Manuela Wenger (née Unterberger)
Dipl.-Ing. (FH) Dipl.-Ing.

Design and Systems Engineering of Advanced Nanosatellite Missions

DOCTORAL THESIS

to achieve the university degree of

Doktorin der technischen Wissenschaften

submitted to

Graz University of Technology

Supervisor
Univ.-Prof. Dipl.-Ing. Dr. techn. Otto Koudelka
Institute of Communication Networks and Satellite Communications

Second Advisor
Dr. Wiley J. Larson
School of Systems and Enterprises, Stevens Institute of Technology

Graz, August 2018

EIDESSTATTLICHE ERKLÄRUNG

AFFIDAVIT

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Das in TUGRAZonline hochgeladene Textdokument ist mit der vorliegenden Dissertation identisch.

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present doctoral dissertation.

Datum / Date	Unterschrift / Signature

Abstract

The use of small satellites represents a cost efficient way to accomplish various science and observation tasks in space in LEO orbit. Due to their small size and low weight they are of main interest in performing specific scientific tasks at manageable costs.

Although literature is available on how to design and conduct space missions, most of the information is only applicable to a limited extent for small and especially nanosatellite mission. This thesis shall therefore provide an innovative guideline on how a nanosatellite mission can be designed, taking into account the systems engineering approach and supporting disciplines, based on the insights and experience gained as systems engineer of the BRITE-Austria spacecraft. The mission is dedicated to the field of asteroseismology, and already gained an excellent reputation in the scientific community.

The focus of this thesis is laid on the mission planning and performance analysis of BRITE-Austria in the first six years in orbit. In addition, a description of the challenges faced and the elaborated strategies is given, that allowed to maximise the quality and amount of scientific output and to keep or even increase the functionality and overall performance in attitude control and instrument sensitivity over the years.

Keywords: Space design, systems engineering, nanosatellite, mission planning and operations

Kurzfassung

Kleinsatelliten im erdnahen Orbit stellen eine kostengünstige Alternative zu größeren Weltraummissionen dar, um verschiedene wissenschaftliche Aufgaben und Beobachtungen durchzuführen. Aufgrund ihres kleinen Volumens, geringem Gewicht und vergleichbar kurzen Entwicklungszeiten sind die Kleinsatelliten von hohem Interesse für verschiedene Institutionen.

Obwohl eine Auswahl an Fachliteratur bezüglich Missionsdesign und Systems Engineering vorhanden ist, ist die Information hauptsächlich auf größere Weltraummissionen und nur in einem gewissen Ausmaß auf Klein- im speziellen auf Nanosatelliten anwendbar. Diese Arbeit gibt einen Überblick über das innovative Design einer Nanosatellitenmission, unter der Berücksichtigung des Systems Engineering-Ansatzes und programmatischer Rahmenbedingungen. Das Missionsdesign basiert auf den gewonnenen Erfahrungen und Wissen aus den Entwicklungs- und Testphasen von BRITE-Austria, ein Nanosatellit optimiert für die Beobachtung sehr heller Sterne im Wissenschaftsfeld der Asteroseismologie.

Das Hauptaugenmerk dieser Arbeit liegt jedoch auf dem Gebiet der Missionsplanung und Missionsdurchführung, gefolgt von der parallelen Auswertung der wissenschaftlichen Daten und Analyse der Satellitenperformance während der ersten sechs Jahre im Orbit.

Um die Qualität der wissenschaftlichen Daten zu maximieren, und die Performance der Lageregelung über die Jahre zu halten bzw. zu verbessern, wurden einige Optimierungen am Satelliten sowie am Bodensegment durchgeführt. Die daraus gewonnenen Erkenntnisse werden als sogenannte ”Lessons learned” dargestellt.

Schlagwörter: Satellitendesign, Systems Engineering, Nanosatellit, Missionsplannung, Missionsbetrieb

Acknowledgements

Remember to look up at the stars
and not down at your feet.
Stephen Hawking

I especially wish to thank my advisor Prof. Otto Koudelka for the supervision of the thesis work, for the possibility to participate in the nanosatellite projects and the chance to gain valuable knowledge and experience in the field of systems engineering.

A special thanks to my second advisor Dr. Wiley J. Larson for his valuable directions and support.

I would like to express my gratitude to all my friends and colleagues who enabled me to complete this thesis, especially:

- the colleagues at the Institute of Communications and Satellite Communications and the partner institutes for their appreciated collaboration in the execution of the nanosatellite projects.
- the team of UTIAS/SFL, especially Dr. Rob Zee, Freddy Pranajaya, Cordell Grant, Daniel Kekez and Monica Chaumont, for their excellent cooperation and team play.
- the operations teams at Toronto and Warsaw, for assisting in troubleshooting and exchange of valueable insights.
- Prof. Martin Friedrich for the language revision of the thesis.

Special thanks also go to the funding agency FFG for providing the financial support to conduct the BRITE-Austria project, as well as the Indian Space Research Organisation ISRO for providing the pictures of the launch and the hospitality during the launch campaign.

Particularly I would like to thank Patrick Romano and Rainer Kuschnig, for endless hours of discussions and excellent team play in the course of the BRITE-Austria project.

In addition, I want to thank my parents and family for their unconditional support and encouragement to pursue my interests.

Last, but not least, I wish to thank my husband Robert for supporting me through the toughest moments of my life and for opening my mind and heart every day - without his confidence, patience and love this thesis would not have been possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

During the last years Earth and space observations from space have grown in importance and significance. Remote sensing, disaster monitoring or even astronomical measurements are only some of possible application fields. To fulfill the mission goals and perform measurement tasks simultaneously, satellites are equipped with lots of instruments, which result in huge satellites with high weight, growing complexity and rising mission costs [1].

The use of small satellites represents a cost efficient way to accomplish various science and observation tasks in space in low Earth orbit. Due to their small size and low weight they are of main interest in performing specific scientific tasks at manageable costs.

1.1 Definition and Applications of Small Satellites

When talking about ”small” satellites, satellites with an overall mass of 150 kg or less are meant. Depending on the actual mass of the spacecraft, additional categories are commonly used.

Although technology evolves and capabilities are growing, there are still limitations to physical and other constraints. However, the use of small satellites forms a cost-efficient solution for many applications, besides gaining space heritage on mechanisms, materials, items or even subsystems as technology demonstration.

- **Remote sensing**
  Passive and active observations of the Earth's surface as well as its immediate surroundings (e.g., atmosphere) can be performed from space. Small satellite can provide useful information, measurements and images of various phenomena occurring on Earth, such as:

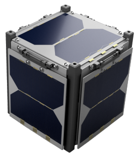
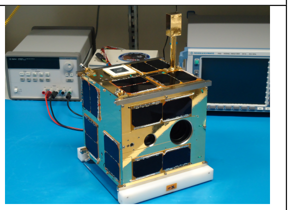
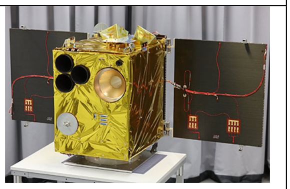
Small Satellite Class	Mass (kg)	Typical Cost Range	Typical Human Resources Required	Example	
Picosatellite	<1 kg	<100 k$	5-10	CubeSat	
Nanosatellite	1-20 kg	<500 k$	10-50	3U-CubeSats, GNB/BRITE	
Microsatellite	20-150 kg	<10 M$	50-100	Flying Laptop	

Table 1.1: Categories of small satellites: Depending on the mass of the spacecraft, different categories of small satellites are commonly used. [2][3][4]

  - atmosphere, magnetosphere, ionosphere, and the radiation environment
  - data on geodesy, gravity, or meteorology
  - environmental monitoring
  - observations of oceans (maps of water temperature, currents, surface topography) and of land (snow and ice cover, temperature distribution, vegetation and natural resources, mapping of infrastructure, land use)
  - data for disaster monitoring (fires, floods, earthquakes)

- **Navigation and tracking**
  The applications in this field are diverse, e.g. the monitoring and tracking of aircraft, vessels, ships etc. can be used to optimise the transport routes, or combat illegal fishing.

- **Communications**
  A variety of communication applications can be performed by the use of small satellites, like asset tracking or disaster monitoring. It can be only space based or used as an expansion to terrestrial systems to maximise the quality of service or increase the service areas.

In the event of a disaster, like earthquakes or floods, terrestrial infrastructure might no longer be available or even destroyed. Immediate medical support and efficient distribution of resources and services is very critical, in which case communication satellites can be of great importance.

Due to the recent developments in the fields of Software Defined Radios (SDR), small satellites have the ability to accommodate more advanced and powerful communication payloads and are therefore of great interest for the communications industry. Not only as a replacement, but also as complementary solution to their global services.

- **Earth and space science**
  Also in the field of Earth and space science, the use of small satellites can be advantageous. The fields of application include solar science, lunar and planetary, space environment, as well as astrophysics.

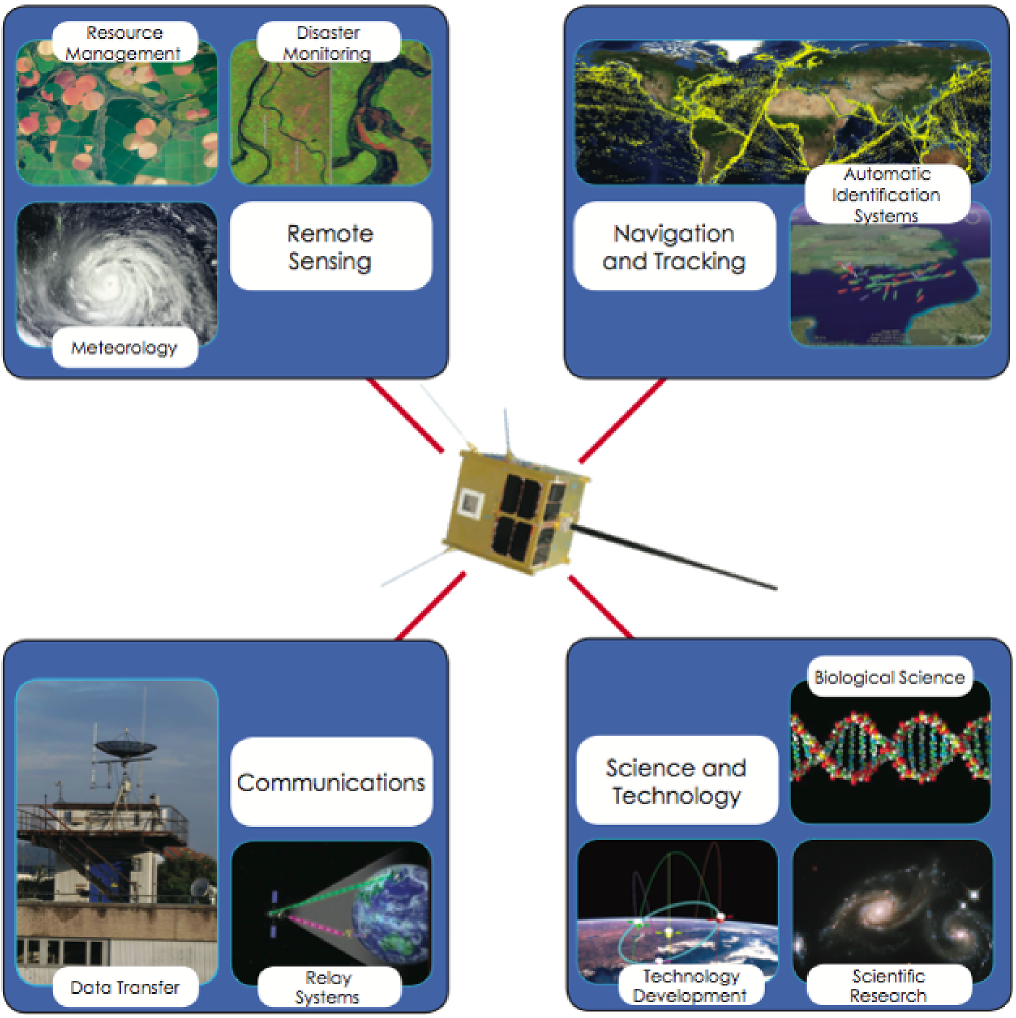


Figure 1.1: Applications of small satellites: Small satellites can be used for accomplishing various mission tasks. [5]

1.1.1 Nanosatellites and their Advantages

In the recent years a growing interest in miniaturisation emerged. Next to the small size and the low weight there are several further advantages of nanosatellites compared with large spacecrafts [1]:

- Lower costs and shorter development time
- Lower launch costs and less effort as they only occupy small slots on the launcher
- In-orbit testing of new developments and technologies
- Educational aspect / hands-on training for students

One major disadvantage however is that due to power and space restrictions a single nanosatellite can not be equipped with many instruments to perform several tasks simultaneously. Therefore a trend to constellations of nanosatellites is emerging to overcome these limitations.

A constellation of nanosatellites would allow sharing resources efficiently, where major tasks may be assigned to different spacecrafts. Not only the overall costs would be decreased, but also the risk is mitigated, as a failure in one element may not cause severe loss of the whole mission. The benefits of constellations are various:

- Small, lighter and inexpensive satellites can be introduced
- Simple and flexible interfaces due to modular bus system
- Increase of revisit rates, ground coverage and measurement frequency
- Faulty elements or spacecraft can be replenished with reduced costs and effort
- Improve of system robustness, as a distributed network is more reliable

When combined the satellites may act like a ”virtual” spacecraft and perform their dedicated tasks simultaneously. This approach allows the execution of distributed measurements, e.g. for applications in the field of stereoscopic remote sensing, differential photometry, synthetic aperture radar, or allows to increase in measurement frequency and rate. In addition, within the constellation, a dedicated spacecraft may act as data relay for the others. Normally each satellite is equipped with its own system to communicate with the ground segment. The introduction of a data relay satellite would have clear advantages, as all other host nodes have low requirements on their communication subsystem. Due to short link distance and low data rate the communication equipment can be simpler and consumes less power. The saved power can be therefore used for other instruments. Nevertheless, this approach is still a challenge as communication is a key topic; the information must be interchanged reliably.

1.2 The BRITE Mission

The BRITE (BRIght Target Explorer) mission is aimed at long-term investigations of the brightness variations of massive, luminous stars in the sky. The mission goal shall be achieved by a constellation of nanosatellites, the so-called BRITE-Constellation, each equipped with a scientific telescope to observe the brightness oscillations of only 1 ppm of star brightness, gaining significant insight in the field of asteroseismology [6].

The main scientific goals were defined as follows:

- Observations of massive luminous stars (with a visual magnitude of +3.5 and brighter) with the help of a precise photometric instrument
- Investigations of oscillation periods from hours to months using dual broadband, and high precision photometric time series
- Provision of insights and possible studies of
  - Variability and structure of the most luminous stars, which might answer:
  - The life-cycle of matter, e.g. the creation of planets, the generation of heavy elements, and the ecology of the universe

These goals can be achieved by the use of a pair of satellites, which are equipped with different spectral filters allowing to providing colour information next to the brightness information.

To achieve these ambitious goals, the spacecraft however need to be three-axis stabilised and provide an pointing accuracy of better than 1.5 arcminutes during an observation time of at least 15 minutes.

1.2.1 The BRITE Satellites

As first part of the mission, the BRITE-Austria mission was initiated in early 2006. Its goal was to design, build, and test the first Austrian satellite BRITE-Austria and its ground infrastructure, followed by the launch and a two-years mission in orbit [7]. A second satellite UniBRITE was developed in parallel to BRITE-Austria, sharing the same spacecraft design, but using different instruments and filters to achieve the goal of parallel observations. The satellite was financed by the University of Vienna, and the Space Flight Laboratory at the University of Toronto (UTI-AS/SFL) was in charge of its development, building and testing.

Although only BRITE-Austria and UniBRITE were proposed in the early phase of the BRITE project, four other satellites (two from Canada and two from Poland) were added in the upcoming years, forming the first nanosatellite constellation in space. Each satellite pair is equipped with one instrument sensitive to the blue and the other instrument sensitive to the red spectrum. The proposed spacecraft and their final launch specifications are given in Table 1.2.

The BRITE-Montreal satellite unfortunately is considered lost, as no deployment from the upper stage occurred. The remaining five spacecraft however are operational to this day and are providing outstanding scientific data.

Satellite	**Country**	**Launch Specifications**	**Orbit Parameters**
BRITE-Austria (TUGSAT-1)	Austria	February 25th 2013 PSLV/India	780 km, 6:00
UniBRITE	Austria	February 25 2013 PSLV/India	780 km, 6:00
BRITE-PL1 (Lem)	Poland	November 21 2013 DNEPR/Russia	600x900 km, 10:30
BRITE-Toronto	Canada	June 19 2014 DNEPR/Russia	600x700 km, 10:30
BRITE-Montreal(*)	Canada	June 19 2014 DNEPR/Russia	N/A
BRITE-PL2 (Heweliusz)	Poland	August 19 2014 Long March/China	630 km, 10:30

Table 1.2: List of proposed BRITE satellites: The BRITE-Constellation was planned to consist of three satellite pairs from Austria, Canada, and Poland. BRITE-Montreal unfortunately was not released from the upper stage of the DNEPR rocket and is therefore considered lost (PSLV = Polar Satellite Launch Vehicle).

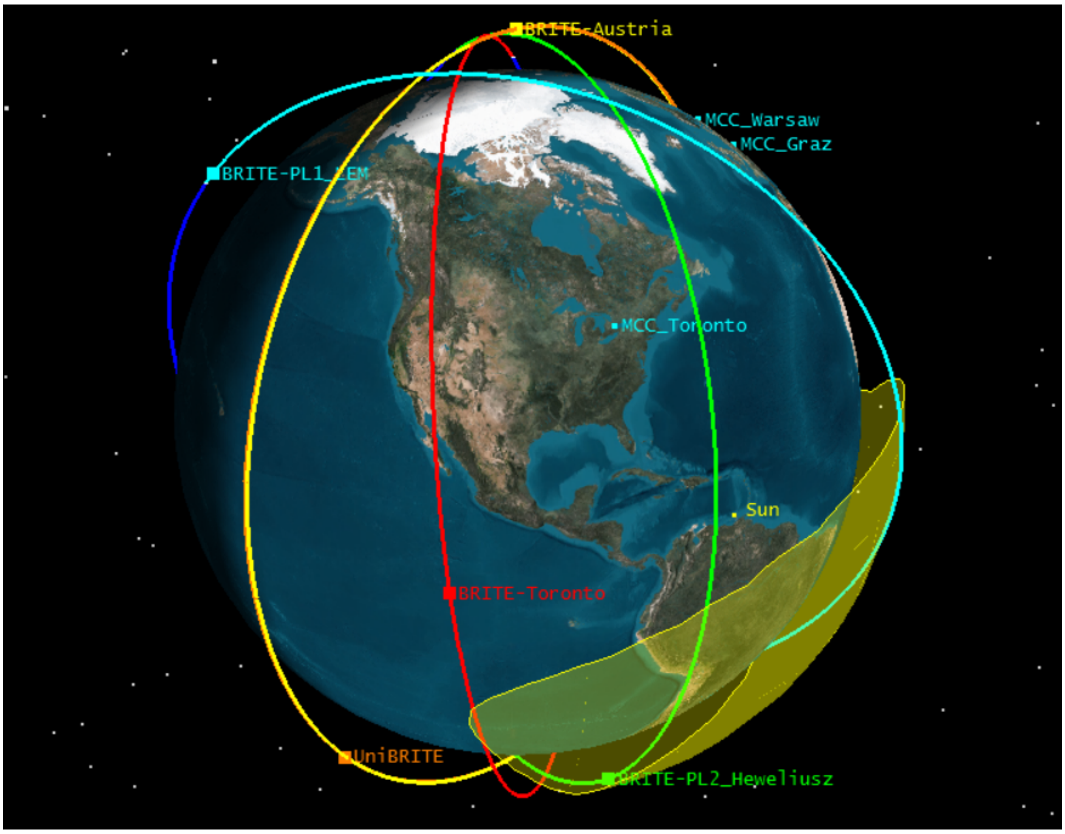


Figure 1.2: BRITE-Constellation: The orbits of the five operational BRITE satellites including the ground station locations (Toronto, Graz, and Warsaw) are depicted. (Image courtesy: AGI Systems Tool Kit (STK) [8])

1.2.2 The BRITE-Austria Project

The Austrian Research Promotion Agency (FFG) funded the BRITE-Austria mission in the framework of the Austrian Space Application Programme (ASAP) [9]. The Austrian consortium of BRITE-Austria consisted of the following three partners:

- the Institute of Communication Networks and Satellite Communications at the Graz University of Technology (IKS/TUGraz), responsible for the project implementation and coordination, technical realisation of the space and ground segment, execution of AIT activities, as well as preparation of launch and satellite operations.
- the Institute of Astrophysics (former Astronomy) of the University of Vienna (UV), responsible for the scientific payload design and characterisation, science data analysis and science software development.
- the Institute of Telecommunications of the Vienna University of Technology (TUV), responsible for establishing and providing a backup ground station.

The Austrian consortium formed a partnership with the Space Flight Laboratory of the University of Toronto/Institute for Aerospace Studies (UTIAS/SFL) from Canada. UTIAS/SFL had already gained substantial expertise in the development of nanosatellites and agreed to a joint activity using their Generic Nanosatellite Bus (GNB) platform for the mission.

The **technology transfer** between UTIAS/SFL and TUGraz was a major asset of the project. The core team at TU Graz was in regular contact with the engineering team at UTIAS. The design and AIT documentation of previous SFL missions were made available and in cooperation with SFL and TUGraz adapted for the BRITE mission. In addition, the parallel development and testing of the UniBRITE satellite allowed the comparison and exchange of test results, know-how and experience.

In the first year TU Graz personnel spent several weeks at UTIAS to familiarise with the design and development philosophy of the nanosatellite project. In the following years engineers from UTIAS visited TU Graz to support the joint program. Visits were carried out to support at various development and testing phases, like:

- laydown of the solar cells
- testing of the power supply system
- integration of the flatsat
- as well as during the Assembly, Integration and Testing (AIT) phase of the satellite, namely for the assembly of the spacecraft and for vibration testing.

Although the subsystems used on-board the BRITE-Austria spacecraft were designed and mainly built by UTIAS/SFL, the final integration and testing of all the subsystems on unit-level, flatsat and system-level was performed by TUGraz. In addition, the systems engineer (author) was involved in all phases since CDR, including launch campaign, commissioning and is responsible for mission planning, operations and telemetry analysis.

The project started in February 2006 and originally envisaged a launch in late 2009. However, due to the launch opportunities available and various delays by the launch provider itself, the launch date was significantly moved finally to early 2013. This delay was used to intensify the testing and prepare the commissioning and operations phase. The following figure gives the timeline of the BRITE-Austria project.

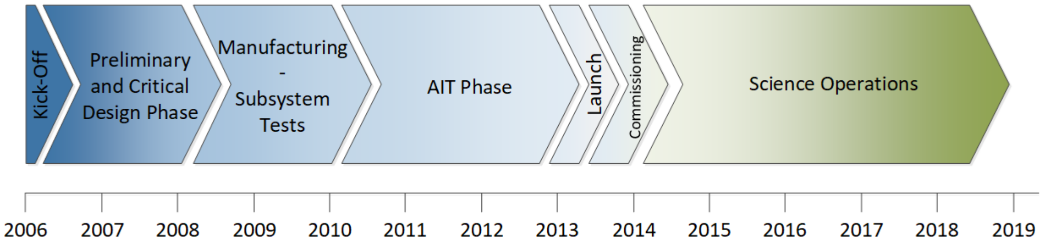


Figure 1.3: BRITE-Austria mission timeline: The BRITE-Austria mission was initiated in early 2006 and although envisaged for an operational lifetime of two years, BRITE-Austria is currently in its 6^{th} year in-orbit, still producing outstanding scientific data.

1.3 Motivation and Scope of this Work

The thesis has been realised in the context of the BRIght Target Explorer (BRITE)-Austria mission [10]. The motivation for this work was the participation in a project with the goal to bring the first Austrian nanosatellite into space and perform ambitious scientific observations.

The international BRITE mission has gained an excellent reputation in the scientific community, as outstanding scientific data could be recorded by the use of an advanced nanosatellite platform, which provided excellent capabilities in attitude control performance and instrument sensitivity [11].

Although literature is available on how to design and conduct space missions, most of the information is only applicable to a limited extent for small and especially nanosatellite mission. This thesis shall therefore provide an innovative guideline on how a nanosatellite mission in the field of New Space can be designed, taking into account the systems engineering aspect and supporting disciplines and ensuring the required data quality.

To tie the theory to a concrete and real-life case, the BRITE-Austria/TUGSat-1 mission is described in depth. In the context of the work as systems engineer and flight operator, an insight in the design and constraints of a nanosatellite mission was gained.

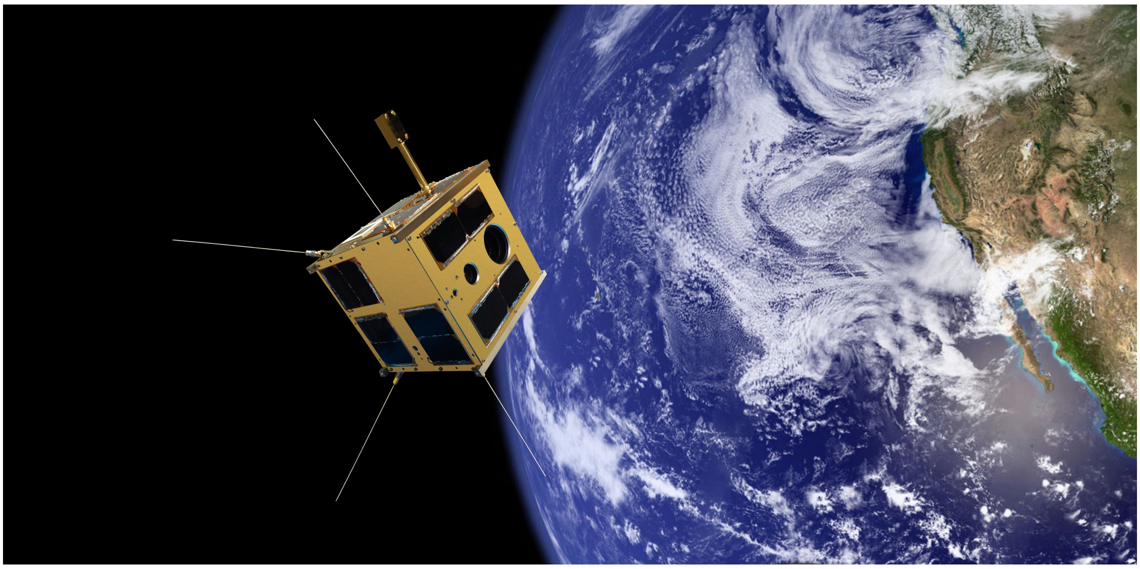


Figure 1.4: BRITE-Austria/TUGSAT-1 in space: Graphical representation of the first Austrian satellite BRITE-Austria/TUGSAT-1 is given. (Image courtesy: TU Graz)

Various tests were performed on unit-, subsystem- and system-level to gain the flight readiness of the spacecraft, which are described in this thesis. During this work test procedures were prepared and adapted to the respective test facilities. Besides, various regulatory tasks have been performed, e.g. frequency coordination.

Furthermore, the launch campaign of BRITE-Austria was prepared and conducted, followed by a successful launch in February 2013.

The commissioning and the operations of a nanosatellite mission are fascinating and also challenging tasks, as the ambitious scientific operations have to be fulfilled and the technical challenges in-orbit have to be thoroughly investigated.

A key aspect of this work was the mission planning and conduction of nominal operations. Operational procedures were developed to fulfill the mission objectives, scientific observations were planned and prepared, the behaviour and performance of the spacecraft was analysed thoroughly and optimised to successfully operate the BRITE-Austria spacecraft way beyond its envisaged lifetime of two years.

Especially the mission planning is a critical task, as such a mission has not been flown before and operations is not really comparable to bigger missions dedicated to astrophysics like Hubble, as no service or alterations can be performed. In addition, a thorough analysis of the telemetry and attitude performance of the spacecraft was performed on a regular basis and used as an input for further planning of scientific observations.

Although BRITE-Austria was only designed for a lifetime of 2 years, the spacecraft is currently in its sixth year in orbit. During the years some challenges have been faced and strategies elaborated to maximise the quality and amount of scientific output and to keep or even increase the functionality and overall performance.

The knowledge and experience gained during the course of the BRITE mission, as well as the procedures established will play a major role in the conduction of future nanosatellite missions.

1.4 Structure of the Thesis

The thesis is structured in the following manner:

In **Chapter 2** the mission design of BRITE-Austria is outlined. A detailed description of the elements involved and the spacecraft design is provided.

One focus of this thesis is laid on the Systems Engineering aspect in the BRITE-Austria mission. **Chapter 3** describes the assembly, integration and testing phases, their results and gives some impressions on the work performed.

Chapter 4 deals with the planning and execution of the launch campaign, as well as the early operations of the BRITE-Austria satellite.

Chapter 5 gives an insight into the mission planning and nominal operations of the BRITE-Austria.

In addition, a verification of the satellite's performance over the first five years in orbit is given in **Chapter 6**. Due to the behaviour and performance of the BRITE-Austria satellite, improvements were performed, to guarantee the scientific data quality. The challenges faced and the enhancements implemented are therefore described in **Chapter 7**.

Chapter 8 gives a description of the lessons learned, based on the experience and knowledge during the execution of nanosatellite missions.

The thesis concludes with an overview of the main achievements [**Chapter 9**].

Additional information on the general conduction of small spacecraft missions can be found in the appendix:

- **Chapter A** gives an insight on the elements of a space mission and their design, focussing on small and nanosatellite missions.
- The interdisciplinary approach of systems engineering is explained in **Chapter B**. The phases of design, integration and verification are described and the common strategies and philosophies explained.
- An overview of the support disciplines, which are typically involved in the conduction of space missions is given in **Chapter C**.

Chapter 2

Mission Design

When designing a space mission, it has to be taken into account that several disciplines and elements mesh with each other like gearwheels. The elements interact with each other, and a change on one side might have an impact on another.

A mission architecture represents a fundamental organisation of a whole system, its components, their relationships to each other and the environment. The mission design describes the creation of a system and a plan to develop and use it (see also Appendix B Systems Engineering) [12].

The mission architecture and design as it is described within this thesis is a combination of two philosophies: the mission architecture, as it is proposed by Wertz-Larson [13] and the division into segments, as defined in the European Cooperation for Space Standardization (ECSS) standards of the [14]. A general description of the common philosophies and detailed information on the system elements can be found in Appendix A Mission Design and Architecture.

The following sections describe the various mission elements and their realisation in the BRITE-Austria project in more detail (Figure 2.1):

1. Mission Objective
2. Space Segment
3. Orbit and Constellation
4. Launch Segment
5. Ground Segment
6. Mission Operations
7. User Segment

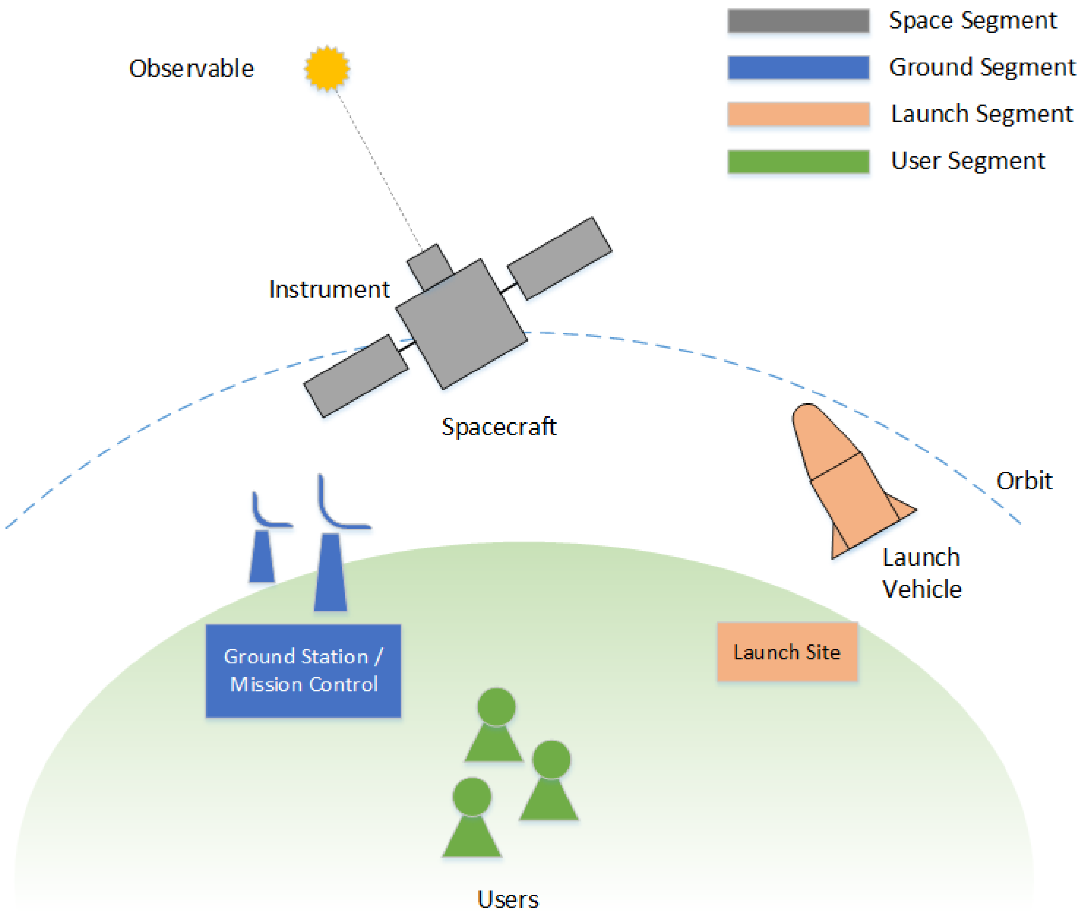


Figure 2.1: Mission design: The elements of a small satellites space mission, as described throughout the thesis.

2.1 Mission Objectives

The satellites of the BRITE-Constellation, one of which is BRITE-Austria, are measuring the low-level oscillations and temperature variations in star with an visual magnitude of 3.5 and brighter. The most luminous stars are typically: either massive stars during all of their evolutionary phases, or medium-mass stars at the end of their nuclear burning phase. Massive stars are hotter, are developing faster and die earlier, but are also rarer than the less massive ones.

Massive, luminous stars are dominating the ecology of the universe: During their relatively short lives and in their astonishing deaths as supernovae, they project enriched gas into the universe and with that adding heavy elements crucial for the future formation of stars, terrestrial planets, as well as organics.

Although the luminous stars play a major role in the universe and form the brightest stars in the night sky, they are the least understood. The BRITE satellites have the task to observe these luminous stars and give insight on their structures and histories.

The small photometric instruments on BRITE investigate the role of stellar winds, and measure the stellar pulsations to examine the history and age of the respective luminous star with the help of asteroseismology.

Complementary spectroscopy of high spectral and time resolution of the envisaged bright target stars is also obtainable via moderate-sized ground-based telescopes, as the findings can round out and fully exploit the scientific information gather by the BRITE satellites [15]. Therefore, the BRITE-Constellation Ground-Based Observing Team (GBOT) was founded, with the aim to provide a platform for both BRITE scientists and observers worldwide, and of course to support collaborations and to maximize the scientific output of BRITE-Constellation [6].

Primary targets

The luminous target stars to be observed by the BRITE-Constellation can be divided into two groups [16]:

1. **Hot luminous stars:** O and B stars which make up about half of the stars brighter than V = 3.5 mag. A study of the variability in O and B stars has the potential to lead to the solution of two of the outstanding problems of stellar structure and evolution: the size of convective cores in massive stars and the influence of rotation
2. **Cool luminous stars:** Asymptotic Giant Branch (AGB) Stars, Red Giants and Red Supergiants. High precision, long-time monitoring of these stars will help to measure the typical time scales involved in surface fluctuations and thus to constrain convection models in AGB stars and red supergiants.

Additional Science

The BRITE-Constellation provides some additional scientific insight on various astronomical target fields [16]:

- Pulsations in K giants
- Solar-like oscillations in solar-type stars
- Study and discovery of delta Scuti stars and of gamma Doradus stars
- Clusters and associations
- Planet detection around massive stars
- Investigation of large-scale structures, like spots, on stars which require long term photometric monitoring
- Unexpected events (e.g. a bright comet)
- Individual stars of special interest
- Known constant stars, which can be used as photometric standards

Although BRITE-Austria is a nanosatellite dedicated to an astronomical mission, several additional stakeholders have expressed their interest and motivation in the mission (see Section 2.7 User Segment).

Taken these interests into account, several secondary objectives have been identified. Table 2.1 summarises the objectives that were addressed during the conduction of the BRITE-Austria mission.

BRITE-Austria Mission Objectives	
Primary objective	• Observe the brightness oscillations and investigate the properties of the brightest luminous stars in the sky
Secondary objectives	• Science – Demonstrate the scientific potential of realising a low-cost nanosatellite mission – Increase the science output by the observation in two spectral ranges with the sister satellite UniBRITE • Technology – Demonstrate precise three-axis stabilisation and attitude control on a nanosatellite platform – Establish a low-cost platform to built capacity for future space missions • Education – Provide hands-on training for students – Train and involve students in the testing phases • Gain experience and know-how in the conduction of space projects, including technical, scientific, and administrative aspects

Table 2.1: BRITE-Austria objectives: Several objectives were addressed during the course of the BRITE-Austria mission.

2.2 Space Segment

The BRITE-Austria satellite is a nanosatellite based on the Generic Nanosatellite Bus (GNB) developed by UTIAS/SFL. The main technical specifications and subsystems used are listed in the tables below. The subsystems are mainly defined and developed at UTIAS/SFL and their characteristics are described in the upcoming subsections [17] [18].

Main Characteristics	
Volume	20 cm x 20 cm x 22 cm (including launch rails, excluding appendages)
Mass	6.93 kg
Material of structure	Aluminum alloy, additional plating of electroless nickel
Power	6-10 W
Frequency ranges	Ultra-High Frequency (UHF) - 437.365 MHz, (Very High Frequency [VHF] - 145.89 MHz) and S-band - 2234.4 MHz

Table 2.2: BRITE-Austria fact sheet: The main specifications of the BRITE-Austria satellite are listed.

Subsystems	
PAY	Photometric instrument is used to capture images of bright massive stars
MEC	A dual-tray structural concept is used, which maintains mechanical integrity of subsystems on the satellite during launch and on-orbit activities
THM	Passively controlled with the help of temperature sensors; active heater elements are attached to critical items
PWR	Solar cells are used for energy generation, energy is stored in batteries and distributed to the other subsystems
ADCS	Sensors and actuators are used to provide three-axis stabilisation with arc-minute precision
OBDH	Three on-board computer are used for decoding Earth station commands, controlling the subsystems, managing data and telemetry handling and preparing the telemetry and science data for download
COM	Commands are received from the Earth station via UHF, telemetry and scientific data is transmitted to Earth via S-band

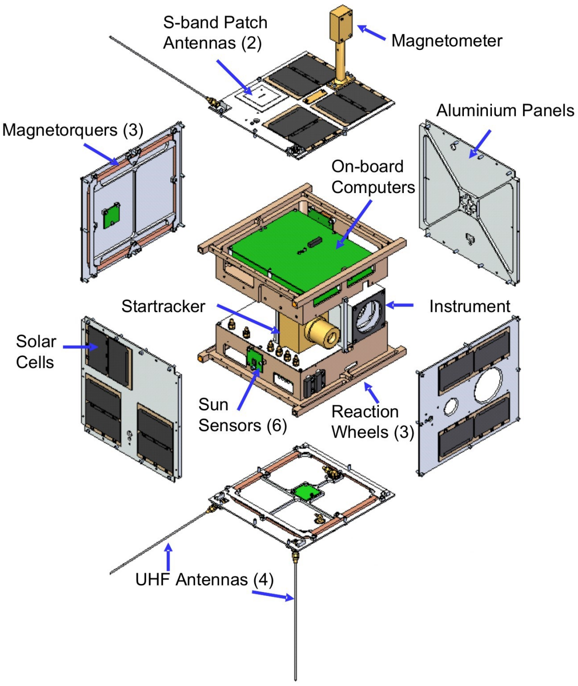


Table 2.3: BRITE-Austria subsystems: Several subsystems are implemented on-board the BRITE-Austria satellite (CAD image courtesy: UTIAS/SFL) (PAY - Payload; MEC - Mechanical; THM - Thermal; PWR - Power; ADCS - Attitude Determination and Control; OBDH - On-board Data Handling; COM - Communications).

The following figure shows the block diagram of the spacecraft subsystems and their interconnections. A detailed description of the individual subsystems is given in the next paragraphs.

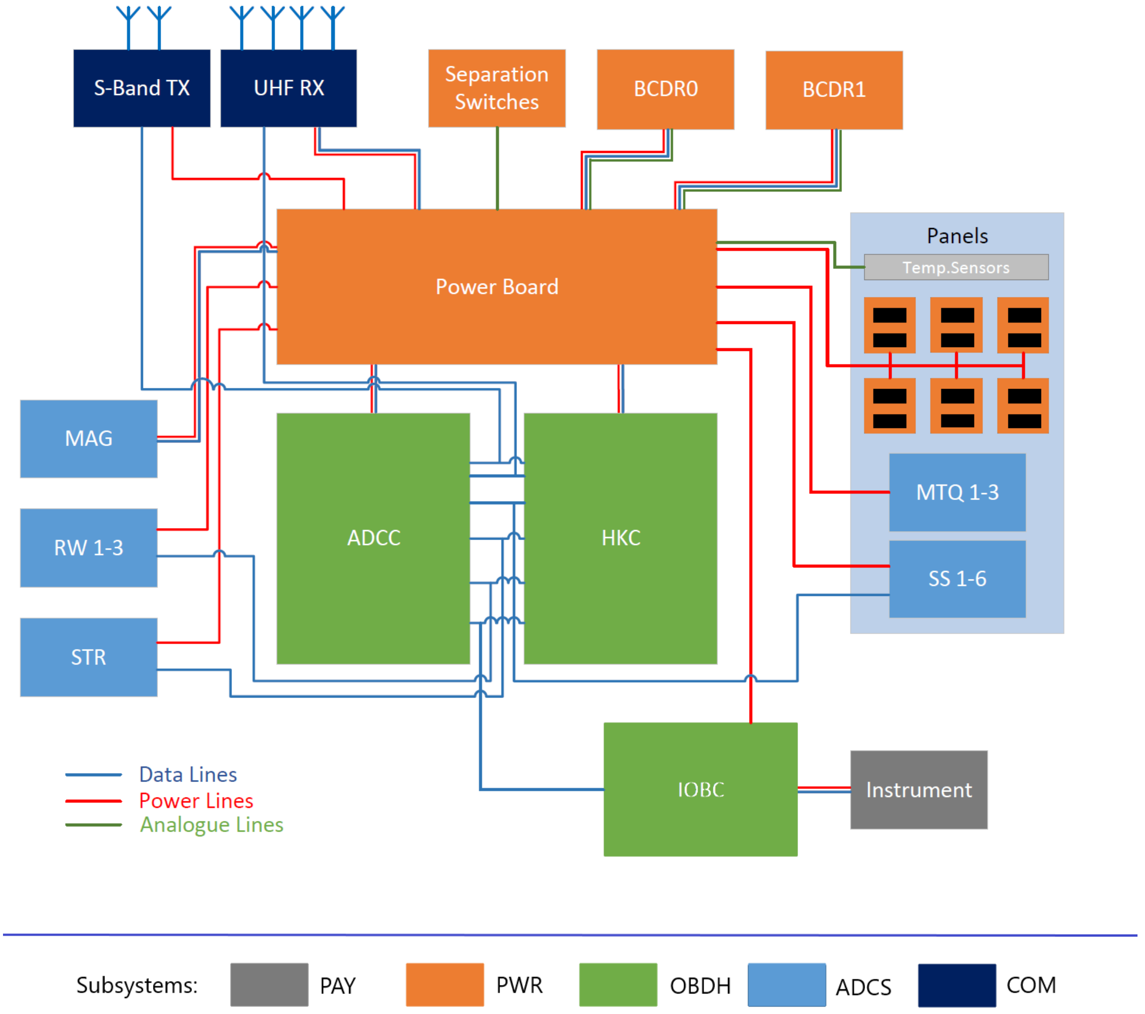


Figure 2.2: BRITE-Austria block diagram: The spacecraft subsystems and their interconnections are shown. Concerning the interconnections, the power lines are depicted in red, the data lines in blue, and analogue lines are highlighted in green. (ADCC - Attitude Determination and Control Computer; HKC - HouseKeeping Computer; IOBC - Instrument On-board Computer; BCDR - Battery Charge and Discharge Regulator; MAG - Magnetometer; RW - Reaction Wheels; STR - Startracker; MTQ - Magnetorquers; SS - Sun Sensors; TX - Transmit; RX - Receive)

2.2.1 Payload

For the observation of bright luminous stars, BRITE-Austria is equipped with a photometric instrument with an aperture of 3 cm and an interline Charge Coupled Device (CCD) detector from Kodak, a KAI 11002-M, with 11M pixels. The field of view (FOV) of the BRITE-Austria instrument is 24°and a resolution of about 30 arcseconds per pixel is achieved. The instrument is mainly composed of three parts: the baffle/pupil stop, the optical cell (containing the lens system), and the header tray (housing the CCD and electronics).

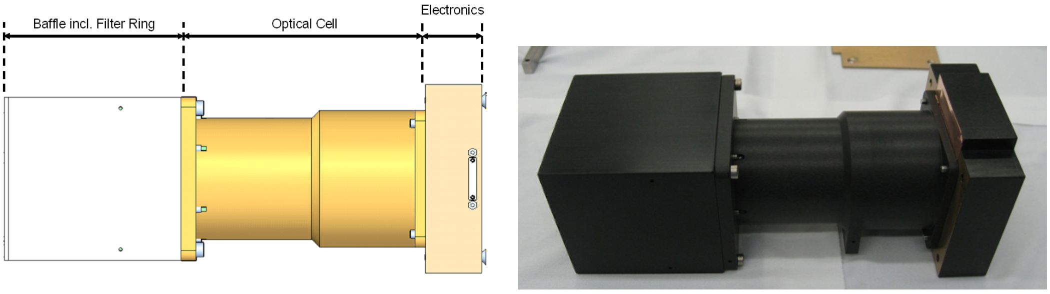


Figure 2.3: Instrument design: A cross-section of the instrument is given (Image courtesy: UTIAS/SFL), as well as the final BRITE-Austria telescope after assembly.

