lines. To evaluate the transmission line, the user first needs to know the transmission power expressed in [dBm].
Downlink case: Power value obtained directly from the worksheet "Components" made the choice of the radio.

Uplink case: variable value depending on the selected ground station, the user can choose in complete autonomy the value in Watts, which is automatically converted to dBm.

To evaluate the Link budget for the transmission line you need this set of parameters:

- The first parameter indicating the goodness of the transmitting system to be evaluated is the Effective Isotropic Radiated Power (EIRP) expressed in dB, which includes:
  - Line Loss, obtained as expressed in (16)
  - Transmission Power
  - Transmission antenna Gain
- All propagation losses in space are considered in the second parameter that includes:
  - Losses due to missed antenna pointing (18)
  - Space losses: due to the distance between transmitter and receiver (22)
  - Atmospheric losses (20):
    - L_{pm}: losses due to polarization mismatch, or a small variation in the polarization of the wave when it passes through the atmosphere.
    - L_{gas}: Losses due to oxygen and ozone in the atmosphere.
    - L_{rain}: Losses due to rain.
    - L_{ion}: Losses due to high electron concentration in the ionosphere.
- Data Rate conversion in dBW (19)

$$Line\ Loss_{Tx} = Wire\ Length * Wire\ Loss\ \ in\ dB \tag{15}$$

$$Total\ Loss_{Tx} = -(Line\ Loss_{Tx} + Stages\ Losses)\ \ in\ dB \tag{16}$$

$$EIRP = Power_{Tx} + Total\ Loss_{Tx} + Gain_{Tx\ antenna}\ \ in\ dBm \tag{17}$$

$$Pointing\ Loss = -12 * \left(\frac{Pointing\ Error\ [deg]}{\frac{Beamwidth\ [deg]}{2}}\right)^2\ in\ dB \tag{18}$$

$$Data\ Rate = 10 * log_{10}(Data\ Rate\ [bps])\ \ in\ dBW \tag{19}$$

$$Atmospheric\ Loss = -(L_{gas} + L_{rain} + L_{ion} + L_{pm}) \tag{20}$$

$$Slant\ Range = R_{earth} * \sqrt{\left(\frac{R_{earth} + Perigee\ Altitude}{R_{Earth}}\right)^2 - cos^2(Elevation_{min})} - sin(Elevation_{min}) \tag{21}$$

$$Space\ Loss = -\left[22 + 20 * log_{10}\left(\frac{Slant\ Range\ [km]}{\lambda\ [km]}\right)\right]\ in\ dB \quad (22)$$

$$Total\ Space\ Loss = Pointing\ Loss + Atmospheric\ Loss + Space\ Loss\ \ in\ dB$$

After you have completed the evaluations on the transmit line, you can switch to the receive line, which requires a different set of parameters, as follows:

- System Noise Temperature (25) which includes the following contributes:
  - Equivalent noise temperature that is subject to interference due to external events
  - Contribute due to wires and filters connecting the receiving antenna and the receiver.
  - Contribute due to receiver noise figure (F)
- Receiver antenna Gain
- Boltzmann's Constant

The Link margin is considered closed if the equation (28) between Eb/No obtained with the equation (27) and Eb/No required has a positive value, in the negative case it is necessary to change the chosen parameters..

$$Line\ Loss_{Rx} = Wire\ Length * Wire\ Loss\ \ in\ dB \quad (23)$$

$$Total\ Loss_{Rx} = 10^{\frac{(-(Line\ Loss_{Tx} + Stages\ Losses) + LNA_{gain})}{10}} \quad (24)$$

$$System_{Temperature}[K] = Noise_{Antenna} + \left(290 * \left(\frac{1 - (Total\ Loss_{Rx})}{Total\ Loss_{Rx}}\right)\right) + \left(290 * \left(\frac{F - 1}{Total\ Loss_{Rx}}\right)\right) \quad (25)$$

$$System_{Temperature} = 10 * log_{10}\left(System_{Temperature}[K]\right)\ in\ dBK \quad (26)$$

$$Eb/No = EIRP + Total\ Space\ Loss + Gain_{Rx} - \left(System_{Temperature} + Data\ Rate + Kb\right)\ in\ dB \quad (27)$$

$$where\ Kb = -229\ dB$$

$$Link\ Margin = Eb/No - Eb/No_{required} \quad (28)$$

In Figure 29 and Figure 30 below, for downlink and uplink respectively, you can see the graphical interface of the tool that the user will use to get the respective link margins.

Transmission Power [dBm]	30,00	
Transmission Line SATELLITE		
Wire lenght [m]	2	User Input
Wire loss [dB/m]	0,16	User Input
Line loss [dB]	0,32	
Stages losses [dB]	0,3	User Input
TOTAL Loss transmitter [dB]	0,62	
Gain antenna [dBi]	7	
EIRP [dBm]	36,38	
Pointing Error [°]	2,00	User Input
Beamwidth [°]	90,00	
Antenna Pointing Loss [dB]	-0,024	
Data Rate [dBW]	96,02	
Lgas [dB]	1,1	User Input: • Lgas • Lion • Lrain • Lpm
Lrain [dB]	2	
Lion [dB]	0	
Lpm [dB]	0,3	
Atmospheric Loss [dB]	-3,4	
Min elevation angle [°]	10,00	User Input
Slant Range [km]	1756,04	
Space Loss [dB]	-163,58	
Total Space Loss [dB]	-167,01	

Receiver Line GS		
Gain antenna GS [dBi]	58,4	User Input
Wire length [m]	10	User Input
Wire loss [dB/m]	0,057	User Input
Line loss [dB]	0,57	
Stages losses [dB]	0,1	User Input
LNA Gain [dB]	0,1	User Input
Total Loss receiver GS [dB]	-0,57	
Total Loss receiver GS	0,877	
Equivalent noise temperature [K]	25	User Input
Receiver noise figure	1,2	User Input
System Noise Temperature [K]	131,81	
System Noise Temperature [dBK]	21,199	
Boltzman's constant [dB]	-228,6	
Required Eb/No [dB]	12,00	
Eb/No [dB]	39,15	
Link Margin [dB]	27,15	