- **Baffle**

  The baffle is directly mounted to the optical cell. Directly machined into the baffle are features that create the aperture or pupil stop, and allow the mounting of the optical filter. Additional vanes are inserted for straylight suppression. According to the scientific objectives a pair of satellites, each housing a telescope sensitive to a specific wavelength is flown. According to the target stars to be observed, two main spectral ranges in the blue and red spectrum were defined.

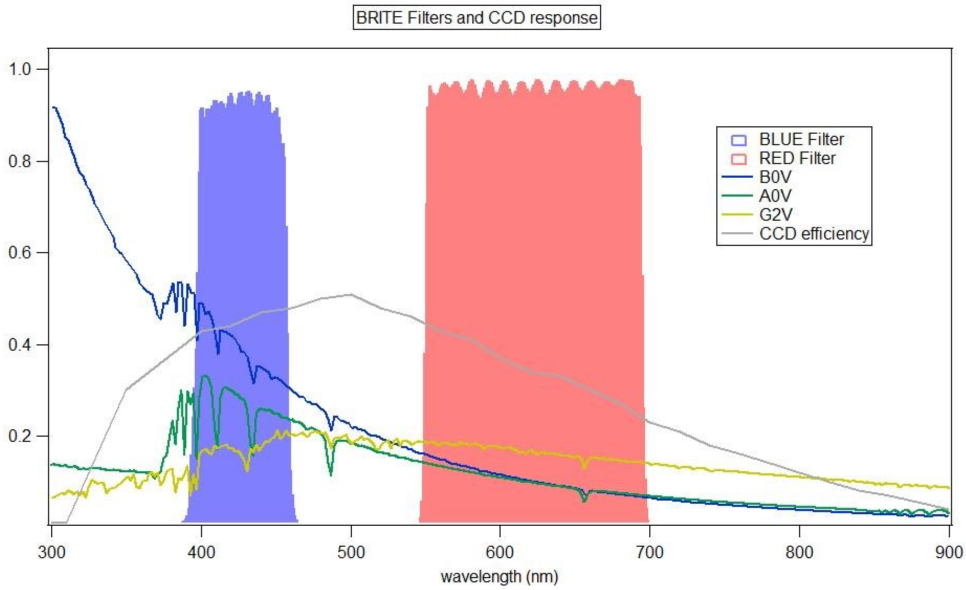


Figure 2.4: BRITE filter passbands: The blue area indicates the filter passband used for BRITE-Austria [17].

In case of BRITE-Austria, to limit the wavelengths of light entering the instrument, an optical multilayer interference filter in the blue spectrum (390 - 460 nm) was mounted inside the baffle.

- **Optical cell**

  The optical cell is machined from a single piece of aluminum and holds the five-lens system. By the use of spacers, the lenses are stacked into the optical cell.

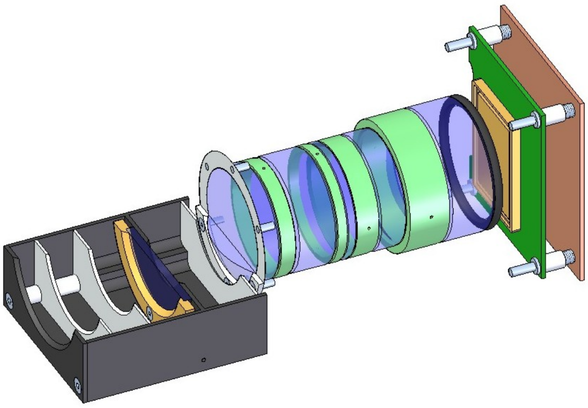


Figure 2.5: Blue lens system: As the BRITE-Austria instrument is sensitive in the blue spectrum, the lens system was designed accordingly by Peter Ceravolo Optics/Canada (Image courtesy: UTIAS/SFL).

- **Header tray**
  The header tray houses the header board, where the CCD detector is mounted and the electronics are placed. The header tray is mounted directly to the optical cell and not the structure, to minimise the stress and deflection of the electronics board. The header board is connected to the instrument computer for data communication and bias power transfer.

2.2.2 Structural Subsystem

The structural subsystem has to maintain the mechanical integrity of the spacecraft. To minimize the overall mass, the structural components were made out of nickel-plated aluminum.

BRITE-Austria uses the GNB dual-tray system, in which all of the core components are mounted to or inside the respective trays. The +Z tray houses all on-board computers, whereas the -Z tray houses the batteries, the reaction wheels, the UHF receiver and S-band transmitter unit. The trays are positioned on opposing faces, leaving a payload volume between them. In case of BRITE-Austria this volume is filled by the scientific instrument payload and the startracker.

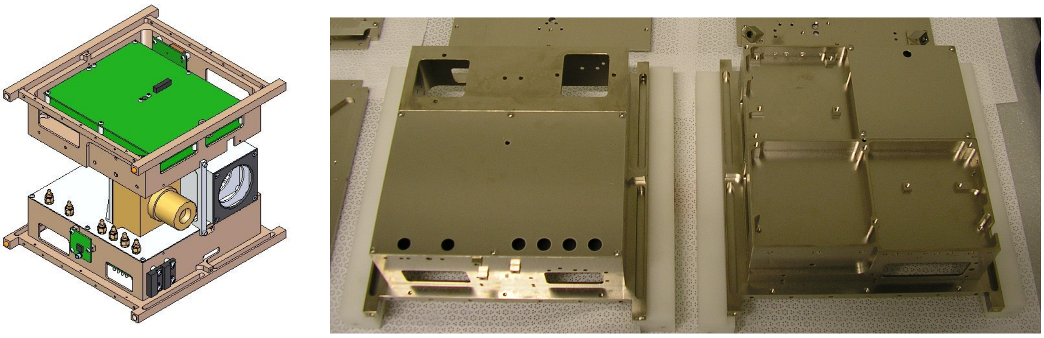


Figure 2.6: Internal layout: The dual-tray structure leaves a volume between the trays, which can be used to host the mission specific payloads (CAD image courtesy: UTIAS/SFL).

Once the trays and the payload are fully integrated, the spacecraft is completed with six panels. The panels are used to mount components external to the spacecraft (like solar cells, antennas, magnetometer boom) as well as on their inside face (e.g. magnetorquers and sun sensors).

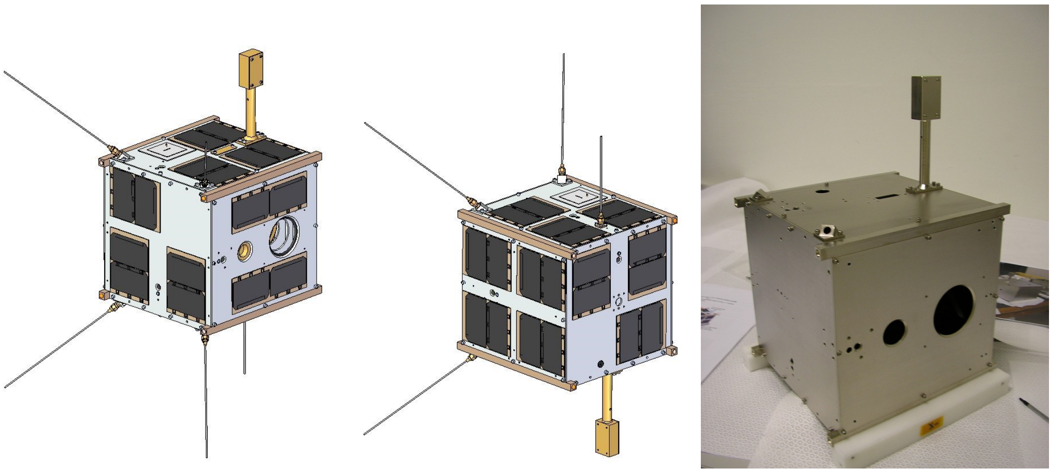


Figure 2.7: External layout: The external layout of the BRITE-Austria satellite is made of aluminum panels, placed on each face (CAD image courtesy: UTIAS/SFL).

The cubic form factor simplifies the design and analysis of the thermal subsystem, as the thermal state is less dependent on the satellite's attitude. In addition, as the payload is centred in the satellite's volume, the physical properties of the satellite (e.g. moments of inertia, centre of mass) are fairly independent on the payload to be flown. Hence the performance of the ADCS subsystem (if the spacecraft bus elements are reused) would be fairly consistent on various missions.

2.2.3 Thermal Subsystem

The primary driver in developing a thermal control strategy for BRITE-Austria was the fact, that the telescope detector must be kept thermally stable and as cool as possible. Therefore, several thermal control measures were implemented:

- Keep the spacecraft relatively cool using appropriate external coatings
- Thermally isolate the telescope from the rest of the spacecraft
- Thermally isolate the optics (lenses and CCD) from telescope components with a view of space (i.e. the baffle)
- Minimize the amount of heat dissipated in the telescope itself

Keeping the satellite cool to ensure optimal function of the telescope detector favourably impacts subsystems with great heat dissipation (like UHF receiver and S-band transmitter). However, the batteries might get colder than desired, hence these elements were also equipped with dedicated heaters.

According to the orbit boundaries defined, the following worst case scenarios were identified:

- Worst Case Hot:
  - 900 km Sun-synchronous dawn-dusk (SSDD) (no eclipses)
  - A corner of the spacecraft is pointed to the Sun and three faces are illuminated (maximal area)
  - Winter solstice (Solar flux = 1,418 W/m^2)
- Worst Case Cold:
  - 550 km Sun-synchronous noon-midnight (SSNM)
  - Only a single face is pointed towards the Sun (minimal area)
  - Summer solstice (Solar flux = 1,323 W/m^2)

To save power and volume, only the temperature-critical items (batteries and detector) are equipped with heater elements. The rest of the spacecraft uses passive thermal control measures, on one hand by the use of sensors on all elements inside the spacecraft and on the other hand by the application of thermal tapes on the outside of the panels. The thermal tape was chosen once the launch was decided to have the ideal emissivity and absorptivity properties for the target orbit.

2.2.4 Power Subsystem

BRITE-Austria is equipped with 36 solar cells for energy generation, six cells on each face (except the -X face with the telescope opening (4) and the opposing +X face (8)). The satellite uses Triple Junction InGaP2/GaAs/Ge solar cells with a nominal efficiency of 26.8 % (begin of life), each capable of generating approximately 960 mW maximum.

For energy storage the satellite is equipped with two 5300 mAh lithium-ion batteries. Only one battery is primarily used during operations, the second one acts as backup and fall-back in case a power reset was triggered. This type of battery was chosen due to the higher energy density and optimal charge/discharge performance over a wide temperature range. To prevent overcharging the battery and providing peak power tracking for the solar arrays, each battery is equipped with a battery charge and discharge regulator (BCDR).

All power electronics and power switches are located on a single power board. Different power busses are provided (unregulated, 3.0/5.0/10.0 VDC). The power system collects telemetry from various sensors, including currents, voltages and temperatures and is responsible of controlling the separation switches.

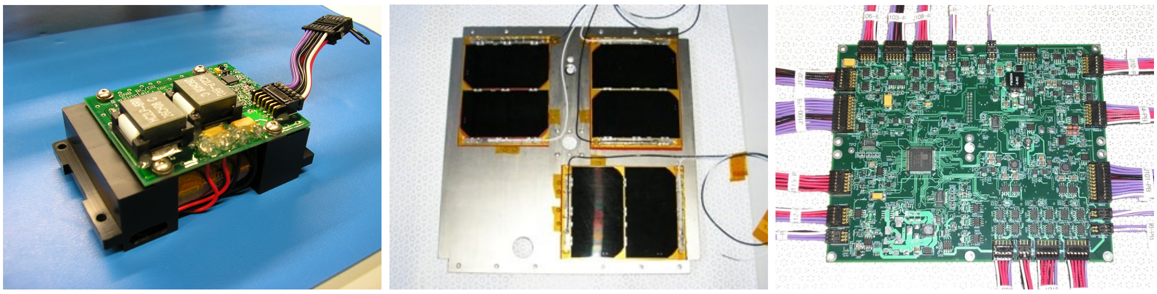


Figure 2.8: Power subsystem: The power subsystem on board the BRITE-Austria satellite consists of two batteries for energy storage, solar cells for energy generation and a power board for distribution (Image courtesy: UTIAS/SFL and TUGraz).

The power board also provides a direct umbilical connection to the ”outside” via the test port. The test port allows turning the spacecraft on or off via a jumper, charging the battery although the satellite is powered off, allows external powering of the spacecraft and disabling the S-band transmitter.

Besides, a so-called firecode detector is implemented. A firecode represents a specific 64-bit data sequence, that does not form a valid High-Level Data Link Control (HDLC) frame (as used for communication) and is therefore ignored by the on-board computers (OBCs).

For each OBC, three firecodes are defined:

- Power ON firecode - toggles the enable line and powers the OBC
- Power OFF firecode - toggles the enable line and turns the OBC off
- RESET firecode - resets the OBC and drops it back to bootloader

The firecodes are used to either power cycle the OBC to clear latch-ups or even shut down a faulty OBC. A firecode is also available to reset the entire power board.

2.2.5 Attitude Determination and Control Subsystem

The ADCS subsystem is one of the most critical subsystems on-board the BRITE-Austria satellite. To achieve the mission objectives, attitude knowledge and precise attitude control are needed for observations.

The ADCS subsystem can mainly be divided into three branches:

- **attitude determination** - sensor measurements are made
- **control software** - according to the sensor inputs, the control efforts are calculated to achieve the desired attitude
- **attitude control** - given the outputs of the software, the actuators are commanded

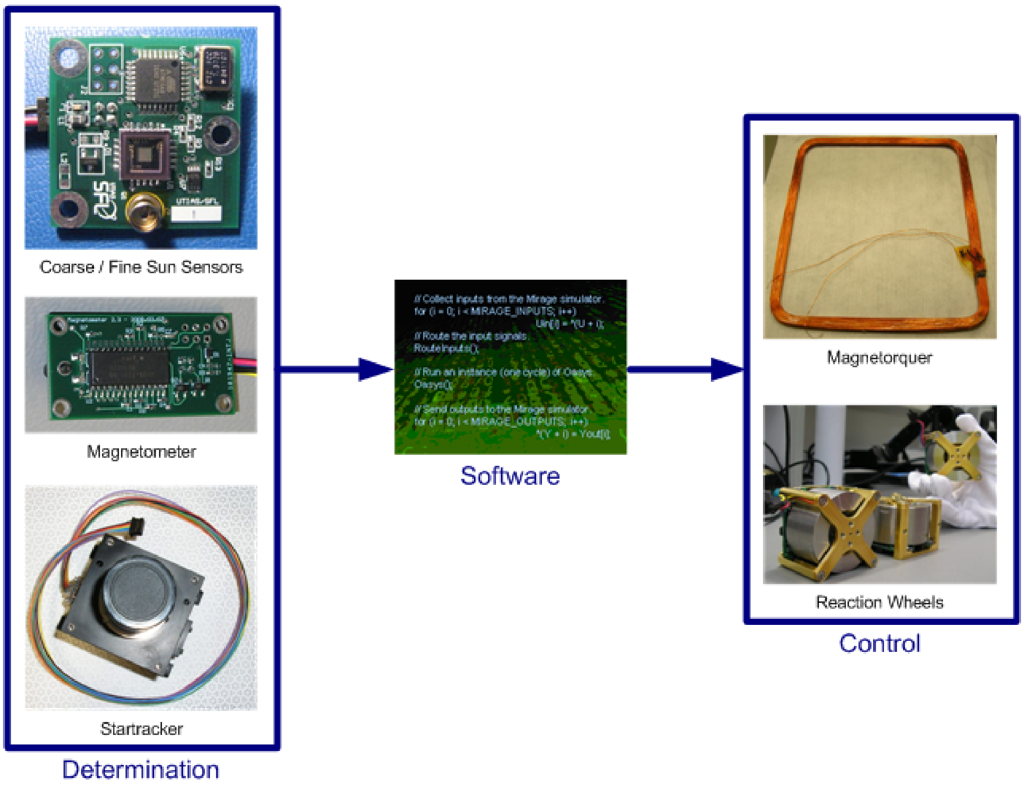


Figure 2.9: Attitude determination and control subsystem: An ADCS cycle mainly consists of determining the attitude, calculating the control efforts and activate the actuators [17] (Image courtesy: UTIAS/SFL and TUGraz).

For determination of the attitude, various sensors are implemented. Six sun sensors, each equipped with a phototransistor and digital arrays, offer coarse (± 10°) or fine (± 5°) attitude estimation by measuring the local Sun vector. To measure the magnetic field, a three-axis magnetometer is installed on an boom (to reduce the impact of the satellite's dipole) and can provide a ± 5° coarse estimate.

The implementation of these determination sensors offer an overall of ± 1° (in eclipse ± 5°) determination accuracy, which is unfortunately not enough to fulfill the mission requirements. Therefore, an additional COTS sensor, a startracker, is included in the determination suite. It gives a direct attitude measurement in the satellite's body frame, with an accuracy of better than ± 70 arc-seconds in all three axes.

Attitude control is performed by three magnetorquers (electromagnetic coils that interact with the ambient magnetic field), installed in each axis. They provide magnetic torque to control the spacecraft's attitude and trim the momentum in the reaction wheels.

Full three-axis control is achieved by the use of three orthogonal reaction wheels. The wheels are able to provide minute (mNm level) torque for precise attitude control.

Several ADCS modes were implemented on BRITE-Austria, respectively:

- **Safe-hold mode** - sensors and actuators are turned on and initialized according to the device mask commanded. The attitude cycles are started, however no further determination or control is performed.
- **Passive mode** - the coarse attitude sensors, the magnetometer and the sun sensors, are read out and their respective values are sent to the attitude control thread to determine the satellite's attitude.
- **B-dot mode** - the magnetorquers are included in the attitude cycle. In this mode, the satellite is detumbled until the acceptable tumbling rate is achieved.
- **Three-axis control mode** - in this mode the sensors and actuators, as defined in the device mask, are actively included in the attitude cycle. A distinction between Coarse (CTAP) and Fine Three Axis Control (FTAP) can be made: during CTAP, the magnetometer and the sun sensors are used for attitude determination; during FTAP, attitude determination is exclusively performed by the startracker.

2.2.6 Communications Subsystem

The communication subsystem of BRITE-Austria consist of two main entities:

- A **receiver unit** in the UHF band (437.365 MHz)
- A **transmitter unit** in the S-band (2234.4 MHz)

The UHF uplink provides the sole method of commanding the spacecraft and its subsystems. The receiver unit must be active at all times, when power is available on the spacecraft, hence it had to be designed robust, simple and with low power requirements.

The UHF radio system consists of six main components - descrambler, modem, receiver, low-noise amplifier (LNA), antenna interface and power regulation. The antenna system comprises four monopole antennas, mounted on the edges of the +Y face. This configuration allows to establish a more omni-directional pattern compared to single monopoles used.

The S-band downlink comprises a two-board transmitter, equipped with a configurable, high-performance FPGA to get the desired flexibility. It is possible to select the data transmission rate and modulation format on-the-fly. The transmitter is configured to achieve data rates of 32 up to 256 kbps in Binary and Quadrature Phase Shift Keying (BPSK/QPSK) format. In addition, automatic active RF output power regulation is implemented allowing controlled operations at different temperature ranges.

The S-band antenna system comprises two patch antennas, that are fed in-phase. The antennas are mounted on opposing faces, allowing a near omni-directional pattern.

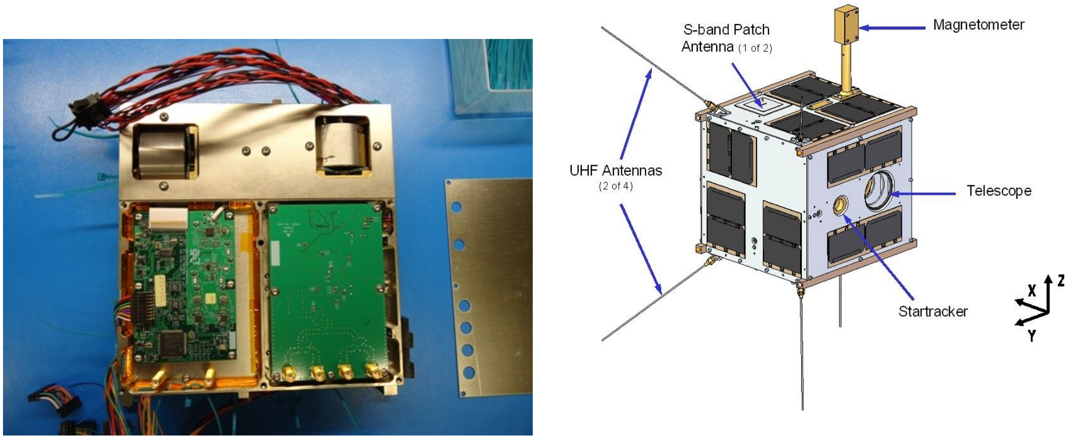


Figure 2.10: Communication subsystem: The S-band transmitter and the UHF receiver were integrated on the bottom of the -Z tray. (left) Two patch antennas were realised on opposing faces (± Z faces) and four monopole antennas were mounted to the edges of the +Y face. (right - Image courtesy: UTIAS/SFL)

During the early design phase, transmitter improvements were examined to increase the throughput, but were not realised due to schedule constraints [1].

Originally a VHF transmitter and beacon signal was planned to be implemented. The frequency coordination had been performed as well for this communication link, however, during the testing it appeared that the VHF transmitter interferes with the UHF receiver. As the UHF receiver is most critical for the mission as it is the only means of commanding the spacecraft, the VHF transmitter unfortunately was withdrawn.

2.2.7 On-board Data Handling Subsystem

Three different on-board computer (OBCs) are realised on the BRITE-Austria spacecraft, each dedicated to specific tasks:

- **Housekeeping computer (HKC):**
  The HKC is responsible for decoding the ground commands, communicating with the subsystems, continuously collecting and storing telemetry data (referred to as whole orbit data (WOD)) and forwarding the data to the transmitter
- **Attitude determination and control computer (ADCC):**
  The tasks of the ADCC comprise the execution of attitude control by reading of the sensors and controlling the actuators, and providing an interface to the HKC.
- **Instrument computer (IOBC):**
  The IOBC is responsible for controlling and setting up the scientific experiment, performing the observations and storing the science data records (SDRs) including metadata for further download.

The OBCs are based on the TMS470R1B1M Texas Instruments processor, a 2 MB Static Random-Access Memory (SRAM) system and a Flash memory of 256 MB are provided. The subsystems as well as the OBCs themselves are connected via various interfaces (e.g. i2C - Inter-Integrated Circuit, SPI - Serial Peripheral Interface, UART - Universal Asynchronous Receiver Transmitter). Both HKC and ADCC share the same hardware design and are connected to the rest of the subsystems in parallel. This redundancy allows transferring tasks between the computers or, in an event of a failure of one OBC, even take over its full functionality. The IOBC however is a of its own design. Its tasks comprise the controlling and configuring of the payload, the scientific instrument.

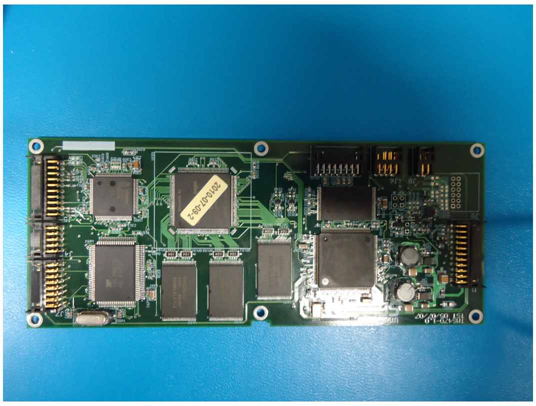


Figure 2.11: On-board computer: BRITE-Austria houses three on-board computers, each dedicated to specific tasks (HKC is shown).

Concerning the operating environment and on-board software, a two-level approach was implemented:

- **Bootloader:**
  The bootloader provides the basic functionality necessary to monitor the vital systems, and loads and executes the higher level software. It has to be noted, that the bootloader is non-autonomous and replies only to ground commands.
- **Application code:**
  The application code provides all functionality to control the spacecraft. The satellite's operating system CANOE (Canadian Advanced Nanospace Operating Environment) has a multithreaded design, hence arbitrary threads can be loaded to control various subsystems or units on-board. CANOE is capable of allocating resources, performing thread scheduling and managing other tasks.

The IOBC has implemented the Science Data Generation Code (SDGC) acting as application code, allowing to configuring the exposure settings and handling the data flow between the header board electronics and the house-keeping computer.

All three OBCs are interconnected and interface with themselves as well as other subsystems. The radios are connected over the serial communication controller using the High-Level Data Link Control (HDLC) protocol. For communication with ground a higher layer protocol, the Nanosatellite Protocol (NSP) is used. Simple communication forwarding is implemented between the OBCs.

2.2.8 Deployment Mechanism

As the structural concept of BRITE-Austria is based on the GNB by UTIAS/SFL, an appropriate nanosatellite separation system was needed. The XPOD GNB (eXperimental Push Out Deployer) was designed bei UTIAS/SFL to deploy a 20x20x22cm spacecraft up to 7.5 kg.

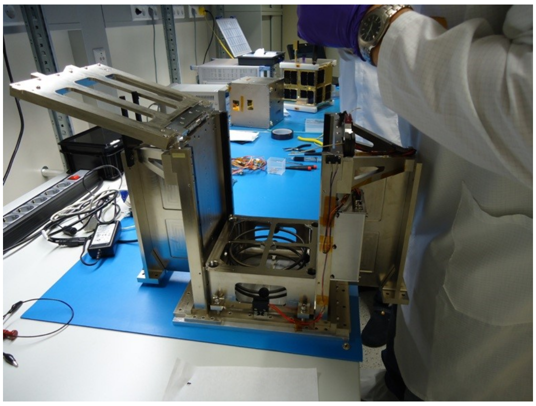


Figure 2.12: Deployment mechanism: The XPOD GNB was used as deployment mechanism for the BRITE-Austria satellite.

The separation system is essentially made of five structural components: the door, front and rear panels, a base panel and the pusher plate. The door is secured with a cord. When a release command from the launch vehicle is received, the electronic package attached to the structure activates a heater element that cuts the cord. This allows the door to open and the pusher plate with a deployment spring underneath pushes the spacecraft out of the XPOD. During this process, the spacecraft slides with its launch rails along the front and rear panels.

2.3 Orbit and Constellation

Given the mission objective(s), a decision on the orbit has to be made. The orbit is one of the main drivers of a mission and can have huge impacts on the space segment and ground segment design.

In case of BRITE-Austria, several assumptions had to be kept in mind in the definition phase:

- The main objective is the observation of light changes in bright luminous stars, due to their location on the sky, a polar orbit was desired by the scientific team.
- The ground segment is located in the Northern hemisphere.
- The spacecraft is not equipped with a propulsion system or something similar, hence only attitude control can be achieved.
- As BRITE-Austria was launched as secondary payload, the orbit was defined by the primary payload and the selected launch vehicle.

Given these constraints, BRITE-Austria was designed to operate in various Sun-synchronous orbits and different altitudes:

- A 550 km Sun-synchronous noon-midnight (SSNM) orbit was used as lowest altitude boundary. This orbit represented a worst-case cold thermal situation, a worst-case power situation, maximum Doppler shift conditions and a worst-case atmospheric drag situation.
- A 900 km Sun-synchronous dawn-dusk (SSDD) orbit was used as upper boundary for the possible launch altitude. This orbit was used to determine the maximum power generated, was used as worst-case hot thermal situation for analysis and as worst-case condition for the link budget analysis.

These boundaries were used to find a suitable launch provider in the envisaged time frame and to design the satellite according to these specifications.

The final orbit parameters are given in the table below, the information was submitted upon launch to the ITU and UN.

BRITE-Austria orbit parameters	
Inclination	98.6295 deg
Apogee	781.45 km
Perigee	766.19 km
Nodal period	100.32 min

Table 2.4: BRITE-Austria orbit parameters: The orbital parameters were forwarded to the ITU and UN after the successful launch of BRITE-Austria.

At the beginning of the BRITE-Austria mission it was not decided to realise a whole constellation of BRITE satellites in the future, hence requirements on the specification and operation of a constellation were not defined in the course of this project.

2.4 Launch Segment

Once the orbit boundaries were specified, the search for launch opportunities was initiated. It has to be stated that launch delays are quite common and often depend on the flight readiness of the primary payload, hence patience is required. In addition, in case more opportunities are available, trade-offs have to be made. If a target orbit on a later flight is better suited for the mission it might be advisable to wait rather than using earlier launch opportunities just to get quick access to space. In case of BRITE-Austria, that is exactly what happened, a later launch to a Sun-synchronous dawn-dusk orbit at an higher altitude turned out to be a good choice for meeting the science objectives.

The search for launch opportunities for BRITE-Austria started mid-2007. At first, contact to already existing partners in Russia (Soyuz, Dnepr) were re-established. Additionally European launchers from Arianespace (Ariane 5, Soyuz, Vega) and Indian launch opportunities of the Indian Space Research Organisation (ISRO) (PSLV) were investigated [19].

Piggy-back possibilities were not that common at the time of launch opportunity search. A comparison of all the available launchers with respect to science, schedule, licensing, and technical issues was made to assist the decision finding (Table 2.5).

Sun-synchronous orbits were rare or even not envisaged in several launch manifests. Besides, some launchers either required additional qualification, yielding to schedule extension and cost increase, or even were maiden flights, increasing significantly the risk of a launch failure.

It was decided to further investigate the launch possibilities on the Indian PSLV rocket, as additional rationales were found:

- **Secondary payloads** - ISRO was quite willing to launch additional secondary payloads.
- **Success rate** - At the time of launch negotiations, already 14 out of 15 successful launches were conducted (only maiden flight failed).
- **Launch costs** - The costs for the launch were lower than for a launch by Soyuz or VEGA.
- **Deployment mechanism** - The interface control document (ICD) was already available as a similar pod was flown in April 2008.
- **Environmental testing** - As the BRITE satellites share the same frequencies as the previously launched GNB satellites, there was no need to perform additional EMC tests. Besides, the spacecraft is OFF in launch pod, the power system is only activated after ejection.

	Requirement	**PSLV**	**VEGA**	**SOYUZ Kourou**	**SOYUZ Baikonur**
Science	SSO, ideally dawn-dusk	Available: 650 km SSO, 1020 LTDN; 800 km SSDD	Available: 710 km SSO, 1030 LTDN	No launch parameters yet available	Available: 820 km SSO, METEOR primary payload
Schedule	Availability	Mid 2010 - Jan 2011	Late 2011	Late 2011	Dec 2010
	Project duration	Compliant	Extended	Extended	Compliant
Licensing	ITAR Re-Export License	Available	Application necessary (Impact on schedule)	Application necessary (Impact on schedule)	Application necessary (Impact on schedule)
Technical	Spacecraft	Compliant	Compliant	Compliant	Compliant
	Launch tube/ interface	Compliant	Partly compliant	Partly compliant	Partly compliant
	Interface adaption	Not required	To be done	To be done	To be done
	Launch qualification	Flight proven	Delta-qualification required	Delta-qualification required	Delta-qualification required
	Launcher success rate	93%, last 14 missions successful	Maiden flight still to be performed	Maiden flight still to be performed	Not available in this configuration
	Launch	Cost effective offer available	Preliminary figure, higher than PSLV	No established figures yet, expected to be in same range as VEGA	Preliminary figure, higher than PSLV
	Additional qualification	Not required	Required, 6 months	Required, 6 months	Required, 6 months

Table 2.5: Launch Opportunities: Several possible launch opportunities were found and a comparison concerning their scientific value, schedule, licensing, and technical implications was provided. [19] (LTDN = Local Time of Ascending Node)

At that time, two launch possibilities were annouced in the launch manifest of the Antrix Corporation Limited for the PSLV:

- a Sun-synchronous orbit (SSO) at 650 km altitude, envisaged launch date in June/July 2010
- a Sun-synchronous orbit (SSO) at 800 km altitude, envisaged launch date in January 2011

From the scientific point of view it was desired to launch BRITE-Austira and its sister satellite UniBRITE on the same launcher. Having both satellites in the same orbit would allow parallel observations in the blue and red spectral ranges of a specific star field.

Furthermore, this would ensure similar satellite life-times, environmental conditions (e.g. temperatures) and overall operations span. Due to the fact, that both satellites were planned to be ready for flight at the same time (around mid 2010), it was decided to launch both spacecraft on the same launch vehicle at the later launch for schedule risk mitigation.

Due to the good relationship between UTIAS/SFL and ISRO gained in previous missions, UTIAS/SFL carried out the launch negotiations on behalf of TUGraz acting as launch service provider (an Memorandum of Understanding [MoU] concerning launch services and launch integration was signed between UTIAS/SFL and TUGraz in 2008).

2.4.1 Launch Configuration

BRITE-Austria was launched as secondary payload on February 25th 2013, at 12:31 Universal Time Coordinated (UTC) (18:01 local time) on-board the PSLV-C20 rocket. The launch occured on the First Launch Pad (FLP) at the Satish Dhawan Space Centre (SDSC/SHAR) in Shriharikota, India.

Figure 2.13: PSLV-C20 rocket: The rocket is waiting for launch on the First Launch Pad (FLP) at the Satish Dhawan Space Centre (SDSC/SHAR) in Sriharikota/India. (Image courtesy: ISRO)

The payload fairing of the PSLV-C20 rocket hosted seven satellites, which were launched into a Sun-synchonous dawn-dusk orbit at an altitude of 780 km. Table 2.6 lists the specifications of the individual spacecraft on-board of the rocket.

The following pictures show the launch configurations of the BRITE satellites and the entire payload fairing. The primary payload SARAL was placed on top, below inside the dual launch adapter (DLA) the spacecraft SAPPHIRE and NEOSSAT were placed.

On the Equipment Bay Deck (EBD) underneath, the four other satellites were mounted. Normally the EBD is used for hosting the flight computers, as well as the telemetry, inertial guidance and avionics system. Excess space was made available on previous flights for secondary payloads.

Satellite	**Country (Organisation)**	**Purpose/Description**	**Size, Mass**	**Role**
SARAL	India (ISRO) / France (CNES)	Oceanography / Satellite with ARgos and ALtika	Minisatellite, 400 kg	Primary Payload
Sapphire	Canada (MDA)	Space debris and MEO artificial object tracking	Microsatellite, 150 kg	Secondary Payload
NEOSSat	Canada (MSCI)	Near Earth Objects Surveillance Satellite	Microsatellite, 74 kg	Secondary Payload
BRITE-Austria	Austria (TUG)	BRIght Target Explorer	Nanosatellite, 7 kg	Secondary Payload
UniBRITE	Austria (UV)	BRIght Target Explorer	Nanosatellite, 7 kg	Secondary Payload
AAUSAT3	Denmark (Aalborg University)	Automated Identification System (AIS) receiver technology demonstration	1U CubeSat, 1 kg	Secondary Payload
STRaND-1	United Kingdom (SSTL)	Surrey Training, Research, and Nanosatellite Demonstrator 1	3U CubeSat, 4.3 kg	Secondary Payload

Table 2.6: Launch configuration: Next to the primary payload SARAL six other satellites were launched on the PSLV-C20 rocket on February 25, 2013. (CNES = Centre National d'Etudes Spatiales, MDA = MacDonald, Dettwiler and Associates, MSCI = Microsat Systems Canada Incorporated, SSTL = Surrey Satellite Technology Limited) [19][20]

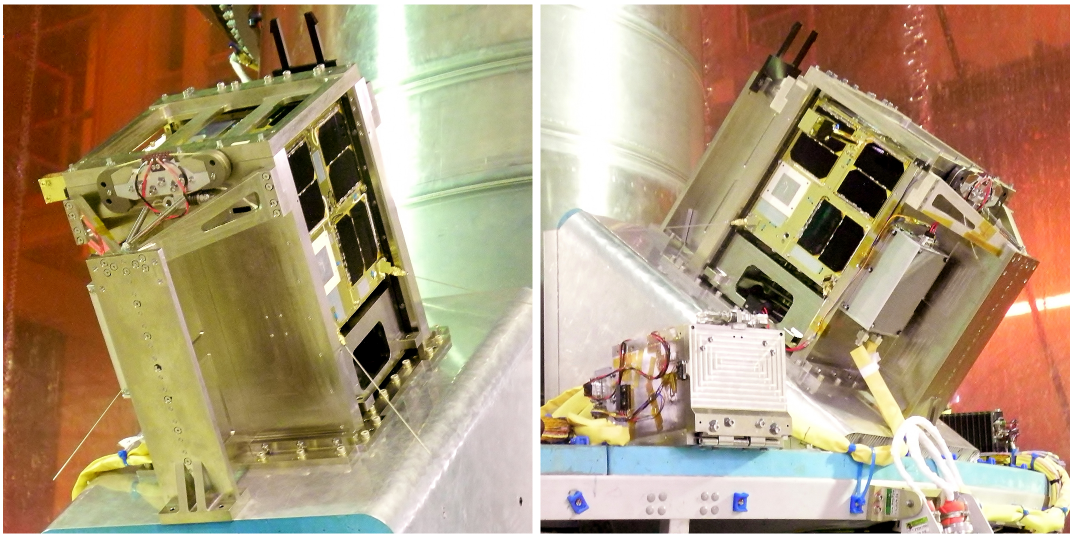


Figure 2.14: UniBRITE and BRITE-Austria waiting for launch: The two Austrian BRITE satellites were secured in their deployers, and mounted on the equipment bay of the payload stage. (Image Courtesy: ISRO)

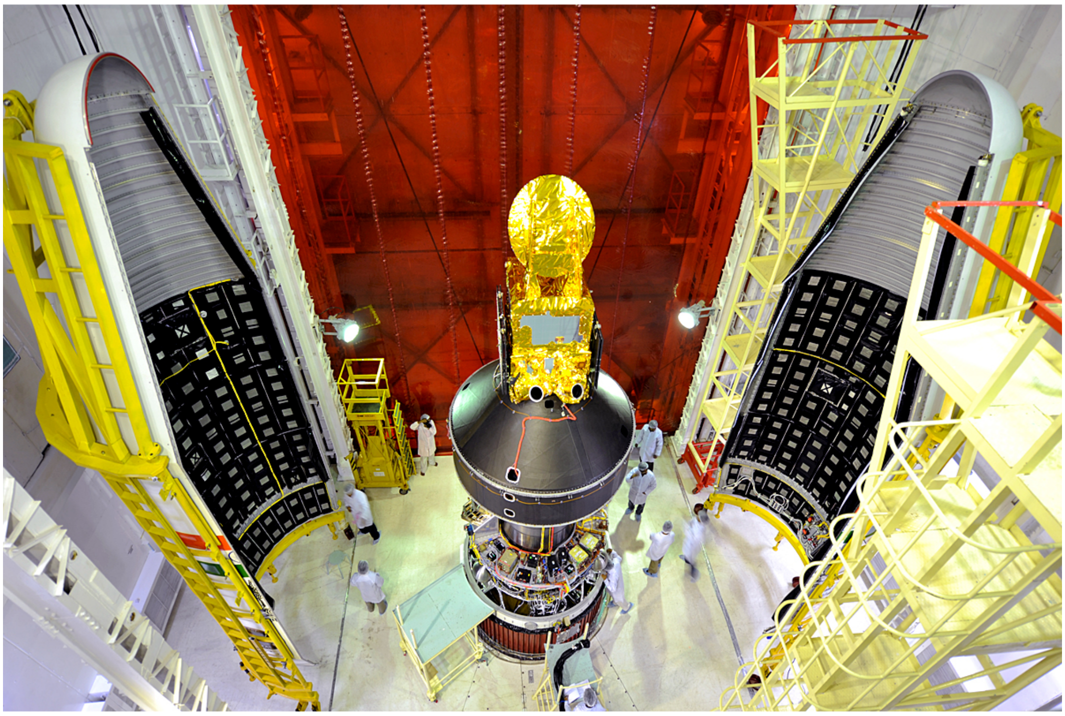


Figure 2.15: PSLV-C20 launch configuration: The payload fairing seen from above hosting the satellites (SARAL on top, smaller satellites below) before final closure of the heat shield. (Image courtesy: ISRO)

The impact on the testing and qualification of the satellite and its deployment mechanism is described in Chapter 3 BRITE-Austria Systems Engineering. In addition, more details on the launch campaign itself including impressions are given in Section 4.1.

2.5 Ground Segment

The ground segment concept for the BRITE-Constellation foresees, that one master mission control and ground station is in charge of the operation and monitoring of its dedicated satellite(s). In the case of BRITE-Austria, the spacecraft is operated via Graz. To increase the availability and redundancy in operations, a BRITE ground station network was established [21].

The following table lists the current participating BRITE ground stations and mission control centres (MCC), and states their role in the network.

Ground Station	Institution	Role in the Network
Graz/Austria	TUG	BRITE-Austria MCC, since June 2016 UniBRITE MCC
Toronto/Canada	UTIAS/SFL	BRITE-Toronto MCC, until June 2016 UniBRITE MCC
Warsaw/Poland	SRC/PAN	BRITE-Lem and BRITE-Heweliusz MCC

Table 2.7: BRITE ground stations: The ground station network of the BRITE-constellation currently consists of three ground stations, located in Austria, Poland, and Canada.

Originally an additional backup and relay station at the Vienna University of Technology was envisaged in the BRITE-Austria mission, however this station was never operative. The ground tracks of the BRITE-satellites, including their footprints and the ground stations in the network are shown in the following figure.

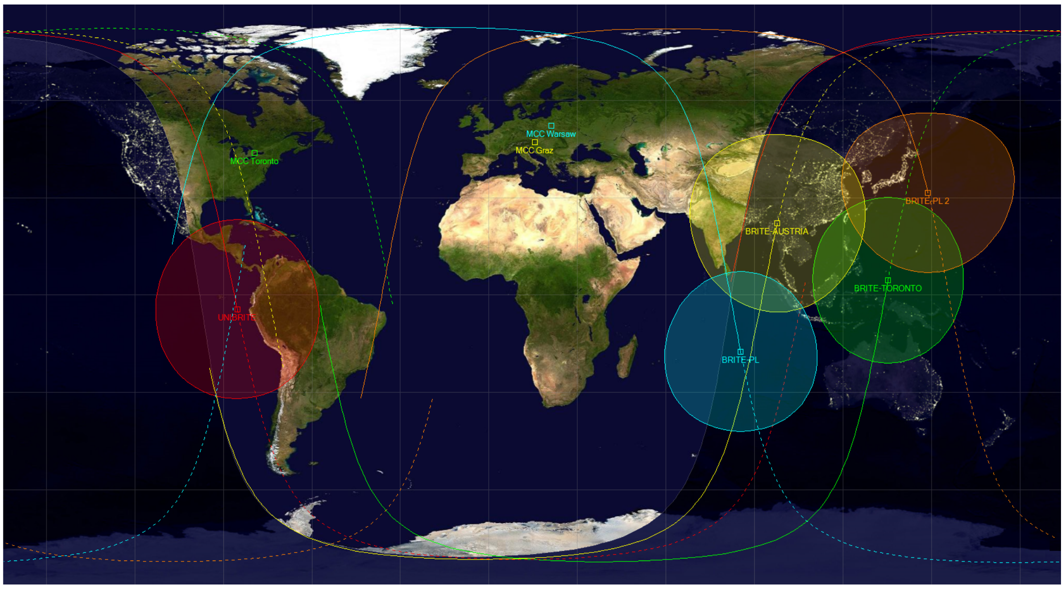


Figure 2.16: BRITE satellites and their groundtracks: The footprints of the satellites including the location of the ground stations are shown using the SUMUS Tracker ® [22].

The master ground station, as mentioned above, is responsible for its assigned satellite(s). The other stations in the network however may act as relay stations, they can upload the incoming commands and scripts received by the master ground station to the satellite, and download the data of the satellite and forward it to the master ground station again. In addition, in case the dedicated master ground station is unavailable (due to breakdown or weather conditions), other stations can temporarily take over all duties [21]. Although all ground stations are capable of establishing contact with each spacecraft, the entire information and data flow is handled by the respective master control centre and station. This is achieved by the use of a distributed ground software concept.

2.5.1 Communications Architecture

BRITE-Austria uses two different frequencies for the uplink and downlink. The downlink frequency is in the Space Research Services [SRS] Space-to-Earth band (2200 - 2290 MHz) and is an assigned frequency by the ITU. The S-band is used for the transmission of telemetry data and scientific payload data to the ground station(s). The uplink frequency is in the amateur radiolocation Earth exploration-satellite UHF band (432 - 438 MHz). It is used for command upload to the spacecraft.

The overall communications architecture giving the main data products and information exchanged between the segments is depicted in Figure 2.17.

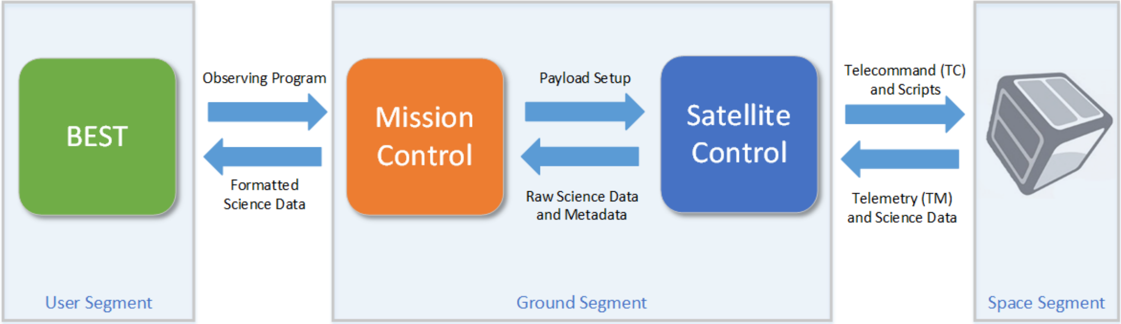


Figure 2.17: BRITE-Austria communications architecture: The mission segments as well as the communication architecture of the BRITE-Austria mission is shown. (BEST = BRITE Execution Science Team, see Section 2.7)

2.5.2 Ground Station

The ground station design is mainly driven by the satellite's orbit, the communications architecture and the data volume to be up-/downloaded. As BRITE-Austria is flying in a Sun-synchronous LEO orbit at an altitude of around 780 km, the ground station has to provide the required tracking capabilities and pointing precision [23][24].

BRITE-Austria uses two different frequency bands, therefore two antenna systems are used for the operation of BRITE-Austria. A 3 m parabolic S-band antenna is used for telemetry and data downlink. For the uplink of telecommands and software images two 18-element cross-Yagi antennas for UHF are used. Both antenna systems were mounted on the same antenna tower using the same rotators. This allows to achieving the same tracking performance for uplink and downlink.

The antenna tower was installed on the roof of the IKS/TUGraz building, as the visible horizon limit in every azimuth orientation is $\leq 5°$. In addition, this location allowed to setting up the ground station control room and the mission control centre just in the room underneath the platform, leading to short cable lengths needed. Besides, as the ground station was established at the same building as the IKS/TUGraz. Its location was very advantageous for the operating team, which was formed from staff members of the IKS.

Figure 2.18: Ground station in Graz: Antenna tower and indoor RF equipment used for operations of BRITE-Austria/TUGSAT-1, located at the IKS/TUGraz.

In the UHF uplink an amateur radio transceiver and a linear power amplifier are used for generation of the desired RF output signal. The circular polarisation needed is achieved by the use of phase-shifted feed lines. The maximum available effective isotropic radiated power (EIRP) of the UHF uplink ground station is 43 dbW.

In the S-band downlink path, the received signal is amplified and downconverted to an intermediate frequency in the L-band for the satellite modem, which acts as receiver in the downlink. The figure of merit (G/T) of the S-band antenna system is about 14 db/K.

The interface between the RF components and the ground station software is the terminal node controller (TNC). It is responsible for

- scrambling and modulating the incoming data stream from mission control, forwarding it to the transmitter unit
- descrambling the received baseband signal from the satellite modem, forwarding the data to mission control.

Another driver for the ground station design is the amount of data volume to be downloaded. Due to the orbit, the contact times with the spacecraft are limited to 10-15 min per pass, summing up to a total contact time of about one hour daily. The data volume to be downloaded from BRITE-Austria is about 10 MB per day. Given a minimum downlink data rate of 32 kbit/s, the data volume generated on-board can be downloaded in about 42 minutes, which provides sufficient margins.

2.5.3 Mission Control Centre

The ground station in Graz also serves as mission control centre for BRITE-Austria, and since June 2016 also for UniBRITE. The mission control centre is used to operate the spacecraft and guarantees data integrity and storage of raw satellite telemetry and raw scientific data.

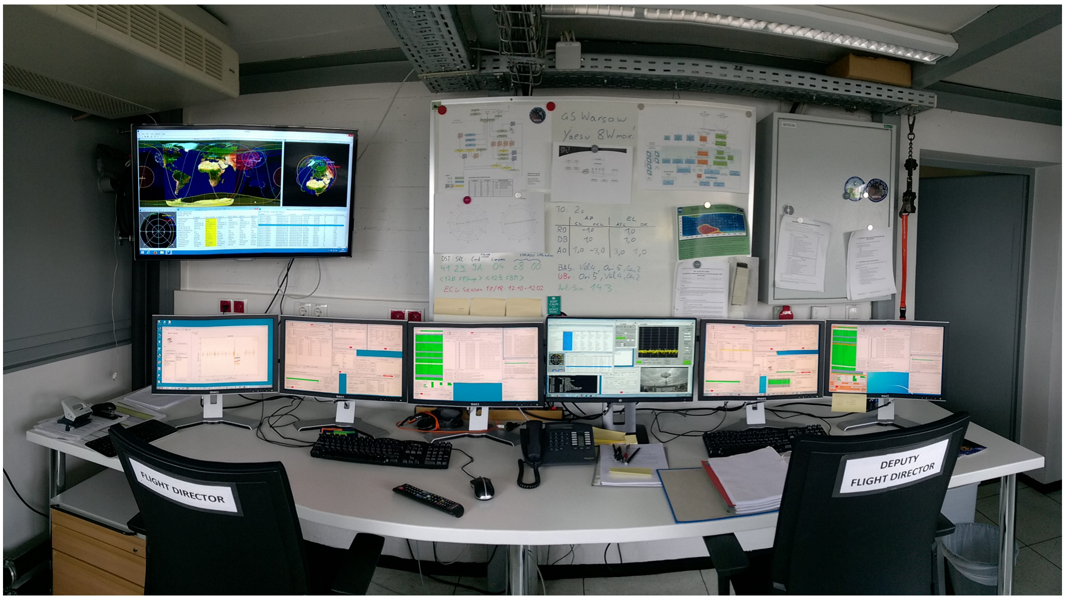


Figure 2.19: Mission control centre in Graz: Several workstations are used for operations of the BRITE-Austria satellite. Starting from the left side, the first three screens are used for operating BRITE-Austria. The fourth monitor shows the ground station interface, while the fifth and sixth screens state the software modules to operate UniBRITE.

As already indicated, BRITE uses a distributed software concept. The software makes a distinction between the mission control centre and the ground station control, to allow to using the distributed ground station network.

The mission control centre implements the mission specific software:

- Control software, for uploading commands, retrieving OBC states and downloading data from their mass memory
- Housekeeping telemetry validation software, real-time and post-processing modules
- Script and command preparation software
- Science software, which includes a target selection software, planning tool for observations and generation of observation files, as well as data download, transfer, processing, and evaluation software.

The major part of the ground segment software used for the BRITE-Constellation has been developed by UTIAS/SFL and has been adapted for the operation of the BRITE-Austria mission. Concerning the planning of the scientific observations, the post-analysis of telemetry and scientific data, as well as the ground station specific tasks, own processes and tools were developed at TUGraz.

The interface between the separate worlds, mission control and physical ground station, is a data packet multiplexing software (MUX). All other software modules connect to this entity for receiving and transmitting data. At the MCCs, the server version of the MUX software is running, whereas on the ground stations a client version is installed, which interacts with the ground station hardware. The client version can connect to the server at the MCC via TCP/IP (Transmission Control Protocol/Internet Protocol). The mission control centre is running the entire ground software suite. The ground station only receives the incoming packets for upload and relays the downloaded data to the MCC again. As the ground station only runs a client version of the MUX software, it just acts as relay station and does not perceive, which exact operations are carried out [23].

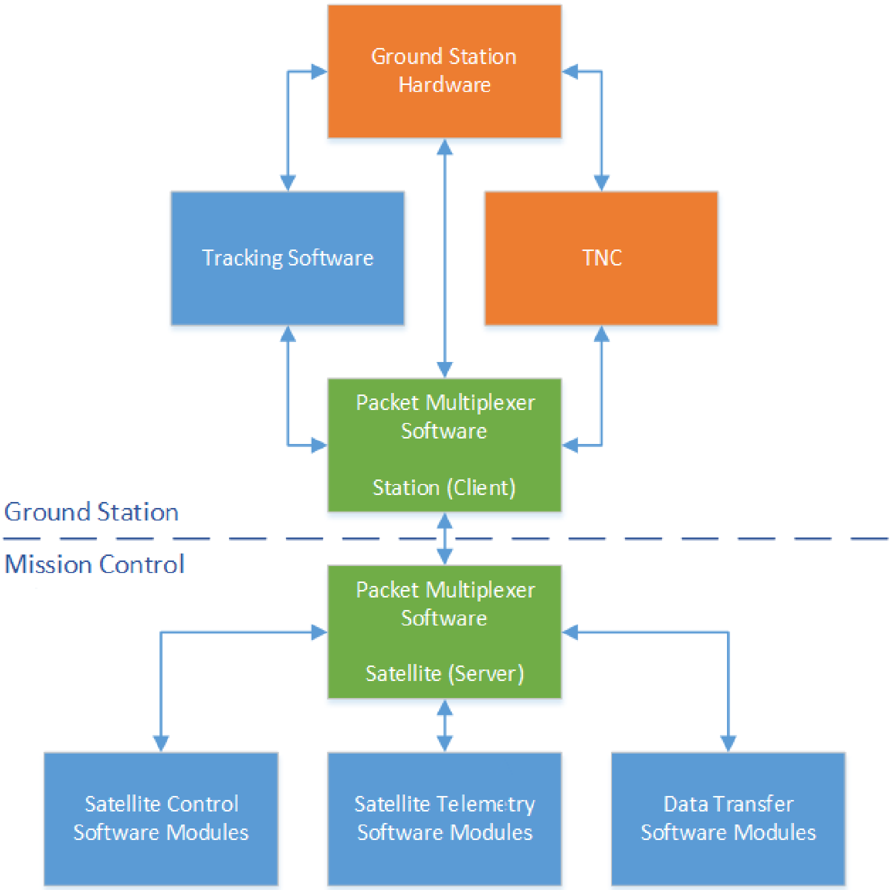


Figure 2.20: BRITE distributed ground segment concept: The orange boxes represent the hardware units needed at each ground station. The blue boxes represent the software items needed for operations, while the green boxes represent the pair of software modules that allow the interconnection between different ground stations.

On the ground station side, some additional modules are typically realised, like the tracking software, the TNC and the hardware itself. With this distributed ground segment approach, it is possible to physically separate the MCC from the ground station.

2.5.4 Data Processing, Archiving and Dissemination

In the case of BRITE-Austria, the telemetry and scientific data downloaded is integrity checked and locally stored at the MCC in raw format. In near-real time, the scientific data packet is partitioned in the individual exposures and converted into a Flexible Image Transport System (FITS) format (which is quite common for imaging data). The raw packets and parsed exposures are then transferred to an FTP server, where the BRITE-Austria mission scientist can further analyse the data and finally forward it to the Mission Data Archive (MDA) at Warsaw/Poland, where the data from all the BRITE satellites is stored.

2.6 Mission Operations

The operations phase of BRITE-Austria is dedicated to the observation of bright luminous stars. However, this phase is a quite complex one, and has therefore to be prepared accordingly. Before describing the different mission operation phases, a short overview of the satellite modes is given.

2.6.1 Satellite Modes

On BRITE-Austria different satellite modes are implemented, the four highest-level modes are:

- **Kickoff** - In this mode, the only items on-board, that are powered on, are the power subsystem and the UHF receiver unit. This mode is entered after deployment of the launch vehicle, after a power system reset firecode is received, or if an unexpected power event occured, which resets the power system.
- **Safehold** - In this mode, the OBCs are turned on and are running in bootloader mode. The major health telemetry can be read out and individual subsystems can be turned on manually on ground command. Their control however can be limited due to the bootloader functionality.
- **Passive application** - The OBCs are performing automated tasks, like collecting telemetry and Whole Orbit Data (WOD). In this mode, as a second-level mode, the attitude thread might be started. The attitude software can then be used in *safe mode* (devices are only initialised and power on) or *passive determination mode* (only coarse sensor readout). However, no dedicated control over the power switches is given to the OBCs.
- **Active application** - The application thread is given control to command and readout the sensors and control the actuators accordingly to perform the dedicated attitude control (*B-dot/detumbling*, *CTAP*, or *FTAP*). During *FTAP*, the startracker is used for determination, allowing to performing the payload operation on a third level.

The hierachy of the modes implemented on BRITE-Austria is shown in Figure 2.21.

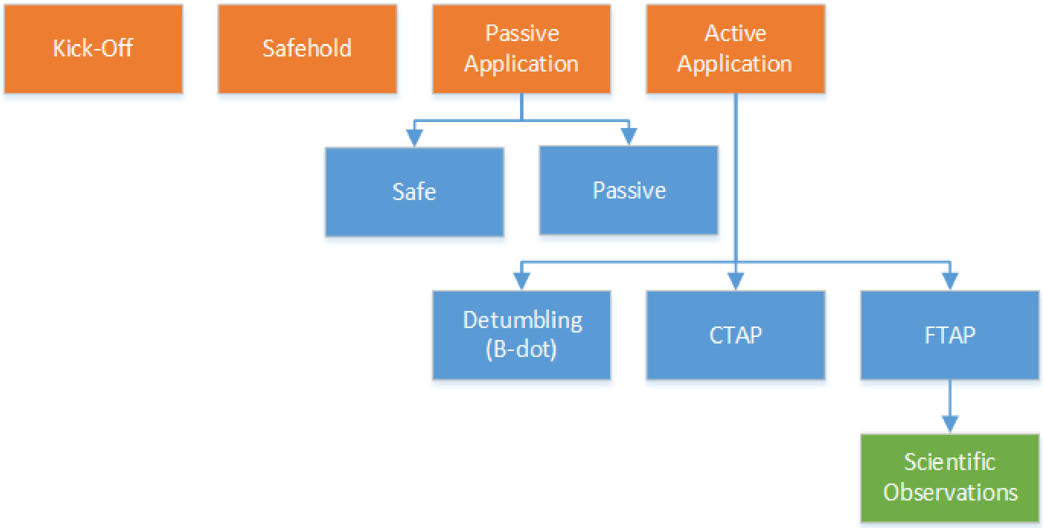


Figure 2.21: BRITE-Austria operational modes: Several modes are realised on-board of BRITE-Austria. Next to the kickoff and safehold mode, the passive and active application modes (orange boxes) have various submodes mainly for the attitude thread implemented (blue boxes). Payload operations (green box) are only performed in FTAP mode.

2.6.2 Launch and Early Operations Period (LEOP)

The LEOP phase of BRITE-Austria was defined as the 24-48 hours after launch, during which contact with the spacecraft should be established. After launch, the satellites deployed are monitored by the North American Aerospace Defense Command (NORAD) and the orbital data in form of Two Line Elements (TLEs) is provided to the operators. However, although the deployment sequence is known, the spacecraft are deployed in various directions, and only a set of TLE data for the launched objects are provided. Therefore, it might last several hours and passes to identify which TLE data corresponds to which satellite.

During the first contact(s) with BRITE-Austria, it was planned to turn on the HKC, and verify the satellite's health (especially positive power and expected thermal conditions), followed by the load of the application software and start of automatic telemetry gathering.

2.6.3 Commissioning

The concept for the commissioning of BRITE-Austria states that all systems should be checked out and their performance verified in a sequential and rather quick way, to minimize the overall duration of this phase. Once the communication with the spacecraft is stable, commissioning of the individual bus systems can be initialised.

The individual units are functionally checked and their performance, telemetry and data output verified. Besides, a performance verification of the ADCS system is planned, in case needed, sensor calibration is performed.

Once the spacecraft bus behaviour is verified, the functionality of the payload is examined and the instrument is further calibrated and characterised.

2.6.4 Nominal Operations

During the nominal operations, it is planned to perform observations of the respective target field:

- up to 15 stars in one field
- up to 15 minutes every orbit (about 14 orbits/day)
- one exposure every 30 seconds
- given an observation duration of a star field between 10 and 100 days

The main operations sequence comprises the planning and execution of observations and is mainly defined as the following [16]:

- Collect target fields from BEST
- Verify the target feasibility and visibility windows
- Prepare commmands for observation campaign
- Manage uplink commands over the distributed scenario
- Provide transparent management and data interface
- Collect telemetry and scientific data
- Forward singled out data to science processing

2.6.5 End of Life

Once the spacecraft has reached its end-of-life, it has to be ensured that no interference with operational satellites or ground stations occurs and no additional space debris is generated. In case of BRITE-Austria, it is envisaged to permanently disabling the communication by deactivating the transmitter. In addition, depletion of the batteries will be performed.

2.7 User Segment

The coordination of the scientific efforts of the overall BRITE mission is performed by the Bright Executive Science Team (BEST). BEST is the steering committee and represents the BRITE-Austria user segment, as it has the authority to select the science target fields and prepare the observation plan for the respective BRITE satellites. Each of the BRITE satellites send their observation data, after initial consistency checks, to a mission data archive, which is located at Warsaw. The further processing, publication or distribution to the BRITE International Advisory Science Team (BIAST) and the science community is also the responsibility of BEST.

During the conduction of the BRITE-Austria project however, several additional stakeholder have indicated their interest to the mission [25].

BRITE-Austria Stakeholders	
Active stakeholders	• BRITE-Austria project consortium (IKS/TUGraz, IfA/UV, ITC/TUV, UTIAS/SFL) • BEST and BIAST consortium • Austrian Research Promotion Agency (FFG) • Austrian Ministry of Transport, Innovation and Technology (BMVIT) • TUGraz • ITU and IARU • National radio regulations office • Radio amateur club (RCCW) at the IKS/TUGraz • Austrian Government, concerning legal issues
Passive stakeholders	• City of Graz and province of Styria • Subsystem, GSE and COTS providers • Students of the consortium institutes

Table 2.8: BRITE-Austria stakeholders: Next to the Austrian project consortium and funding agency, various other active and passive stakeholders were identified.

This page intentionally left blank.

Chapter 3

Systems Engineering

Systems engineering is an interdisciplinary approach governing the full technical effort of transforming requirements into an operable system solution within given contraints [26]. This definition is independent of scale and applicable on various complex systems, not only the development of spacecraft. A system hereby includes elements like hardware, software, firmware, human resources, techniques, information, facilities, services, and other support elements.

When talking about systems engineering of space missions, the major goal is to successfully combine the two cultures ”technical leadership” and ”systems management” as stated in [12].

- **Technical leadership** - The *Art* of systems engineering focuses on the system’s technical design and its integrity throughout its lifecycle. It balances broad technical domain knowledge, problem solving, curiosity and creativity, communication and leadership with the goal to develop a successful mission and system.

- **Systems management** - The *Science* of systems engineering focuses on managing the interaction of several technical disciplines, multiple organisation and partners, and all people involved in the technical execution of the mission. The emphasis hereby is laid on the organisational skills, the patience and persistence to define and control the processes needed to ensure an effective and efficient implementation of the mission. The integrated system shall be developed, operated and maintained throughout the project’s lifecycle.

Both disciplines blend into a complete systems engineering. The objective of space systems engineering is therefore to design, build, test, and operate a system while insuring it accomplishes its purpose in the most cost-efficient way possible - considering performance, cost, schedule and risk. Depending on the phases the project is currently in, the role of the systems engineer can change and the focus has to be laid on different tasks and elements. A systems engineer is more a generalist than a specialist and should have the ability to always see the so-called big picture.

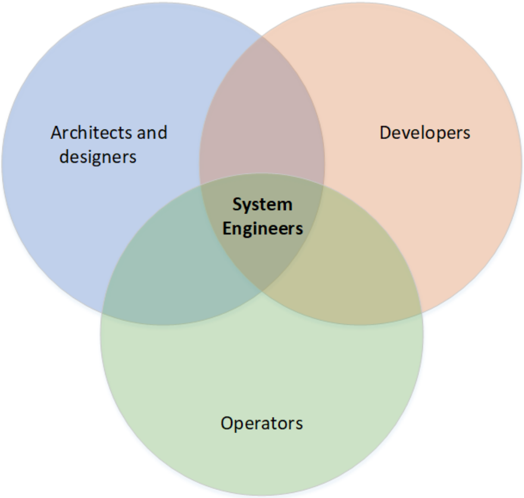


Figure 3.1: Scope of systems engineering: A systems engineer should have knowledge of and experience in all lifecycle phases [12].

Systems engineering comprises several sub-functions and disciplines [26]:

- **Requirements engineering** - Definition of requirements, their analysis and validation, and maintenance.
- **Analysis** - Performed during the entire mission lifecycle for various purposes:
  - resolving requirements conflicts, decomposing and allocating requirements with the help of functional analysis
  - assessing system effectiveness and analysing risk factors
  - complementing testing evaluations
  - provide trade studies
- **Design and configuration** - The design of the mission architecture, and its complete system including all functional, physical and software characteristics.
- **Integration and control** - The coordination of various engineering disciplines and participants involved throughout the mission lifecycle.
- **Verification and validation** - The demonstration, that the products delivered comply with the specified requirements.

Figure 3.2 shows the boundaries of systems engineering, its relations and interfaces with other disciplines (such as production, management, product assurance, as well as operations and logistics) and its internal sub-functions.

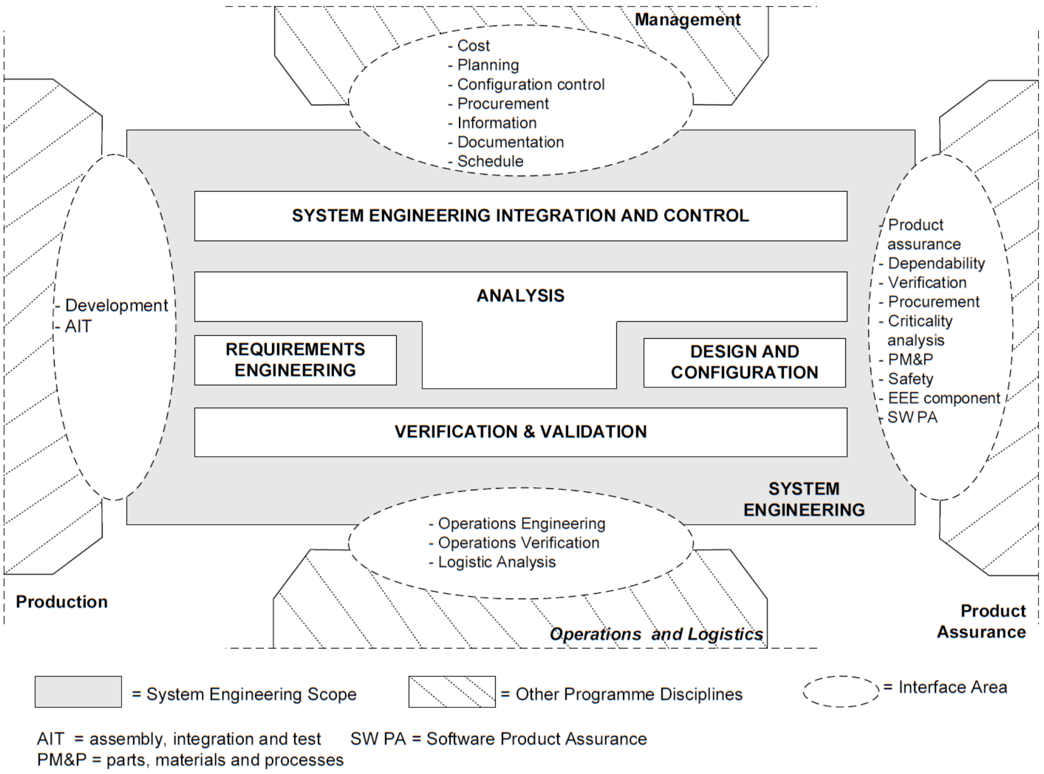


Figure 3.2: Systems engineering disciplines: The interactions and boundaries between the systems engineering scope and other disciplines is shown. [26]

Developing a space mission is an iterative process, starting with a mission concept design, followed by a requirements definition. The task of a systems engineer is to find options, compare and evaluate them, and finally select them by weighing the result against the original concept, given the technical and programmatical constraints (e.g. expertise and capabilities, facilities and tools available, risk, cost and schedule).

More general information on the system design, the system integration as well as the system verification methods can be found in Appendix B.

In addition, during the conduction of small space missions programmatical and regulatory aspects have to be considered early in the project. A description of the most relevant disciplines can be found in Appendix C.

3.1 Systems Engineering Approach of BRITE-Austria

The BRITE-Austria spacecraft design is based on the Generic Nanosatellite Bus (GNB), developed by UTIAS/SFL. The fact that several subsystems (with identical or slightly modified designs) have already achieved flight heritage in previous missions, helped significantly in reducing the development time, cost and risk.

During the early project phases of BRITE-Austria, technical and scientific requirements were defined. To ensure that the requirements are met during the spacecraft's lifecycle, a compliance matrix was generated to keep track of the requirements and to compare the current status and developments against them [27]. It was set up in a tabular form, indicating the requirements, their compliance status, the verification method (by design, inspection, analysis or test), and the link to the documentation as evidence.

Primarily due to cost reasons, only a flight model was built and qualified for BRITE-Austria. An engineering model for the BRITE instrument was paid by UV for intense characterisation and testing. Due to the parallel development of UniBRITE at the premises of UTIAS/SFL however, a spare flatsat with the main spacecraft bus components was established, which was of vital assistance concerning debugging, especially in the commissioning phase also for BRITE-Austria.

The testing philosophy of BRITE-Austria was adapted from the existing philosophy of the project partner UTIAS/SFL [28]. The test plan was customised for the selected launcher and further revised and approved by the funding agency FFG. A rough picture of the test plan of BRITE-Austria is shown in Figure 3.3.

The unit, subsystem and flatsat tests were performed in an ElectroStatic Discharge (ESD) protected laboratory at the IKS/TUGraz with defined humidity and temperature. The final assembly and integration of the flight spacecraft reoccurred in a cleanroom environment in the same building as the IKS/TUGraz.

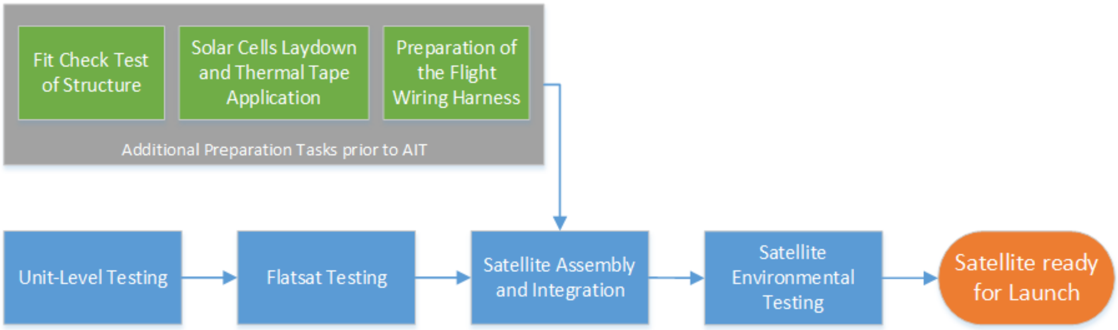


Figure 3.3: BRITE-Austria testing philosophy: The test philosophy of the BRITE-Austria spacecraft is depicted.

Several Ground Support Equipment (GSE) and tools supported the assembly and testing of BRITE-Austria, and consisted of

- Mechanical GSE (MGSE), e.g. for the support for the individual panels, a lunch box for storage of the entire spacecraft
- Electrical GSE (EGSE), e.g. various interface boards, programmable loads, power supplies, logic analyser
- Optical GSE (OGSE), e.g. spotlights and lightsources for instrument testing

- Radio Frequency (RF) equipment, e.g. transceivers, test antennas, satellite modem, spectrum analyser
- various tools, epoxies and Room Temperature Vulcanisers (RTVs)

Figure 3.4: Cleanroom environment and tools used for assembly: The picture shows some of the tools and MGSE (panel supports) used during assembly of the spacecraft.

Concerning the test facilities, most of them were available at short distance from the IKS/TUGraz. The only system-level tests, which had to be performed elsewhere, was the vibration test (Munich/Germany) and the thermal-vacuum test (Warsaw/Poland). The suitability and availability of such external facilities was a critical aspect in the AIT phase, which can have a huge impact on costs and schedule.

The following sections describe the testing performed at unit-, flatsat- and system-level in more detail, and give some impressions during the assembly and test campaigns.

3.2 Unit-level Testing

This section gives an overview of the tests conducted on unit and component level [29].

3.2.1 Functional Testing

At several stages during the qualification or acceptance testing campaign, functional tests on unit-level were performed:

- After initial build and inspection
- Before and after thermal shock (if applicable)

- Before start of and during any environmental test (if applicable)
- Before release to flatsat integration

To keep the number of connector cycles at a minimum, all connectors on all units were equipped with connector savers.

3.2.2 Thermal Shock Testing

Most flight units underwent thermal shock testing. Only some items were not thermally shocked, as the test was declared not useful or suitable to avoid damaging the units (e.g. wiring harness, batteries).

During the thermal shock testing, the devices under test (DUT) experienced 25 full cycles. The temperature ranges of -40 and +80° C inside the chamber representing the survival temperatures, units experienced temperatures between -30 and +60° C (Figure 3.5).

As the requirement of the temperature transition of at least 25° C per minute was not feasible for the current chamber, a second thermal chamber of the Institute of Electronics in the same building was used. One chamber was set to +80° C to represent the hot-case and the other one was set to -40° C. The DUT was then switched between those two chambers (Figure 3.6).

Figure 3.5: Thermal shock testing: Thermal shock testing was performed during the unit-level test campaign on several components (power board is shown).

3.2.3 Thermal Testing

Only acceptance testing was performed for BRITE-Austria, as the design had already been qualified by UTIAS/SFL. The temperature limits during the thermal testing were set to -20° C and +60° C, representing the expected operational temperature limits.

3.2.4 Thermal Vacuum Testing

For BRITE-Austria, thermal vacuum (TVAC) testing was only performed on new designs, therefore only the proto-flight instrument experienced TVAC testing (performed by UTIAS/SFL).

Figure 3.6: Test setup with two chambers for thermal shock testing: Two chambers were used to represent the hot- and cold-case, to ensure the temperature transition of at least 25° C per minute.

3.2.5 Low Vacuum Testing

This test was only performed on the fully populated panels, including solar cells, S-band patch antennas and thermal tape. The reason was primarily to ensure that no air was trapped that

- eventually can vent in a specific manner or
- cause a pressure differential

and therefore might damages a unit.

3.2.6 Vibration Testing

Just as TVAC testing, vibration testing was only performed on new, complex designs. In case of BRITE-Austria, vibration testing on unit-level was only performed by UTIAS/SFL on the following items:

- Proto-flight instrument
- Reaction wheels (as part of design qualification)

Summarizing, the following tests on the individual units have been performed at TUGraz [28][29]:

Unit-Level Tests					
Subsystem	**Unit**	**Functional**	**T-Shock**	**Thermal**	**Low-Vacuum**
PWR	Solar cells	-	x	-	x
	Power board	x	x	x	-
	Batteries	x	-	-	-
ADCS	Magnetometer	x	-	-	-
	Sun sensors	x	x	-	-
	Startracker	x	-	-	-
	Magnetorquer	x	-	-	-
	Reaction Wheels	x	-	-	-
OBDH	HKC	x	-	-	-
	ADCC	x	x	-	-
	IOBC	x	-	-	-
COM	UHF	x	x	x	-
	S-band	x	-	x	-

Table 3.1: BRITE-Austria unit-level tests: During the unit-level testing phase several tests were performed by TUGraz.

3.3 Payload Testing

As the proto-flight intrument at UTIAS/SFL was qualification tested, the instrument payload of BRITE-Austria was only acceptance tested. To assess the behaviour, both functional and thermal testing were performed with the instrument electronics including[29]:

- Bias level and stability tests
- Gain and saturation tests
- CCD dark current and readout tests

The testing of the instrument's imaging properties was not only performed in the laboratory, but also was verified under real sky conditions at the Lustbühel Observatory near Graz.

Next to the instrument characterisation, hardware verification and functional checks of the IOBC were performed [30].

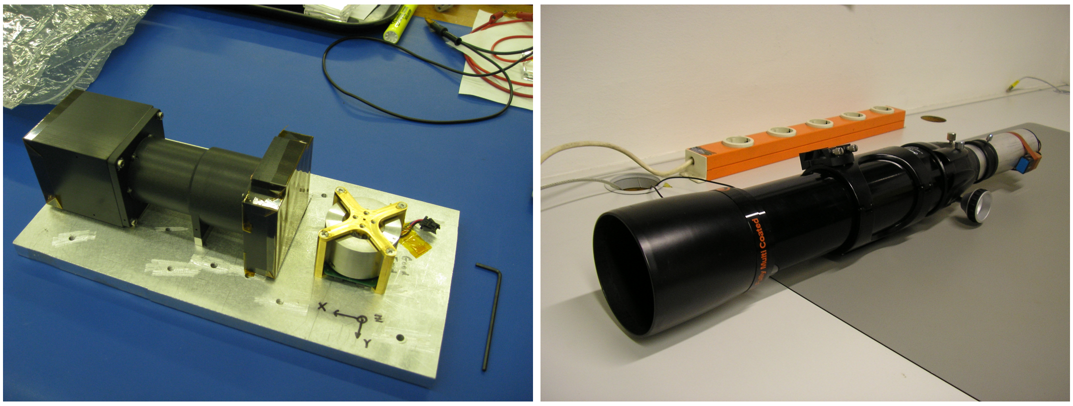


Figure 3.7: Payload testing: An engineering model was sponsored by UV. It was used for qualification testing and for characterising the flight instruments (Image courtesy: UTIAS/SFL and TUGraz).

3.4 Flatsat Assembly, Integration and Testing

Prior to flight assembly, all subsystems have to be tested on system-level. The components were mounted on a flat rigid plate (so-called flatsat) and interconnected in the same way as in the flight configuration. The flatsat plate was designed such, that both sides of each electronic board/component were accessible during debugging operations. The fully populated BRITE-Austria flatsat is shown in the following picture:

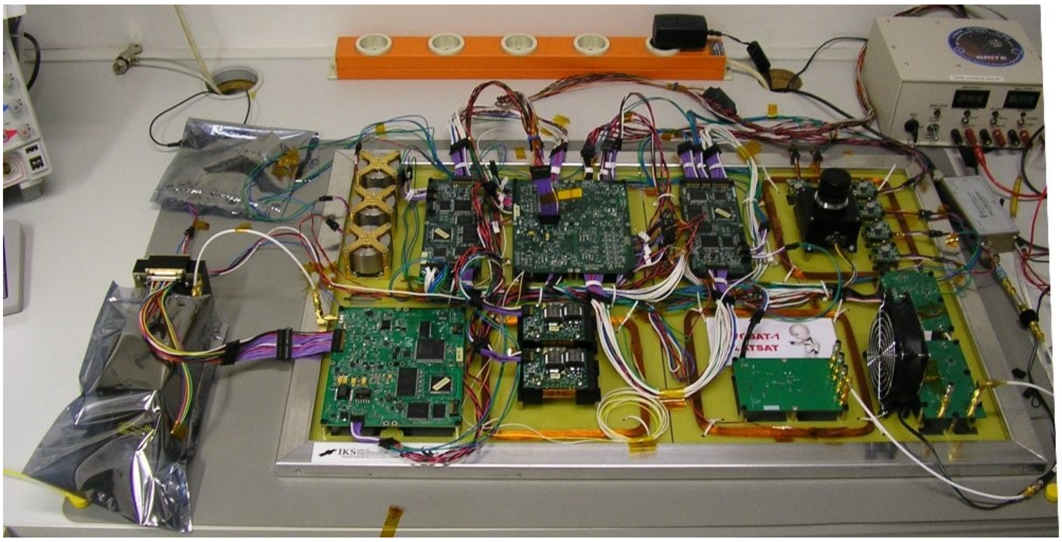


Figure 3.8: Flatsat testing: Spacecraft units are mounted on a flat plate and interconnected as in flight.

Individual units were turned on sequentially and their correct behaviour was tested. In addition, software builds, various communication channels (over test port and radios) and the interaction with the ground software were tested.

Next to the functionality and stability at room temperature, the flatsat was additionally tested at the extreme operational temperatures in a thermal chamber at the IKS/TUGraz.

Figure 3.9: **Flatsat thermal testing:** The functionality of the flatsat was tested at extreme operational temperatures in the thermal chamber.

3.5 Spacecraft Assembly and Integration

This section of the thesis describes the steps involved during the assembly of BRITE-Austria and gives some impressions [29].

3.5.1 Fit Checks

After plating and installation of the helicoils, a fit check of the main structural components was performed. The structure was assembled according to the assembly procedure to ensure the correct alignment of the elements.

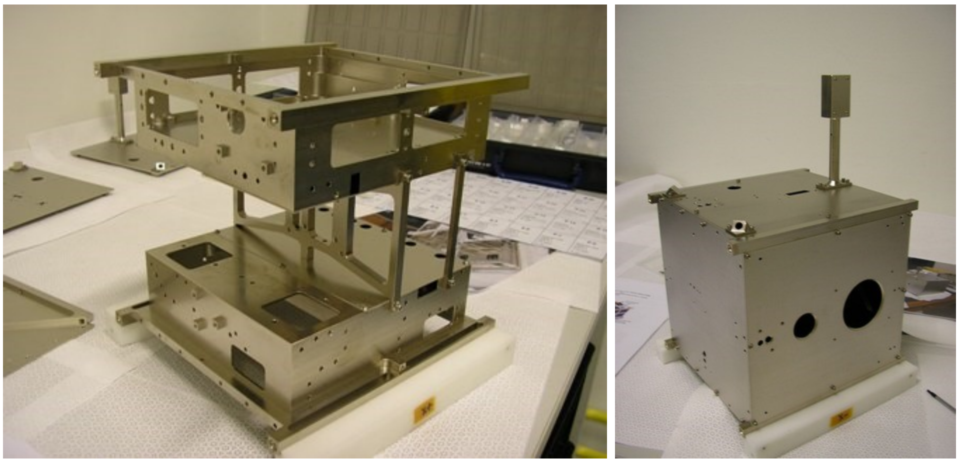


Figure 3.10: **Fit check of structural parts:** The main structural elements were assembled in a first round of fit checks.

In a second round, and as soon as the components became available, the units were fit checked by mounting them directly to the spacecraft structure. The insights gained during this activity was used as input for the overall assembly procedure.

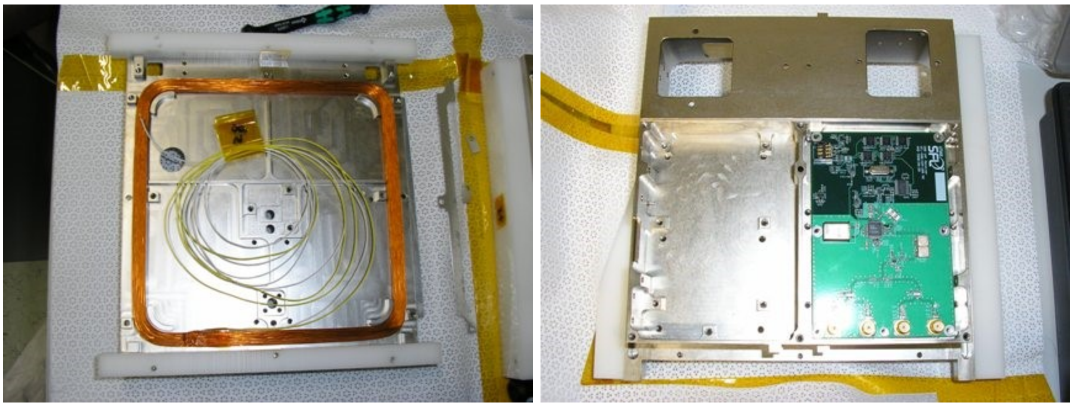


Figure 3.11: Fit check of units: The subsystems were mounted individually to their predetermined positions.

3.5.2 Laydown of Solar Cells and Patch Antennas

After the fit check, the laydown of the solar cells and S-band antennas was performed. The laydown was performed in two consecutive stages, three panels at a time. The following steps were performed:

1. **Panel preparation**
   With the help of slightly larger mockup coupons, Kapton tapes were placed over the area not covered by solar cells. Two layers of tape were used
   - to achieve the acquired thickness as needed for the room temperature vulcaniser (RTV)
   - to serve as enclosure to the RTV
   - and to limit the amount of RTV waste.
2. **Workarea preparation**
   All necessary tools, panels, patch antennas and solar cell coupons (two solar cells were premounted on a coupon) were places in such a way, that all tools were easily accessible without reaching over the panels and enough space for handling was available.
3. **Preparation of solar cells**
   A fit check of the respective solar coupons or antennas was performed, and the position and orientation was noted.
4. **Primer application on coupons and panels**
   To allow optimal mating of the RTV to the aluminum panels and the coupons/antennas, a primer was applied on the panels and coupons.
5. **RTV preparation**
   While the primer had to cure for 15 minutes, the RTV mixture was prepared. The RTV was blended with the hardener and the mixture was placed in a bell jar and depressurised.

During this procedure trapped air could escape from the mixture to allow proper curing of the RTV and to ensure that the solar cells do not de-bond in the vacuum environment.

6. **RTV application and laydown**
   After mixing the two components, the laydown had to occur within 45 minutes, therefore it was very important to proceed without delay and combine the efforts. With the help of a plastic spatula, the RTV was applied to the Kapton free panel area by one person. The second person then gently placed the respective coupon on its designated position.

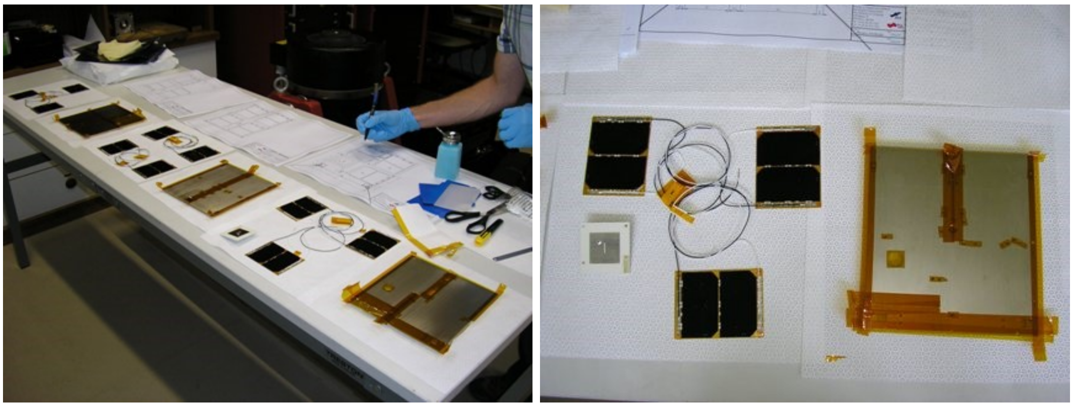


Figure 3.12: Preparation of solar cell and antenna laydown: The workarea and the panels have been prepared before starting with the RTV application.

7. **Covering of cells and antennas for room temperature curing (24 h)**
   To avoid shifting of the coupons during curing, weights had to be applied. To avoid cracking of the cells, pieces of rubber foam were placed on top of the cells, before applying weight (1.5 kg per coupon) on the panels. The stability of the weights was checked every once in a while to ensure that no movement of the coupons occured.

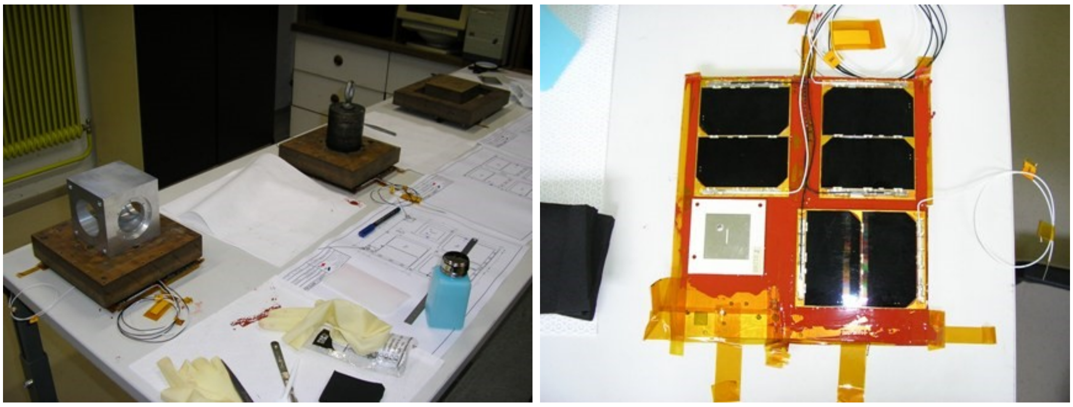


Figure 3.13: Room temperature curing: Impressions during and after the RTV was curing for 24 h at room temperature is given.

8. **RTV curing at high temperature in thermal chamber (48 h)**
   After 24 h the weights and rubbers were removed, and the panels were placed inside the thermal chamber. The panels were left inside at +80° C for at least 48 h.

9. **Cleaning of the panels and storing**
   After cooling down of the panels, the Kapton tape was removed. Excessive RTV was removed with the help of a surgical knife, or clean wipes with alcohol. The panels were then mounted on their MGSE and stored accordingly.

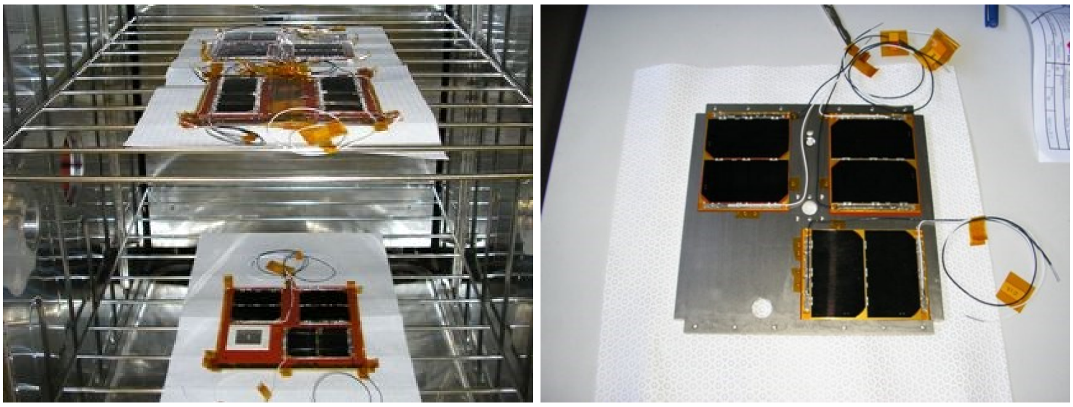


Figure 3.14: Solar cell and antenna laydown impressions: After room temperature curing, the panels were placed inside the thermal chamber for further RTV curing (left). A panel after cleaning and removal of excess residues is shown (right).

To ensure that no physical damage/cracking has occurred to the solar cells during bonding, a thermal shock test was performed on the panels.

3.5.3 Thermal Tape Application

According to the system requirements, passive thermal measures should be used to control the satellite's temperature. Consequently, thermal coatings were applied on the outside of the spacecraft. The main requirements for the application of the tapes were:

1. The tapes shall be free of bubbles.
2. The properties of the tape shall remain unchanged during application, e.g. they do not get damaged.
3. The tapes shall be applied in a straight manner by using fewest pieces possible.

A self-adhesive thermal tape made of Kapton and aluminum was chosen and the panels and workarea prepared.

After application of the tapes, each panel was placed inside the bell jar and de-pressurised to see if any air is trapped underneath the tape. In case bubbles were observed, the location was marked and the bubble was popped, and the procedure was repeated until no bubbles occurred.