Figure 29: Link Budget for Downlink

Transmission Power [W]	75,00	User Input
Transmission Power [dBm]	48,75	
Transmission Line GS		
Wire lenght [m]	10	User Input
Wire loss [dB/m]	0,057	User Input
Line loss [dB]	0,57	
Stages losses [dB]	0,3	User Input
TOTAL Loss transmitter [dB]	0,87	
Gain antenna GS [dBi]	58,4	User Input
EIRP [dBm]	106,28	
Pointing Error [°]	0,10	User Input
Beamwidth [°]	1,02	User Input
Antenna Pointing Loss [dB]	-0,458	
Data Rate [dBW]	96,02	
Lgas [dB]	1,1	User Input: • Lgas • Lion • Lrain • Lpm
Lrain [dB]	2	
Lion [dB]	0	
Lpm [dB]	0,3	
Atmospheric Loss [dB]	-3,4	
Min elevation angle [°]	10,00	User Input
Slant Range [km]	1756,04	
Space Loss [dB]	-163,58	
Total Space Loss [dB]	-167,44	

Receiver Line SATELLITE		
Gain antenna [dBi]	7	User Input
Wire length [m]	2	User Input
Wire loss [dB/m]	0,1	User Input
Line loss [dB]	0,2	
Stages losses [dB]	0,3	User Input
LNA Gain [dB]	0,1	User Input
Total Loss receiver GS [dB]	-0,4	
Total Loss receiver GS	0,91	
Equivalent noise temperature [K]	290	User Input
Receiver noise figure	1,2	User Input
System Noise Temperature [K]	381,5744123	
System Noise Temperature [dBK]	21,19938232	
Boltzman's constant [dB]	-228,6012091	
Required Eb/No [dB]	12,00	
Eb/No [dB]	57,22	
Link Margin [dB]	45,22	

Figure 30: Link Budget for Uplink

4 Implementation of SPEISAT study case in 3SD

What is the Spei Satelles mission? And what is its purpose?

As expressed in the first chapter Spei Satelles is a telecommunications space mission, specifically consists of a 3U CubeSat which has the following objectives:

As Primary mission objectives:

- To host the Nanobook and bring it to LEO.
- To transmit text messages of hope to ground stations. The messages are sentences collected in a file saved on the onboard computer memories. They are transmitted in three languages: Italian, English and Spanish.

Secondary mission objectives:

- To characterize the internal and external thermal environment of the spacecraft.
- To characterize the internal magnetic field of the spacecraft and map the Earth magnetic field.
- To characterize the angular motion of the spacecraft.

In this chapter, 3SD will be tested with the inputs from the mission just mentioned, and then the output of the tool will be compared with the real ones, thus verifying the accuracy of the calculations performed by the tool.

Each sub-section below will be specifically concerned with one of the three steps in the validation of 3SD output:

1. Input: All the inputs required to perform the calculations are listed, including the characteristics of the mission, satellite, and ground station.
2. Output: All budgets are generated by the tool based on the inputs considered.
3. Comparing: The generated outputs are compared with the actual outputs to assess the accuracy of the results obtained.

4.1 Input from SPEISAT mission

The tool requires specific inputs to correctly generate the outputs specific to the mission:

- Mission type: Telecommunications
- CubeSat format and characteristics: 3U CubeSat with body mounted solar panels.
- Orbital data:
    - Circular altitude [km]: 525 ± 25
    - Inclination [deg]: Sun Synchronous Orbit ± 0.1
    - Mean Local Time of Descending Node [hh:mm]: 13:00 + 60.

In order to obtain valid results on the budgets, the masses, the required power and the characteristics of the components are necessary, which have been shown in the Table 10 and Table 11 below.

Component	Mass [kg]	Quantity	Total Mass [kg]
Antenna group	0.018	2	0.036
ComSys 1	0.051	1	0.051
ComSys 2	0.051	1	0.051
Solar Panel	0.146	4	0.584
Battery Pack	0.450	1	0.450
DET	0.04	1	0.04
Sensing Suite	0.081	1	0.081
C&DH 1	0.052	1	0.052
C&DH 2	0.052	1	0.052
ACS	0.008	1	0.008

Table 10: Masses of components

Component	Power Consumption [W]
C&DH 1	0.72
C&DH 2	0.72
ComSys 1	5.65
ComSys 2	0.35
Sensing Suite	0.26
Backplane	0.1
DET	0.09

Table 11: Power consumption of the components

Other factors to be considered are the satellite's operative modes, how the components are switched ON and OFF during these modes, and any margins. A description of each of the operating modes considered is given in the following list:

- Commissioning Mode: Both onboard computers are active, and the sensor suite is active and collecting sensor data. Both buses send telemetry packets which contain basic telemetry integrated with data collected by the sensing suite. The telemetry messages are alternated between the two buses so that each bus sends one message every three minutes. This mode of operation automatically transitions to Payload Hot Mode when the timer of 14 days runs out.
- Payload Hot Mode: Both buses onboard computers are active, and the sensor suite is active and collecting data. Both buses send four consecutive messages. The first three messages contain the same payload hopeful sentence in Italian, English, and Spanish, while the fourth message contains a telemetry packet made up of the system and the sensor suite telemetry data. The four messages are alternated between the two buses so that each bus sends one sequence every two minutes.
- Payload Cold Mode: Only the BUS 1 onboard computer is active, while BUS 2 is shut down. The sensing suite is active and collects sensor data. BUS 1 sends four consecutive messages. The first three messages contain the same payload hopeful sentence in Italian, English, and Spanish, while the fourth message contains a telemetry packet made up of the system and the sensor suite telemetry data. The four messages are sent one sequence every two minutes.
- Downlink Mode: Both buses onboard computers are active, and the sensing suite is active and collecting data. A selected bus (BUS 1 or BUS 2) transmits the system telemetry data or the data from the sensing suite, according to the command received from the ground operators. If the previous mode is Payload Cold Mode or Recharge Mode, only BUS 1 can be selected, and BUS 2 remains shut off in this mode. The Downlink Mode can be personalized by ground operators by setting some parameters, such as the transmission rate of telemetry, the timeout that interrupts the downlink transmission, and whether system or sensing suite data are requested for downlink. If system telemetry data is sent, a periodic telemetry message is transmitted with a frequency defined in the command arguments and the transmission is interrupted when the timeout is reached. If sensing suite data is sent, the selected bus transmits a single long message with the sensing suite data logs from the most recently collected data. The transmission is interrupted when the downlink timeout is reached. After the transmission timeout, the satellite automatically reverts to the previous operative mode.
- Recharge Mode: Only the BUS 1 onboard computer is active, while BUS 2 is shut down. The sensing suite is active and collects sensor data. BUS 1 transmits telemetry packets which contain the system telemetry data, the payload telemetry data, and the sensing suite data every 2 minutes. This mode of operation is triggered automatically when the battery voltage goes below 11.4 V. This mode of operation is timed and automatically reverts to the previous operative mode when the timer

of 11 hours runs out. Its duration is designed so that it reverts to the previous mode when the battery is at full charge. The timer duration can be modified if this mode of operation is triggered by a command.

To perform the link budget are also required the specifications of the reference Ground Station (GS) of the mission, in the table below are the input data of the antenna of the ARI-BRA station and the transmission power.

Description	Value
Frequency Range	430 to 438 MHz
Gain	18.9 dBi
Beamwidth	20 deg
Maximum Transmission Power	1kW

Figure 31: UHF Antenna data - Model 436CP42UG

The ARI-BRA station can transmit a signal in Uplink at a maximum power of 75W that correspond to about 48.8 dB, this data is particularly important for the generation of the link margin of Uplink.

4.2 Output from 3SD

4.2.1 Power Budget

The output of the power budget shows the power required by the generation to properly power the satellite, and the colours in Figure 32 show which of the operative modes are the most expensive in terms of energy.

Subsystem	Commissioning	Payload Hot	Payload Cold	Downlink	Recharge
ComSys	0,7	6	6	6	0,7
TCS	0	0	0	0	0
EPS	0,09	0,09	0,09	0,09	0,09
PS	0	0	0	0	0
ADCS	0	0	0	0	0
Payload	0,26	0,26	0,26	0,26	0,26
C&DH	1,44	1,44	0,75	1,44	0,72
Total with Margin [W]	2,49	7,79	7,10	7,79	1,77
Required Power Generation [W]	2,63	8,22	7,49	8,22	1,87

Figure 32: Spei Satelles Power Budget

4.2.2 Duty Cycle

The alternation of the operating modes within a single mission phase is crucial to obtain an Average Required Power.

Operative Mode	Commissioning+Downlink	Payload hot+downlink	Payload cold+downlink	Recharge
Commissioning	30,00%			
Payload Hot		30,00%		
Payload Cold			30,00%	
Downlink	70,00%	70,00%	70,00%	
Recharge				100,00%

Figure 33: Spei Satelles Duty Cycle

The ARP values contained in Table 12 are the inputs for energy budget generation.

ARP - Commissioning + Downlink [W]	ARP - Payload Hot + Downlink [W]	ARP - Payload Cold + Downlink [W]	ARP – Recharge [W]
6.54	8.22	8	1.87

Table 12: Spei Satelles ARPs

4.2.3 Energy Budget

In the following section are analysed two different cases of power budget:

- Case 1: Two solar panels are considered for power generation.
- Case 2: One solar panel is considered for power generation.

4.2.3.1 Case 1

In case 1 were considered only two solar panels facing the sun for the generation of energy, the outputs of this case are shown in Figure 34 and even better in the zoom of Figure 35 below. Based on the operative phase enabled you get a different graph; the worst combination is the same as case two better discussed in section 4.2.3.2. In each orbit you have a loss of soc of about 0.48wh propagating this value over time you get that the soc reaches the value of DoD after more than 50 orbits corresponding to about 3 days.

	Commissioning + Downlink	Payload Hot + Downlink	Payload Cold + Downlink	Recharge
SOC initial [Wh]	65,98	65,98	65,98	65,98
SOC after Eclipse Period [Wh]	62,09	61,10	61,23	64,87
SOC after Sunlight Period [Wh]	65,13	65.30	63.54	65.98
	65,98	65,50	65,85	65,98

Table 13: Spei Satelles Energy Budget – Mission Phases Case 1

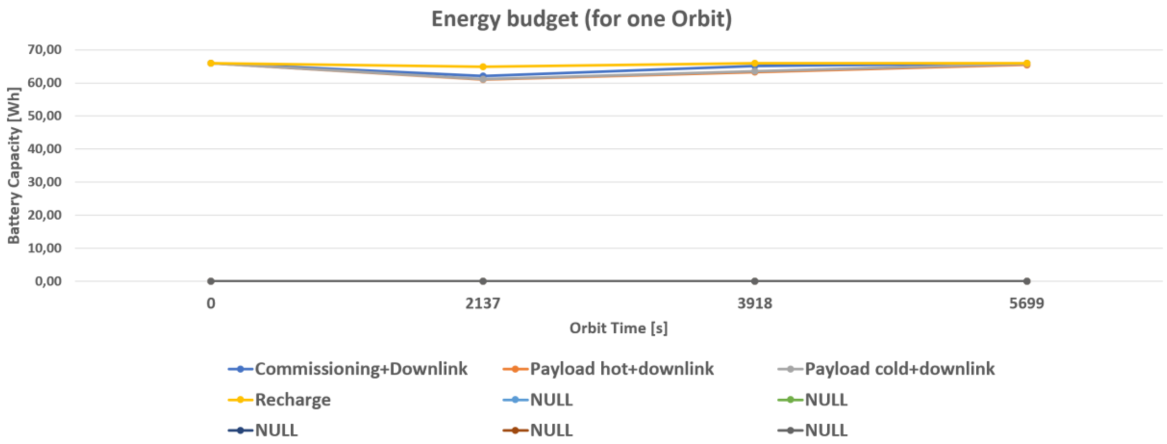


Figure 34: Spei Satelles Energy Budget - Case 1

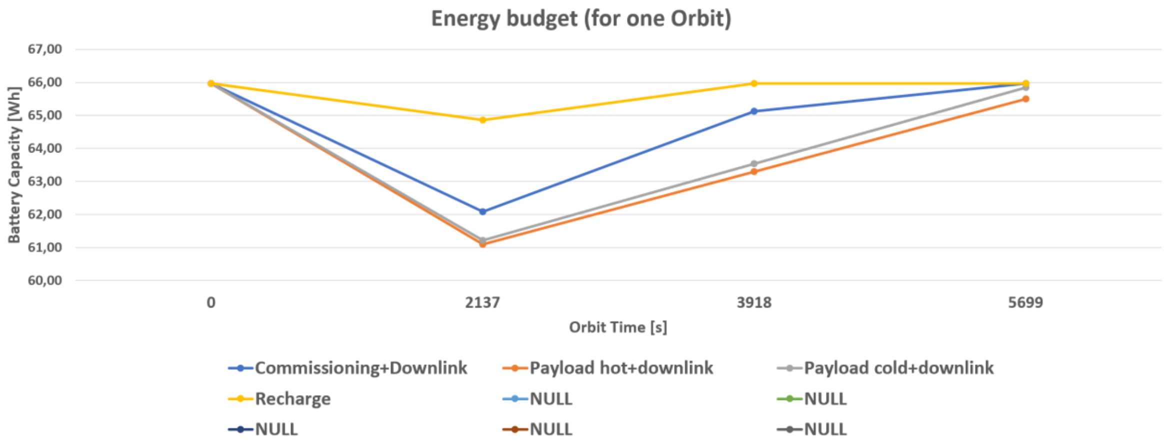


Figure 35: Spei Satelles Energy Budget -Case 1 Zoom

4.2.3.2 Case 2

In case 2 was considered only a solar panel facing the sun for the generation of energy, the outputs of this case are shown in Figure 36 and even better in Figure 37 below. Based on the operational phase enabled you get a different graph, you can observe that in the worst case, that is also in this case the combination between Payload Hot Mode and Commissioning Mode each orbit has a loss of SoC of about 6.75Wh propagating this value you get that the soc reaches the value of DoD after about 5 orbits.

	Commissioning + Downlink	Payload Hot + Downlink	Payload Cold + Downlink	Recharge
SOC initial [Wh]	65,98	65,98	65,98	65,98
SOC after Eclipse Period [Wh]	62,09	61,10	61,23	64,87
SOC after Sunlight Period [Wh]	61.99	60.17	60.40	65.98
	61.89	59.23	59.58	65.98

Table 14: Spei Satelles Energy Budget - Mission Phases Case 2

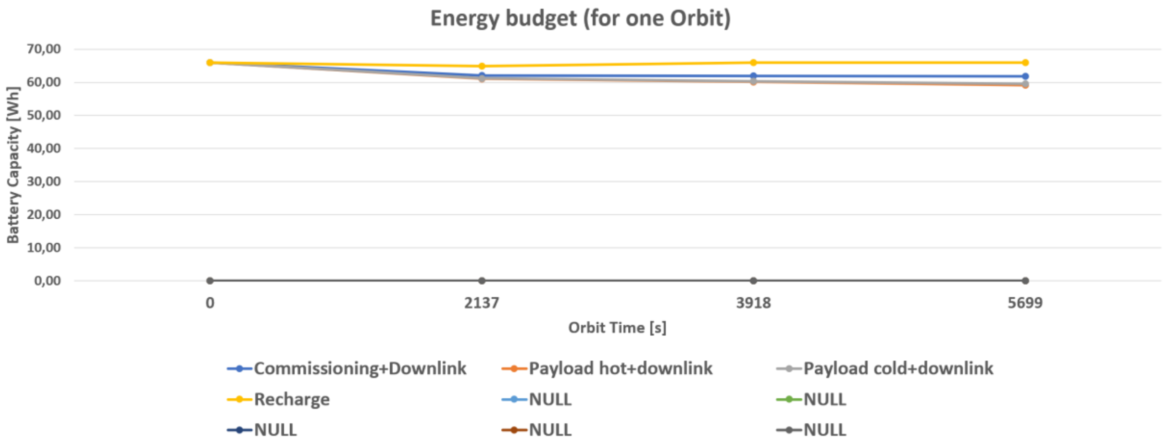


Figure 36: Spei Satelles Energy Budget - Case 2

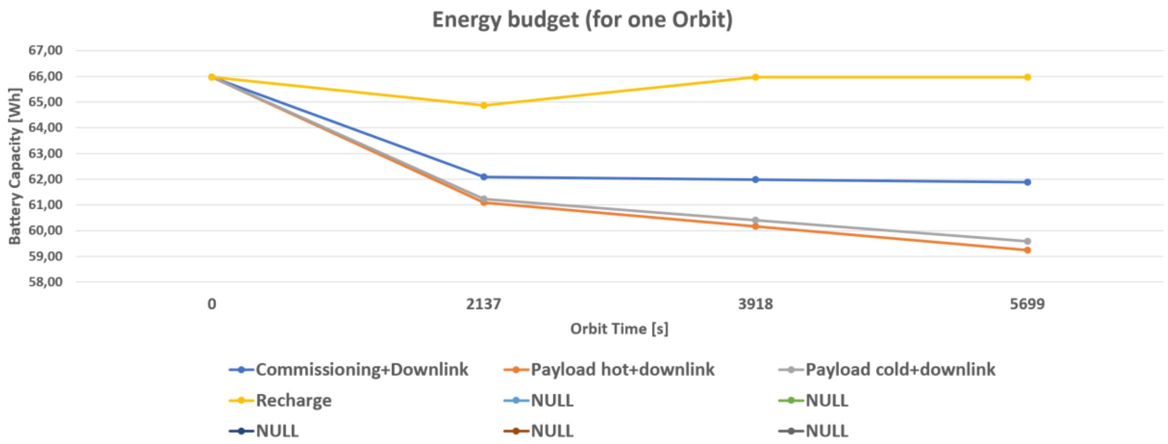


Figure 37: Spei Satelles Energy Budget - Case 2 Zoom

In section 4.3, the values of the analyses are compared with the values obtained in orbit.