Figure 3.15: Preparation of thermal tape application: The workarea with panels and all necessary tools for application was prepared.

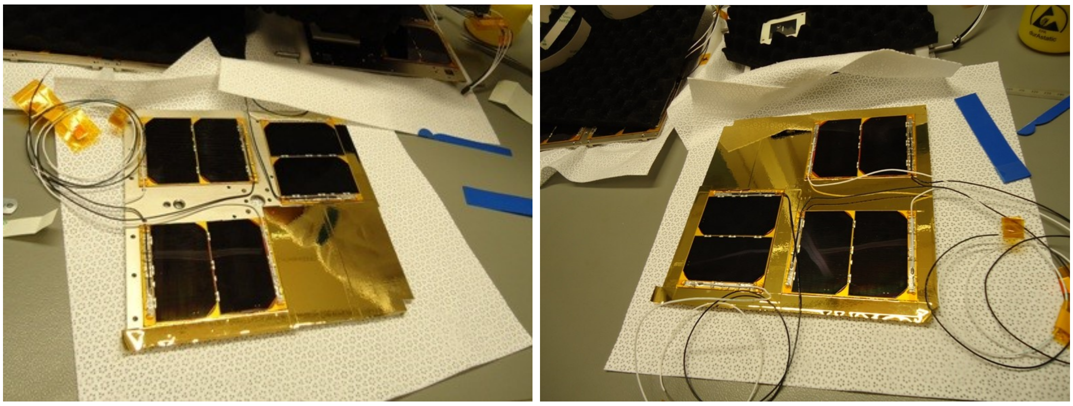


Figure 3.16: Thermal tape application: Impressions during and after the application of the tape are given.

3.5.4 Configuration of the Wiring Harness

The wiring harness used on BRITE-Austria is divided in sub-harnesses, each dedicated for a specific subsystem. Depending on the sub-harness, different gauges of wires were used (22/24 AWG for Power lines, 28 AWG for data/control lines). Teflon insulated wires were used to survive the space environment.

To help during assembly, a coloring scheme was defined, which was implemented throughout the satellite and helped significantly during the assembly. For each subsystem harness, wiring harness diagrams were prepared.

All power lines were twisted and all splices were soldered (lash-splice according to NASA-STD-8739.4).

All crimped pins and sockets were documented (photos) and their exact length was checked. The wires were safe-to-mate checked by the use of digital multimeters and the respective harness was assembled and labeled according to the harness diagrams.

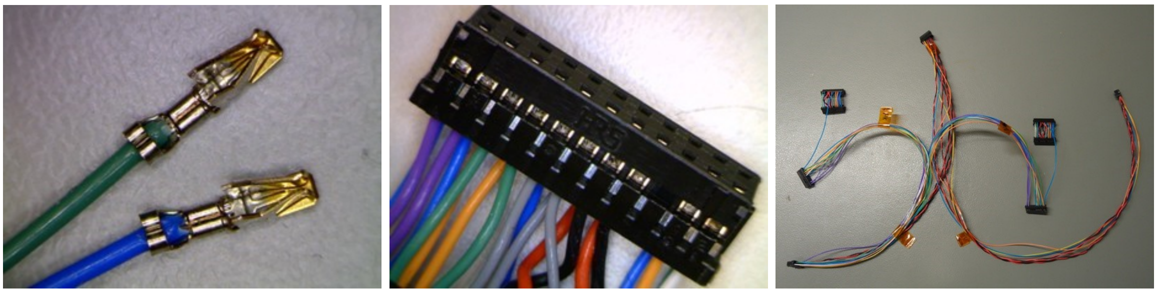


Figure 3.17: Connectors, pins and harness: All the pins and assembled connectors were visually and functionally checked and documented. The subsystem harnesses were assembled according to the wiring harness diagrams, see Figure 3.18.

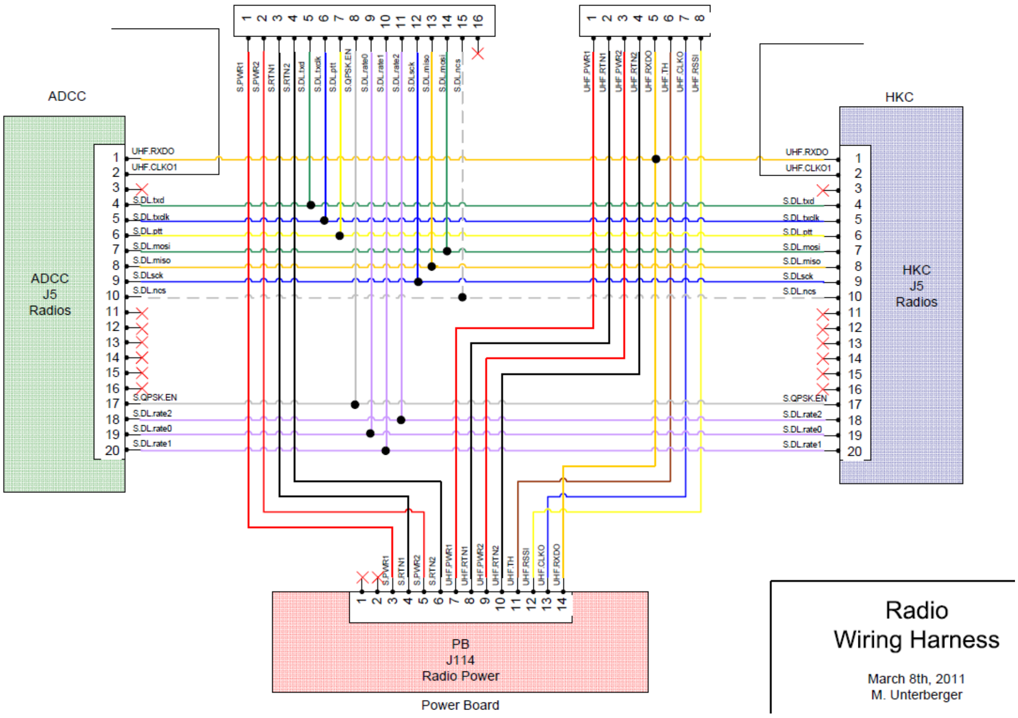


Figure 3.18: Radio wiring harness: Wiring harness diagrams were drawn to ensure the correct assembly of the flight harness (the radio and inter-OBC harness is shown).

3.5.5 Flight Assembly

The assembly of the spacecraft occurred in a cleanroom environment. All items were therefore entirely cleaned and transferred to the cleanroom for final flight assembly. The assembly was performed by the systems engineer and operations director, under the supervision of C. Grant from UTIAS/SFL [29].

Before describing the major steps during the assembly of the spacecraft, a cross-reference to the satellite design is given. The main body of the satellite has a volume of 20x20x22 cm not including UHF antennas and magnetometer. The internal structure consists of dual-tray system. Launch rails run along two parallel edges on each tray, and are used as interface for the deployment housing.

The trays are placed on opposing sides and the remaining volume in between is used to accomodate the scientific instrument and the startracker.

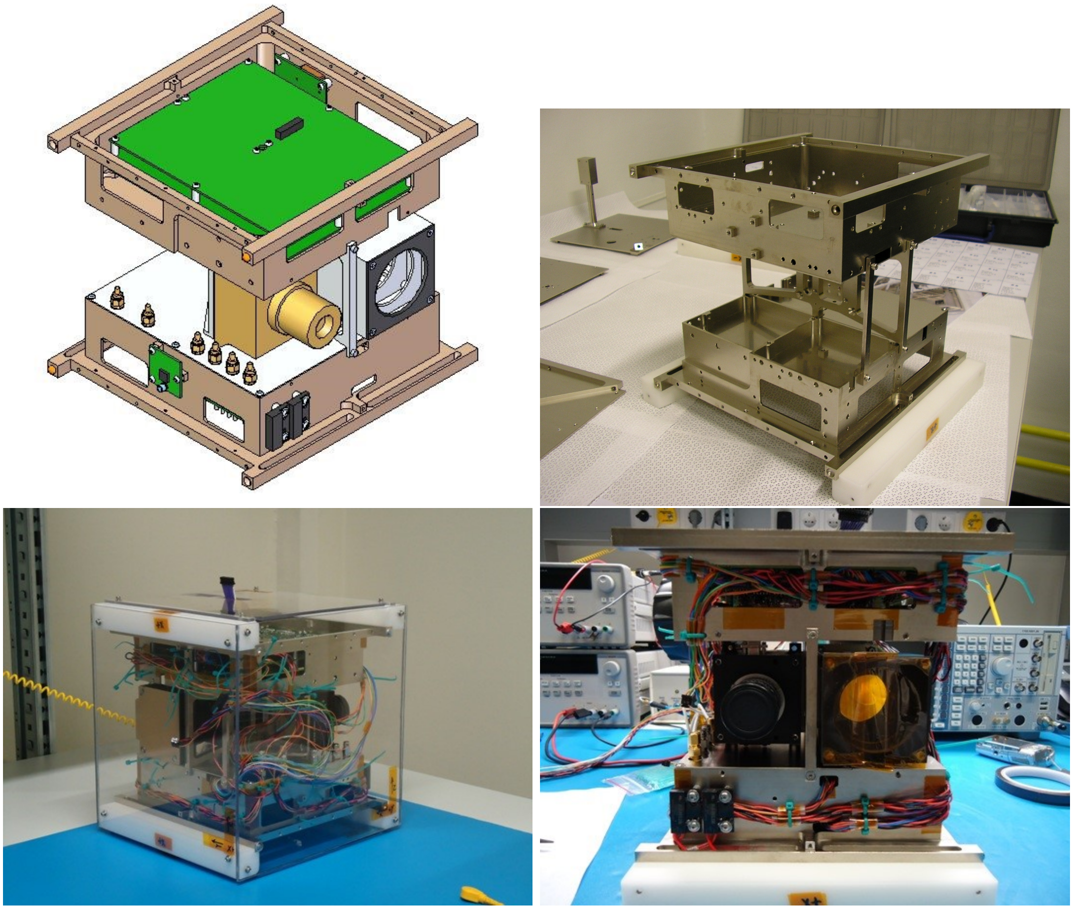


Figure 3.19: Inner core of BRITE-Austria: The dual-tray structure hosts most of the subsystems (CAD image courtesy: UTIAS/SFL).

Most of the core components are mounted to one tray or the other. During the design phase focus was laid on the efficient placement of the components inside the tray, to maximise the volume available for the payload and, in addition, to facilitate optimal component grouping to simplify wiring and assembly.

The pictures in Figure 3.20 show the fully integrated -Z tray. This tray hosts the three reaction wheels and two batteries including BCDRs on the inside. On the bottom side of the tray between the cross braces, the UHF receiver and S-band transmitter were mounted.

Two sun sensors are mounted on the opposing Y-faces of the trays. In addition, separation switches, which are used to turn OFF the satellite inside its deployment housing, are mounted on one of the X-faces.

The fully integrated +Z tray is depicted in the Figure 3.21. This tray houses the power board and all OBCs. To allow connecting the wiring harness with each of the dedicated OBCs, cutouts on the side of the trays are provided.

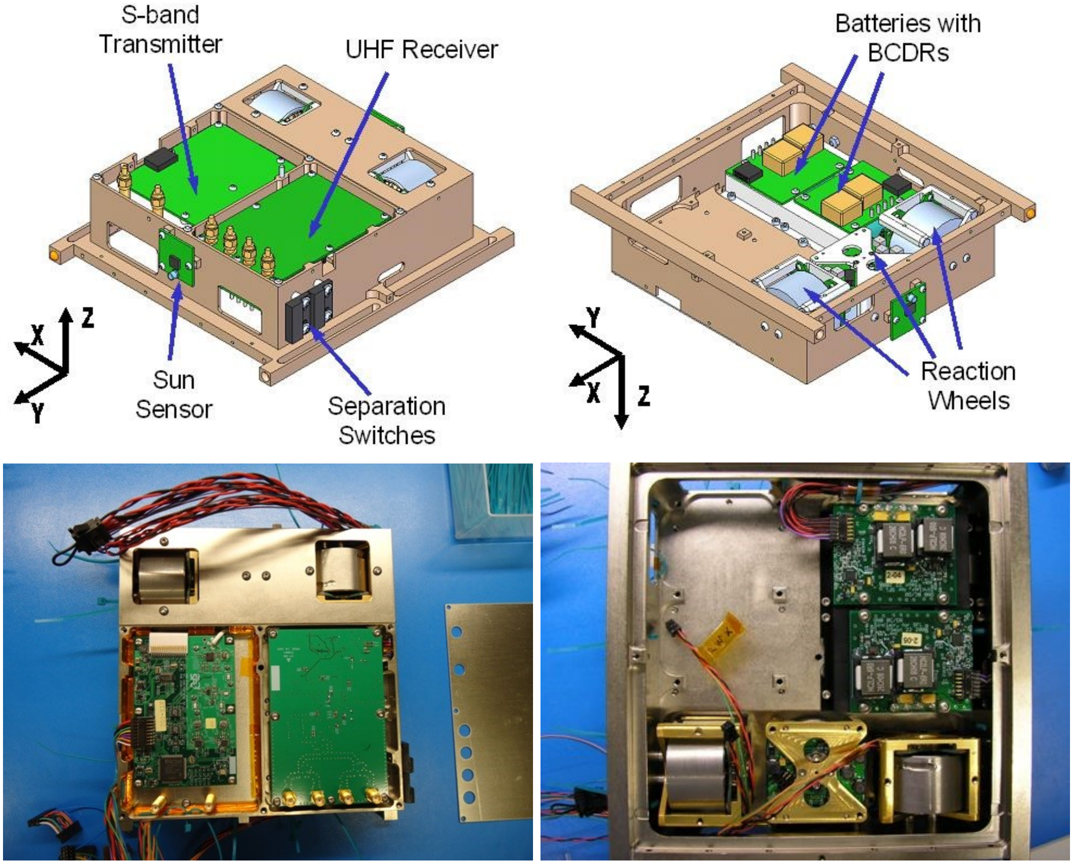


Figure 3.20: Fully integrated -Z tray: The -Z tray houses the receiver and transmitter unit, the batteries and BCDRs, as well as the three reaction wheels (CAD image courtesy: UTIAS/SFL).

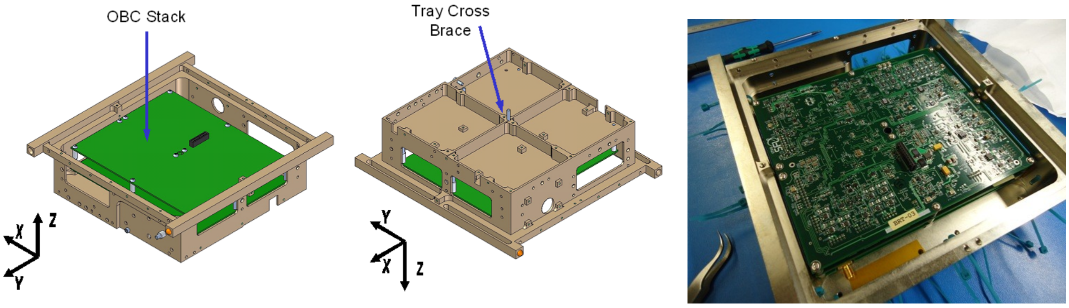


Figure 3.21: Fully integrated +Z tray: The +Z tray houses all OBCs and the power board (CAD image courtesy: UTIAS/SFL).

As mentioned before, due to the dual tray structure of the GNB, a volume between the trays is available to host the mission payload, in case of BRITE-Austria the scientific instrument and the startracker.

It is necessary to align the instrument and the startracker as good as possible. It was decided to mount both units on the same support structure, to ensure alignment also in case of thermal stress.

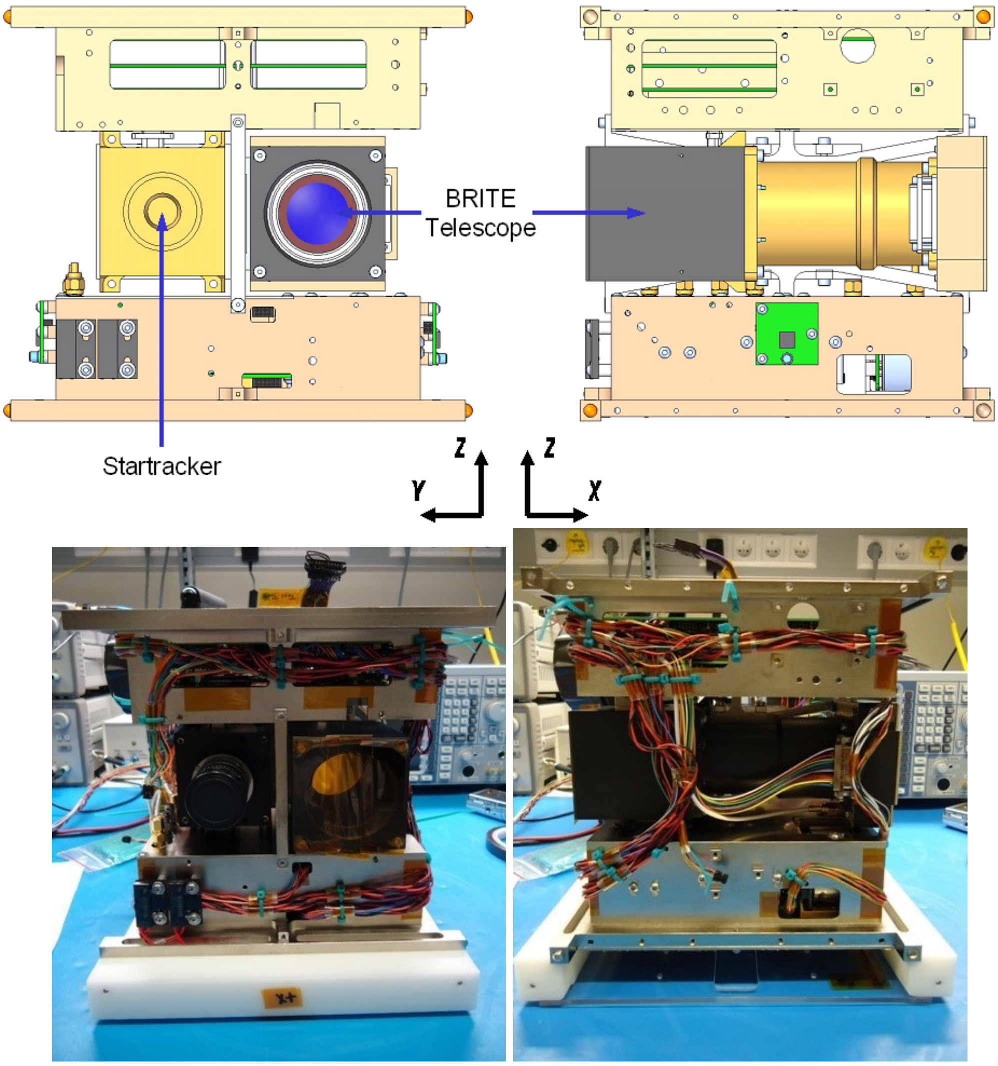


Figure 3.22: Payload volume: The payload volume on BRITE-Austria is occupied by the startracker and scientific payload (CAD image courtesy: UTIAS/SFL).

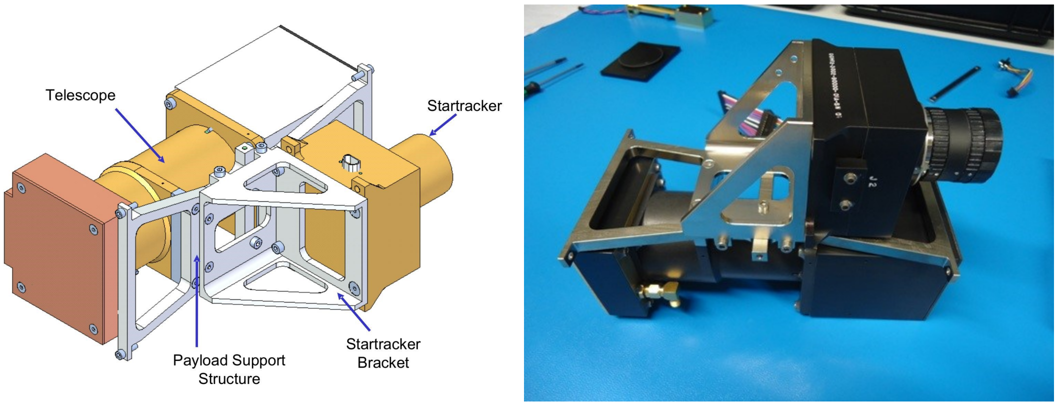


Figure 3.23: Payload and startracker: Both units are mounted on the same support structure (CAD image courtesy: UTIAS/SFL).

In addition, the individual panels were prepared by installing the temperature sensors. If applicable, the magnetorquers and sun sensors were installed, and the patch antennas connected.

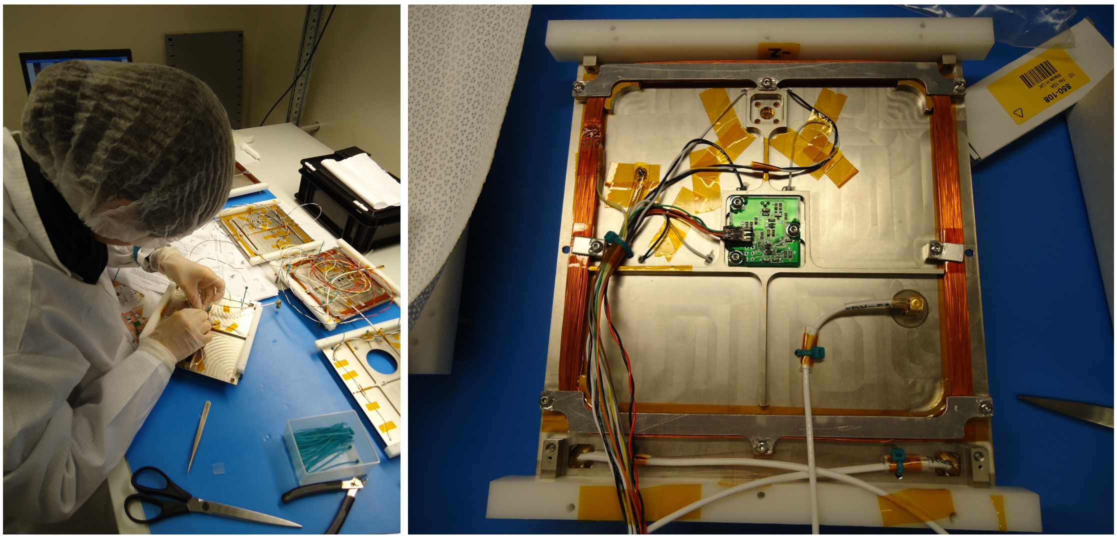


Figure 3.24: Panel finalisation: The temperature sensors were installed on the inside of the panels, and if applicable, the magnetorquers and sun sensors.

After each major step of the assembly procedure, functional tests of the subsystems involved were carried out. The results were documented in a test matrix and pictures were taken throughout the assembly process. This approach ensured that problems could be identified early and hence could be handled in an efficient manner, without unnecessary assembly/disassembly steps or additional connector cycles.

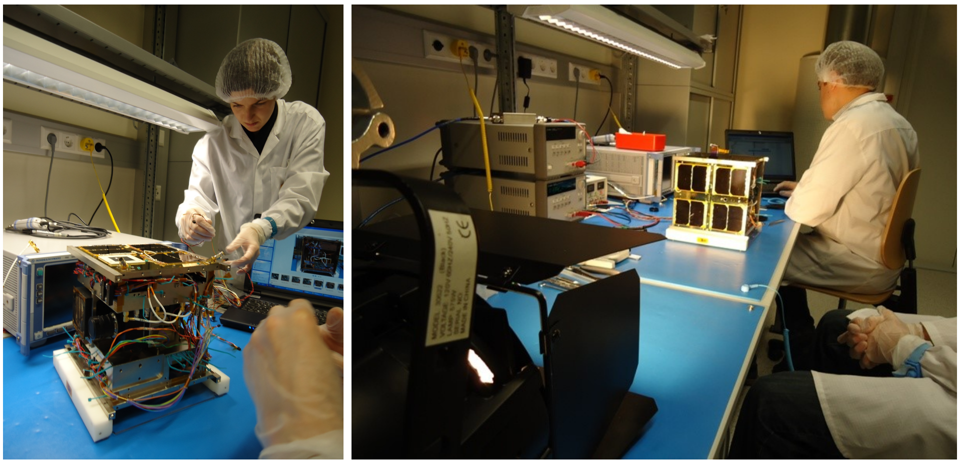


Figure 3.25: Functional testing during assembly: After each major step in the assembly a functional check was performed (left); The solar cell generation was verified by illuminating the cells with a spotlight (right).

The structure has been designed such that all structural components are at the same electrical potential. The structure defines the ground on the spacecraft. During the assembly, checks for proper grounding were introduced [30]. The resistance of all components, which should be electrically connected to each other, were checked by the use of digital multimeters.

Especially the resistance between the following units were measured:

- Support structure and trays
- +Z tray and -Z tray
- Panels and trays
- Radio covers and trays
- Antenna connectors to panels
- Solar cell coupons to panels

In case insufficient grounding occurred, a respective conductive epoxy was applied. All grounding checks have been performed successfully during assembly. Furthermore, after each environmental test, in the context of the long form functional test a magnetorquer check was performed in order to avoid possible shorts.

In addition, during the assembly all screws and connectors were secured by the application of an RTV, to ensure they do not get loose during vibration testing and launch.

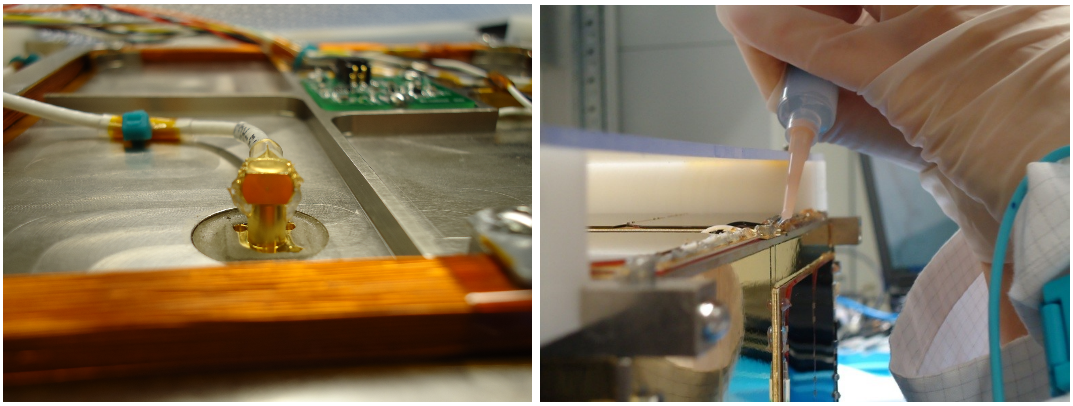


Figure 3.26: Application of epoxies and RTVs: Conductive epoxy was applied to ensure proper grounding between the elements (here: antenna connector and panel) (left); All connectors and screws on the satellite were secured with two points of RTV (right).

The following pictures give some impressions during the assembly of BRITE-Austria.

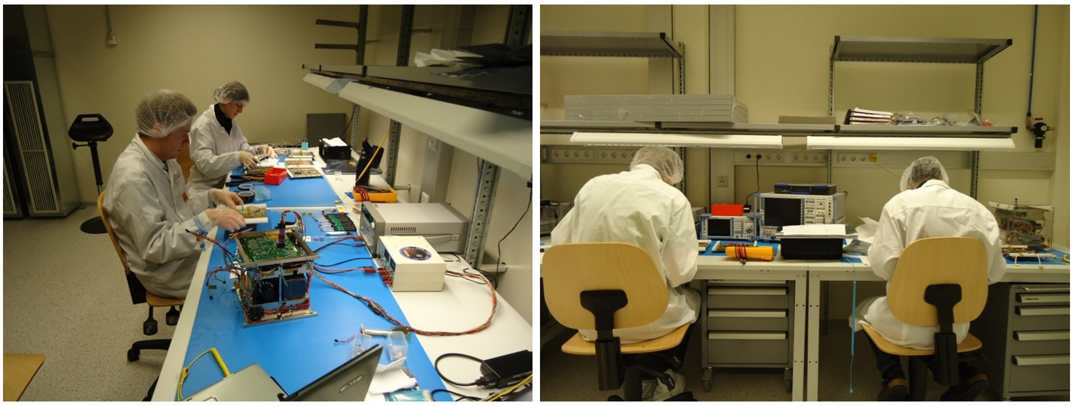


Figure 3.27: Cleanroom area for flight assembly: The flight assembly of the spacecraft was performed in a cleanroom environment.

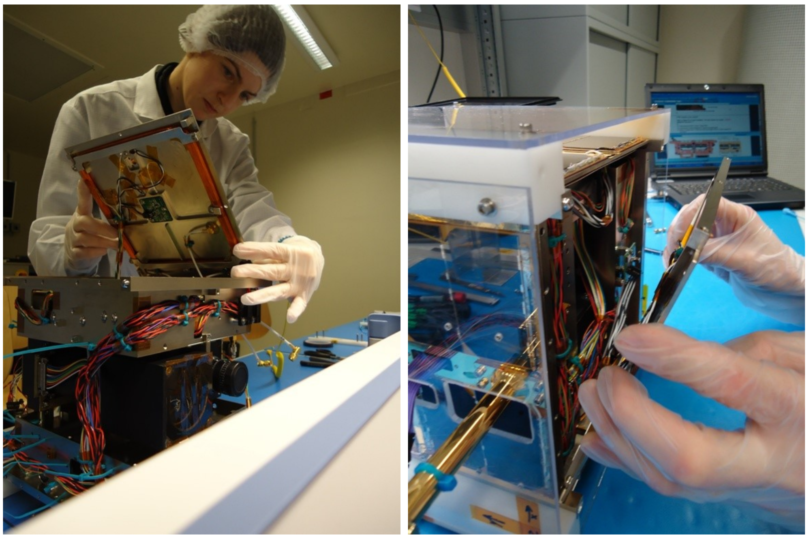


Figure 3.28: Final integration of panels: The individual panels were connected to the dual-tray structure.

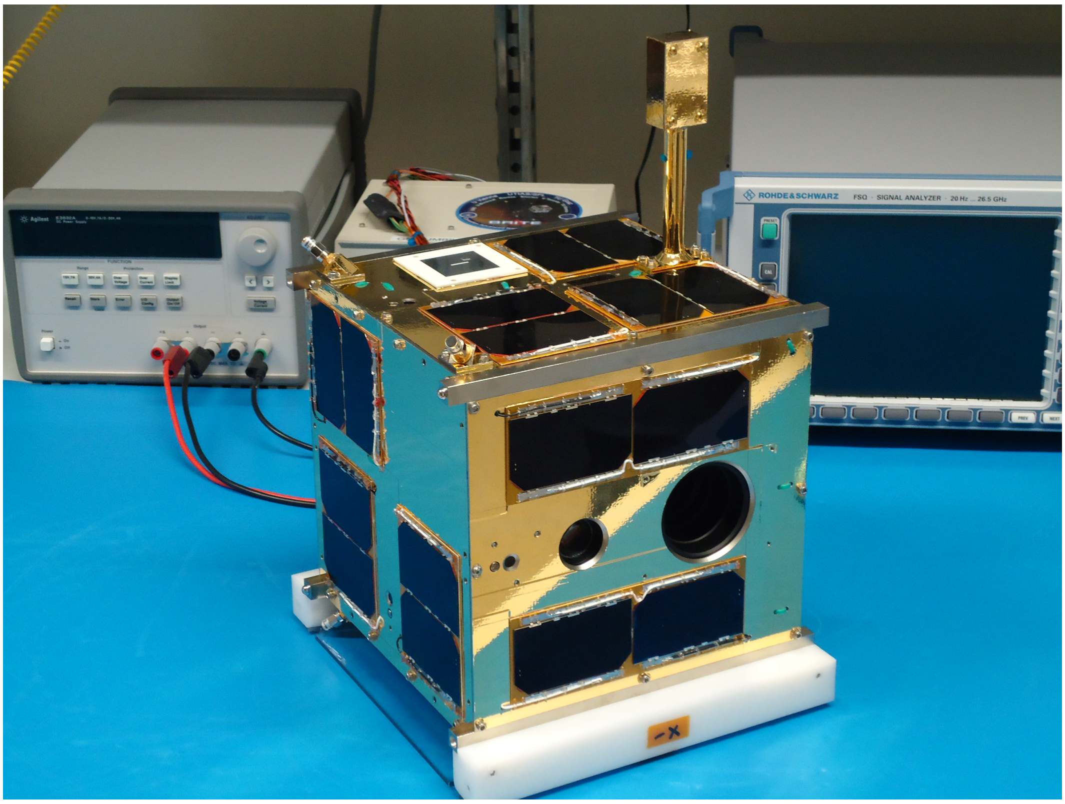


Figure 3.29: Assembled BRITE-Austria: After 10 days of assembly and a final functional check, the BRITE-Austria satellite was ready for environmental testing.

3.6 System Level Testing

To achieve its flight readiness, the spacecraft had to be fully functionally tested under specific environmental conditions. In addition, a characterisation of the ADCS subsystem on unit and system-level was performed. Conclusively, to identify early part failures, a 1000 hour burn-in was performed on all units [28] [29].

3.6.1 Functional Testing

During the AIT phase, functional testing was performed at many points:

- During and after assembly
- Before, during and after vibration testing
- Before, during and after thermal vacuum testing
- After the spacecraft was transferred from one facility/institute to another
- After the spacecraft was loaded into the deployer
- After any non-normal event of the spacecraft

There were two level of functional tests:

- Long form functional test (LFFT) - verifies all hardware and software on the spacecraft and should ensure nominal functionality. This test is modular and represents a variety of functionalities, therefore also subsets of the tests can be executed if necessary during the spacecraft's lifecycle. In addition, this test has a high degree of automation.
- Short form functional test (SFFT)- verifies the core functionality and the satellites health. This test represents only a subset of tests, which can be set up and run in short time, with immediate review of results.

3.6.2 Vibration Testing

Vibration testing should be performed to the acceptance levels of the selected launch vehicle. In case of BRITE-Austria, the levels for the PSLV rocket were taken [31].

The test was performed on the flight configuration, meaning the satellite was secured in its XPOD. In addition, no GSE or Remove Before Flight (RBF) items (e.g. lens caps or umbilical connector) were attached.

The tests were carried out at the Center for Quality Engineering in Munich, Germany, and under supervision of S. Mauthe (UTIAS/SFL). The satellite was loaded into the XPOD in Graz and packed into its Pelican case (which is also used for the final transfer to the launch site) for further transport to Munich.

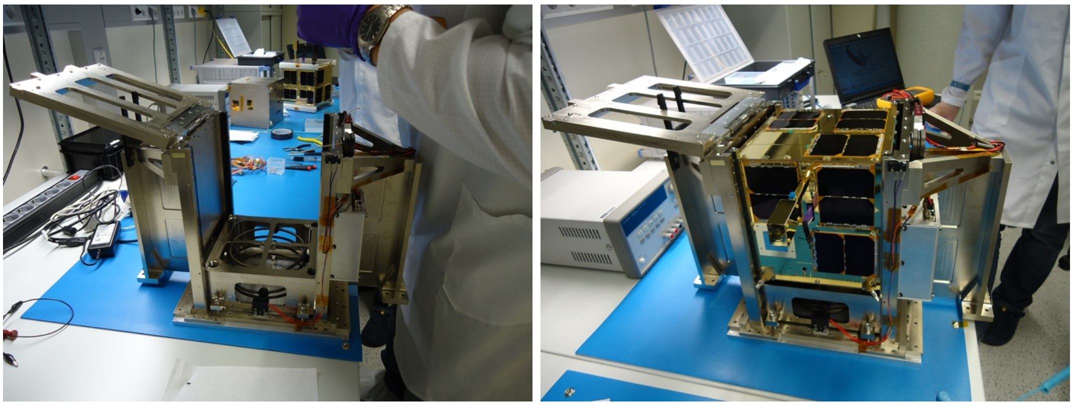


Figure 3.30: Loading of XPOD: As BRITE-Austria was vibration tested in its flight configuration, the satellite was loaded into its deployment housing.

After the transport a full functional test was performed. The flight configuration was then mounted on the shaker with a wooden adapter plate. Five accelerometer were attached to the DUT: on the control plate of the shaker, on the adapter plate, and on each axis of the deployment housing [31].

Figure 3.31: Vibration testing: To test a representative flight configuration, the UHF antennas were attached and the test port cover installed (left). In the meantime, the test profile was prepared in the room nearby (right).

The test profile consisted of a sine burst test, a sine test and a random vibration test, with resonance searches between them. Given the acceptance levels of the PSLV, the following tests were performed:

Vibration (sinusoidal)				
Test	**Acceleration/ Amplitude**	**Frequency Range**	**Sweep Rate**	**Duration**
Resonance Search	0.25 g	10 - 2000 Hz	4 Oct/min	1 sweep before and after each test (sine burst, sine sweep, random vibration)
Sine Burst	7.7 g	14.9 - 15.1 Hz	1 Oct/min	1 sec/axis
Sine Sweep	8mm - 3 g	5 - 8 Hz / 8 - 100	4 Oct/min	1.25 min/axis

Vibration (broad-band random)				
Test	**Frequency**	**Power Spectral Density**	**Frequency Range**	**Duration**
Random	20	0.010 g^2/Hz	20 - 2000 Hz	60 sec
	110	0.010 g^2/Hz		
	250	0.015 g^2/Hz		
	1000	0.015 g^2/Hz		
	2000	0.004 g^2/Hz		
	total gRMS	4.686 g		

Table 3.2: Vibration profile: During vibration testing of BRITE-Austria several tests were performed on the DuT in each axis [31].

The test concluded with a visual inspection and an SFFT. The profile was repeated in all three axes and documented. At the end of the vibration testing a deployment test was performed and both units (satellite and XPOD) were inspected. Due to time constraints, the LFFT was performed after arrival in Graz.

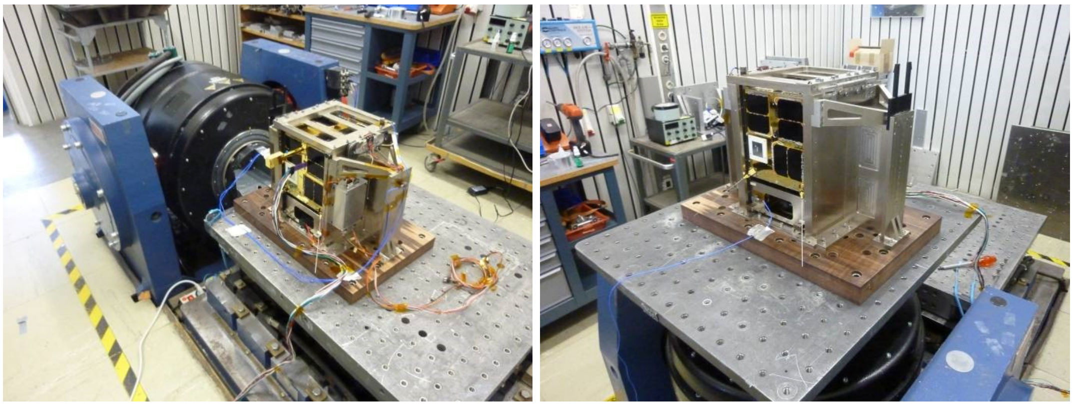
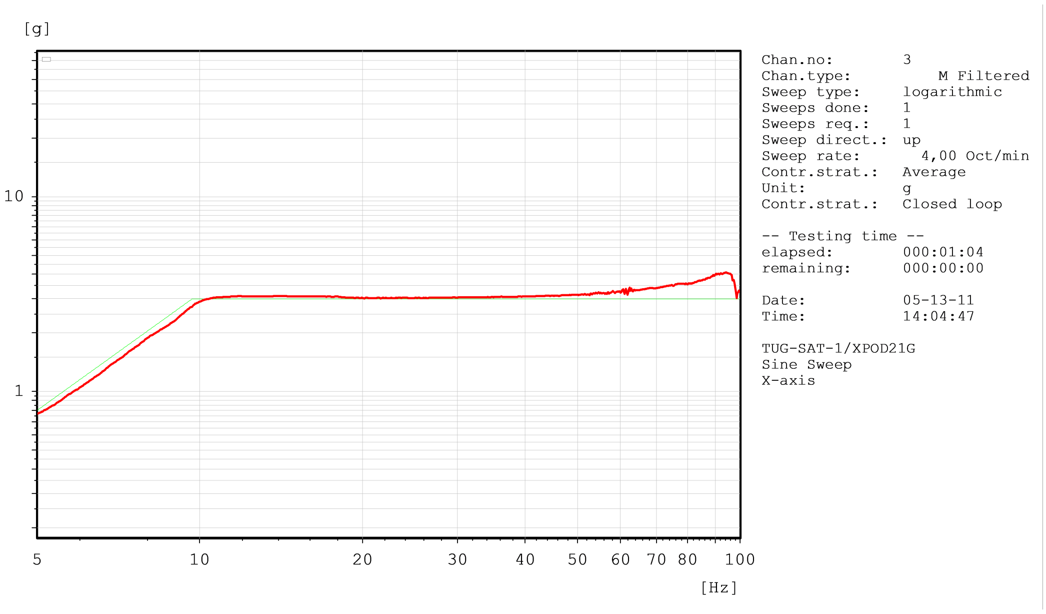


Figure 3.32: Vibration testing of BRITE-Austria: The flight configuration was tested in all three axes.

The readouts of the sensors during the respective tests were documented. As an example, the following diagrams give the results during the testing in the X-axis of the sensor, which was placed on the front panel of the XPOD.



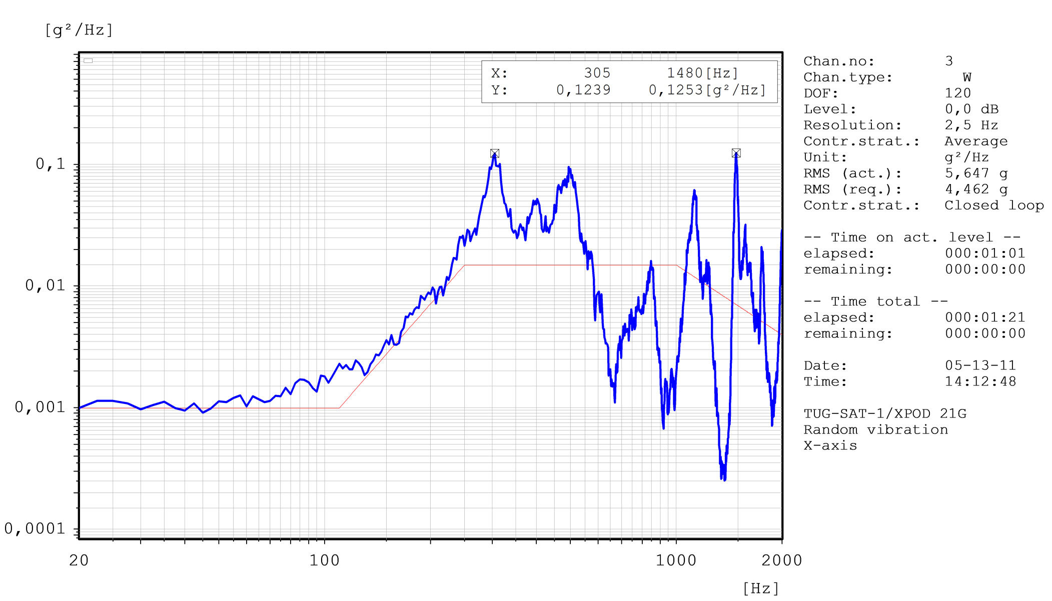
```
Chan.no:        3
Chan.type:           M Filtered
Sweep type:     logarithmic
Sweeps done:    1
Sweeps req.:    1
Sweep direct.:  up
Sweep rate:       4,00 Oct/min
Contr.strat.:   Average
Unit:           g
Contr.strat.:   Closed loop

-- Testing time --
elapsed:        000:01:04
remaining:      000:00:00

Date:           05-13-11
Time:           14:04:47

TUG-SAT-1/XPOD21G
Sine Sweep
X-axis
```

Figure 3.33: Sinusoidal Sweep in the X-axis: This diagram depicts the readout from the sensor, which was mounted on the smaller front of the XPOD during the sine sweep from 20 to 2000 Hz [31].



```
X:          305       1480[Hz]
Y:       0,1239     0,1253[g²/Hz]
```

```
Chan.no:        3
Chan.type:         W
DOF:            120
Level:          0,0 dB
Resolution:     2,5 Hz
Contr.strat.:   Average
Unit:           g²/Hz
RMS (act.):     5,647 g
RMS (req.):     4,462 g
Contr.strat.:   Closed loop

-- Time on act. level --
elapsed:        000:01:01
remaining:      000:00:00

-- Time total --
elapsed:        000:01:21
remaining:      000:00:00

Date:           05-13-11
Time:           14:12:48

TUG-SAT-1/XPOD 21G
Random vibration
X-axis
```

Figure 3.34: Random vibration testing in the X-axis: This diagram depicts the readout from the sensor, which was mounted on the XPOD front during random vibration. The peaks at 305 and 1480 Hz indicate the resonance frequencies [31].

As no deviations in the lines of the resonance search in all three axes could be seen, no change in structural behaviour was sensed, which would have indicated a damage. Therefore, the vibration test was considered successful.