4.2.4 Mass Budget

The mass budget, which is the sum of the individual masses of the enabled components, can be easily calculated as shown in Table 15 below.

Subsystem	Subsystem total Mass [kg]
Communication System	0.138
Thermal Control System	0
Electrical Power System	1.072
Propulsion System	0
Attitude Control System	0.008
Command and Data Handling System	0.104
Payload	0.081
Total [kg]	1.402
Total With Margin [kg]	1.543
Total Mass from CDS [kg]	3.990
Remaining Mass [kg]	**2.447**

Table 15: Subsystems Mass Budget

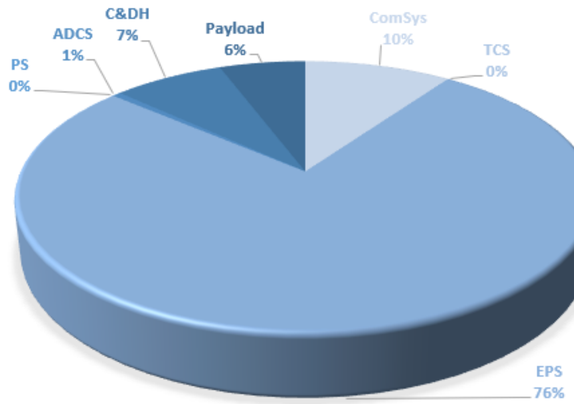


Figure 38: Spei Satelles Mass Budget - Pie chart

In the total calculation of the mass budget as you can see are never mentioned the structure or the harness, this is because they do not result in any component list being mission specific, for this reason in Table 16 below these two items are mentioned with their mass.

Item	Mass [kg]
Structure	0.997
Harness	0.194

Table 16: Other Components masses

In this way a total mass of the satellite of 2.593 kg can be obtained.

4.2.5 Link Budget

In Figure 39 and Figure 40 the final outputs can be observed respectively for Downlink and Uplink of the mission.

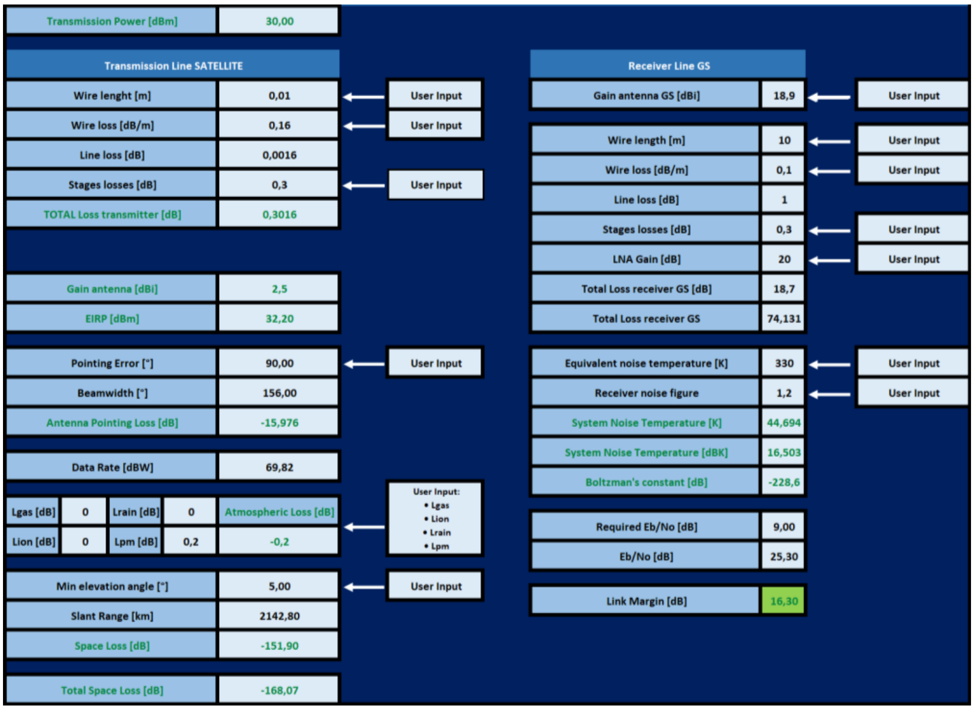


Figure 39: Spei Satelles Downlink Tool Output

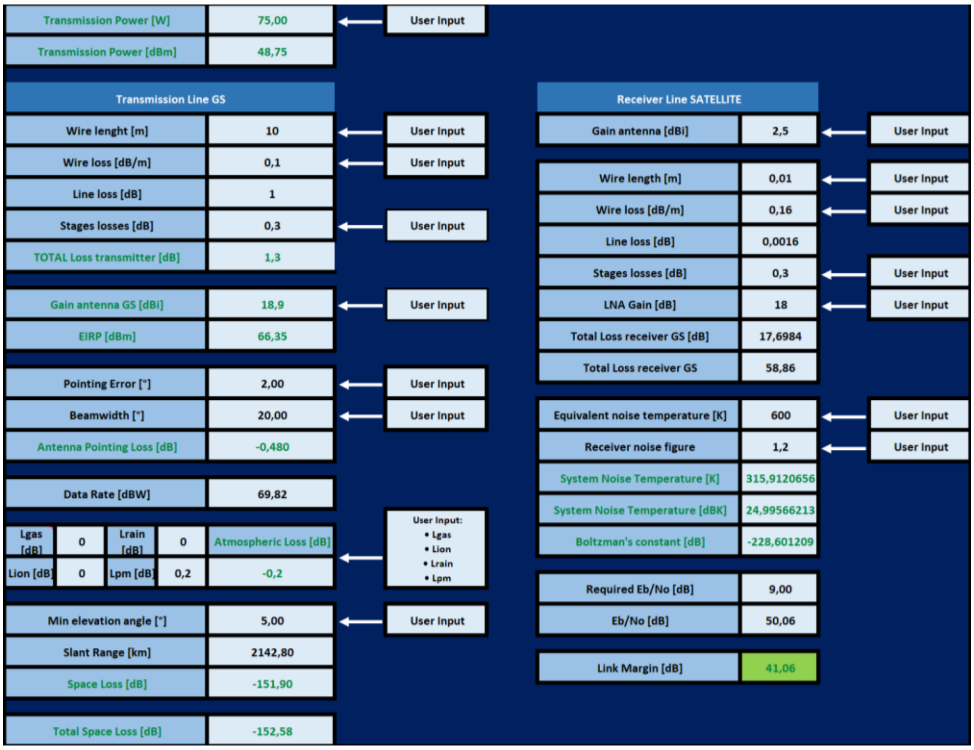


Figure 40: Spei Satelles Uplink Tool Output

4.3 Comparison of the outputs

In this section the outputs obtained during section 4.2 will be compared in some cases with the orbital data in other cases with the outputs obtained during the phases of testing and assembly of the satellite on the ground.

4.3.1 Power Budget

Table 17 shows the Power Budget of the Spei Satelles mission that is compatible with the data reported in section 4.2.1, the absolute errors between the Output of the 3SD and the value obtained during design can also be observed in Table 18.

	Commissioning Mode	Payload Hot Mode	Payload Cold Mode	Downlink Mode	Recharge Mode
C&DH 1 [W]	0.72	0.72	0.72	0.72	0.72
ComSys 1 [W]	0.35	5.65	5.65	5.65	0.35
C&DH 2 [W]	0.72	0.72	0	0.72	0
ComSys 2 [W]	0.35	0.35	0.35	0.35	0.35
Sensing Suite [W]	0.26	0.26	0.26	0.26	0.26
Backplane [W]	0.1	0.1	0.1	0.1	0.1
Total [W]	**2.50**	**7.80**	**7.08**	**7.80**	**1.78**

Table 17: Spei Satelles Power Budget

	Commissioning Mode	Payload Hot Mode	Payload Cold Mode	Downlink Mode	Recharge Mode
Total with Margin [W]	**2.49**	**7.79**	**7.10**	**7.79**	**1.77**
Required Power Generation [W]	**2.63**	**8.22**	**7.49**	**8.22**	**1.87**
Absolute Error	**0.4 %**	**0.12 %**	**0.28 %**	**0.12 %**	**0.56 %**

Table 18: 3SD power budget

Since the total power with the margin for each of the operative mode between Table 17 values and Table 18 values gives a relative error of less than 1%, and since the required power generation is used for the subsequent calculations, the two results agree.

4.3.2 Energy Budget

In Figure 41, Figure 42 and Figure 43 are shown the actual trends of the current and voltage of the battery in orbit, those one are compatible with the data reported in section 4.2.3.