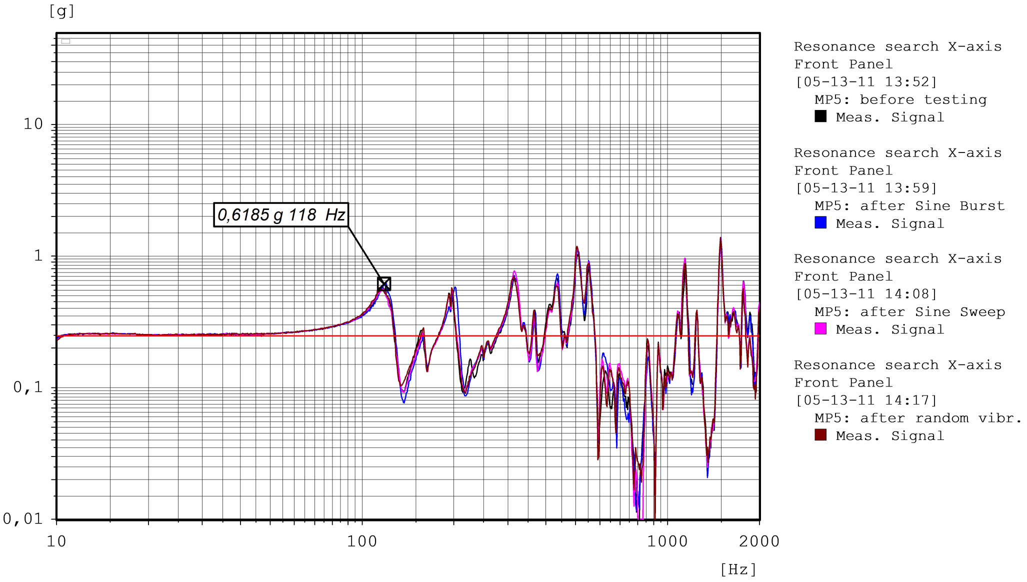


Figure 3.35: Resonance search in the X-axis: This diagram depicts the readout from the sensor, which was mounted on the XPOD door. Significant deviations in the lines, which were measured before and after the respective tests, would indicate a change in structural behaviour and hence a damage, which fortunately was not the case [31].

3.6.3 Thermal Vacuum Testing

The thermal vacuum test serves two main purposes [32]:

1. verification of spacecraft's performance within representative environmental conditions. This is the first time that the satellite is exposed to vacuum and will be operated in representative orbital temperature ranges.
2. verification of the thermal model.

As no TVAC facility was available at TUGraz, the tests were performed at the Centrum Badan Kosmicznych PAN (Space Research Centre SRC) in Warsaw, Poland. This test facility was planned to be used for the TVAC tests of the 3^{rd} BRITE satellite LEM in a later step [33]. During the testing of BRITE-Austria, the Polish colleagues gained insight in the preparation and execution of the test, and the knowledge could be directly transferred to their AIT activities.

After a functional test of the spacecraft, the satellite was mounted on a mechanical support structure and temperature sensors were attached on each face and on the magnetometer boom.

Figure 3.36: Thermal vacuum chamber and control units: The thermal vacuum chamber, the control rack and the control unit for the heater elements are shown.

Figure 3.37: Pre-TVAC testing: Before starting with the TVAC testing, the spacecraft had to be functionally tested and the ground support equipment set up and configured.

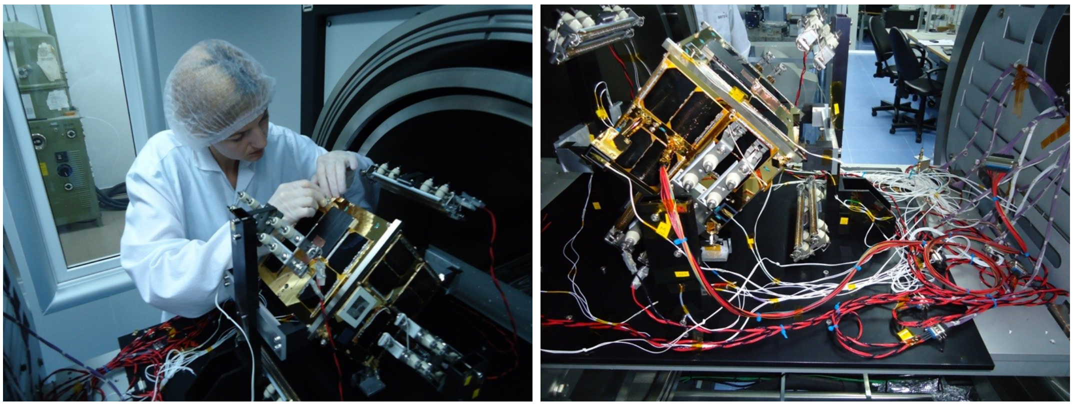


Figure 3.38: Preparation of the TVAC setup: The temperature sensors were attached to the spacecraft (left). The final setup including wiring of umbilical connection, lamp control and antenna supply is shown (right).

While the chamber was cooled down below -50° C, the heating of the satellite was accomplished with the help of infrared heater elements.

The test procedure comprised a temperature cycle (+25° C -▷ +50° C -▷ -15° C -▷ +25° C), followed by a representative orbital scenario (83 minutes in sunlight / 17 minutes in eclipse). Given the requirements and specifications of the facility, the thermal vacuum profile (Figure 3.40) was prepared. The detailed steps were the following:

1. PreTVAC testing including LFFT
2. Integration to chamber and pre-pumpdown SFFT
3. Pumpdown incl. SFFT
4. Cold Wall transition and setup of IR-lamps
5. +25° C testing incl. LFFT
6. Transition to 50° C
7. +50° C testing incl. LFFT
8. Transition to -15° C
9. -15° C testing incl. LFFT
10. Transition to +25° C
11. +25° C testing incl. SFFT
12. Orbital test sequence setup
13. Orbits
14. Transition to +25° C
15. +25° C testing incl. LFFT
16. Return from Cold Wall incl. SFFT
17. Repressurization incl. SFFT
18. PostTVAC testing incl. LFFT
19. PostTVAC testing after transport to Graz incl. LFFT

As preparation for the test, a detailed TVAC checklist was formulated in advance, indicating the commands and tasks to be executed at the respective points during the test. In addition, a detailed packing list (indicating the MGSE/EGSE, ground station and other test equipment) was prepared.

Before starting the test, a detailed documentation of the harness and pin out was made. Besides, in consultation with the Polish colleagues, emergency procedures for various failure cases (e.g. loss of power at test facility, temperature rise in cold wall, failure of heating system or loss of vacuum) were defined and a contact list was established.

Figure 3.39: Thermal vacuum testing: The thermal vacuum test lasted 6 days non-stop and was one of the most intense tests.

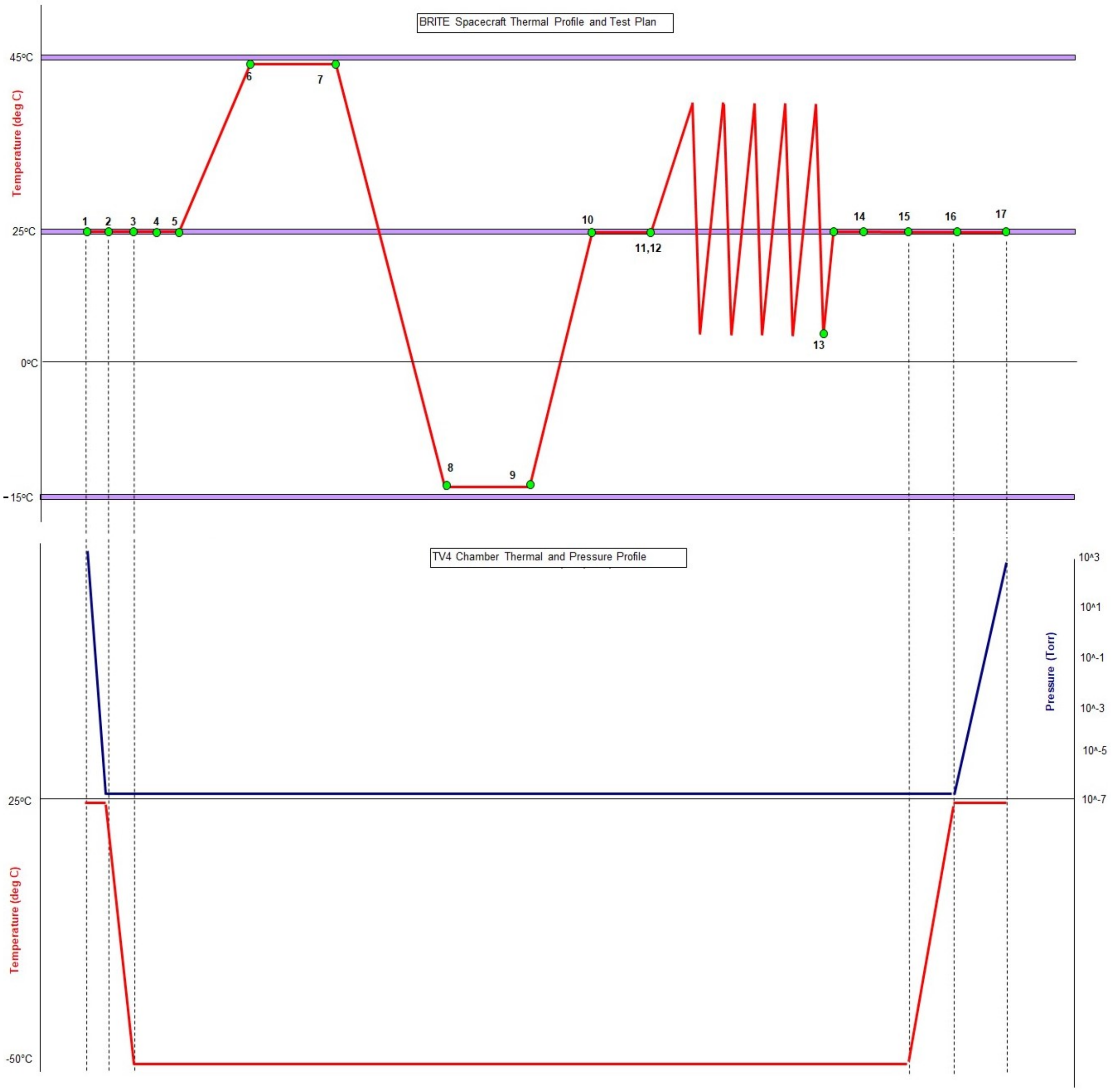


Figure 3.40: Thermal vacuum testing profile: Given the requirements and the specifications of the TVAC facility, a test profile was defined, indicating the major transitions and phases with numbers. The upper profile states the temperatures for the BRITE-Austria spacecraft, whereas the lower profile indicates the pressure (blue line) and temperature values (red line) for the TVAC chamber.

All the steps performed and the functional tests were documented in the TVAC checklist. In addition, the temperature and vacuum data was recorded. The following picture shows an excerpt of the filled out TVAC checklist, during the first orbit of the orbital scenario the checkout of the HKC and ADCC was performed.

During the conduction of the test, no degradation or problem of any subsystem at the various temperature levels were detected and the nominal operation was verified at the predefined temperatures in an vacuum environment.

	T/VAC Operators Procedure Checklist		
☑			
	Actual Start	**Task**	**notes**
	Orbit 1 - HKC Commissioning		
☑	07:27:00	Set PS, lamps to SUN settings	
☑		Confirm satellite telemetry is as expected	
☑	07:30:00	Connect to Satellite using UHF uplink, S-band Downlink	
☑		Firecode HKC On and TxSelect S-Band	0,142 mA
☑		Take snapshot and confirm telemetry	
☑		Switch to BCDR0	
☑		Take snapshot and confirm telemetry	
☑	07:35:00	Run HKC LFFT	switch to testport
☑	07:36:00	Load CANOE from Flash on HKC	Load HKC-CANOE-Load.txt from the main command dialog in GNBControl
☑		Take snapshot and confirm telemetry	HKC snapshot: 073246
☑		Clock Sync	20110607 07:37:18
☑		Take snapshot and confirm telemetry	
☑		Pass End	
☐		Connect to Satellite using Test Port for uplink and downlink	
☐		Poll Telemetry through SNAPSHOT - Confirm telemetry is as expected	
☐		Set PS, lamps to ECLIPSE settings	
	Orbit 2 - ADCC Commissioning		**combined with Orbit 1**
☐		Set PS, lamps to SUN settings	
☑		Confirm satellite telemetry is as expected	
☑		Connect to Satellite using UHF uplink, S-band Downlink	
☑		Snapshot Get All - Verify Telemetry	
☑		Download WOD	under GMTP HKC: Connect --> Flash Info --> New WOD log --> Flash Info --> select File and "File Read" WOD: 157fe930
☑	07:41:00	Firecode ADCC On	
☑		Take snapshot and confirm telemetry	snapshot: 074114 problem with ADCC snapshot via radios
☑		Disable HKC-to-ADCC Communication (TxSelect HKC to Test Port)	
☑		TxSelect ADCC to S-Band	
☑	07:46:00	Run ADCC LFFT	switch to testport
☑		Load CANOE on ADCC	load ADCC-CANOE.txt --> failure with txselect --> via write upload of srec & init
☑		Enable HKC-to-ADCC Communication	From HKC, TxSelect to ADCC_PUNT_ADDR, Data: 22
☑		Take snapshot and confirm telemetry	
☑	08:22:00	Pass End	
☑		Connect to Satellite using Test Port for uplink and downlink	
☑		Poll Telemetry through SNAPSHOT - Confirm telemetry is as expected	
☑		Archive WOD Download for later inspection	
☑	08:50:00	Set PS, lamps to ECLIPSE settings	snapshot: 082254

Figure 3.41: Thermal vacuum testing checklist: The task to be performed including additional information, like timestamps and log designators are compiled in the TVAC checklist (excerpt shown), which was prepared in advance in consultation with UTIAS/SFL.

3.6.4 Electromagnetic Compatibility Testing

Electromagnetic compatibility (EMC) testing was performed to ensure [34]:

1. that emissions from the satellite meet the launcher specifications and
2. that the spacecraft does not produce electromagnetic interference (EMI) itself, e.g. due to the operation of attitude actuators, which might interfere with its own operation.

Concerning point 1, as the satellite is launched in an OFF configuration, no testing requirements were imposed by the selected PSLV launcher and emission testing was omitted.

The EMC test was mainly split into two subtests. At first an LFFT at system-level of the assembled satellite was performed, to verify the proper functionality of the EMC sensitive units. Units considered at high risk for EMC problems were the UHF receiver, the S-band transmitter and the analogue part of the payload's signal chain. Intense functional testing of the radios was also conducted. In addition, a characterisation of the noise present in the CCD electronics was performed with the fully integrated spacecraft.

Overall, no disturbances were detected.

The second self-compatibility test was a UHF receiver sensitivity test. The test was performed in a clean small anechoic chamber, located at the Institute of Electronics at TUGraz. Shortly after this test, a new anechoic chamber for high frequency antenna measurements was established at the Institute of Microwave and Photonic Engineering at TUGraz, and the test was repeated in this chamber. The ground station equipment was set up next to the chamber to keep the cable lengths at a minimum.

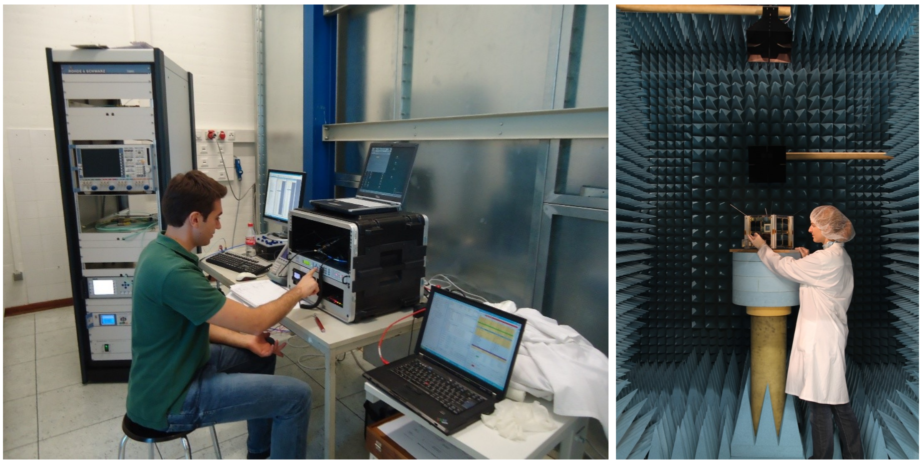


Figure 3.42: Electromagnetic compatibility testing: The electromagnetic compatibility testing was performed inside the anechoic chamber at the Institute of Microwave and Photonic Engineering, TU Graz.

Several operational modes were investigated and the respective performance of the UHF receiver was tested.

- *Safe-hold mode*, where the attitude subsystem is inactive
- *Passive determination mode*, where only the sensors are turned on
- *B-dot/rate dumping mode*, where the magnetorquers are used to detumble the satellite and minimize the body rates
- Payload operations during *b-dot*

The test was performed by sending 1000 pings to the spacecraft while the operators slowly ramped down the input signal level [34]. The following plot indicates the Received Signal Strength Indicator (RSSI) versus packet failure rate at the various operational modes.

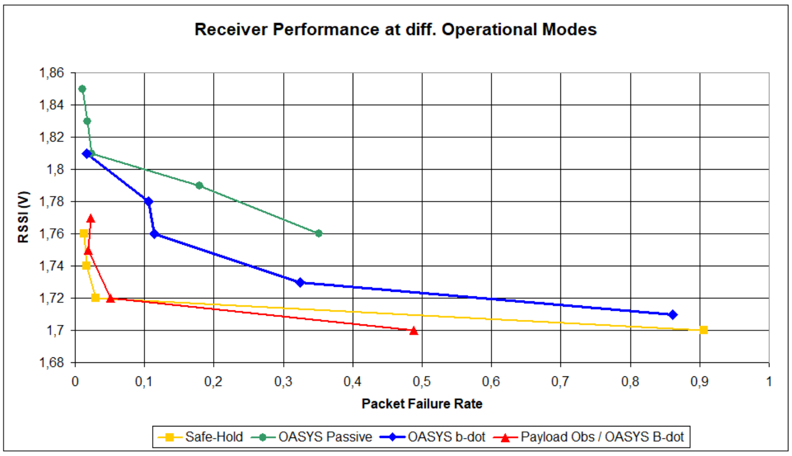


Figure 3.43: RSSI measurement: The RSSI values versus Packet Failure Rates at different operational modes are depicted [34].

3.6.5 Open-Field Testing

During the open-field testing, the satellite spent its only time outside a cleanroom environment. Therefore, several precautions were taken to ensure the cleanliness, especially for the optical instrument. A transparent lens cap was installed on the instrument aperture. The spacecraft was placed inside a plexiglass enclosure, the so-called lunch box, and sealed with Kapton tapes and RTV. A temporary sun shade was placed in front of the instrument aperture on the outside of the box, to avoid long exposure to UV radiation from the Sun. Although the temperature and humidity when entering and leaving the building was checked to ensure that no condensation on the satellite occurs, the box was equipped in addition with silica pads to avoid humidity. The only items exposed were the UHF monopole antennas, which needed to be recleaned after the test.

The satellite was mounted on a tripod at the observatory Lustbühel in Graz. The observatory is located at a 3 km distance of the IKS/TUGraz and hence the ground station.

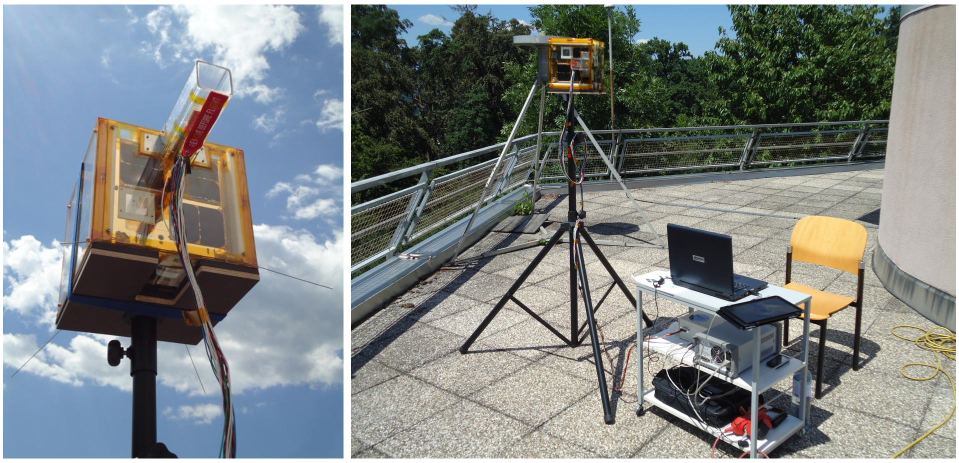


Figure 3.44: Open-field testing of BRITE-Austria/TUGSAT-1: An open-field test was performed at the observatory Lustbühel, Graz including observations of the scientific instrument during the night.

During this testing phase, several subtests were conducted [35]:

- **Solar panel testing**
  to verify that each coupon is delivering the expected amount of current when exposed to unclouded sunlight. An excerpt of the results and values of the individual solar coupons is given in the following table:

	Solar Coupon 1	**Solar Coupon 2**	**Solar Coupon 3**	**Solar Coupon 4**
+X panel	0.297 A	0.293 A	0.296 A	0.280 A
+Y panel	0.288 A	0.285 A	0.282 A	-
+Z panel	0.121 A	0.164 A	0.310 A	-
-X panel	0.269 A	0.260 A	-	-
-Y panel	0.287 A	0.291 A	0.302 A	-
-Z panel	0.245 A	0.310 A	0.269 A	-
Notes	Unequal distribution of sunlight on +Z panel due to magnetometer and its protective cap			

Table 3.3: Energy generated by solar coupons: The currents from the individual solar coupons (2 solar cells) were measured and verified against the requirements [35].

- **Sun sensor testing**
  to verify that the sun sensors function under real sunlight conditions at predefined incident angles. Up to this point the sun sensors, as well as the solar cells were only subjected to simulated sun sources, like spotlights, which do not have the same spectrum and intensity as real sunlight. During this test, the sun sensor profiles were logged, analysed and their correct behaviour was verified.

- **Communication testing**
  to verify the wireless communication with the groundstation. A full duplex connection with the satellite and groundstation was established, and the link was evaluated.

  To ensure that the UHF receiver on the spacecraft is not exposed to dangerously high signal levels, the attenuation levels at the UHF groundstation were adapted and tests with a spare UHF receiver unit were performed beforehand. In addition, the power consumption of the receiver and transmitter units were verified.

  The expected signal strength received and the power consumption of lower than 120 mW, as defined in the systems requirements, was verified.

- **Startracker testing**
  to verify that the startracker is capable of generating quaternions when looking at real stars at night. Due to the location of the observatory, light pollution of the city of Graz is low.

  The quaternions delivered by the startracker corresponded to the centre coordinates of the captured stars, therefore the startracker functionality was verified.

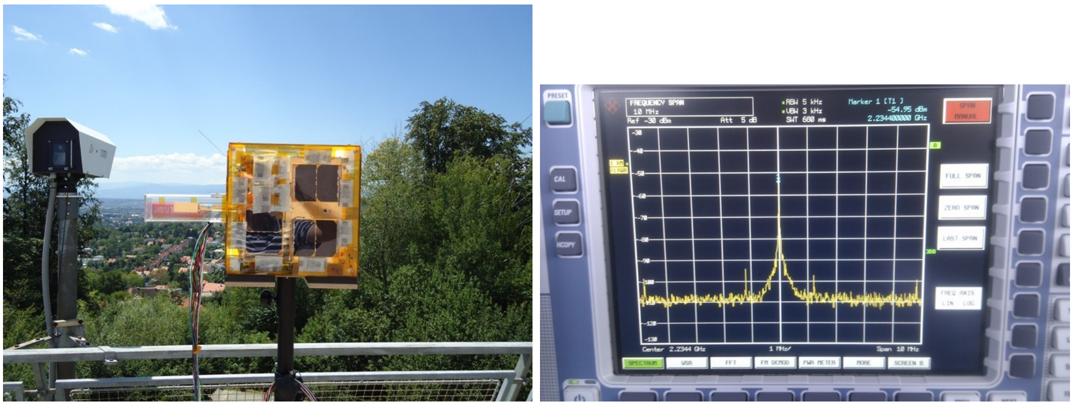


Figure 3.45: Communication link testing during open-field test campaign: The full communication chain between the BRITE-Austria satellite and the ground station was tested.

- **Instrument testing**
  to verify that the instrument is adequately focused. In addition, the point spread functions (PSF) of actual stars were recorded and their correspondence to the synthetic stars, which were used to focus the instrument in the lab, was checked.

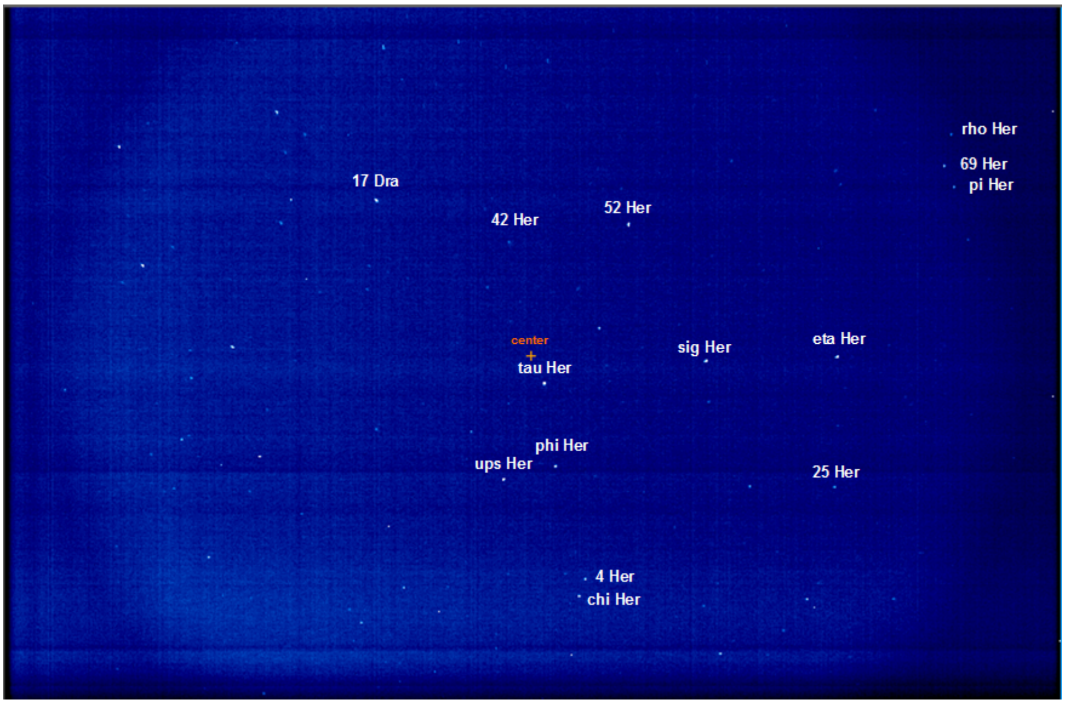


Figure 3.46: Full frame image gathered by BRITE-Austria during the open-field testing: A 3 second exposure was taken by BRITE-Austria during the open-field testing campaign. The stars were identified post-testing and their PSFs analysed [35].

The PSFs as captured during the real-night exposure corresponded to the PSFs of the synthetic stars, hence the test was considered successful.

3.6.6 ADCS Testing

To characterise the ADCS subsystem, several tests have been performed on the integrated satellite [36]:

- on **unit-level**
    - polarity checks of magnetometer, sun sensors, startracker, magnetorquers, and reaction wheels
    - magnetometer distortion check
    - field-of-view and blind spot identification of sun sensors
    - reaction wheel spin-up/spin-down
- on **system-level**
    - centre of mass measurement
    - moments of inertia determination (performed by UTIAS/SFL on UniBRITE)
    - magnetic mapping
    - software stability and mode transitions
    - end-to-end analysis

3.6.6.1 Unit Specific Tests

The following ADCS tests have been performed on BRITE-Austria on unit-level:

- **Magnetometer polarity and distortion check**
  The goal of this test was to ensure, that the direction of the measured magnetic field by the magnetometer is properly mapped into the body frame of reference. The magnetometer measurements are used in the ADCS cycle for attitude estimation.

  The test was performed inside a Helmholtz coil, which provides a nearly uniform magnetic field. A calibrated magnetometer was placed near the BRITE-Austria magnetometer boom. Its measurements were compared to the magnetometer's raw telemetry and mapped conversion into the body frame of reference. This test showed that the polarity of the integrated magnetometer was correct.

  To test the impact of ferromagnetics on the magnetometer, the calibrated magnetometer was measuring the field while located next to the satellite (which was powered off). In a next step the satellite was removed, followed by an additional measurement with the calibrated magnetometer of the ambient field was taken. Only minimal distortion was seen and after further analyses was considered as negligible.

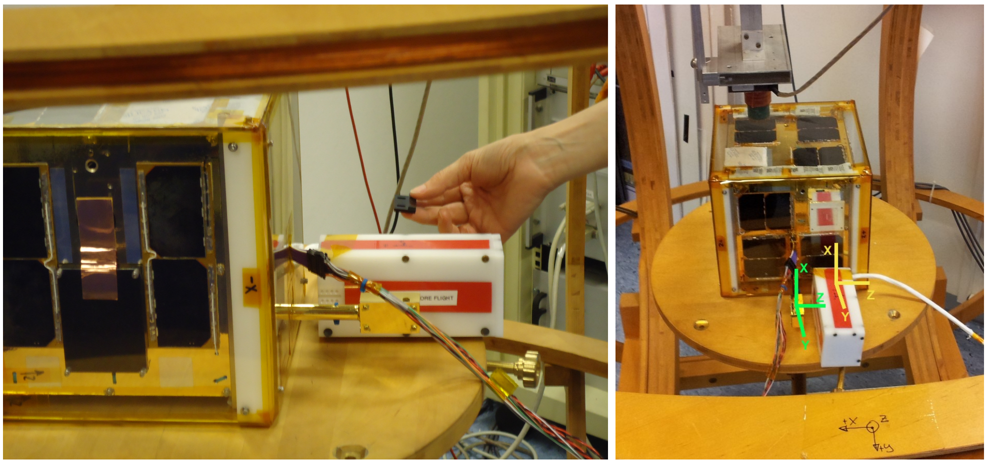


Figure 3.47: Magnetometer polarity and distortion checks: A calibrated magnetometer was placed next to the satellite inside a Helmholtz coil during the conduction of the test.

- **Sun sensor polarity and dead-bands**

  The goal of this test was to ensure, that the direction of the measured sun vector is properly mapped into the satellite's body frame. A halogen spotlight was used to illuminate the individual quadrants of each fine sun sensor. Given the telemetry and mapped conversion into the body frame of reference, it was verified, that the location of the light source was on the expected quadrant.

  A further test was conducted to ascertain the dead-bands in the Field of View (FOV) of the fine sun sensors. BRITE-Austria was therefore placed on a rate table, a halogen spotlight was placed nearby at predefined incident angles (0/30/60°). While the satellite was spun at a low rate, the fine sun sensor outputs were collected and analysed.

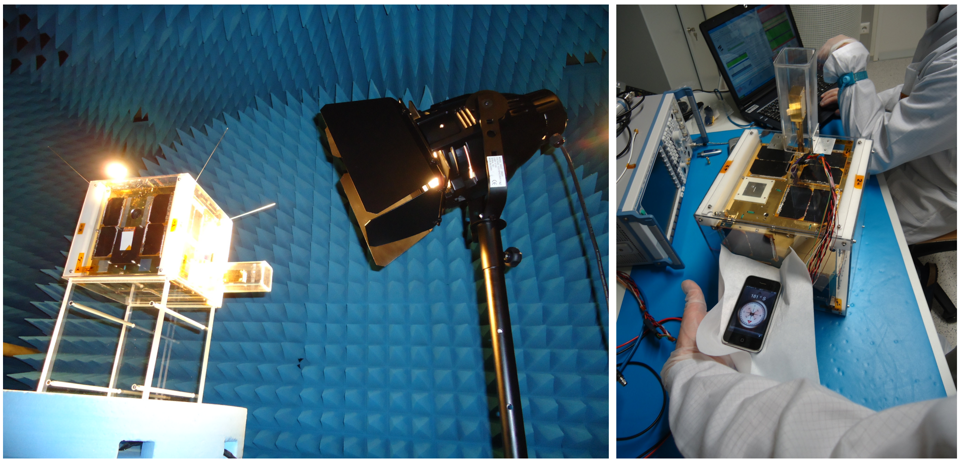


Figure 3.48: Sun sensor testing and magnetorquer polarity checks: The FOV of the sun sensors was determined while the satellite was illuminated and spinning on a rotating table (left). The polarity of the magnetorquers was verified by the use of a compass (right).

As example, some screenshots of the fine sun sensor readings are depicted in Figure 3.49. It can be seen, that the light intensity in one axis is changing while the satellite is spun on the rate table.

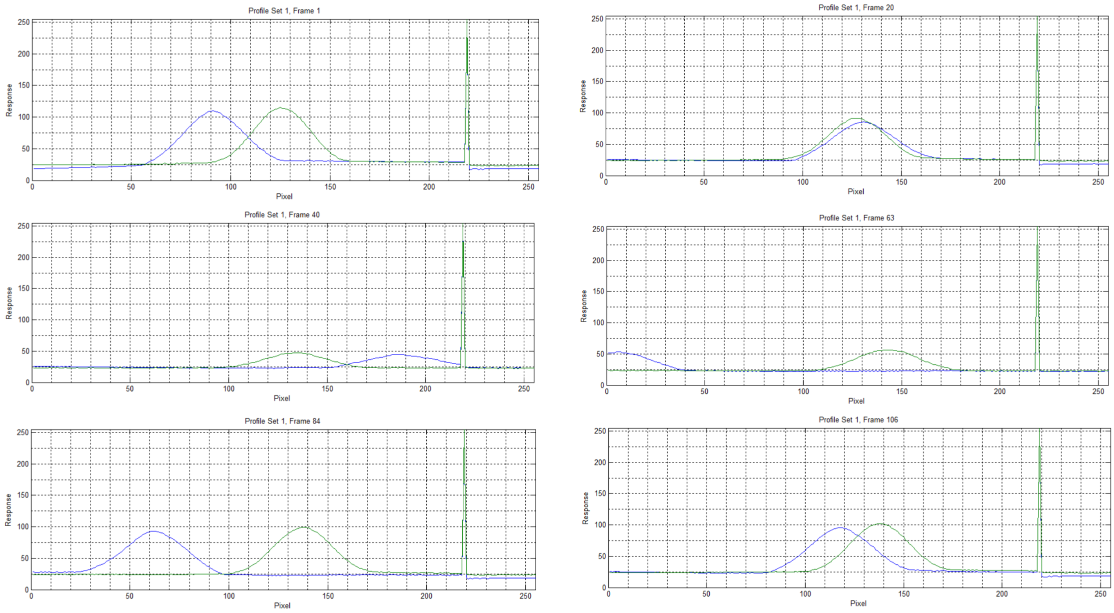


Figure 3.49: Fine sun sensor readouts: The fine sun sensor outputs were analysed, while BRITE-Austria was spun on a rate table and illuminated by a halogan lamp with predefined incident angles.

- **Magnetorquer polarity**

  The goal of this test was to check, whether the commanded dipoles (from the attitude control software) are implemented correctly. Various constant current values and positive directions were defined in the control structure for the magnetorquers. With the help of a compass, the correct sense of the magnetorquer's dipole was checked. One magnetorquer showed the opposite dipole sense, therefore the attitude software was updated [Table 3.4].

Magnetorquer	**Magnetic Direction**		
	Pre-Test	**+ Direction (1)**	**- Direction (0)**
+ X MTQ	North	In body axis	Towards sat centre
+ Y MTQ	North	In body axis	Towards sat centre
- Z MTQ	North	Towards sat centre	In body axis

Table 3.4: Magnetorquer polarity check: The polarities of the magnetorquers were checked and the attitude software updated [36].

- **Reaction wheel polarity**

  The goal of this test was to determine the direction of the wheel spin relative to the satellite's body frame. On the flatsat, the wheels were commanded with a specific torque and speed and their direction of rotation was observed. Once integrated in the satellite, direct observation is no longer possible. Their known orientation inside the satellite was then used to infer the polarity of the wheels.

- **Startracker polarity**
  This test was used to check the polarity of the startracker. The startracker was placed in front of a light source and a still-frame exposure was taken. The light source was pointed to different positions on the startracker and the comparison with the captured images determines the orientation and hence polarity of the startracker to the body frame of reference.

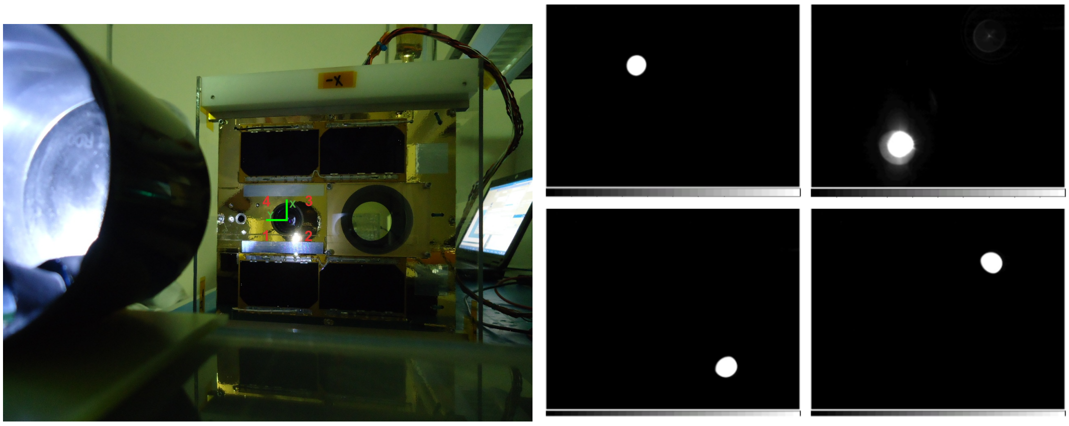


Figure 3.50: Startracker testing: A light source was placed in front of the startracker at different locations and the read-outs were captured.

The location of the quaternions was then used as input for the attitude control software thread.

3.6.6.2 System Level Tests

Concerning the ADCS tests on system-level, the following tests were conducted:

- **Centre of mass**
  To determine the location of the spacecraft's centre of mass relative to the body frame of reference, a test has been performed. Although an estimate of the centre of mass was already predicted during the solid-model analysis, the location and implementation of the wiring harness might impact the actual centre. The test was performed in all three axes.

  The DUT was placed on two straight edges (two Delrin rods), each at the end of the DUT. One support rested on an electronic scale, the other one on a support structure, to achieve the same height. The mass measurement from the scale is used for further calculation of the centre of gravity in the respective axis.

  At first the lunch box without the spacecraft was measured, afterwards, the spacecraft was placed inside and the test was repeated.

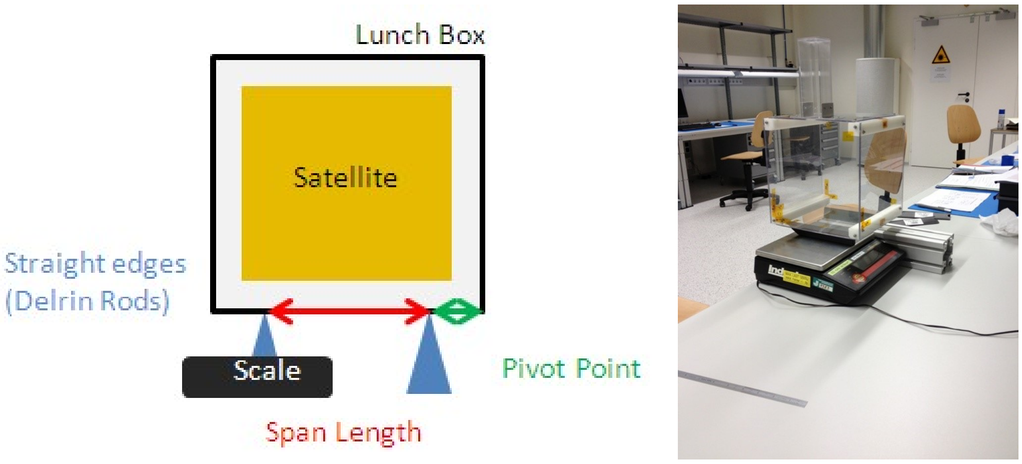


Figure 3.51: Centre of mass measurement: To verify the finite elements calculations, the exact centre of mass of the assembled satellite was measured.

Given the accuracy values of the span, the scale and the pivot, the following values for the centre of mass of BRITE-Austria were derived:

- The X centre of mass is 0.802 ± 3.052 mm from the geometric centre towards the +X face.
- The Y centre of mass is -8.034 ± 3.049 mm from the geometric centre towards the +Y face.
- The Z centre of mass is -6.478 ± 3.177 mm from the geometric centre towards the +Z face.

The actual centre of mass location formed an input in the attitude control software. In addition, the overall mass of the spacecraft was determined, as the CAD design did not take into account the final wiring harness.

According to the system requirements, the mass of the satellite should not exceed 7 kg. The final flight configuration had a mass of 6.68 kg and therefore met the requirement.

- **Magnetic mapping**
  During the magnetic mapping test the parasitic dipoles of static and dynamic origin (due to operations) of the BRITE-Austria satellite were measured. In addition, it was determined whether any of the parasites or torquers influence the readings of the on-board magnetometer.

  The spacecraft was therefore placed inside the Helmholtz coil and an external calibrated magnetometer was used to measure the ambient magnetic field (structural and operational). Variations in these readings will be used to estimate parasitic dipoles along each axis.

  The test was performed under several operating conditions (various subsystems powered on in diverse attitude modes) and in each orientation. The measurements were compared to the reference powered-off case, to determine whether the readings of the magnetometer were affected, which was not the case.

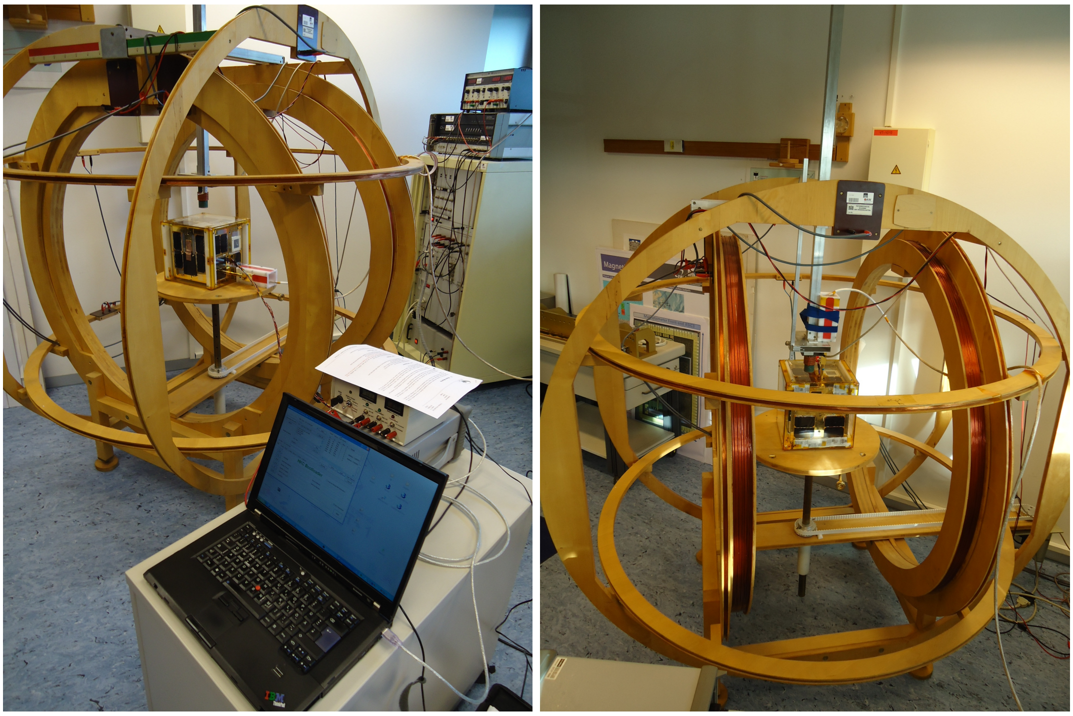


Figure 3.52: Magnetic mapping test: During the magnetic mapping test, BRITE-Austria was placed inside the Helmholtz coil at the Space Research Institute, Graz.

- **Software stability and mode transitions**

  During this test phase, two purposes were pursued. One goal was to ensure that the attitude control software was not crashing or diverging over a longer period of time. Therefore, the attitude control software and the b-dot mode was initialised, and the software stability was tested on the integrated satellite, if no crashes occurred for several days. During this test, the estimated state and the various software outputs were monitored and verified.

  Another goal was to check the error codes and consequent mode transistions were detected and properly handled by the attitude control software. For each pre-defined error code, conditions were set to trigger the fault event. The reactions of the attitude control software were monitored and the correct execution of the mode transitions were reviewed and verified.

- **End-to-end analysis**

  The goal of this test was to ensure that the entire attitude subsystem functions correctly and as expected. For a given set of inputs, the Extended Kalman Filter (EKF), the controllers and implemented actuations were reviewed.

  Although in a ground environment, the exact system behaviour and performance of the ADCS system cannot be determined, the relative validity of the actuator data given the input values of the sensors was of main interest.

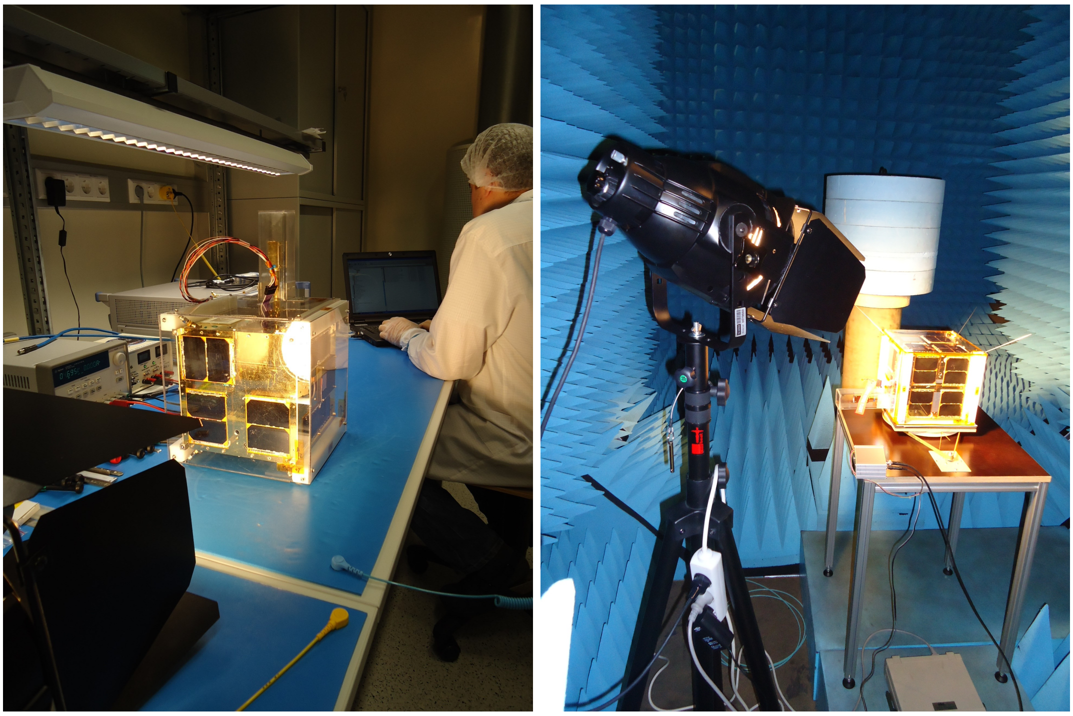


Figure 3.53: Software stability and end-to-end testing: The stability of the attitude control software was checked and a full functional test of the entire ADCS subsystem was performed during the end-to-end test.