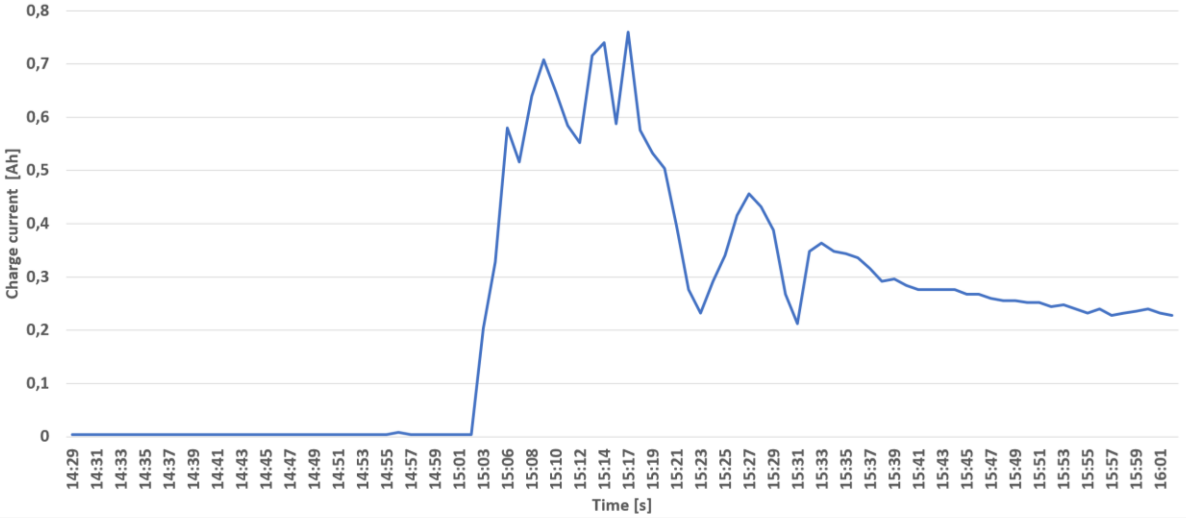


Figure 41: Spei Satelles Charge current

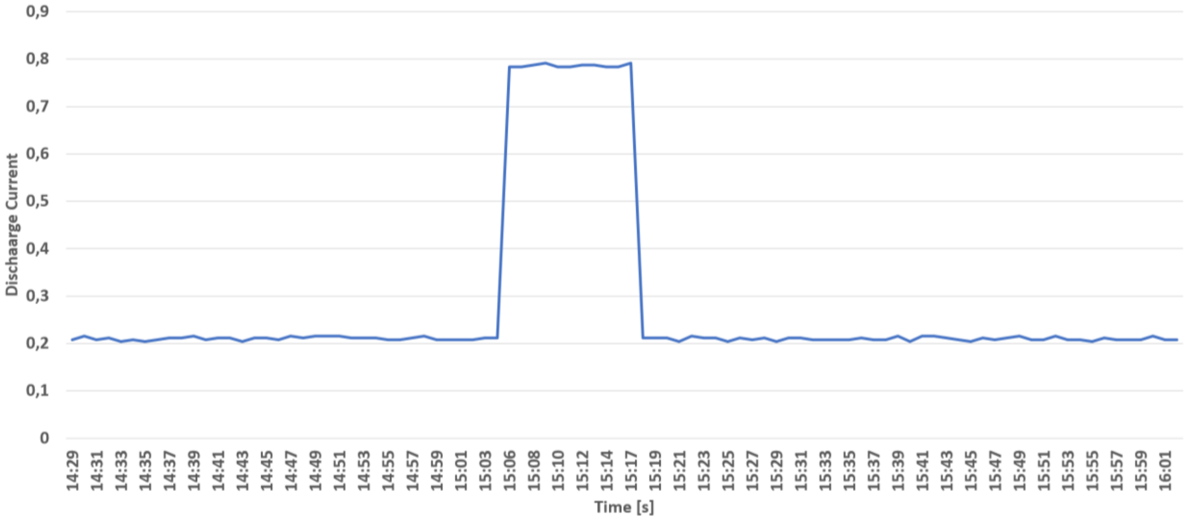


Figure 42: Spei Satelles Discharge current

In particular, the trend of figure 43 allows to observe how the tension increases and decreases depending on the periods of light and shadow.

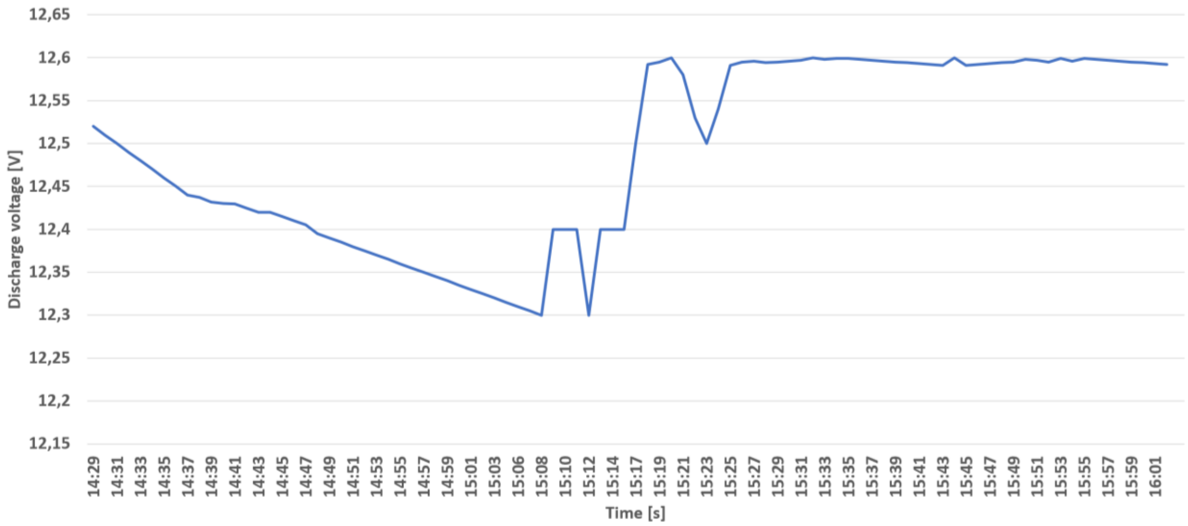


Figure 43: Spei Satelles Discharge Voltage

4.3.3 Mass Budget

Component	Subsystem	Quantity	Unit mass [g]	Total mass [g]
+X Primary structure	Structure	1	223.25	223.25
-X Primary structure	Structure	1	217.75	217.75
Stiffener	Structure	6	16.33	97.98
Battery stiffener	Structure	2	11.98	23.96
C&DH's Cross-member	Structure	2	28.14	56.28
Hysteresis rods' cross-member	Structure	2	19.83	39.66
C&DH's case	Structure	2	38.28	76.56
C&DH's cover	Structure	2	37.52	75.04
Cross-stiffener	Structure	1	68.43	68.43
Z skin	Structure	2	59.09	118.18
Antenna	Communication System	2	18.00	36.00
CommSys board	Communication System	2	30.79	61.58
UHF Transceiver	Communication System	2	20.23	40.46
C&DH Board	Command & Data Handling System	2	51.08	102.16
Backplane	Command & Data Handling System	1	100.00	100.00
Sensing suite board	Sensing Suite	1	76.13	76.13
Thermistor	Sensing Suite	30	0.11	3.30
Permanent magnet	Attitude Control System	2	1.00	2.00
Hysteresis rods	Attitude Control System	6	0.65	3.92
Solar panel	Electrical Power System	4	149.50	598.00
Battery pack	Electrical Power System	1	454.00	454.00
DET board	Electrical Power System	1	15.00	15.00
Deployment switch	Electrical Power System	2	2.00	4.00
Nanobook	Payload	1	1.00	1.00
Harness	-	-	-	193.51
Total				2688.15
Total with Margin				2930

Table 19: Spei Satelles Mass Budget

Table 19 shows the Mass Budget of the Spei Satelles mission, as can be seen by comparing the total mass of the satellite is perfectly comparable with the value obtained in the tool, in Table 20 there is a direct comparison between the results.