3.6.7 1000 Hours Burn In

To identify early hardware problems, each unit should experience 1000 operative hours (burn-in) in an representative operational state. It is preferred to accumulate the hours on system-level, as some units interact with each other [30].

The burn-in time from flight and flight-spare units was logged in an spreadsheet. A total of at least 1000 h was specified in the systems requirements, however critical elements, like the reaction wheels and batteries, did not exceed this limits significantly to avoid early degradation. Therefore, the reaction wheels were operated at low speed, and the battery charge and discharge cycles were kept at a minimum.

Chapter 4

Launch Campaign and Early Operations

The BRITE-Austria/TUGSAT-1 satellite was launched on February 25^{th} 2013 as secondary payload on-board of the PSLV-C20 rocket from Sriharikota/India. The satellite is currently in its sixth year in-orbit and still fully operational. The first part of this chapter deals with the launch campaign and describes the individual phases in more detail. Starting with the shipment to India, followed by the integration and test phase at the launch site until its final launch, impressions and descriptions of the actions executed are given.

The second part describes the early mission operations of BRITE-Austria. An insight into the following operational phases is given:

- Launch Early Operations Period (LEOP) - the first hours after launch
- Commissioning phase - the checkout of the individual subsystems

4.1 Launch Campaign

BRITE-Austria was launched together with its sister satellite UniBRITE on board the Indian PSLV-C20 rocket from Sriharikota/India, as part of the NLS-8 (Nanosatellite Launch Service) [37].

The Satish Dhawan Space Centre (SDSC/SHAR) is located in Sriharikota in East India, around 120km North of Chennai. Sriharikota is a barrier island between the Pulicat Lake and the Bay of Bengal, and is only accessible via a causeway [Figure 4.1].

The following sections describe the planning and preparation of the launch campaign, as well as the individual phases from shipping, to arrival and integration, up to the actual launch [38] [39]

Figure 4.1: Location of the launch site: The launch site of the PSLV-C20 was located in Sriharikota/India, a barrier island about 120 km North of Chennai (Google Maps).

4.1.1 Launch Campaign Preparations

In order to successfully conduct the launch campaign, several preparations were carried out beforehand.

- **Launch campaign team**
  The launch campaign team for the two Austrian BRITEs was made of five persons, each dedicated for specific tasks. Table 4.1 indicates the personnel participating in the launch campaign and their assigned roles.

  An official letter by the launch negotiator Antrix Corporation Limited was provided to assist in the application of multiple-entry business visas. Multiple-entry visas are recommended in case of short-notice launch delays that lead to a split in launch campaign.

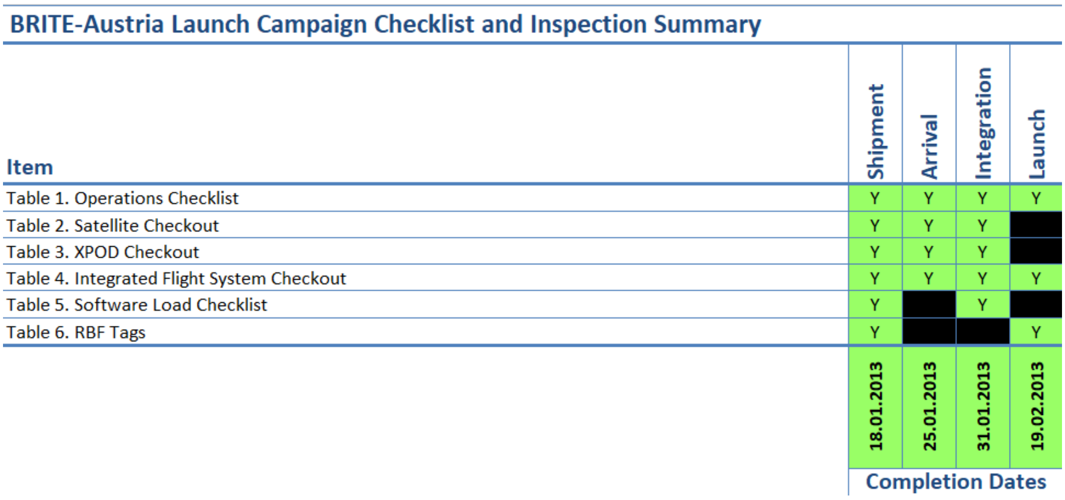
- **Shipping details**
  To ensure the spacecraft arrival at the launch site in due time, the transport had to be arranged beforehand. A packing list including value declaration of the necessary GSE, tools and cleanroom garments was prepared and exchanged with the shipping courier (World Courier) as export customs declarations had to be organised in advance.

  As the flight system (spacecraft and XPOD) was ”exported to space” and therefore not re-imported to Austria, an official letter from ANTRIX confirming the launch was provided to the Austrian customs to avoid export duties. In addition, compliance with safety regulations had to be ensured.

Name	Responsibility	Affiliation
Manuela Wenger (née Unterberger)	BRITE-Austria Systems Engineer and Launch Campaign Manager - Overall responsibility for BRITE-Austria launch campaign activities	IKS/TUG
Patrick Romano	BRITE-Austria LEOP Activities Engineer - Responsible for BRITE-Austria checkout activities - Responsible for BRITE-Austria software finalisation	IKS/TUG
Cordell Grant	BRITE Project Manager - Overall responsibility for BRITE launch campaign activities - Responsible for final loading and arming of all NLS-8 deployment systems (incl. BRITE-Austria)	UTIAS/SFL
Monica Chaumont	UniBRITE LEOP Activities Engineer - Responsible for UniBRITE checkout activities - Responsible for UniBRITE software finalisation	UTIAS/SFL
Freddy Pranajaya	NLS-8 Project Manager - Overall responsibility for NLS-8 launch campaign activities	UTIAS/SFL

Table 4.1: Launch campaign personnel: During the conduction of the BRITE-Austria launch five people were involved [38].

- **Checklists preparation**
  In preparation of the launch campaign, the tasks to be performed (e.g. inspections, tests, software loads) in the individual phases have been planned and checklists have been prepared in consultation with UTIAS/SFL. The following figure gives a screenshot of the checklist overview page at the end of the launch campaign.



BRITE-Austria Launch Campaign Checklist and Inspection Summary

Item	Shipment	Arrival	Integration	Launch
Table 1. Operations Checklist	Y	Y	Y	Y
Table 2. Satellite Checkout	Y	Y	Y	■
Table 3. XPOD Checkout	Y	Y	Y	■
Table 4. Integrated Flight System Checkout	Y	Y	Y	Y
Table 5. Software Load Checklist	Y	■	Y	■
Table 6. RBF Tags	Y	■	■	Y
Completion Dates	18.01.2013	25.01.2013	31.01.2013	19.02.2013

Figure 4.2: Launch campaign checklists: The list states an overview of the inspections and checks performed in each phase (status at end of launch phase), the single tasks to be performed on the respective system were summarized in individual tables (not depicted).

4.1.2 Shipment Phase

The shipment phase comprised all activities and pre-shipment testing to ensure the secure transport to the launch site.

After a long form functional test (LFFT) of the spacecraft, the satellite was integrated and secured in its deployment housing. Protective panels were mounted on each side to avoid any mechanical interference. All Remove Before Flight (RBF) items were identified, marked and the flight system was packed inside its shipment container, a Pelican case equipped with shock and humidity sensors on the inside and shock sensors on the outside.

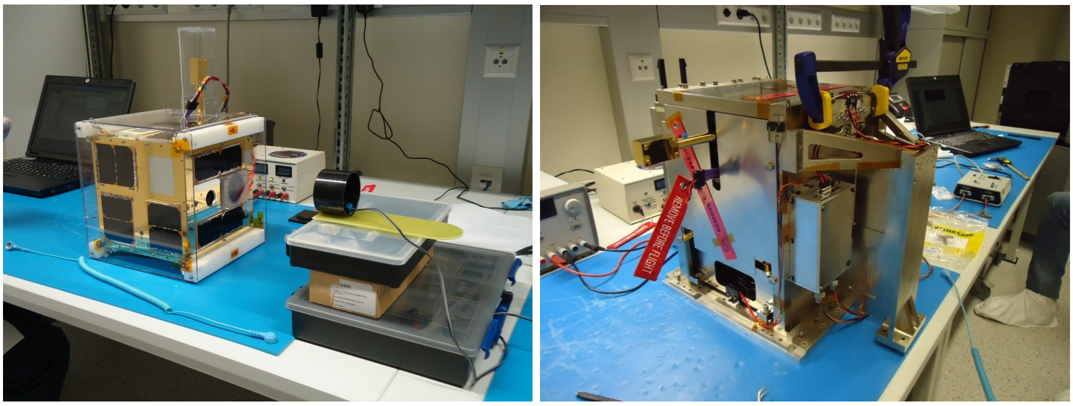


Figure 4.3: Last tests before shipment to the launch site: Before shipping the flight system to the launch site, functional tests were performed and the satellite was loaded into its deployment housing.

In addition, two separate transport boxes were prepared, hosting the necessary GSE, clean-room tools and garments needed at the launch site.

Figure 4.4: Packaging and farewell: The flight system was packaged inside a Pelican case equipped with humidity and shock sensors and handed over to the shipping company.

4.1.3 Arrival Phase

The launch campaign team arrived in Chennai on January 21^{st}, two weeks prior to the envisaged launch date. On January 22^{nd}, customs clearance was facilitated by ISRO under supervision of the team.

While the satellites and their GSE was transported subsequently to the launch site with a dedicated explosives truck, the team was taken directly to the space centre. On the following day, access to the premises and cleanroom facilities was granted and the launch campaign activities were started.

Figure 4.5: Arrival at launch site: The transport containers arrived at the launch site, and were transferred to the cleanroom and unpacked.

After visual inspection of the transport containers, all containers were transferred into the cleanroom facility in the satellite processing building SP1-B and unpacked. After the deployment test and first visual inspections, an LFFT of the satellite and the XPOD was performed.

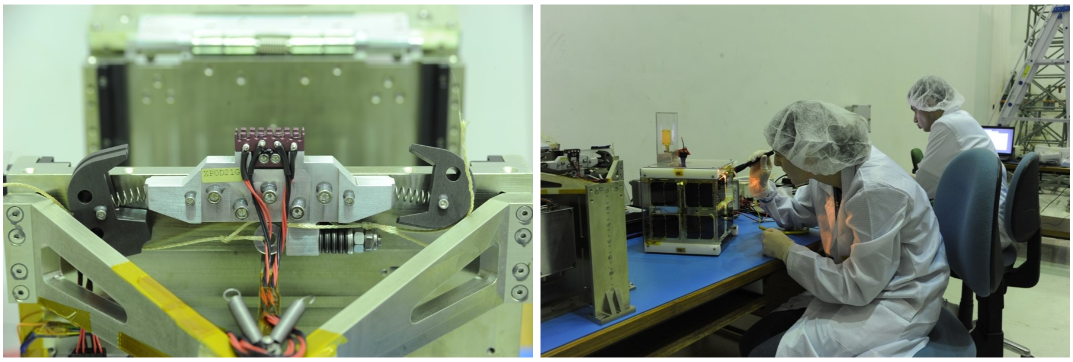


Figure 4.6: Deployment test and visual inspections: After the flight system was unpacked, a deployment test was performed, followed by an visual inspection of the satellite and the XPOD.

For redundancy and fail safety reasons, multiple copies of the application code were prepositioned to the on-board computer's Flash memory. Two identical copies of the HKC and ADCC flight software were stored in different Flash blocks on both computers. The IOBC represents a standalone unit, hence only two copies of the SDGC were stored. Besides, two copies of the individual LFFTs were pre-positioned on each OBC's Flash.

As described in Section 2.4 Launch Segment, the flight system was placed on the equipment bay deck of the payload fairing during launch. Before the integration at the Mobility Service Tower (MST) - SP3 could have started, a fit check of the XPOD with the used adapter plate was performed, followed by a final check on the rocket itself.

Figure 4.7: Last functional tests and fit check: Before the flight integration of the satellite into its deployer could occur, a final functional check was conducted including software loading. Besides, a fit check of the deployment system on its adapter plate of the payload fairing was performed.

4.1.4 Integration Phase

After a final LFFT and charging of the batteries, the satellite got prepared for its final integration into its deployer. Once the satellite was secured in the deployment housing, an SFFT was performed and all software loads were tested on all computers. This activity was followed by the removal of the test port and installation of the test port cover, the staking of all external screws and antennas and the final check of the RBF items (only protective panels were installed for storage). Impressions on the tasks performed are given in the following figures.

Figure 4.8: Final loading of the deployer: The flight system was prepared for final integration on the rocket by loading the XPOD.

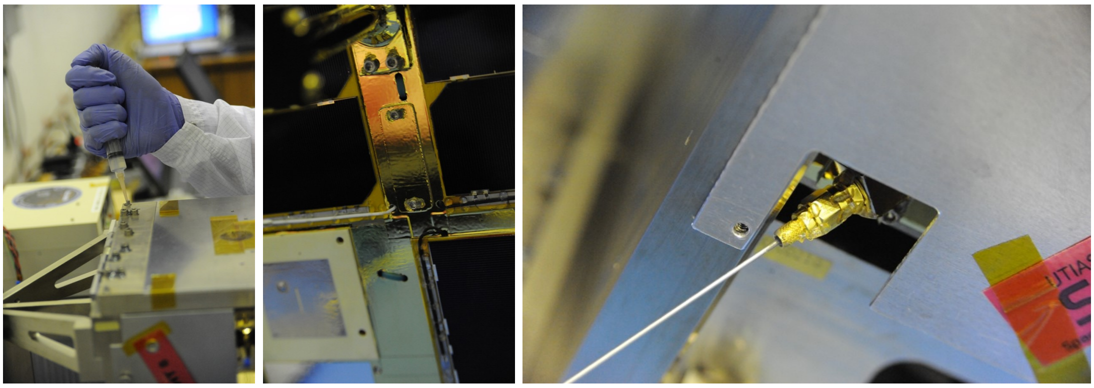


Figure 4.9: Final preparations: All external screws on the deployer and the UHF antenna connections on the satellite were staked, the batteries of the flight system were charged, followed by the final removal of the umbilical connection and application of test port cover.

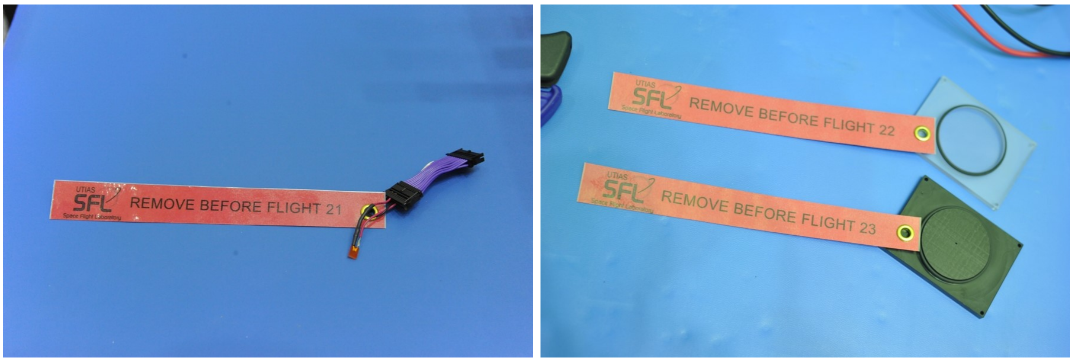


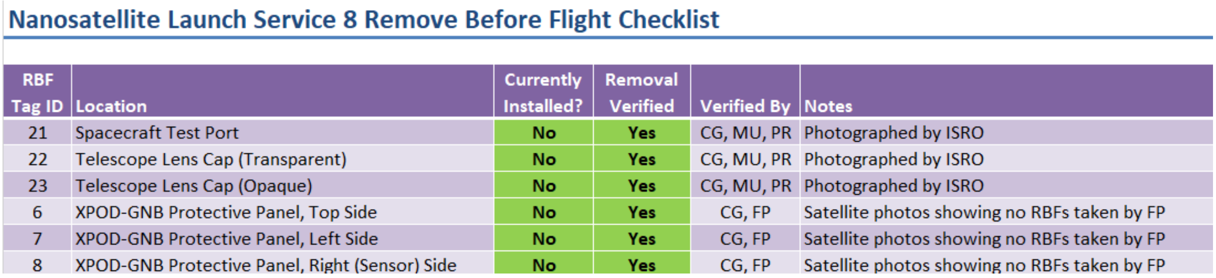
Figure 4.10: Remove before flight items: It was ensured that the RBF items were removed.

The final flight configuration was prepared for temporary storage until it was ready to be forwarded to the MST-SP3 for final integration on the PSLV-C20 upper stage.

Figure 4.11: Preparing for storage: As the launch was delayed by two additional weeks, it was decided to secure and store the flight system in the cleanroom, until the final go-ahead by the launch provider was received.

4.1.5 Launch Phase

Due to a launch delay of two weeks, it was decided that the final integration on the rocket was performed by two colleagues, C. Grant and F. Pranajaya from UTIAS/SFL, while the Austrian launch campaign team performs the first passes of the Austrian spacecrafts over Graz. During this phase the last RBF items were removed and the flight system was mounted on its adapter plate and connected to the EBD.



Nanosatellite Launch Service 8 Remove Before Flight Checklist

RBF Tag ID	Location	Currently Installed?	Removal Verified	Verified By	Notes
21	Spacecraft Test Port	No	Yes	CG, MU, PR	Photographed by ISRO
22	Telescope Lens Cap (Transparent)	No	Yes	CG, MU, PR	Photographed by ISRO
23	Telescope Lens Cap (Opaque)	No	Yes	CG, MU, PR	Photographed by ISRO
6	XPOD-GNB Protective Panel, Top Side	No	Yes	CG, FP	Satellite photos showing no RBFs taken by FP
7	XPOD-GNB Protective Panel, Left Side	No	Yes	CG, FP	Satellite photos showing no RBFs taken by FP
8	XPOD-GNB Protective Panel, Right (Sensor) Side	No	Yes	CG, FP	Satellite photos showing no RBFs taken by FP

Figure 4.12: Remove before flight checklist: The RBF checklist was updated as soon as an RBF item was installed or removed. The picture shows the status at the end of the launch phase.

BRITE-Austria was mounted on the EBD of the PSLV upper stage, next to six other satellites. The following pictures state the planned launching configuration and show the last picture of the spacecraft taken before the launch.

Figure 4.13: Final integration on PSLV: The location of all satellites on the upper stage is depicted (left); An impression of BRITE-Austria (next to C. Grant) shortly before launch is shown (right). (Image courtesy: ISRO)

On February 25th 2013, at 18:01 local time (11:31 UTC) BRITE-Austria was launched on-board the PSLV-C20 rocket from the FLP at the Satish Dhawan Space Centre in Shriharikota/India.

Figure 4.14: Launch impressions: The ISRO PSLV-C20 rocket during lift-off on the first launch pad, the assembly tower (MST) is seen in the background. (Image courtesy: ISRO)

4.2 Early Operations

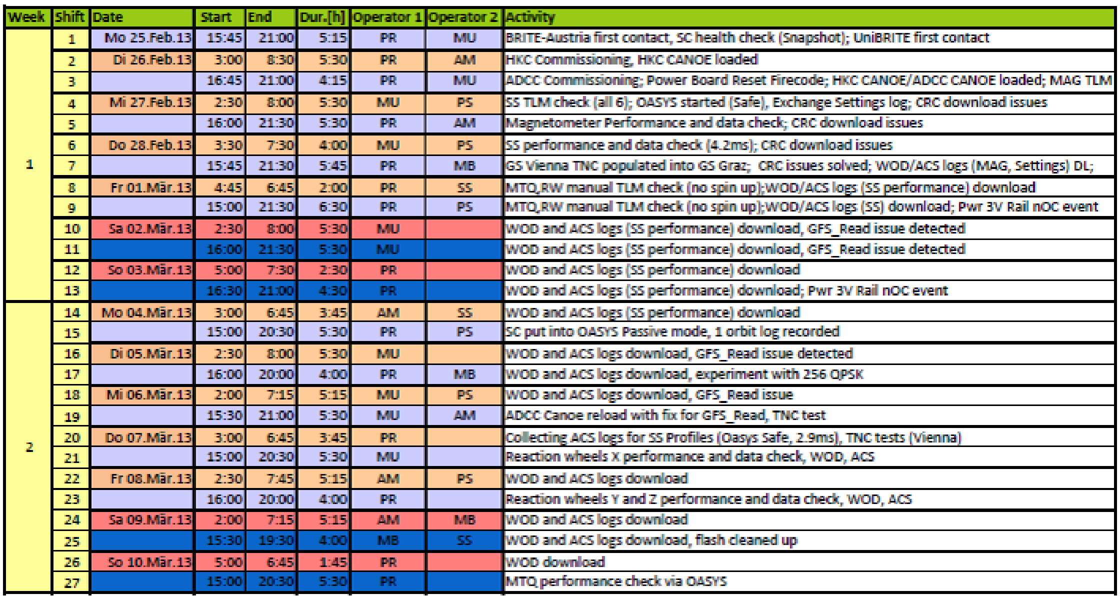
The nominal mission operations phase of BRITE-Austria was two years. After these two years however, the spacecraft was still providing excellent and highly valuable scientific data. A decision was made to ask for further funding and continue with the operations. Currently the spacecraft is already in its sixth year in-orbit and still fully operational.

This section is dedicated to give an insight on the tasks that were performed during the early operational phases, especially the commissioning phase. Prior to this, an overview of the pre-launch planning and preparations is presented.

4.2.1 Planning and Preparation of Mission Operations

The orbit of BRITE-Austria is a Sun-synchronous dawn-dusk orbit at an altitude of about 780 km. Given the ground station in Graz, the passes occur in the early morning (4 to 8 a.m. local time) and in the late afternoon/evening (6 to 10 p.m. local time). These timings are quite challenging, and especially during LEOP and early commissioning phase, a substantial amount of human interaction is needed and shift work is required.

- **Operating Teams**
  Regarding human resources, four additional staff members from the IKS, next to the BRITE-Austria operations director and the BRITE-Austria systems engineer, were trained to commission and operate BRITE-Austria. While a single operator can interact with the satellite, a second operator was foreseen to ensure the correct execution of the procedures and to perform the required documentation tasks. Especially during the commissioning phase, shift operations of a team of two operators were mandatory. During the first weeks of commissioning the teams were assigned for each shift, according to their availability, their expertise and the planned tasks. The screenshot in Figure 4.15 shows the shift assignments during the first two weeks of commissioning, including the activity performed.



Week	Shift	Date	Start	End	Dur.[h]	Operator 1	Operator 2	Activity
1	1	Mo 25.Feb.13	15:45	21:00	5:15	PR	MU	BRITE-Austria first contact, SC health check (Snapshot); UniBRITE first contact
	2	Di 26.Feb.13	3:00	8:30	5:30	PR	AM	HKC Commissioning, HKC CANOE loaded
	3		16:45	21:00	4:15	PR	MU	ADCC Commissioning; Power Board Reset Firecode; HKC CANOE/ADCC CANOE loaded; MAG TLM
	4	Mi 27.Feb.13	2:30	8:00	5:30	MU	PS	SS TLM check (all 6); OASYS started (Safe), Exchange Settings log; CRC download issues
	5		16:00	21:30	5:30	PR	AM	Magnetometer Performance and data check; CRC download issues
	6	Do 28.Feb.13	3:30	7:30	4:00	MU	PS	SS performance and data check (4.2ms); CRC download issues
	7		15:45	21:30	5:45	PR	MB	GS Vienna TNC populated into GS Graz; CRC issues solved; WOD/ACS logs (MAG, Settings) DL;
	8	Fr 01.Mär.13	4:45	6:45	2:00	PR	SS	MTQ,RW manual TLM check (no spin up);WOD/ACS logs (SS performance) download
	9		15:00	21:30	6:30	PR	PS	MTQ,RW manual TLM check (no spin up);WOD/ACS logs (SS) download; Pwr 3V Rail nOC event
	10	Sa 02.Mär.13	2:30	8:00	5:30	MU		WOD and ACS logs (SS performance) download, GFS_Read issue detected
	11		16:00	21:30	5:30	MU		WOD and ACS logs (SS performance) download, GFS_Read issue detected
	12	So 03.Mär.13	5:00	7:30	2:30	PR		WOD and ACS logs (SS performance) download
	13		16:30	21:00	4:30	PR		WOD and ACS logs (SS performance) download; Pwr 3V Rail nOC event
2	14	Mo 04.Mär.13	3:00	6:45	3:45	AM	SS	WOD and ACS logs (SS performance) download
	15		15:00	20:30	5:30	PR	PS	SC put into OASYS Passive mode, 1 orbit log recorded
	16	Di 05.Mär.13	2:30	8:00	5:30	MU		WOD and ACS logs download, GFS_Read issue detected
	17		16:00	20:00	4:00	PR	MB	WOD and ACS logs download, experiment with 256 QPSK
	18	Mi 06.Mär.13	2:00	7:15	5:15	MU	PS	WOD and ACS logs download, GFS_Read issue
	19		15:30	21:00	5:30	MU	AM	ADCC Canoe reload with fix for GFS_Read, TNC test
	20	Do 07.Mär.13	3:00	6:45	3:45	PR		Collecting ACS logs for SS Profiles (Oasys Safe, 2.9ms), TNC tests (Vienna)
	21		15:00	20:30	5:30	MU		Reaction wheels X performance and data check, WOD, ACS
	22	Fr 08.Mär.13	2:30	7:45	5:15	AM	PS	WOD and ACS logs download
	23		16:00	20:00	4:00	PR		Reaction wheels Y and Z performance and data check, WOD, ACS
	24	Sa 09.Mär.13	2:00	7:15	5:15	AM	MB	WOD and ACS logs download
	25		15:30	19:30	4:00	MB	SS	WOD and ACS logs download, flash cleaned up
	26	So 10.Mär.13	5:00	6:45	1:45	PR		WOD download
	27		15:00	20:30	5:30	PR		MTQ performance check via OASYS

Figure 4.15: Shift operations assignments: During LEOP and early commissioning phase, the six operators were assigned to the respective shifts. An excerpt covering the first two weeks including the activity performed is given.

A flight director was assigned for each shift. The flight director had absolute authority and was in charge of the appropriate execution of the procedures and tasks during the respective shift. In addition, the flight director had full power to decide, in the case of anomalies, which steps are taken according to the contingency procedures. However, any critical changes to the nominal procedures had to be approved in advance by the systems engineer and/or operations director [21] (Figure 4.16).

- **Status reports and logging**
  To document the actions performed during a specific set of contacts, a status report in form of a spreadsheet was prepared during the first two years of operations. This status report comprised the following information [40]:

- Operators on duty
- Pass information (date, contact times, elevation, current TLEs, ground station status)
- Main satellite health data including satellite mode, battery status and attitude control state
- Log names / identifiers
- Description of pass actions
- Shift summary
- Actions and notes for the next shifts

Due to the generation of these daily reports as well as keeping records of operations logs, the smooth and seamless handover between the operators in different shifts was ensured.

Figure 4.16: BRITE-Austria flight director: The flight director is in charge of the actions taken during the dedicated shift.

Besides, the parallel commissioning of the sister satellite UniBRITE via Toronto allowed the operators to exchange experiences gained and lessons learned. In particular, in case of unexpected behaviour of a subsystem, possible countermeasures were and still are developed together.

- **Commissioning plan and procedures**
  During the AIT phase of the satellite, a commissioning plan comprising general procedures was elaborated. Once the development of both, on-board and ground segment software, was frozen before launch, the commissioning plan was refined and finalised.

  Various commissioning procedures for the checkout of the individual subsystems as well as the attitude control modes were prepared. Each procedure consisted of the following tables:

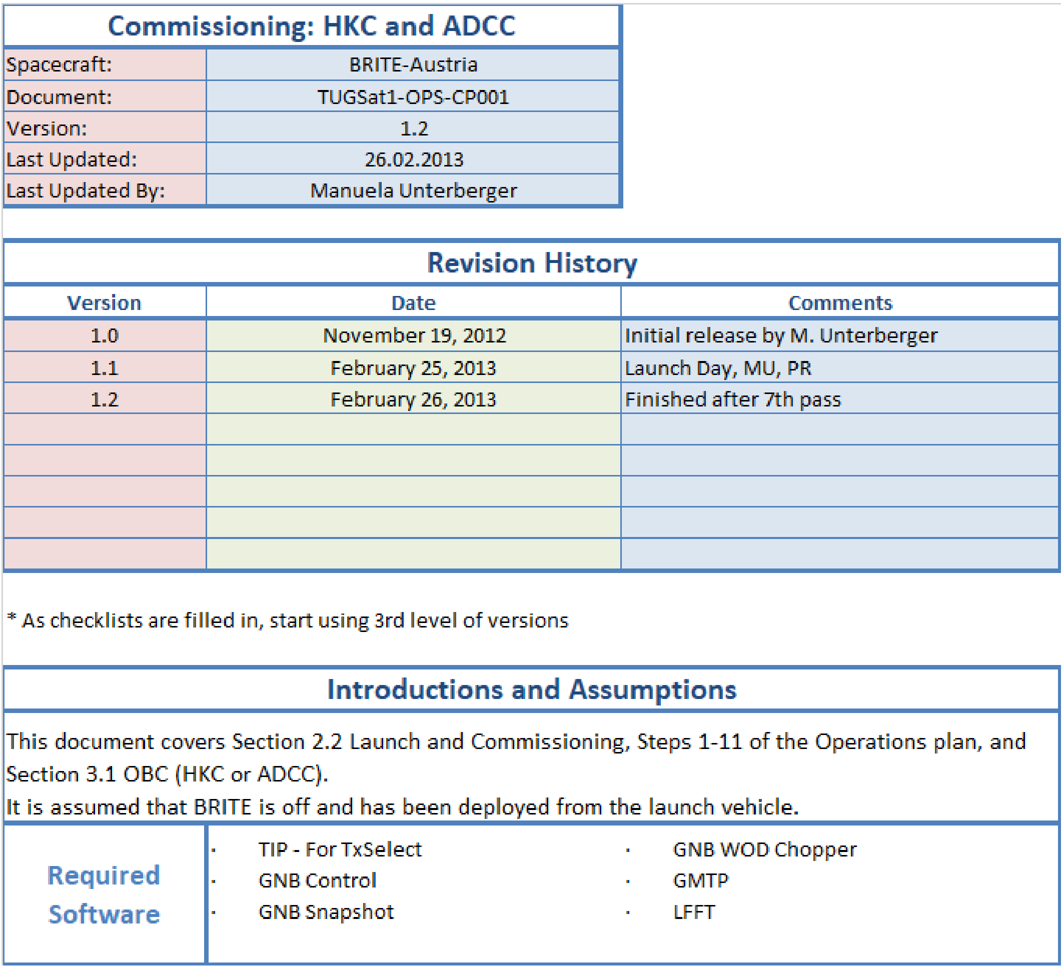
  - **Procedure overview** - indicating the version, revisions and assumptions, and the software required
  - **Pre-pass start-up process** - indicating the operation team in charge, as well as the record of the logs
  - **Procedure - telemetry check** - all steps that need to be performed in the various ground software models and on the satellite itself, finally followed by the WOD analysis
  - **Procedure - performance and data check** - all the steps that need to be performed on the satellite while running in the specific operational mode(s), including download and analysis of the respective mode logs
  - **Settings/configuration** - indicating the configuration, that is needed during setup of the respective operational mode

  The first page of the start-up commissioning procedure is shown as example in Figure 4.17.

  In case several configurations and settings had to be loaded, commissioning scripts stating the different commands to set the configurations had been prepared to increase the efficiency of the pass and avoid type errors of the operators.

- **Nominal Operations Plan and Procedures**
  Similar to the commissioning plan and procedures, a top-level operations plan was developed prior to the launch. The operations plan states the general operations procedures for spacecraft setup and control, indicating the sequence of actions and tasks to be taken to perform star field observations.

- **Emergency and Contingency Procedures**
  In case of unexpected behaviour of either the BRITE-Austria satellite or the Graz ground station, emergency and contingency procedures have been elaborated already during the AIT phase. In particular, the procedures cover common issues that may occur during commissioning and operations of the satellite or the ground station, and a respective set of in-pass and post-pass corrective actions are defined. More information is given in Section 5.5.



Commissioning: HKC and ADCC

Spacecraft:	BRITE-Austria
Document:	TUGSat1-OPS-CP001
Version:	1.2
Last Updated:	26.02.2013
Last Updated By:	Manuela Unterberger

Revision History

Version	Date	Comments
1.0	November 19, 2012	Initial release by M. Unterberger
1.1	February 25, 2013	Launch Day, MU, PR
1.2	February 26, 2013	Finished after 7th pass

* As checklists are filled in, start using 3rd level of versions

Introductions and Assumptions

This document covers Section 2.2 Launch and Commissioning, Steps 1-11 of the Operations plan, and Section 3.1 OBC (HKC or ADCC).
It is assumed that BRITE is off and has been deployed from the launch vehicle.

Required Software

- TIP - For TxSelect
- GNB Control
- GNB Snapshot
- GNB WOD Chopper
- GMTP
- LFFT

Figure 4.17: Start-up commissioning procedure overview: The title page of the procedure indicates the version, revisions and assumptions, and the software required.

4.2.2 Launch and Early Operations Period (LEOP)

BRITE-Austria was launched on February 25^{th} 2013, on-board the PSLV-C20 into a SSDD orbit with an altitude of 780 km. Shortly after launch, ISRO provided the planned orbital data of the BRITE-Austria satellite including its preliminary TLEs. The ground station and tracking software was configured accordingly, and the first overflight over the Graz ground station was planned to happen about four hours after launch, at a maximum elevation of 7° above the horizon.

The essential task after launch of the spacecraft was to establish contact with the satellite. After deployment of the XPOD, the spacecraft was in kickoff mode, meaning only the power system and the UHF receiver were active. Therefore, the satellite and its on-board computer had to be turned on by sending a dedicated HKC ON firecode from ground.

First contact was successfully established with BRITE-Austria from the Graz ground station already during the first pass, despite the low elevation and the use of the coarse launch injection TLEs. During the first pass, the HKC was firecoded on, the core satellite health was confirmed and the application code on the HKC was loaded to start health monitoring and logging.

The exact filled out start-up procedure of the first two passes over Graz is shown in Figure 4.18.

Start-up, HKC, ADCC and Power Reset Check

	P/F		Steps	Notes
1			**Firecode the HKC ON**	
	🟩	A	In TIP (Scheduler), start sending TxSelect the HKC S-Band, 32 kbps, BPSK.	Pass Start at 15:46:18
	🟩	B	While the TxSelect is sending, start sending the HKC ON firecode.	
	🟩	C	Continue sending the HKC ON firecode until a lock is seen on the downlink modem and TIP receives a TxSelect acknowledgement packet.	
	🟩	D	In TIP, note the HKC On-Board time and the memory from which the bootloader is running. Internal RAM is expected.	OBC Time: 11.58.57 Memory Location: HKC - BL - 04 Internal Memory
2			**Get a telemetry Snapshot and check core satellite health**	
	🟩	A	In Snapshot, send a ping, click “Query Switches” and “Get All”.	
	🟩	B	Snapshot will show an alarm state because (1) the HKC is in bootloader, and (2) the ADCC is off, showing a low current. No other alarms are expected.	
	🟩	C	Check and note the HKC current and temperature, and verify they are within safe limits.	0.065 30.95 °C
3			**Leave the HKC on until at least 20 Snapshot frames have been collected.**	
	🟩	A	Set Snapshot to Poll Every 1 second, and click “Poll Telemetry”	
4			**Load the HKC Application Software from Flash and begin collecting Whole Orbit Data (WOD).**	
	🟩	A	In GNB Control, run the script “HKC-CANOE-Load.txt”	
	🟩	B	The script will load CANOE from Flash and send the Init command.	
	🟩	C	The S-Band transmitter will turn off when the HKC CANOE starts. In TIP, send a TxSelect S-Band, 32 kbps, BPSK to the HKC.	
	🟩	D	After the TxSelect has been received, GNB Control will complete the script sending a ClockSync and a command to start a new WOD Log (rather than append to the WOD-0 file).	
	🟩	E	Note the OBC time to confirm the ClockSync was successful; if not, manually issue a ClockSync in GNB Control	OBC Time: 15:49:02
	🟩	F	In the Flash tab of GNB Control, issue a “Get List” command and confirm that a new WOD log has been started	WOD-Log: 18bd9c37
5			**Record WOD for at least one orbit, then download it and check telemetry (confirm that the satellite is power positive)**	
	🟩	A	If there is contact time while waiting for this orbit to complete, poll real-time telemetry in Snapshot.	
	🟩	B	To download the WOD, in GMTP send a “Flash Info” command to get a file listing.	
	🟩	C	In GMTP, send a “New WOD Log” command to start a new WOD log.	
	🟩	D	Send a “Flash Info” command to confirm that a new log has been started.	WOD-Log:
	🟩	E	Click on a closed log file and click “File Read”. Only one file can be downloaded at a time.	
	🟩	F	Use this procedure to download WOD-0 and orbit of data on the default BCDR.	
	🟩	G	Allow GNB Chopper to parse the downloaded WOD and examine the WOD.	WOD0 downloaded
			END PASS 1	
6			**Switch to the non-default BCDR and check core satellite health.**	
	🟩	A	In GNB Control, on the Power Tab, turn on “BCDR 0”.	
	🟩	B	Then turn off “BCDR 1”.	
	🟩	C	Take a Snapshot and examine the BCDR 0 telemetry and all the bus telemetry.	WOD-Log: 18bdb20d
7			**Record WOD for at least one orbit, download old WOD and check telemetry (confirm that the satellite is power positive)**	
	🟩	A	If there is contact time while waiting for this orbit to complete, poll real-time telemetry in Snapshot.	
	🟩	B	To download the WOD, in GMTP send a “Flash Info” command to get a file listing.	
	🟩	C	In GMTP, send a “New WOD Log” command to start a new WOD log.	
	🟩	D	Send a “Flash Info” command to confirm that a new log has been started.	WOD-Log:
	🟩	E	Click on a closed log file and click “File Read”. Only one file can be downloaded at a time.	
	🟩	F	Use this procedure to download WOD-0 and orbit of data on the default BCDR.	
	🟩	G	Allow GNB Chopper to parse the downloaded WOD and examine the WOD.	WOD 18bd9c37 downloaded
			END PASS 2	

Figure 4.18: Start-up procedure: Already during its first pass over Graz, contact was established with BRITE-Austria. The tasks and actions to be performed on the satellite were defined in the start-up procedure (first two passes shown)

As the health of BRITE-Austria was verified during the first pass over Graz, the second pass was dedicated to establish contact with UniBRITE, confirm its health as well as start telemetry logging. As the envisaged first ground contact with the station in Toronto would not occur within hours, the operators in Graz were asked by UTIAS/SFL to assist in establishing the first contact.

4.2.3 Commissioning

The concept for the BRITE-Austria commissioning was to verify the correct telemetry, performance and data of all subsystems in a rapid fashion. The systems were checked out sequentially, in a logical order. In case an anomaly or unexpected behaviour occurred, further debugging was needed. A short description of the high-level commissioning tasks, that have been performed on BRITE-Austria, is given [41][24]:

1. **Commissioning of the HKC**
   The functionality of the HKC was tested by running the on-board pre-positioned LFFT, which checks the core hardware blocks and memory boards. However, during the first pass, after confirming the positive power conditions and telemetry values, the application code was immediately loaded. This allowed to starting the automatic collection of the telemetry in form of whole orbit data (WOD), and therefore confirming the health state over a whole orbit, before the LFFT was executed during the upcoming passes.

2. **Switching to non-default BCDR and firecode testing**
   In case a power reset occurs, the satellite is restored running on the default battery/BCDR1. As this is the fall-back battery, it is desired to switch to the non-default battery/BCDR0 to

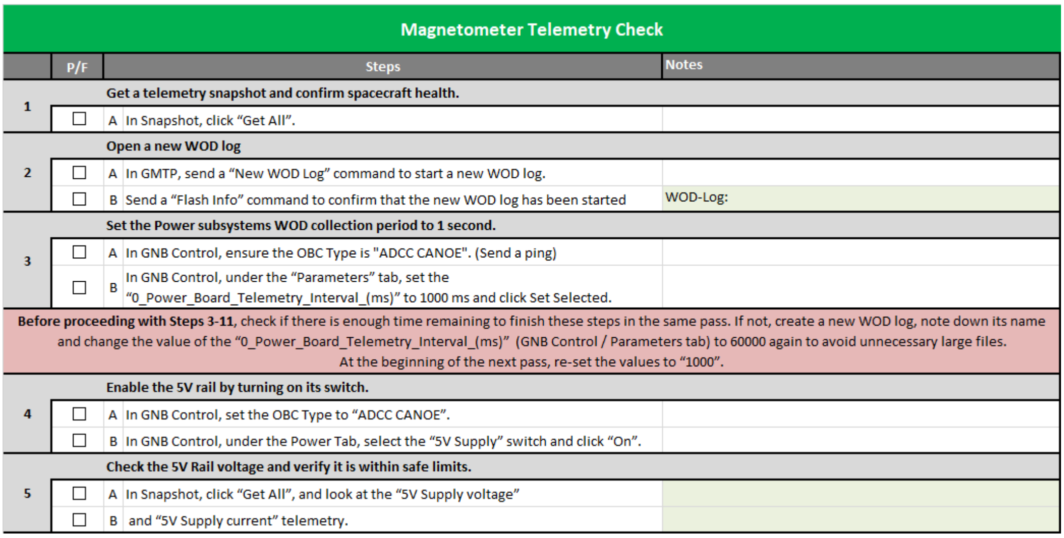
   - ensure a reset recovery in a loadshed event of the non-default battery/BCDR0 or in case of unexpected behaviour.
   - keep the operating hours and cycles on the default battery/BCDR1 at a minimum.

   The telemetry of the non-default BCDR0 was verified over several orbits before continuing. In addition, the functionality of the firecode detector on the spacecraft was tested.

3. **Commissioning of the ADCC**
   As the ADCC shares the same design with the HKC, the commissioning procedure was the same as for the HKC. After the check of the core hardware and memory blocks, the attitude control software was loaded and verified.

4. **ADCS: Start-up and safe mode**
   The attitude thread was started, by initialising all sensors and actuators (except startracker) and starting the ACS cycles. The first attitude thread mode is the *safe mode*, where the sensors and actuators are turned on, but no determination or control is performed. An Attitude Control System (ACS) log (with more specific ACS telemetry compared to the WOD) was recorded for a few orbits, downloaded and analysed to verify the stability of the attitude thread itself.

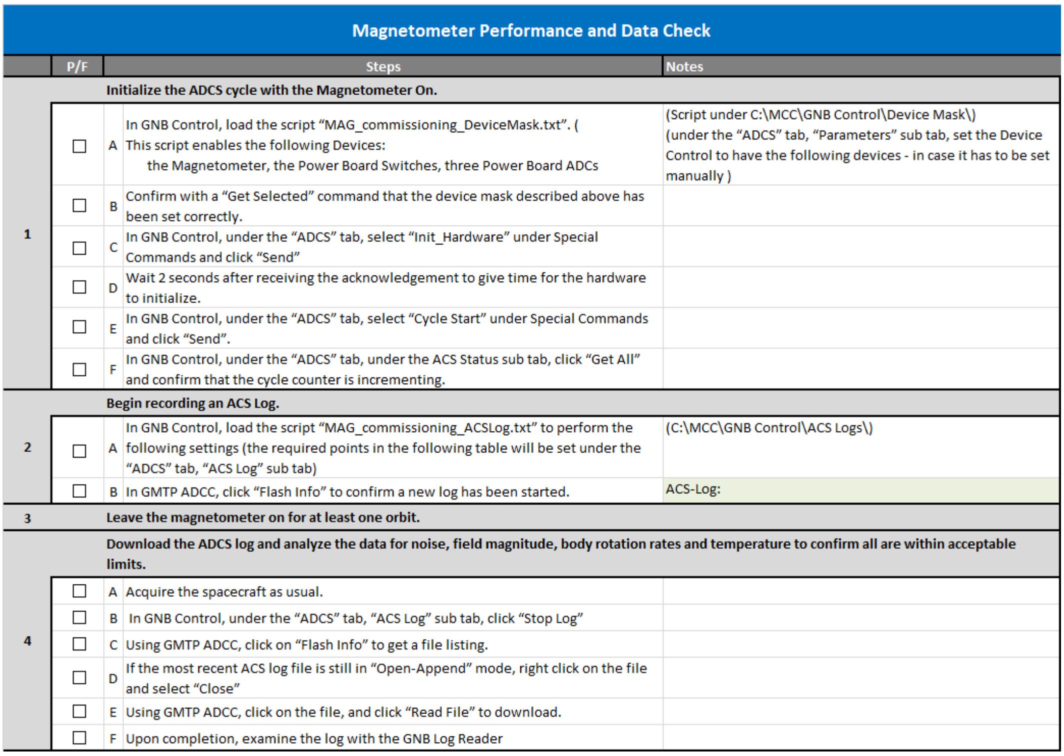
5. **Commissioning of the magnetometer**
   The in-orbit verification of the magnetometer was performed in two steps. The first step was the manual telemetry check, which comprised several power cycles, magnetometer initialisation, telemetry queries and further analysis. An excerpt of the actions performed is given in the procedure in Figure 4.19.



Magnetometer Telemetry Check				
	P/F		Steps	Notes
1			**Get a telemetry snapshot and confirm spacecraft health.**	
	☐	A	In Snapshot, click “Get All”.	
2			**Open a new WOD log**	
	☐	A	In GMTP, send a “New WOD Log” command to start a new WOD log.	
	☐	B	Send a “Flash Info” command to confirm that the new WOD log has been started	WOD-Log:
3			**Set the Power subsystems WOD collection period to 1 second.**	
	☐	A	In GNB Control, ensure the OBC Type is "ADCC CANOE". (Send a ping)	
	☐	B	In GNB Control, under the “Parameters” tab, set the “0_Power_Board_Telemetry_Interval_(ms)” to 1000 ms and click Set Selected.	
			Before proceeding with Steps 3-11, check if there is enough time remaining to finish these steps in the same pass. If not, create a new WOD log, note down its name and change the value of the “0_Power_Board_Telemetry_Interval_(ms)” (GNB Control / Parameters tab) to 60000 again to avoid unnecessary large files. At the beginning of the next pass, re-set the values to “1000”.	
4			**Enable the 5V rail by turning on its switch.**	
	☐	A	In GNB Control, set the OBC Type to “ADCC CANOE”.	
	☐	B	In GNB Control, under the Power Tab, select the “5V Supply” switch and click “On”.	
5			**Check the 5V Rail voltage and verify it is within safe limits.**	
	☐	A	In Snapshot, click “Get All”, and look at the “5V Supply voltage”	
	☐	B	and “5V Supply current” telemetry.	

Figure 4.19: Magnetometer telemetry check procedure: An excerpt of the tasks to be performed during the magnetometer telemetry checkout is shown.

The second step verified the correct interaction between the attitude control software and the sensor itself. The control of the sensor was handed over to the attitude thread, and an ACS log was started, containing the raw magnetometer readings (see procedure in Figure 4.20). The log was downloaded and the performance verified.



Magnetometer Performance and Data Check				
	P/F		Steps	Notes
1			**Initialize the ADCS cycle with the Magnetometer On.**	
	☐	A	In GNB Control, load the script “MAG_commissioning_DeviceMask.txt”. (This script enables the following Devices: the Magnetometer, the Power Board Switches, three Power Board ADCs	(Script under C:\MCC\GNB Control\Device Mask\) (under the “ADCS” tab, “Parameters” sub tab, set the Device Control to have the following devices - in case it has to be set manually)
	☐	B	Confirm with a “Get Selected” command that the device mask described above has been set correctly.	
	☐	C	In GNB Control, under the “ADCS” tab, select “Init_Hardware” under Special Commands and click “Send”	
	☐	D	Wait 2 seconds after receiving the acknowledgement to give time for the hardware to initialize.	
	☐	E	In GNB Control, under the “ADCS” tab, select “Cycle Start” under Special Commands and click “Send”.	
	☐	F	In GNB Control, under the “ADCS” tab, under the ACS Status sub tab, click “Get All” and confirm that the cycle counter is incrementing.	
2			**Begin recording an ACS Log.**	
	☐	A	In GNB Control, load the script “MAG_commissioning_ACSLog.txt” to perform the following settings (the required points in the following table will be set under the “ADCS” tab, “ACS Log” sub tab)	(C:\MCC\GNB Control\ACS Logs\)
	☐	B	In GMTP ADCC, click “Flash Info” to confirm a new log has been started.	ACS-Log:
3			**Leave the magnetometer on for at least one orbit.**	
4			**Download the ADCS log and analyze the data for noise, field magnitude, body rotation rates and temperature to confirm all are within acceptable limits.**	
	☐	A	Acquire the spacecraft as usual.	
	☐	B	In GNB Control, under the “ADCS” tab, “ACS Log” sub tab, click “Stop Log”	
	☐	C	Using GMTP ADCC, click on “Flash Info” to get a file listing.	
	☐	D	If the most recent ACS log file is still in “Open-Append” mode, right click on the file and select “Close”	
	☐	E	Using GMTP ADCC, click on the file, and click “Read File” to download.	
	☐	F	Upon completion, examine the log with the GNB Log Reader	

Figure 4.20: Magnetometer performance and data check procedure: The procedure states the steps to be executed to verify the readouts and performance values of the magnetometer (excerpt).

6. **Commissioning of the sun sensors**
   The six sun sensors, one on each face of the satellite, were checked out individually in the same way as the magnetometer. During the telemetry checkout it was found, that the sensors were partially saturated, as the default exposure time was too long. The procedure was therefore repeated several times and the exposure time was tuned to find the best performance settings. Once an optimal setting was found, the control was handed over to the attitude thread, allowing the readout of three sensors simultaneously. Due to the tumbling of the spacecraft, the test had to be performed several times to make sure that all six sensors were illuminated sufficiently.

7. **Commissioning of the IOBC**
   As the other OBCs, the hardware blocks on the IOBC were checked. In addition, the communication between IOBC and HKC was tested.

8. **ADCS: Passive determination mode**
   Once the attitude sensors had been commissioned, the *passive attitude determination mode* was tested. This mode is used to combine the measurements of the magnetometer and the sun sensors and provide coarse attitude determination. The attitude thread was commanded into *passive mode*, with the sun sensors and magnetometer enabled. An ACS log was collected for one orbit and analysed after download. This step was a critical step in the commissioning, as the sensor readings are actively used in the control loop to estimate the spacecraft's attitude.

9. **Commissioning of the magnetorquers**
   The checkout of the actuators was quite similar to the sensor checkout. First a telemetry checkout was performed, followed by a data check with the attitude thread. However, the commissioning of the actuators was more critical, as their activation affects and changes the satellite's attitude. Each of the three magnetorquers was turned on individually to check their telemetry. Different currents and directions were configured, and the actual current draw was investigated. While running in *passive determination mode* and a log was collected, the magnetorquers were individually activated for a short time period. It was confirmed that the magnetorquers influenced the spacecraft rates in the corresponding orthogonal axis, with little effect on the parallel axis. Besides, a polarity check with the attitude thread was completed.

10. **ADCS: B-dot mode / detumbling**
    As the behaviour and performance of the magnetorquers had been verified, the satellite could be detumbled. Thus the attitude thread was commanded in the *B-dot mode*, in which the spacecraft is stabilised by the use of the magnetorquers. According to the sensor readings, the necessary momentum is provided and the body rates of the satellite are lowered. The coarse sensors and the magnetorquers were activated in the device mask and an ACS log was collected for 10 minutes, followed by a transition to *passive mode* again. After analysis of the log, it was discovered, that the satellite rates decreased significantly and had settled below 1 ° per second.

11. **Commissioning of the reaction wheels**
    The reaction wheels on-board of BRITE-Austria are needed for the three-axis pointing modes. BRITE-Austria is equipped with three reaction wheels, oriented in each axis. An extended telemetry health check was performed, including power cycles, initialisation, different commanded speeds, as well as executing a wheel built-in self test (BIST).

    A wheel spin up test was part of the performance test with the attitude thread. Each wheel was individually commanded up to 300 rad/s speed for at least 20 minutes. This task was performed manually, while the spacecraft was still in *passive determination mode*.

    Although the check and performance verification was not needed for detumbling, this step was performed prior to the detumbling. The rationale behind this sequence was, that in case detumbling of the spacecraft was successful, an intermediate transition to *CTAP* could be attempted.

12. **ADCS: Coarse three axis pointing mode (CTAP)**
    As the performance of the coarse sensors and actuators had been verified, and the satellite had been successfully detumbled, a transition to *CTAP* was attempted. A desired orientation of spacecraft had to be found, and the corresponding quaternion calculated. In case of BRITE-Austria, the -X face with the apertures of the payload and startracker were pointed in an anti-Sun direction. This induced that the +X face with 8 solar cells was pointed directly to the Sun for maximum power generation.

    Furthermore, an upload of the current TLE was necessary to allow accurate determination of the spacecraft's attitude. The device mask was set to use all coarse sensors and actuators, and the warm-up period of the EKF of the attitude thread was already reached before. It has to be noted that the attitude thread itself does not distinguish between coarse and fine three-axis pointing, it takes the sensor readouts as defined in the device mask.

    The attitude control thread should perform the following actions every two seconds:

    (a) read out the sensors
    (b) calculate the parameters and momentum
    (c) command the actuators

    As this task was very critical, the plan was to perform this procedure during two consecutive passes:

    - **First pass:** The attitude status and body rates were verified, and the latest TLE and target quaternions were uploaded to the spacecraft. An ACS log was started, and a transition from *passive mode* to *CTAP* was manually conducted by the operators. During the pass, the telemetry was continuously verified and checked, whether the body rates were decreasing, the output quaternion settles towards the target quaternion commanded, and the panel currents were adjusting (to verify that the +X face is illuminated the most, while the -X face generates no power).

- **Second pass:** During the second pass the ACS log was stopped and downloaded, and the same telemetry checks as during the first pass were performed.

The analysis of the ACS log showed, that in *CTAP mode* the satellite's pointing accuracy was in the range of ± 2.5°, in compliance with the requirements. When activating the magnetorquers and reaction wheels, the body rates were first increased as the spacecraft is aligned with the target field. After about two minutes however, the satellite has been successfully stabilised in *CTAP*, and body rates of only 0.2 - 0.3° per second were observed.

13. **Payload health check and full-frame image exposures**
While the ACS logs gathered during the *CTAP* attempts were further analysed by the attitude experts, the payload was checked out, as the aperture of the payload was already pointing in anti-sun direction with no risk of sun-staring. As the main functionality of the IOBC was already verified in an earlier phase of the commissioning, the application code - the Science Data Generation Code (SDGC) - was loaded. The header board electronics were activated and the power consumption and telemetry while turning on the bias rail, CCD and amplifier were monitored and logged. Afterwards it was decided to take the first exposure with the BRITE-Austria instrument. In the FOV of the instrument, parts of the constellations Corvus, Virgoinis and Crater were located. Several images were taken with one-second exposure times. The image taken on March 23rd 2013, shows the star observed and the corresponding Point Spread Function (PSF) of Delta Corvus B9V with a visual magnitude of 2.95 (shown in Figure 4.21). As the image was obtained in *CTAP* mode, the scientific relevance was limited. However, the operational status of the CCD and optics was confirmed.

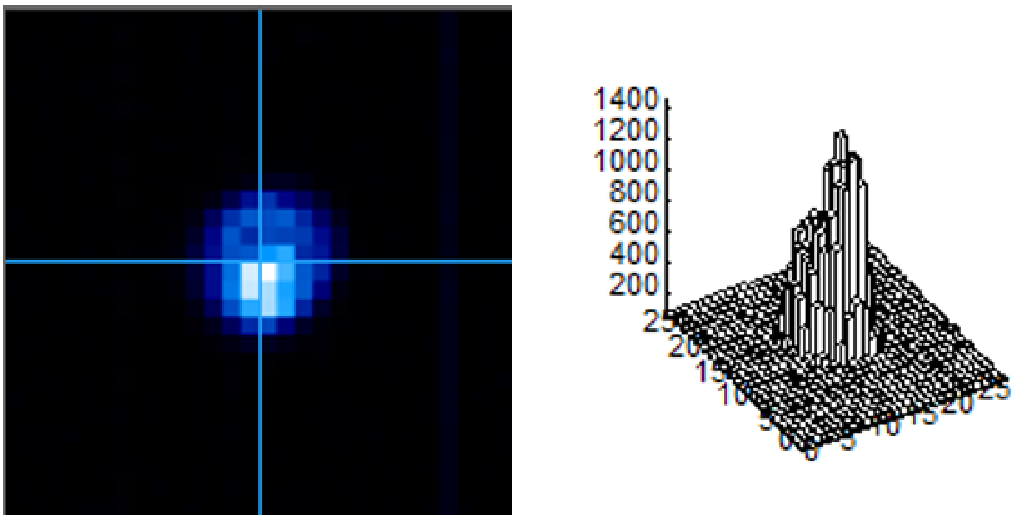


Figure 4.21: The first star observed by BRITE-Austria: On March 23^{rd} 2013 the first full frame image with BRITE-Austria was obtained. One of the stars observed was the Delta Corvus B9V star with a visual magnitude of 2.95. The image and corresponding PSF are shown.

14. **Commissioning of the startracker**
    As the startracker is the only sensor unit during the FTAP mode, the startracker had to be commissioned before transitions to *FTAP* could be attempted. Once the core telemetry of the startracker was examined, suitable parameters for in-orbit operations (e.g. amplifier gain, exposure times) were tested.

    While the attitude thread was in *CTAP*, the startracker was included in the device mask (but not in the control loop) and a warm up test was performed. The startracker was therefore activated for 40-50 minutes and was meanwhile estimating the quaternions. An ACS log was collected to show the reliability of the quaternion readings and detect possible drop-outs. A further characterisation of the FOV contraints (e.g. obstructions by Sun/-Moon/Earth) and the reliability in radiation environments (e.g. South Atlantic Anomaly [SAA]) was performed.

15. **ADCS: Fine three axis pointing mode (FTAP)**
    Scientific observations with BRITE-Austria are only performed in *FTAP* mode. The following commissioning steps were performed:

    - Ensure the stability of the spacecraft's attitude in *CTAP*, verify that the spacecraft is oriented to the target field and start an ACS log
    - Include the startracker in the device mask and ensure the startracker was powered on
    - Set the respective startracker parameters and wait for the startracker warmup period to end (planned for 20 minutes)
    - Include the startracker in the control loop, and after five minutes command transition to *FTAP*
    - After a specific time (typically 15 minutes), disable the startracker from the control loop
    - Exclude the unit from the device mask (turned off to save power), leading to a transition back to *CTAP*
    - Stop the ACS log and download it

    This procedure nearly represents nominal operations, the only difference is that ACS logs are collected instead of observations made. This procedure was performed several times to fully characterise the pointing performance in *FTAP* and in addition find the optimal settings for the startracker (e.g. warm-up period decreased from 20 to 3-5 minutes.)

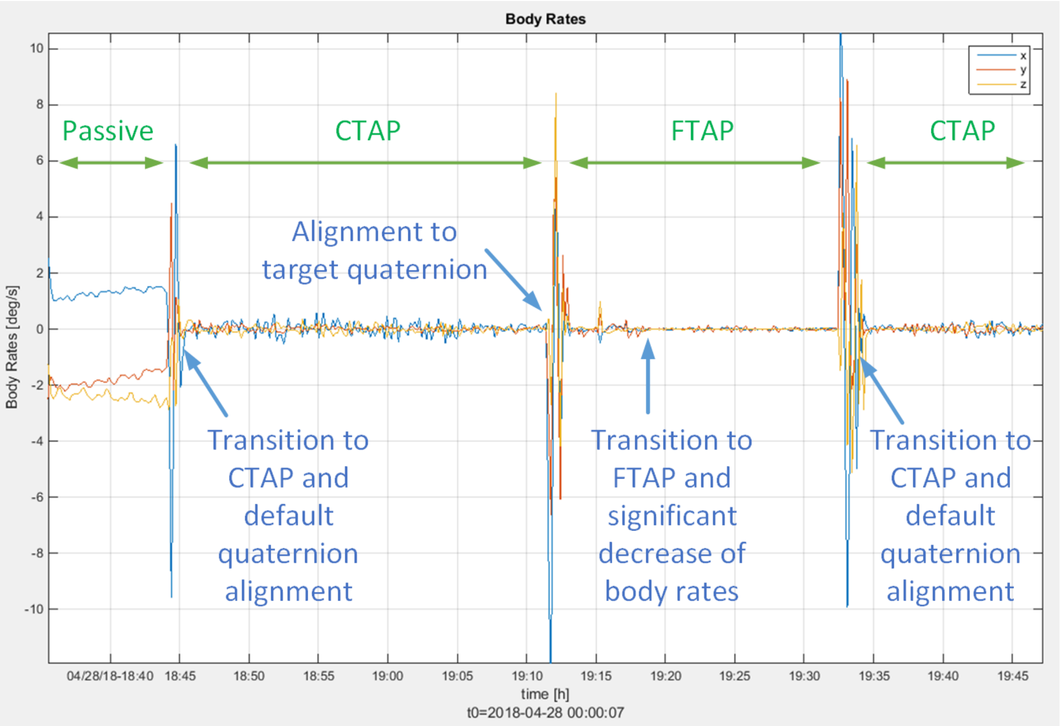


Figure 4.22: Body rates of BRITE-Austria during passive, CTAP and FTAP: The screenshot shows the respective body rates of the spacecraft while transitioning between the attitude modes *passive determination*, *CTAP*, *FTAP*, and *CTAP* again during one hour.

In addition, during several *FTAP* attempts also full frame images and science data records (SDRs) were obtained, to verify the operations cycle on the one hand, and to assess the pointing performance by investigation of the pixel variations of the target stars in the SDR rasters. The analysis of the latter showed that a pointing accuracy of 2 arcminutes was fully compliant with the mission requirements. The respective fine pointing root mean square (RMS) error was within 73 arcseconds.

16. **Payload commissioning**
    Several full frame images and SDRs were obtained in *CTAP*, to characterise the effects on the CCD concerning ”hot pixels” and to verify the observation cycle. Given the data and SDRs, the exposure times and delays between exposures were optimized. In addition, the performance of the instrument was verified by observation of pre-selected commissioning star fields.

Although the commissioning phase has been successfully completed, additional challenges had to be faced during the first months in-orbit and the FTAP performance and stability needed to be optimized (e.g. by calibrating the magnetometer in-orbit, more information on the challenges during operations can be found in Section 7.2) before nominal operations could be started.

Chapter 5

Mission Planning and Nominal Operations

This section describes in detail the nominal operations of the BRITE-Austria spacecraft. An insight is given on observations planning and satellite setup, followed by a short explanation on the ground segment software used for satellite operations and performance analysis. The section concludes with a description of the data dissemination strategy and support processes [42] [43].

5.1 Scientific Observation Planning

The scientific goal of BRITE-Austria is to observe the brightness oscillations of bright stars in observation campaigns, lasting from weeks to several months. The target fields are selected by the BRITE Executive Science Team (BEST), according to proposals received from the scientific community, and an observing programme for the upcoming months is prepared. The individual BRITE satellites are then assigned to the target fields, and the respective observation plan is forwarded to the mission control and operations team of the individual spacecraft.

In case a new target field is selected, the following procedure is executed on the part of the BRITE-Austria operations team, in cooperation with the BRITE-Austria payload scientist [43]:

1. Schedule the observation window
2. Perform fine pointing attempts on the given field
3. Take exposure of the entire Field of View (FOV) and create Setup File (science parameters for observation)
4. Define observation scripts
5. Schedule the individual observations

6. Generate time tagged commands (TTCs) for autonomous execution of observations
7. Upload all scripts, files and commands manually
8. Download of telemetry and science data records (SDRs) and further analysis of:
    - three-axis pointing performance
    - satellite's health status
    - scientific output of the first observation attempts
9. In case a stable configuration is found, nominal operations can start (otherwise restart at step 2)

The steps listed in the procedure above are explained in more detail in the next paragraphs.

5.1.1 Scheduling of Observation Windows

Each observation target is defined by the centre coordinates of the FOV, stating right ascension (RA), declination (DEC), and roll angles of the field. Several observation campaigns have already been conducted with BRITE-Austria (see Section 6.1 Scientific Performance). Table 5.1 highlights the coordinates of the most observed star fields Orion (5), Vela/Puppis (4), Sagittarius (4), and Cassiopeia (3) as example.

Target	**RA**	**DEC**	**Roll**
Orion	05 19 00	-00 45 00	-170
Vela/Puppis	08 40 00	-47 30 00	+180
Sagittarius	17 57 00	-32 50 00	+180
Cassiopeia	00 33 00	+65 00 00	+180

Table 5.1: Target centre coordinates: The target centre coordinates of the star fields with the most observations campaigns conducted with BRITE-Austria are stated.

The centre coordinates have to be converted to a so-called quaternion, which maps the body frame of the telescope/satellite to the inertial frame. It is a four element coordinate, where the last element is the scalar component [q1 q2 q3 q4].

The RA, DEC and roll values are converted to radian and the rotation matrix from inertial to telescope frame is as follows:

$$rot_{in2tel} = \begin{bmatrix} cos(DEC) \cdot cos(RA) & cos(DEC) \cdot sin(RA) & -sin(DEC) \\ \begin{matrix} -cos(roll) \cdot sin(RA) \\ +sin(roll) \cdot sin(DEC) \\ \cdot cos(RA) \end{matrix} & \begin{matrix} cos(roll) \cdot cos(RA) \\ +sin(roll) \cdot sin(DEC) \\ \cdot sin(RA) \end{matrix} & sin(roll) \cdot cos(DEC) \\ \begin{matrix} sin(roll) \cdot sin(RA) \\ +cos(roll) \cdot sin(DEC) \\ \cdot cos(RA) \end{matrix} & \begin{matrix} -sin(roll) \cdot cos(RA) \\ +cos(roll) \cdot sin(DEC) \\ \cdot sin(RA) \end{matrix} & cos(roll) \cdot cos(DEC) \end{bmatrix} \tag{5.1}$$

As the telescope is looking at the target field, a rotation around the Z axis by 180° is needed.

$$rot_{body2tel} = \begin{bmatrix} cos(\pi) & sin(\pi) & 0 \\ -sin(\pi) & cos(\pi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.2}$$

$$rot_{in2body} = rot_{in2tel} \cdot rot_{body2tel} \tag{5.3}$$

Given the final 3 x 3 matrix, the scalar element and the other quaternion values can be calculated.

$$q4 = -0.5 \cdot \sqrt{1 + rot_{in2body}[1,1] + rot_{in2body}[2,2] + rot_{in2body}[3,3]} \tag{5.4}$$

$$q1 = 0.25 \cdot \frac{1}{q4} \cdot (rot_{in2body}[2,3] - rot_{in2body}[3,2]) \tag{5.5}$$

$$q2 = 0.25 \cdot \frac{1}{q4} \cdot (rot_{in2body}[3,1] - rot_{in2body}[1,3]) \tag{5.6}$$

$$q3 = 0.25 \cdot \frac{1}{q4} \cdot (rot_{in2body}[1,2] - rot_{in2body}[2,1]) \tag{5.7}$$

In case q4 equals 0, the equations are the following:

$$q1 = \sqrt{0.5 \cdot (1 + rot_{in2body}[1,1])} \tag{5.8}$$

$$q2 = \sqrt{0.5 \cdot (1 + rot_{in2body}[2,2])} \tag{5.9}$$

$$q3 = \sqrt{0.5 \cdot (1 + rot_{in2body}[3,3])} \tag{5.10}$$

The values are then normalised and the resulting vector corresponds to the target quaternion.

Given the quaternion of the target field as well as the orbit parameters of the satellite, with the help of a prediction tool (AGI Systems Tool Kit (STK) ® [8]) the observation windows (the timeframe, in which a target field is in the FOV of the startracker) are calculated. The screenshot below depicts the satellite on its orbit track and the startracker pointing at the Cassiopeia target field.

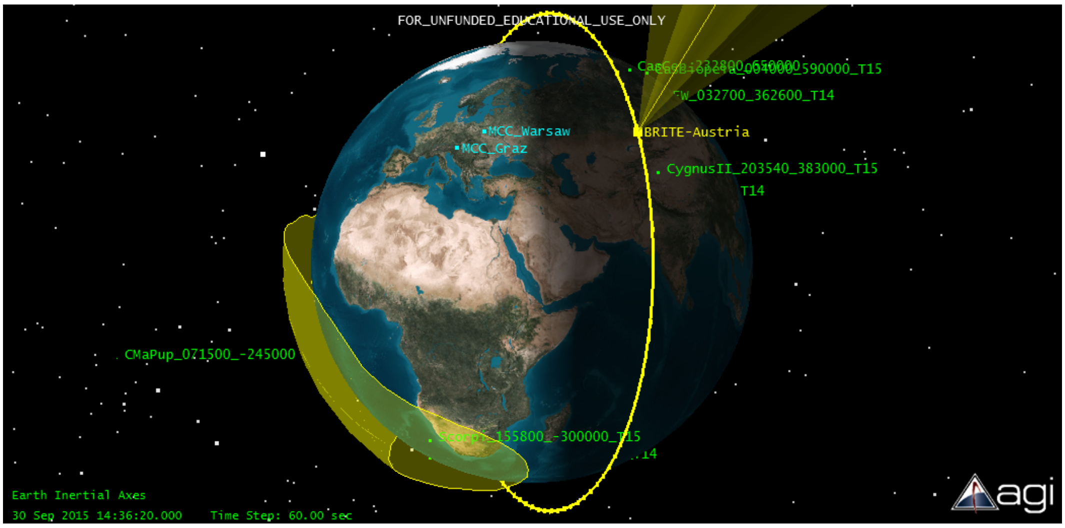


Figure 5.1: BRITE-Austria oriented to Cassiopeia: BRITE-Austria's orbit track and telescope/startracker oriented at the Cassiopeia field is shown. (Image courtesy: STK)

5.1.2 Three-Axis Fine Pointing Attempts on Target Field

After the simulation of the observation windows, the first attempts to achieve *fine pointing* at the target field can be performed. The startracker used on-board of BRITE-Austria is very sensitive to straylight and therefore, in case *fine pointing* is not achieved during the first trials, different approaches have to be investigated.

A tuning of the parameters of the startracker itself (e.g. gain, exposure time) as well as shifting the time when a transition from *CTAP* to *FTAP* occurs might be worth investigating.

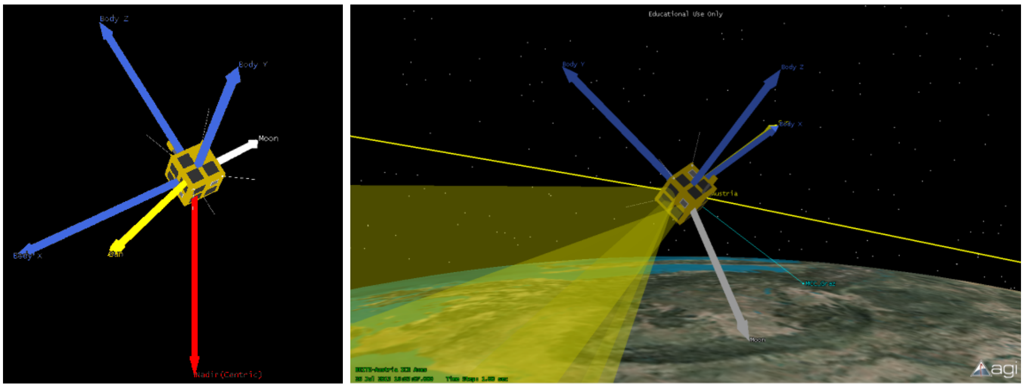


Figure 5.2: Attitude of and sensor location on BRITE-Austria: The attitude of the satellite and the position of the sensors regarding the incoming light sources (Sun, Moon, albedo) are investigated thoroughly. (Image courtesy: STK)

In particular, the arctic regions as well as the Pacific when illuminated by the Sun are very challenging and are influencing the startracker quaternion resolution negatively. The fact, that the startracker is not equipped with a baffle, increases the challenging task of getting into *fine pointing*.

The performance was analysed during several overflights of the satellite over the arctic regions. It was discovered that the different orbits and therefore overflight directions of the satellite yield to different behaviour of the startracker.

To describe the behaviour in more detail, two consecutive orbits of BRITE-Austria, as it crossed the arctic region, are analysed. The respective orbit track and telescope orientation to Cassiopeia is shown. During the *fine pointing* attempt an ACS log was gathered, which gave insight in the startracker quaternion resolution.

1. While crossing the arctic region, in the orientation shown, a transition to *FTAP* was not successful.

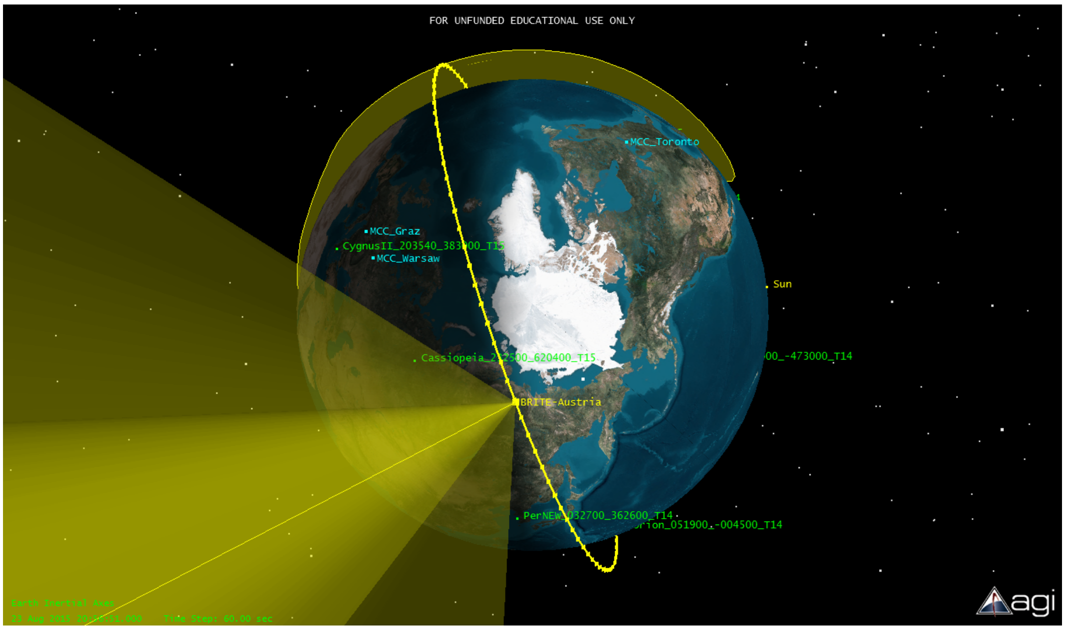


Figure 5.3: BRITE-Austria orbit track 1, passing the arctic regions: The straylight of the arctic regions influence the startracker performance negatively (satellite oriented at Cassiopeia field). (Image courtesy: STK)

The startracker quaternion resolution in Figure 5.4 shows several dropouts, which leads to unsuccessful transition to *FTAP* and hence the loss of attitude stabilisation.

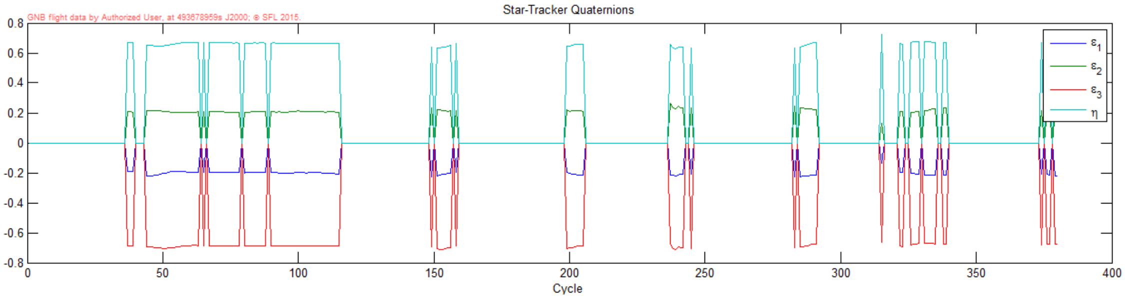


Figure 5.4: Startracker quaternions to orbit track 1: During the overflight, an ACS log was collected and the startracker quaternion resolution at the Cassiopeia field is given.

2. After one orbit (orbit period 1̃00 min), the spacecraft passes again the arctic region, where an ACS log was collected and a transition to *FTAP* was attempted.

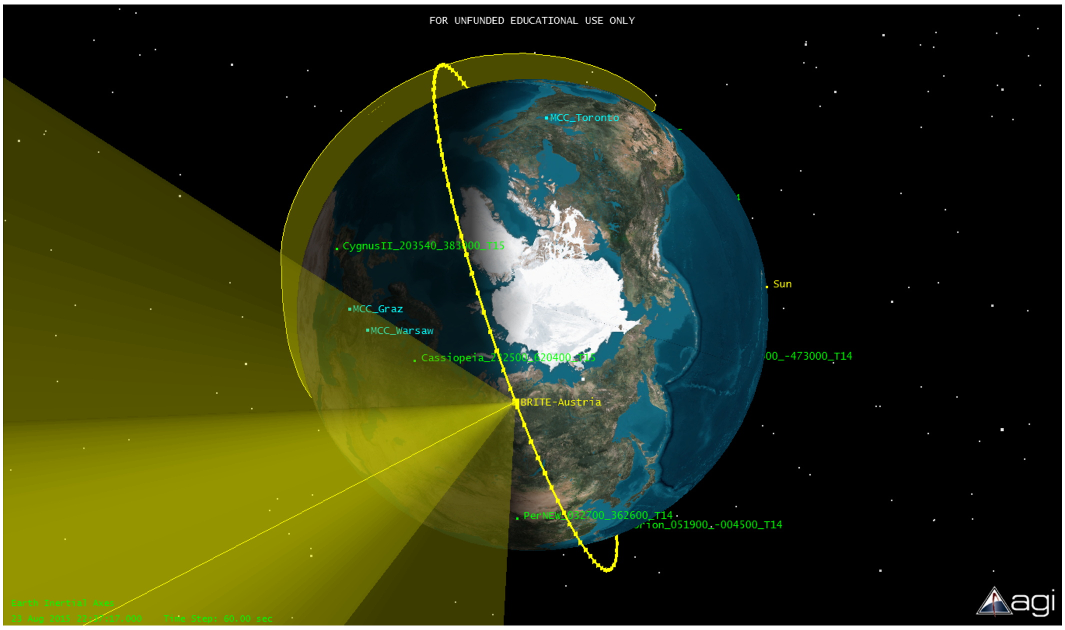


Figure 5.5: BRITE-Austria orbit track 2, passing the arctic regions: The consecutive orbit indicating a slightly different overflight angle (still oriented at Cassiopeia field). (Image courtesy: STK)

Compared to Figure 5.4, Figure 5.6 shows that just on the consecutive orbit the startracker reliably produced quaternions and therefore the transition to *FTAP* was successful.

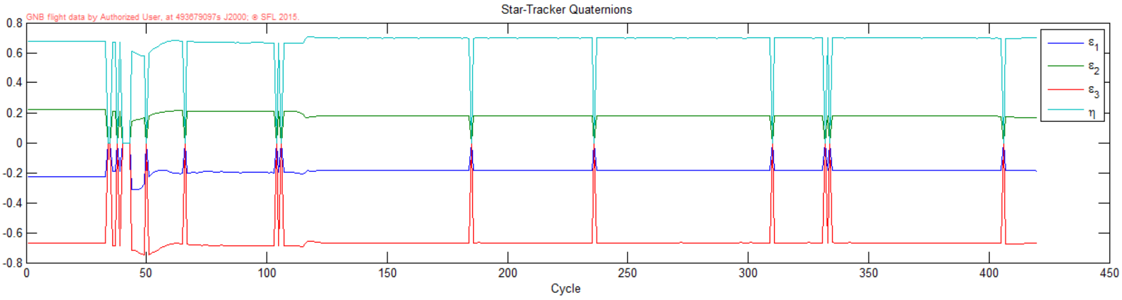


Figure 5.6: Startracker quaternions to orbit track 2: The collected ACS log shows that quaternions are delivered continously by the startracker.

Given these straylight conditions, observations of targets in the northern hemisphere are challenging during the summer, and observations of targets in the southern hemisphere need more investigation during the winter period. The straylight not only influences the startracker performance but also is affecting the instrument. The following two CCD readouts show the effect of straylight on the detector.

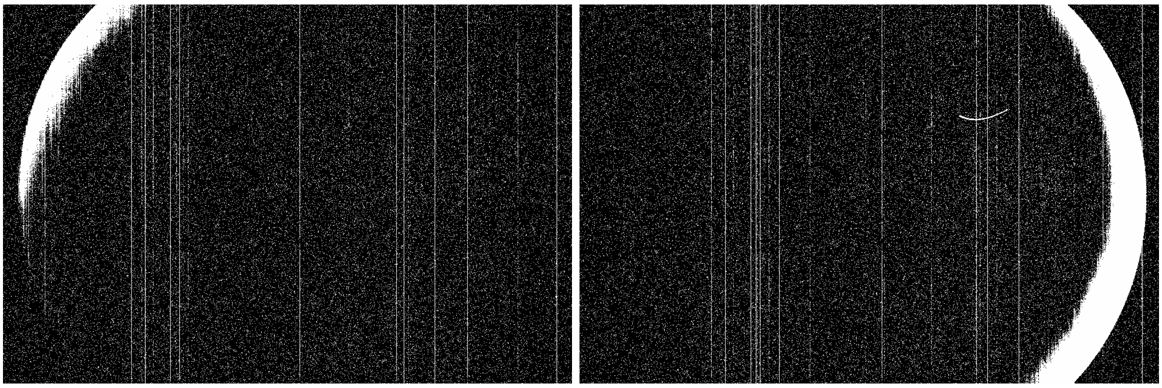


Figure 5.7: Straylight effect on the CCD detector: Depending on the orientation of the spacecraft, various straylight from the Earth or direct light of the Sun or Moon can illuminate parts of the detector.

5.1.3 Full Frame Exposure of Target Field and Setup File Generation

Once *FTAP* could be achieved at the desired target field, a full frame exposure is taken with the instrument. The full frame image is downloaded and analysed by the scientific coordinator / payload engineer. The stars of interest are selected and the regions of interest on the CCD (so-called rasters) are defined.

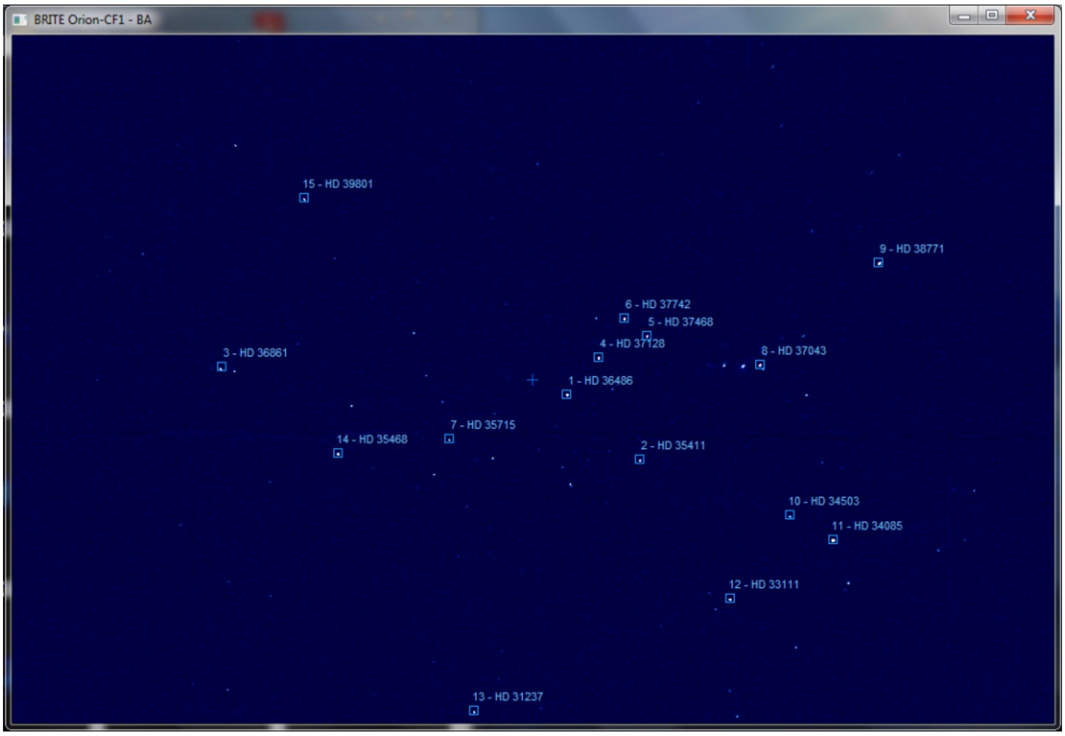


Figure 5.8: Full frame image of Orion: The stars of interest are selected and rasters are defined.

Given the rasters, the science observation setup file is generated. The setup file is generated individually for each target. It contains all relevant parameters needed to carry out the scientific observations, e.g. raster positions and sizes, exposure times and delays.

The setup file is generated by the scientific coordinator and forwarded to the operations team.

5.1.4 Definition of Observation Scripts

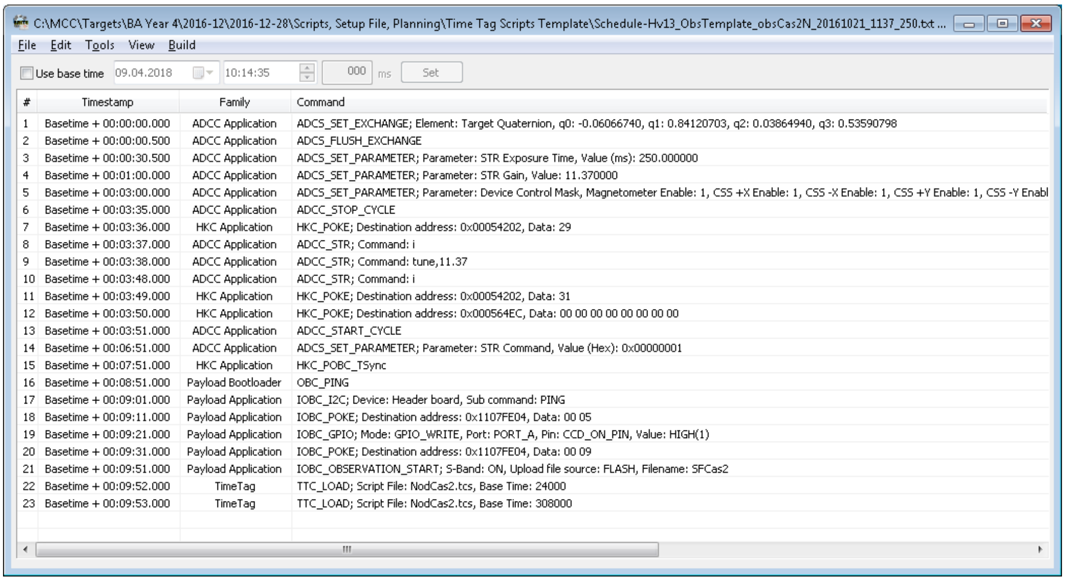
The nominal observation cycle includes the following steps:

- Activation of the startracker by inclusion in the device control mask and awaiting a warm-up period for reliable operation (typically 3 minutes)
- Transition to *FTAP* by actively including the startracker in the attitude determination and control loop
- Start of observation and collection of science data records (SDRs) for typically 10-15 min
- Exclusion of the startracker from the device control mask and transition back to *CTAP*

For this purpose, scripts are defined, which contain the set of commands necessary for the observation cycle. These scripts are generated with *BRITE Schedule*, a software module which provides a list of commands for the different systems on-board the satellite. For each so-called time tagged command script (TTC script), the command sequence with appropriate offset times is generated and exported to a binary script file for upload to the spacecraft.

To be flexible on the observation start/stop time and to optimize the duration taking into account the constraints (see next Point 5.), it was decided to introduce an observation start script and an observation stop script instead of combining all the necessary commands in one script.

At the beginning of the observation start script, a change to the new target field (position is defined by a quaternion) occurs. Afterwards the startracker parameters are set, the device mask is set and the startracker gets included into the Attitude Control System (ACS) cycle. The instrument is then initialised and the observation is started using the respective setup file.

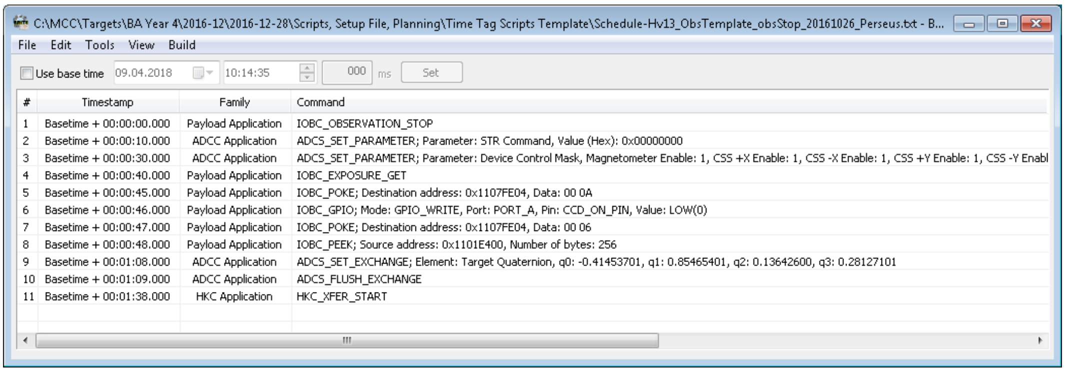


☐ Use base time 09.04.2018 10:14:35 000 ms

#	Timestamp	Family	Command
1	Basetime + 00:00:00.000	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.06066740, q1: 0.84120703, q2: 0.03864940, q3: 0.53590798
2	Basetime + 00:00:00.500	ADCC Application	ADCS_FLUSH_EXCHANGE
3	Basetime + 00:00:30.500	ADCC Application	ADCS_SET_PARAMETER; Parameter: STR Exposure Time, Value (ms): 250.000000
4	Basetime + 00:01:00.000	ADCC Application	ADCS_SET_PARAMETER; Parameter: STR Gain, Value: 11.370000
5	Basetime + 00:03:00.000	ADCC Application	ADCS_SET_PARAMETER; Parameter: Device Control Mask, Magnetometer Enable: 1, CSS +X Enable: 1, CSS -X Enable: 1, CSS +Y Enable: 1, CSS -Y Enabl
6	Basetime + 00:03:35.000	ADCC Application	ADCC_STOP_CYCLE
7	Basetime + 00:03:36.000	HKC Application	HKC_POKE; Destination address: 0x00054202, Data: 29
8	Basetime + 00:03:37.000	ADCC Application	ADCC_STR; Command: i
9	Basetime + 00:03:38.000	ADCC Application	ADCC_STR; Command: tune,11.37
10	Basetime + 00:03:48.000	ADCC Application	ADCC_STR; Command: i
11	Basetime + 00:03:49.000	HKC Application	HKC_POKE; Destination address: 0x00054202, Data: 31
12	Basetime + 00:03:50.000	HKC Application	HKC_POKE; Destination address: 0x000564EC, Data: 00 00 00 00 00 00 00 00
13	Basetime + 00:03:51.000	ADCC Application	ADCC_START_CYCLE
14	Basetime + 00:06:51.000	ADCC Application	ADCS_SET_PARAMETER; Parameter: STR Command, Value (Hex): 0x00000001
15	Basetime + 00:07:51.000	HKC Application	HKC_POBC_TSync
16	Basetime + 00:08:51.000	Payload Bootloader	OBC_PING
17	Basetime + 00:09:01.000	Payload Application	IOBC_I2C; Device: Header board, Sub command: PING
18	Basetime + 00:09:11.000	Payload Application	IOBC_POKE; Destination address: 0x1107FE04, Data: 00 05
19	Basetime + 00:09:21.000	Payload Application	IOBC_GPIO; Mode: GPIO_WRITE, Port: PORT_A, Pin: CCD_ON_PIN, Value: HIGH(1)
20	Basetime + 00:09:31.000	Payload Application	IOBC_POKE; Destination address: 0x1107FE04, Data: 00 09
21	Basetime + 00:09:51.000	Payload Application	IOBC_OBSERVATION_START; S-Band: ON, Upload file source: FLASH, Filename: SFCas2
22	Basetime + 00:09:52.000	TimeTag	TTC_LOAD; Script File: NodCas2.tcs, Base Time: 24000
23	Basetime + 00:09:53.000	TimeTag	TTC_LOAD; Script File: NodCas2.tcs, Base Time: 308000

Figure 5.9: Observation start script: The observation start script combines the commands needed to setup the attitude control system as well as initialise and start the observations (the obs-start script of Cassiopeia is shown).