	Total Mass [g]	Total With Margin [g]
Tool	2593	2734
Actual	2688.15	2930
Error %	3.539%	6.689%

Table 20: Mass comparison

the absolute error can be considered contained because it is less than 10% moreover that on the effective mass is of the 3.5%.

4.3.4 Link Budget

As reported in section 4.2.5 the link margin for the Downlink communication should be approximately 16.3 d. In Figure 44 is reported an example of Spei Satelles Communication in Downlink at Elevation of 5 degrees it is possible to see that the SNR has the same order of magnitude of the Link margin in Figure 29.

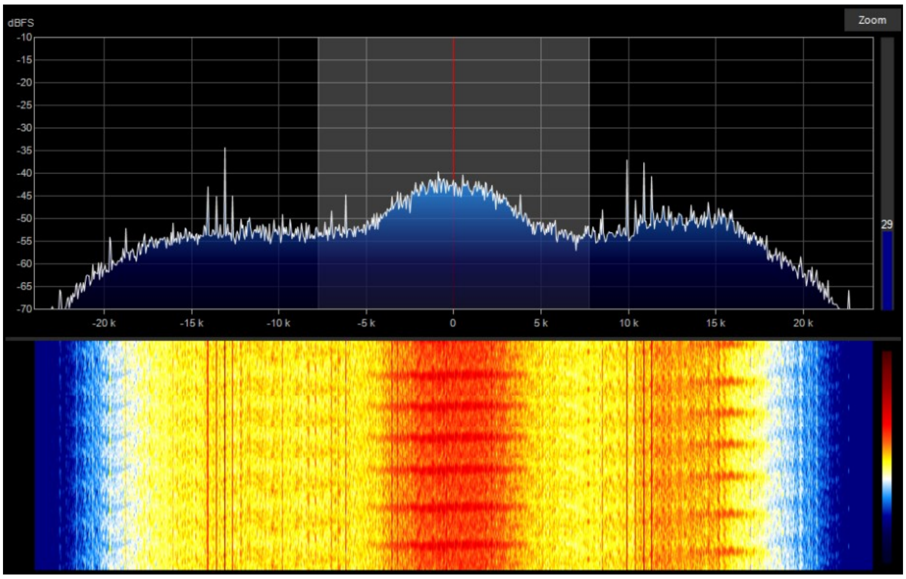


Figure 44: Spei Satelles Downlink Communication

As reported in section 4.2.5 the link margin for the Downlink communication should be approximately 41.06 dB. In Figure 45 is reported an example of Spei Satelles Communication in Uplink at Elevation of 5 degrees it is possible to see that the SNR has the same order of magnitude of the Link margin in Figure 30.

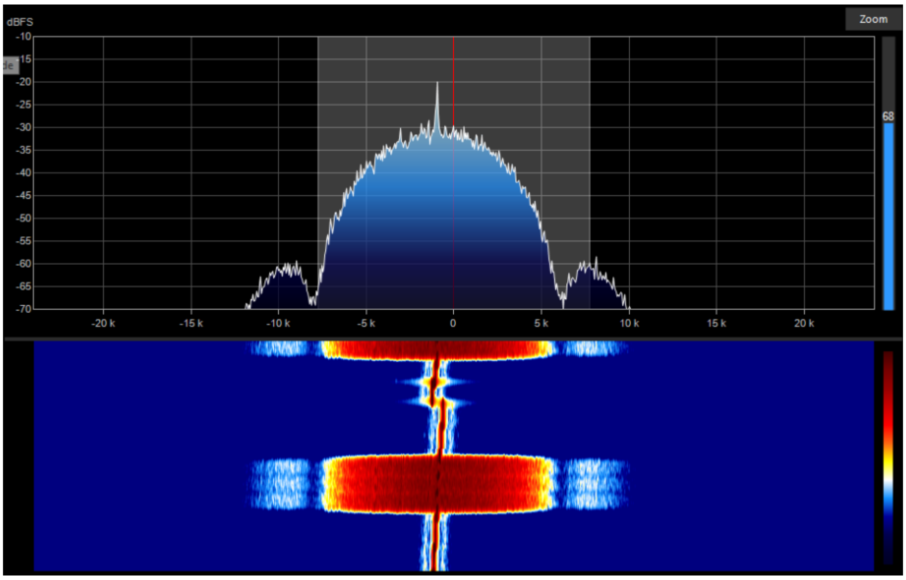


Figure 45: Spei Satelles Uplink communication

5 Conclusions

This thesis work dealt with the development of 3SD, a tool that allows the preliminary definition of a system.

Specifically, after defining the type of mission, the tool allows a set of components to be chosen from an *ad hoc* created database. A series of obtainable information depends on this choice, including the feasibility of the system itself through the definition of various budgets such as power, energy, mass, and link.

Finally, the application case of the Spei Satelles nanosatellite, developed in 2023 by the Politecnico di Torino and launched in mid-June of the same year, was studied in detail. Through the. comparison of results, it was possible to assess the tool on the basis of two aspects: intuitiveness in use and accuracy of output.

In the comparison, a great similarity was noted between the outputs obtained in the tool and the outputs coming from the satellite development documents delivered to the Agenzia Spaziale Italiana (ASI) in the various revisions, but also with the outputs coming directly from the satellite in orbit.

The implementation of additional system budgets represents a key strategy to further enhance the effectiveness of this tool and, likewise, the development and incorporation of new functionalities, improving the flexibility and adaptability of the tool in view of future requirements.

Furthermore, the expansion of the database associated with this tool is crucial to enrich its knowledge base. A larger database would not only increase the accuracy and reliability of the analyses performed by the tool but would also allow it to deal more comprehensively with a wide range of satellite-related scenarios and contexts.

Finally, a final development could be the extension of this tool to other categories of satellites. This would maximise utility. The diversification of the categories covered would allow the tool to be applied to a wider variety of satellite missions, thus satisfying specific needs, and opening new opportunities for use in research and educational activities at the Politecnico di Torino.

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