When executing the observation stop script, the scientific observations are stopped and a transition from *fine* to *coarse pointing* occurs (by excluding the startracker out of the device mask). Besides, the instrument header board is turned off and the data is transferred to the housekeeping computer to allow faster download afterwards. In addition, as the satellite gets heated up in sunlight and cools down during eclipse respectively, a change to a target quaternion is introduced at the end of the script to maintain a better thermal balance within the satellite.



☐ Use base time 09.04.2018 10:14:35 000 ms

#	Timestamp	Family	Command
1	Basetime + 00:00:00.000	Payload Application	IOBC_OBSERVATION_STOP
2	Basetime + 00:00:10.000	ADCC Application	ADCS_SET_PARAMETER; Parameter: STR Command, Value (Hex): 0x00000000
3	Basetime + 00:00:30.000	ADCC Application	ADCS_SET_PARAMETER; Parameter: Device Control Mask, Magnetometer Enable: 1, CSS +X Enable: 1, CSS -X Enable: 1, CSS +Y Enable: 1, CSS -Y Enabl
4	Basetime + 00:00:40.000	Payload Application	IOBC_EXPOSURE_GET
5	Basetime + 00:00:45.000	Payload Application	IOBC_POKE; Destination address: 0x1107FE04, Data: 00 0A
6	Basetime + 00:00:46.000	Payload Application	IOBC_GPIO; Mode: GPIO_WRITE, Port: PORT_A, Pin: CCD_ON_PIN, Value: LOW(0)
7	Basetime + 00:00:47.000	Payload Application	IOBC_POKE; Destination address: 0x1107FE04, Data: 00 06
8	Basetime + 00:00:48.000	Payload Application	IOBC_PEEK; Source address: 0x1101E400, Number of bytes: 256
9	Basetime + 00:01:08.000	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.41453701, q1: 0.85465401, q2: 0.13642600, q3: 0.28127101
10	Basetime + 00:01:09.000	ADCC Application	ADCS_FLUSH_EXCHANGE
11	Basetime + 00:01:38.000	HKC Application	HKC_XFER_START

Figure 5.10: Observation stop script: When executing the observation stop script, the observations are stopped and the header board and startracker are turned off. The scientific data are transferred to the HKC and a change to a target quaternion is commanded (in case of Cassiopeia, a change to the Perseus field is performed for thermal balance).

5.1.5 Scheduling of Individual Observations

A target field is typically visible for half the orbit (about 50 minutes/orbit). However, the system is subject to several restrictions, which need to be taken into account when scheduling the individual observations:

- **Exclusion angles** (Sun, Moon, Earth)
  To operate the ADCS and especially the startracker reliably, it has to be ensured, that the startracker is pointed away from the Sun by 90°and from the Moon by 20°at a minimum. These values were determined and verified during the commissioning phase.

  In addition, the angle between the Earth horizon and the startracker should be at least 40°at the beginning of the visibility and 25°at the end. As the startracker is not equipped with a baffle to reduce the straylight (see next paragraph), these values were optimised during the commissioning phase and first exposure attempts to ensure a high success rate in *FTAP* transitions.

- **Straylight** (Arctica/Antarctica)
  The startracker used on BRITE-Austria is very sensitive to straylight from the Pacific and the arctic regions. Therefore, the time offsets of the start of observation have to be adapted individually. This effect however also increased the degree of manual observation planning to maximise the scientific output.

- **South Atlantic Anomaly** (SAA)
  When flying through the SAA, it was found during the commissioning phase, that the startracker does not yield quaternions reliable due to incoming energised particles. As optical sensors per se (as used in the startracker and the instrument) are quite sensitive to radiation, both subsystems are not turned on when passing the SAA to avoid faster degradation of the systems.

- **Ground station passes**
  Due to heavy interference in the Ultra High Frequency (UHF) band over Europe, nadir tracking was introduced to overcome shortages in the uplink data volume. The satellite is re-oriented to point the antennas to ground shortly before pass start and after 20 minutes it changes the direction to the position used before. In this phase, observations are not possible and therefore ground station passes have to be taken into account (see Section 7.2 for more information on the interference).

- **Eclipse season**
  Special operations procedures are needed as *fine pointing transitions* during eclipse are quite unreliable, as the determination is only performed with the coarse magnetometer; therefore special focus is laid on the time of startracker activation. During the first eclipse season in winter 2013 it was found, that the chance of a successful transition to *FTAP* increases, if the startracker is turned on shortly before or immediately after the eclipse. Therefore, this fact was also considered in the observation scheduling plan.

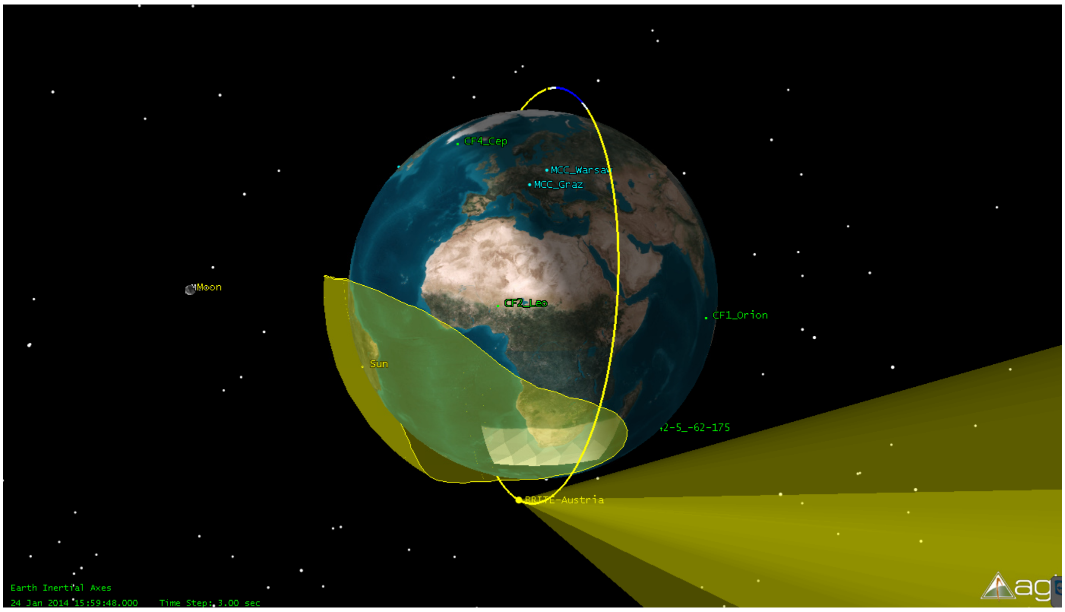
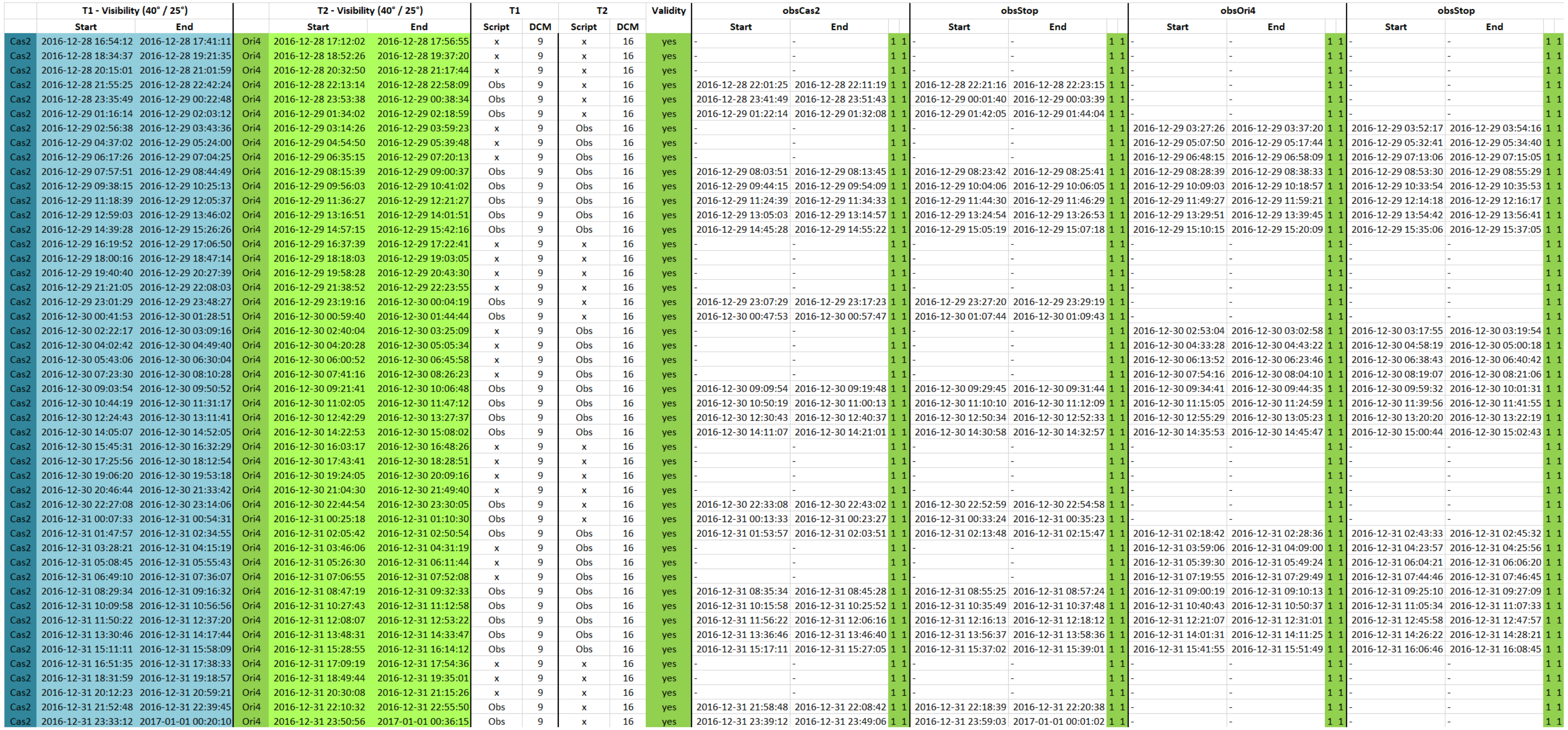


Figure 5.11: Constraints in observations: BRITE-Austria is subject to several operational constraints: the SAA (yellow highlighted area), eclipse season (blue part of the orbit track), ground station passes, straylight and exclusion angles. (Image courtesy: STK)

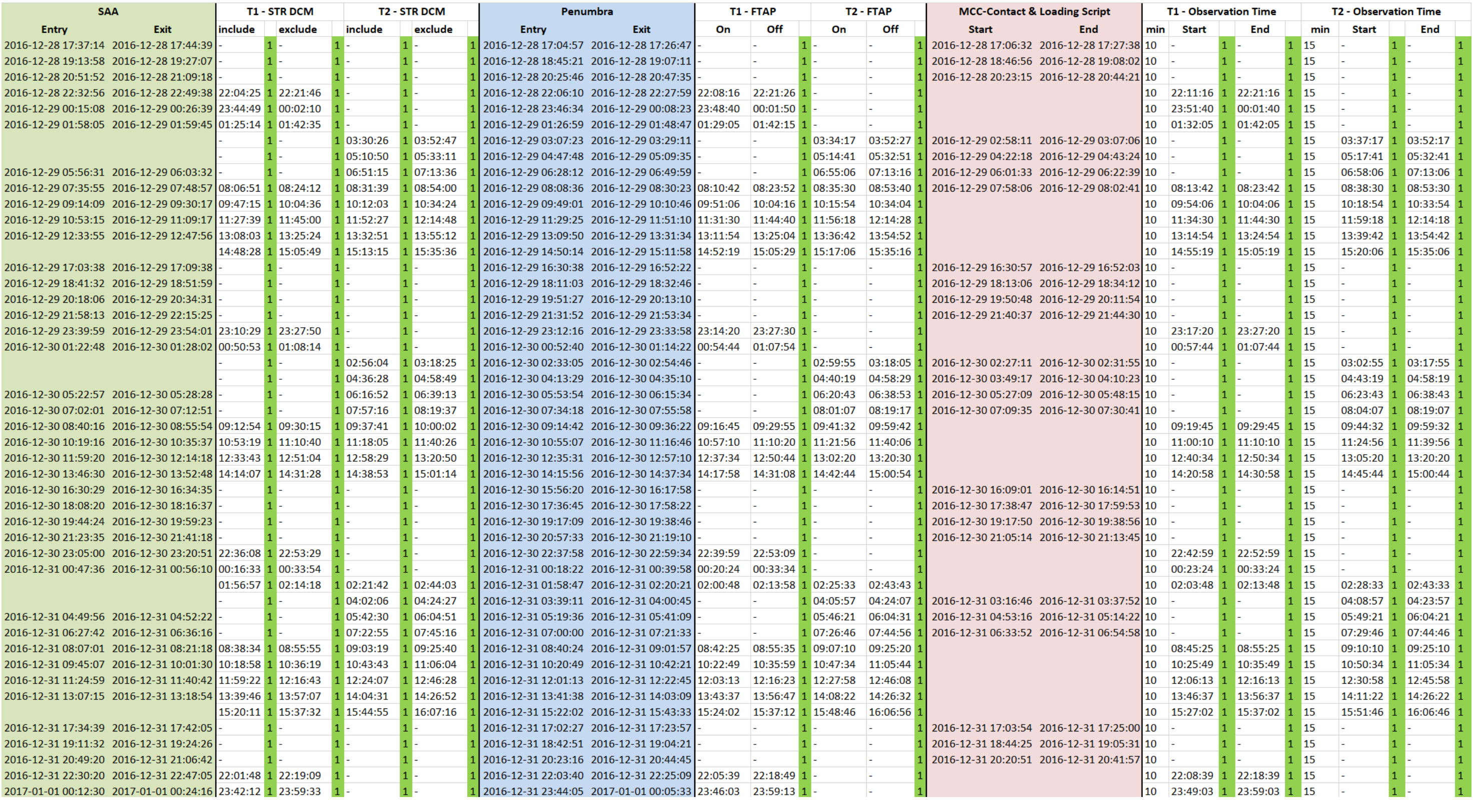
The following table gives an example, how complex the calculation of timestamps for the execution of the observation scripts is. The example shows an extract of a dual observation campaign in the last days of 2016 (Cassiopeia and Orion were observed every orbit if possible).

Given the visibility of the two target fields, the desired observation duration and taking into account the current constraints, the timestamps for the respective start and stop scripts are calculated.



	T1 - Visibility (40° / 25°)			T2 - Visibility (40° / 25°)		T1		T2		Validity	obsCas2				obsStop				obsOri4				obsStop			
	Start	End		Start	End	Script	DCM	Script	DCM		Start	End			Start	End			Start	End			Start	End		
Cas2	2016-12-28 16:54:12	2016-12-28 17:41:11	Ori4	2016-12-28 17:12:02	2016-12-28 17:56:55	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-28 18:34:37	2016-12-28 19:21:35	Ori4	2016-12-28 18:52:26	2016-12-28 19:37:20	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-28 20:15:01	2016-12-28 21:01:59	Ori4	2016-12-28 20:32:50	2016-12-28 21:17:44	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-28 21:55:25	2016-12-28 22:42:24	Ori4	2016-12-28 22:13:14	2016-12-28 22:58:09	Obs	9	x	16	yes	2016-12-28 22:01:25	2016-12-28 22:11:19	1	1	2016-12-28 22:21:16	2016-12-28 22:23:15	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-28 23:35:49	2016-12-29 00:22:48	Ori4	2016-12-28 23:53:38	2016-12-29 00:38:34	Obs	9	x	16	yes	2016-12-28 23:41:49	2016-12-28 23:51:43	1	1	2016-12-29 00:01:40	2016-12-29 00:03:39	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 01:16:14	2016-12-29 02:03:12	Ori4	2016-12-29 01:34:02	2016-12-29 02:18:59	Obs	9	x	16	yes	2016-12-29 01:22:14	2016-12-29 01:32:08	1	1	2016-12-29 01:42:05	2016-12-29 01:44:04	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 02:56:38	2016-12-29 03:43:36	Ori4	2016-12-29 03:14:26	2016-12-29 03:59:23	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-29 03:27:26	2016-12-29 03:37:20	1	1	2016-12-29 03:52:17	2016-12-29 03:54:16	1	1
Cas2	2016-12-29 04:37:02	2016-12-29 05:24:00	Ori4	2016-12-29 04:54:50	2016-12-29 05:39:48	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-29 05:07:50	2016-12-29 05:17:44	1	1	2016-12-29 05:32:41	2016-12-29 05:34:40	1	1
Cas2	2016-12-29 06:17:26	2016-12-29 07:04:25	Ori4	2016-12-29 06:35:15	2016-12-29 07:20:13	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-29 06:48:15	2016-12-29 06:58:09	1	1	2016-12-29 07:13:06	2016-12-29 07:15:05	1	1
Cas2	2016-12-29 07:57:51	2016-12-29 08:44:49	Ori4	2016-12-29 08:15:39	2016-12-29 09:00:37	Obs	9	Obs	16	yes	2016-12-29 08:03:51	2016-12-29 08:13:45	1	1	2016-12-29 08:23:42	2016-12-29 08:25:41	1	1	2016-12-29 08:28:39	2016-12-29 08:38:33	1	1	2016-12-29 08:53:30	2016-12-29 08:55:29	1	1
Cas2	2016-12-29 09:38:15	2016-12-29 10:25:13	Ori4	2016-12-29 09:56:03	2016-12-29 10:41:02	Obs	9	Obs	16	yes	2016-12-29 09:44:15	2016-12-29 09:54:09	1	1	2016-12-29 10:04:06	2016-12-29 10:06:05	1	1	2016-12-29 10:09:03	2016-12-29 10:18:57	1	1	2016-12-29 10:33:54	2016-12-29 10:35:53	1	1
Cas2	2016-12-29 11:18:39	2016-12-29 12:05:37	Ori4	2016-12-29 11:36:27	2016-12-29 12:21:27	Obs	9	Obs	16	yes	2016-12-29 11:24:39	2016-12-29 11:34:33	1	1	2016-12-29 11:44:30	2016-12-29 11:46:29	1	1	2016-12-29 11:49:27	2016-12-29 11:59:21	1	1	2016-12-29 12:14:18	2016-12-29 12:16:17	1	1
Cas2	2016-12-29 12:59:03	2016-12-29 13:46:02	Ori4	2016-12-29 13:16:51	2016-12-29 14:01:51	Obs	9	Obs	16	yes	2016-12-29 13:05:03	2016-12-29 13:14:57	1	1	2016-12-29 13:24:54	2016-12-29 13:26:53	1	1	2016-12-29 13:29:51	2016-12-29 13:39:45	1	1	2016-12-29 13:54:42	2016-12-29 13:56:41	1	1
Cas2	2016-12-29 14:39:28	2016-12-29 15:26:26	Ori4	2016-12-29 14:57:15	2016-12-29 15:42:16	Obs	9	Obs	16	yes	2016-12-29 14:45:28	2016-12-29 14:55:22	1	1	2016-12-29 15:05:19	2016-12-29 15:07:18	1	1	2016-12-29 15:10:15	2016-12-29 15:20:09	1	1	2016-12-29 15:35:06	2016-12-29 15:37:05	1	1
Cas2	2016-12-29 16:19:52	2016-12-29 17:06:50	Ori4	2016-12-29 16:37:39	2016-12-29 17:22:41	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 18:00:16	2016-12-29 18:47:14	Ori4	2016-12-29 18:18:03	2016-12-29 19:03:05	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 19:40:40	2016-12-29 20:27:39	Ori4	2016-12-29 19:58:28	2016-12-29 20:43:30	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 21:21:05	2016-12-29 22:08:03	Ori4	2016-12-29 21:38:52	2016-12-29 22:23:55	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-29 23:01:29	2016-12-29 23:48:27	Ori4	2016-12-29 23:19:16	2016-12-30 00:04:19	Obs	9	x	16	yes	2016-12-29 23:07:29	2016-12-29 23:17:23	1	1	2016-12-29 23:27:20	2016-12-29 23:29:19	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 00:41:53	2016-12-30 01:28:51	Ori4	2016-12-30 00:59:40	2016-12-30 01:44:44	Obs	9	x	16	yes	2016-12-30 00:47:53	2016-12-30 00:57:47	1	1	2016-12-30 01:07:44	2016-12-30 01:09:43	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 02:22:17	2016-12-30 03:09:16	Ori4	2016-12-30 02:40:04	2016-12-30 03:25:09	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-30 02:53:04	2016-12-30 03:02:58	1	1	2016-12-30 03:17:55	2016-12-30 03:19:54	1	1
Cas2	2016-12-30 04:02:42	2016-12-30 04:49:40	Ori4	2016-12-30 04:20:28	2016-12-30 05:05:34	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-30 04:33:28	2016-12-30 04:43:22	1	1	2016-12-30 04:58:19	2016-12-30 05:00:18	1	1
Cas2	2016-12-30 05:43:06	2016-12-30 06:30:04	Ori4	2016-12-30 06:00:52	2016-12-30 06:45:58	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-30 06:13:52	2016-12-30 06:23:46	1	1	2016-12-30 06:38:43	2016-12-30 06:40:42	1	1
Cas2	2016-12-30 07:23:30	2016-12-30 08:10:28	Ori4	2016-12-30 07:41:16	2016-12-30 08:26:23	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-30 07:54:16	2016-12-30 08:04:10	1	1	2016-12-30 08:19:07	2016-12-30 08:21:06	1	1
Cas2	2016-12-30 09:03:54	2016-12-30 09:50:52	Ori4	2016-12-30 09:21:41	2016-12-30 10:06:48	Obs	9	Obs	16	yes	2016-12-30 09:09:54	2016-12-30 09:19:48	1	1	2016-12-30 09:29:45	2016-12-30 09:31:44	1	1	2016-12-30 09:34:41	2016-12-30 09:44:35	1	1	2016-12-30 09:59:32	2016-12-30 10:01:31	1	1
Cas2	2016-12-30 10:44:19	2016-12-30 11:31:17	Ori4	2016-12-30 11:02:05	2016-12-30 11:47:12	Obs	9	Obs	16	yes	2016-12-30 10:50:19	2016-12-30 11:00:13	1	1	2016-12-30 11:10:10	2016-12-30 11:12:09	1	1	2016-12-30 11:15:05	2016-12-30 11:24:59	1	1	2016-12-30 11:39:56	2016-12-30 11:41:55	1	1
Cas2	2016-12-30 12:24:43	2016-12-30 13:11:41	Ori4	2016-12-30 12:42:29	2016-12-30 13:27:37	Obs	9	Obs	16	yes	2016-12-30 12:30:43	2016-12-30 12:40:37	1	1	2016-12-30 12:50:34	2016-12-30 12:52:33	1	1	2016-12-30 12:55:29	2016-12-30 13:05:23	1	1	2016-12-30 13:20:20	2016-12-30 13:22:19	1	1
Cas2	2016-12-30 14:05:07	2016-12-30 14:52:05	Ori4	2016-12-30 14:22:53	2016-12-30 15:08:02	Obs	9	Obs	16	yes	2016-12-30 14:11:07	2016-12-30 14:21:01	1	1	2016-12-30 14:30:58	2016-12-30 14:32:57	1	1	2016-12-30 14:35:53	2016-12-30 14:45:47	1	1	2016-12-30 15:00:44	2016-12-30 15:02:43	1	1
Cas2	2016-12-30 15:45:31	2016-12-30 16:32:29	Ori4	2016-12-30 16:03:17	2016-12-30 16:48:26	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 17:25:56	2016-12-30 18:12:54	Ori4	2016-12-30 17:43:41	2016-12-30 18:28:51	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 19:06:20	2016-12-30 19:53:18	Ori4	2016-12-30 19:24:05	2016-12-30 20:09:16	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 20:46:44	2016-12-30 21:33:42	Ori4	2016-12-30 21:04:30	2016-12-30 21:49:40	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-30 22:27:08	2016-12-30 23:14:06	Ori4	2016-12-30 22:44:54	2016-12-30 23:30:05	Obs	9	x	16	yes	2016-12-30 22:33:08	2016-12-30 22:43:02	1	1	2016-12-30 22:52:59	2016-12-30 22:54:58	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 00:07:33	2016-12-31 00:54:31	Ori4	2016-12-31 00:25:18	2016-12-31 01:10:30	Obs	9	x	16	yes	2016-12-31 00:13:33	2016-12-31 00:23:27	1	1	2016-12-31 00:33:24	2016-12-31 00:35:23	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 01:47:57	2016-12-31 02:34:55	Ori4	2016-12-31 02:05:42	2016-12-31 02:50:54	Obs	9	Obs	16	yes	2016-12-31 01:53:57	2016-12-31 02:03:51	1	1	2016-12-31 02:13:48	2016-12-31 02:15:47	1	1	2016-12-31 02:18:42	2016-12-31 02:28:36	1	1	2016-12-31 02:43:33	2016-12-31 02:45:32	1	1
Cas2	2016-12-31 03:28:21	2016-12-31 04:15:19	Ori4	2016-12-31 03:46:06	2016-12-31 04:31:19	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-31 03:59:06	2016-12-31 04:09:00	1	1	2016-12-31 04:23:57	2016-12-31 04:25:56	1	1
Cas2	2016-12-31 05:08:45	2016-12-31 05:55:43	Ori4	2016-12-31 05:26:30	2016-12-31 06:11:44	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-31 05:39:30	2016-12-31 05:49:24	1	1	2016-12-31 06:04:21	2016-12-31 06:06:20	1	1
Cas2	2016-12-31 06:49:10	2016-12-31 07:36:07	Ori4	2016-12-31 07:06:55	2016-12-31 07:52:08	x	9	Obs	16	yes	-	-	1	1	-	-	1	1	2016-12-31 07:19:55	2016-12-31 07:29:49	1	1	2016-12-31 07:44:46	2016-12-31 07:46:45	1	1
Cas2	2016-12-31 08:29:34	2016-12-31 09:16:32	Ori4	2016-12-31 08:47:19	2016-12-31 09:32:33	Obs	9	Obs	16	yes	2016-12-31 08:35:34	2016-12-31 08:45:28	1	1	2016-12-31 08:55:25	2016-12-31 08:57:24	1	1	2016-12-31 09:00:19	2016-12-31 09:10:13	1	1	2016-12-31 09:25:10	2016-12-31 09:27:09	1	1
Cas2	2016-12-31 10:09:58	2016-12-31 10:56:56	Ori4	2016-12-31 10:27:43	2016-12-31 11:12:58	Obs	9	Obs	16	yes	2016-12-31 10:15:58	2016-12-31 10:25:52	1	1	2016-12-31 10:35:49	2016-12-31 10:37:48	1	1	2016-12-31 10:40:43	2016-12-31 10:50:37	1	1	2016-12-31 11:05:34	2016-12-31 11:07:33	1	1
Cas2	2016-12-31 11:50:22	2016-12-31 12:37:20	Ori4	2016-12-31 12:08:07	2016-12-31 12:53:22	Obs	9	Obs	16	yes	2016-12-31 11:56:22	2016-12-31 12:06:16	1	1	2016-12-31 12:16:13	2016-12-31 12:18:12	1	1	2016-12-31 12:21:07	2016-12-31 12:31:01	1	1	2016-12-31 12:45:58	2016-12-31 12:47:57	1	1
Cas2	2016-12-31 13:30:46	2016-12-31 14:17:44	Ori4	2016-12-31 13:48:31	2016-12-31 14:33:47	Obs	9	Obs	16	yes	2016-12-31 13:36:46	2016-12-31 13:46:40	1	1	2016-12-31 13:56:37	2016-12-31 13:58:36	1	1	2016-12-31 14:01:31	2016-12-31 14:11:25	1	1	2016-12-31 14:26:22	2016-12-31 14:28:21	1	1
Cas2	2016-12-31 15:11:11	2016-12-31 15:58:09	Ori4	2016-12-31 15:28:55	2016-12-31 16:14:12	Obs	9	Obs	16	yes	2016-12-31 15:17:11	2016-12-31 15:27:05	1	1	2016-12-31 15:37:02	2016-12-31 15:39:01	1	1	2016-12-31 15:41:55	2016-12-31 15:51:49	1	1	2016-12-31 16:06:46	2016-12-31 16:08:45	1	1
Cas2	2016-12-31 16:51:35	2016-12-31 17:38:33	Ori4	2016-12-31 17:09:19	2016-12-31 17:54:36	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 18:31:59	2016-12-31 19:18:57	Ori4	2016-12-31 18:49:44	2016-12-31 19:35:01	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 20:12:23	2016-12-31 20:59:21	Ori4	2016-12-31 20:30:08	2016-12-31 21:15:26	x	9	x	16	yes	-	-	1	1	-	-	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 21:52:48	2016-12-31 22:39:45	Ori4	2016-12-31 22:10:32	2016-12-31 22:55:50	Obs	9	x	16	yes	2016-12-31 21:58:48	2016-12-31 22:08:42	1	1	2016-12-31 22:18:39	2016-12-31 22:20:38	1	1	-	-	1	1	-	-	1	1
Cas2	2016-12-31 23:33:12	2017-01-01 00:20:10	Ori4	2016-12-31 23:50:56	2017-01-01 00:36:15	Obs	9	x	16	yes	2016-12-31 23:39:12	2016-12-31 23:49:06	1	1	2016-12-31 23:59:03	2017-01-01 00:01:02	1	1	-	-	1	1	-	-	1	1

Figure 5.12: Observation scheduling - Part 1: Extract of the observation scheduling for BRITE-Austria for four days: the blue and bright green highlighted columns on the far left of the screenshot indicate the overall visibility windows for the two target fields (in this case Cassiopeia and Orion). The script start and stop times are calculated taking into account several constraints and timing offsets (see next figure).



SAA		T1 - STR DCM				T2 - STR DCM				Penumbra		T1 - FTAP			T2 - FTAP			MCC-Contact & Loading Script		T1 - Observation Time					T2 - Observation Time				
Entry	Exit	include		exclude		include		exclude		Entry	Exit	On	Off		On	Off		Start	End	min	Start		End		min	Start		End	
2016-12-28 17:37:14	2016-12-28 17:44:39	-	1	-	1	-	1	-	1	2016-12-28 17:04:57	2016-12-28 17:26:47	-	-	1	-	-	1	2016-12-28 17:06:32	2016-12-28 17:27:38	10	-	1	-	1	15	-	1	-	1
2016-12-28 19:13:58	2016-12-28 19:27:07	-	1	-	1	-	1	-	1	2016-12-28 18:45:21	2016-12-28 19:07:11	-	-	1	-	-	1	2016-12-28 18:46:56	2016-12-28 19:08:02	10	-	1	-	1	15	-	1	-	1
2016-12-28 20:51:52	2016-12-28 21:09:18	-	1	-	1	-	1	-	1	2016-12-28 20:25:46	2016-12-28 20:47:35	-	-	1	-	-	1	2016-12-28 20:23:15	2016-12-28 20:44:21	10	-	1	-	1	15	-	1	-	1
2016-12-28 22:32:56	2016-12-28 22:49:38	22:04:25	1	22:21:46	1	-	1	-	1	2016-12-28 22:06:10	2016-12-28 22:27:59	22:08:16	22:21:26	1	-	-	1			10	22:11:16	1	22:21:16	1	15	-	1	-	1
2016-12-29 00:15:08	2016-12-29 00:26:39	23:44:49	1	00:02:10	1	-	1	-	1	2016-12-28 23:46:34	2016-12-29 00:08:23	23:48:40	00:01:50	1	-	-	1			10	23:51:40	1	00:01:40	1	15	-	1	-	1
2016-12-29 01:58:05	2016-12-29 01:59:45	01:25:14	1	01:42:35	1	-	1	-	1	2016-12-29 01:26:59	2016-12-29 01:48:47	01:29:05	01:42:15	1	-	-	1			10	01:32:05	1	01:42:05	1	15	-	1	-	1
		-	1	-	1	03:30:26	1	03:52:47	1	2016-12-29 03:07:23	2016-12-29 03:29:11	-	-	1	03:34:17	03:52:27	1	2016-12-29 02:58:11	2016-12-29 03:07:06	10	-	1	-	1	15	03:37:17	1	03:52:17	1
		-	1	-	1	05:10:50	1	05:33:11	1	2016-12-29 04:47:48	2016-12-29 05:09:35	-	-	1	05:14:41	05:32:51	1	2016-12-29 04:22:18	2016-12-29 04:43:24	10	-	1	-	1	15	05:17:41	1	05:32:41	1
2016-12-29 05:56:31	2016-12-29 06:03:32	-	1	-	1	06:51:15	1	07:13:36	1	2016-12-29 06:28:12	2016-12-29 06:49:59	-	-	1	06:55:06	07:13:16	1	2016-12-29 06:01:33	2016-12-29 06:22:39	10	-	1	-	1	15	06:58:06	1	07:13:06	1
2016-12-29 07:35:55	2016-12-29 07:48:57	08:06:51	1	08:24:12	1	08:31:39	1	08:54:00	1	2016-12-29 08:08:36	2016-12-29 08:30:23	08:10:42	08:23:52	1	08:35:30	08:53:40	1	2016-12-29 07:58:06	2016-12-29 08:02:41	10	08:13:42	1	08:23:42	1	15	08:38:30	1	08:53:30	1
2016-12-29 09:14:09	2016-12-29 09:30:17	09:47:15	1	10:04:36	1	10:12:03	1	10:34:24	1	2016-12-29 09:49:01	2016-12-29 10:10:46	09:51:06	10:04:16	1	10:15:54	10:34:04	1			10	09:54:06	1	10:04:06	1	15	10:18:54	1	10:33:54	1
2016-12-29 10:53:15	2016-12-29 11:09:17	11:27:39	1	11:45:00	1	11:52:27	1	12:14:48	1	2016-12-29 11:29:25	2016-12-29 11:51:10	11:31:30	11:44:40	1	11:56:18	12:14:28	1			10	11:34:30	1	11:44:30	1	15	11:59:18	1	12:14:18	1
2016-12-29 12:33:55	2016-12-29 12:47:56	13:08:03	1	13:25:24	1	13:32:51	1	13:55:12	1	2016-12-29 13:09:50	2016-12-29 13:31:34	13:11:54	13:25:04	1	13:36:42	13:54:52	1			10	13:14:54	1	13:24:54	1	15	13:39:42	1	13:54:42	1
		14:48:28	1	15:05:49	1	15:13:15	1	15:35:36	1	2016-12-29 14:50:14	2016-12-29 15:11:58	14:52:19	15:05:29	1	15:17:06	15:35:16	1			10	14:55:19	1	15:05:19	1	15	15:20:06	1	15:35:06	1
2016-12-29 17:03:38	2016-12-29 17:09:38	-	1	-	1	-	1	-	1	2016-12-29 16:30:38	2016-12-29 16:52:22	-	-	1	-	-	1	2016-12-29 16:30:57	2016-12-29 16:52:03	10	-	1	-	1	15	-	1	-	1
2016-12-29 18:41:32	2016-12-29 18:51:59	-	1	-	1	-	1	-	1	2016-12-29 18:11:03	2016-12-29 18:32:46	-	-	1	-	-	1	2016-12-29 18:13:06	2016-12-29 18:34:12	10	-	1	-	1	15	-	1	-	1
2016-12-29 20:18:06	2016-12-29 20:34:31	-	1	-	1	-	1	-	1	2016-12-29 19:51:27	2016-12-29 20:13:10	-	-	1	-	-	1	2016-12-29 19:50:48	2016-12-29 20:11:54	10	-	1	-	1	15	-	1	-	1
2016-12-29 21:58:13	2016-12-29 22:15:25	-	1	-	1	-	1	-	1	2016-12-29 21:31:52	2016-12-29 21:53:34	-	-	1	-	-	1	2016-12-29 21:40:37	2016-12-29 21:44:30	10	-	1	-	1	15	-	1	-	1
2016-12-29 23:39:59	2016-12-29 23:54:01	23:10:29	1	23:27:50	1	-	1	-	1	2016-12-29 23:12:16	2016-12-29 23:33:58	23:14:20	23:27:30	1	-	-	1			10	23:17:20	1	23:27:20	1	15	-	1	-	1
2016-12-30 01:22:48	2016-12-30 01:28:02	00:50:53	1	01:08:14	1	-	1	-	1	2016-12-30 00:52:40	2016-12-30 01:14:22	00:54:44	01:07:54	1	-	-	1			10	00:57:44	1	01:07:44	1	15	-	1	-	1
		-	1	-	1	02:56:04	1	03:18:25	1	2016-12-30 02:33:05	2016-12-30 02:54:46	-	-	1	02:59:55	03:18:05	1	2016-12-30 02:27:11	2016-12-30 02:31:55	10	-	1	-	1	15	03:02:55	1	03:17:55	1
		-	1	-	1	04:36:28	1	04:58:49	1	2016-12-30 04:13:29	2016-12-30 04:35:10	-	-	1	04:40:19	04:58:29	1	2016-12-30 03:49:17	2016-12-30 04:10:23	10	-	1	-	1	15	04:43:19	1	04:58:19	1
2016-12-30 05:22:57	2016-12-30 05:28:28	-	1	-	1	06:16:52	1	06:39:13	1	2016-12-30 05:53:54	2016-12-30 06:15:34	-	-	1	06:20:43	06:38:53	1	2016-12-30 05:27:09	2016-12-30 05:48:15	10	-	1	-	1	15	06:23:43	1	06:38:43	1
2016-12-30 07:02:01	2016-12-30 07:12:51	-	1	-	1	07:57:16	1	08:19:37	1	2016-12-30 07:34:18	2016-12-30 07:55:58	-	-	1	08:01:07	08:19:17	1	2016-12-30 07:09:35	2016-12-30 07:30:41	10	-	1	-	1	15	08:04:07	1	08:19:07	1
2016-12-30 08:40:16	2016-12-30 08:55:54	09:12:54	1	09:30:15	1	09:37:41	1	10:00:02	1	2016-12-30 09:14:42	2016-12-30 09:36:22	09:16:45	09:29:55	1	09:41:32	09:59:42	1			10	09:19:45	1	09:29:45	1	15	09:44:32	1	09:59:32	1
2016-12-30 10:19:16	2016-12-30 10:35:37	10:53:19	1	11:10:40	1	11:18:05	1	11:40:26	1	2016-12-30 10:55:07	2016-12-30 11:16:46	10:57:10	11:10:20	1	11:21:56	11:40:06	1			10	11:00:10	1	11:10:10	1	15	11:24:56	1	11:39:56	1
2016-12-30 11:59:20	2016-12-30 12:14:18	12:33:43	1	12:51:04	1	12:58:29	1	13:20:50	1	2016-12-30 12:35:31	2016-12-30 12:57:10	12:37:34	12:50:44	1	13:02:20	13:20:30	1			10	12:40:34	1	12:50:34	1	15	13:05:20	1	13:20:20	1
2016-12-30 13:46:30	2016-12-30 13:52:48	14:14:07	1	14:31:28	1	14:38:53	1	15:01:14	1	2016-12-30 14:15:56	2016-12-30 14:37:34	14:17:58	14:31:08	1	14:42:44	15:00:54	1			10	14:20:58	1	14:30:58	1	15	14:45:44	1	15:00:44	1
2016-12-30 16:30:29	2016-12-30 16:34:35	-	1	-	1	-	1	-	1	2016-12-30 15:56:20	2016-12-30 16:17:58	-	-	1	-	-	1	2016-12-30 16:09:01	2016-12-30 16:14:51	10	-	1	-	1	15	-	1	-	1
2016-12-30 18:08:20	2016-12-30 18:16:37	-	1	-	1	-	1	-	1	2016-12-30 17:36:45	2016-12-30 17:58:22	-	-	1	-	-	1	2016-12-30 17:38:47	2016-12-30 17:59:53	10	-	1	-	1	15	-	1	-	1
2016-12-30 19:44:24	2016-12-30 19:59:23	-	1	-	1	-	1	-	1	2016-12-30 19:17:09	2016-12-30 19:38:46	-	-	1	-	-	1	2016-12-30 19:17:50	2016-12-30 19:38:56	10	-	1	-	1	15	-	1	-	1
2016-12-30 21:23:35	2016-12-30 21:41:18	-	1	-	1	-	1	-	1	2016-12-30 20:57:33	2016-12-30 21:19:10	-	-	1	-	-	1	2016-12-30 21:05:14	2016-12-30 21:13:45	10	-	1	-	1	15	-	1	-	1
2016-12-30 23:05:00	2016-12-30 23:20:51	22:36:08	1	22:53:29	1	-	1	-	1	2016-12-30 22:37:58	2016-12-30 22:59:34	22:39:59	22:53:09	1	-	-	1			10	22:42:59	1	22:52:59	1	15	-	1	-	1
2016-12-31 00:47:36	2016-12-31 00:56:10	00:16:33	1	00:33:54	1	-	1	-	1	2016-12-31 00:18:22	2016-12-31 00:39:58	00:20:24	00:33:34	1	-	-	1			10	00:23:24	1	00:33:24	1	15	-	1	-	1
		01:56:57	1	02:14:18	1	02:21:42	1	02:44:03	1	2016-12-31 01:58:47	2016-12-31 02:20:21	02:00:48	02:13:58	1	02:25:33	02:43:43	1			10	02:03:48	1	02:13:48	1	15	02:28:33	1	02:43:33	1
		-	1	-	1	04:02:06	1	04:24:27	1	2016-12-31 03:39:11	2016-12-31 04:00:45	-	-	1	04:05:57	04:24:07	1	2016-12-31 03:16:46	2016-12-31 03:37:52	10	-	1	-	1	15	04:08:57	1	04:23:57	1
2016-12-31 04:49:56	2016-12-31 04:52:22	-	1	-	1	05:42:30	1	06:04:51	1	2016-12-31 05:19:36	2016-12-31 05:41:09	-	-	1	05:46:21	06:04:31	1	2016-12-31 04:53:16	2016-12-31 05:14:22	10	-	1	-	1	15	05:49:21	1	06:04:21	1
2016-12-31 06:27:42	2016-12-31 06:36:16	-	1	-	1	07:22:55	1	07:45:16	1	2016-12-31 07:00:00	2016-12-31 07:21:33	-	-	1	07:26:46	07:44:56	1	2016-12-31 06:33:52	2016-12-31 06:54:58	10	-	1	-	1	15	07:29:46	1	07:44:46	1
2016-12-31 08:07:01	2016-12-31 08:21:18	08:38:34	1	08:55:55	1	09:03:19	1	09:25:40	1	2016-12-31 08:40:24	2016-12-31 09:01:57	08:42:25	08:55:35	1	09:07:10	09:25:20	1			10	08:45:25	1	08:55:25	1	15	09:10:10	1	09:25:10	1
2016-12-31 09:45:07	2016-12-31 10:01:30	10:18:58	1	10:36:19	1	10:43:43	1	11:06:04	1	2016-12-31 10:20:49	2016-12-31 10:42:21	10:22:49	10:35:59	1	10:47:34	11:05:44	1			10	10:25:49	1	10:35:49	1	15	10:50:34	1	11:05:34	1
2016-12-31 11:24:59	2016-12-31 11:40:42	11:59:22	1	12:16:43	1	12:24:07	1	12:46:28	1	2016-12-31 12:01:13	2016-12-31 12:22:45	12:03:13	12:16:23	1	12:27:58	12:46:08	1			10	12:06:13	1	12:16:13	1	15	12:30:58	1	12:45:58	1
2016-12-31 13:07:15	2016-12-31 13:18:54	13:39:46	1	13:57:07	1	14:04:31	1	14:26:52	1	2016-12-31 13:41:38	2016-12-31 14:03:09	13:43:37	13:56:47	1	14:08:22	14:26:32	1			10	13:46:37	1	13:56:37	1	15	14:11:22	1	14:26:22	1
		15:20:11	1	15:37:32	1	15:44:55	1	16:07:16	1	2016-12-31 15:22:02	2016-12-31 15:43:33	15:24:02	15:37:12	1	15:48:46	16:06:56	1			10	15:27:02	1	15:37:02	1	15	15:51:46	1	16:06:46	1
2016-12-31 17:34:39	2016-12-31 17:42:05	-	1	-	1	-	1	-	1	2016-12-31 17:02:27	2016-12-31 17:23:57	-	-	1	-	-	1	2016-12-31 17:03:54	2016-12-31 17:25:00	10	-	1	-	1	15	-	1	-	1
2016-12-31 19:11:32	2016-12-31 19:24:26	-	1	-	1	-	1	-	1	2016-12-31 18:42:51	2016-12-31 19:04:21	-	-	1	-	-	1	2016-12-31 18:44:25	2016-12-31 19:05:31	10	-	1	-	1	15	-	1	-	1
2016-12-31 20:49:20	2016-12-31 21:06:42	-	1	-	1	-	1	-	1	2016-12-31 20:23:16	2016-12-31 20:44:45	-	-	1	-	-	1	2016-12-31 20:20:51	2016-12-31 20:41:57	10	-	1	-	1	15	-	1	-	1
2016-12-31 22:30:20	2016-12-31 22:47:05	22:01:48	1	22:19:09	1	-	1	-	1	2016-12-31 22:03:40	2016-12-31 22:25:09	22:05:39	22:18:49	1	-	-	1			10	22:08:39	1	22:18:39	1	15	-	1	-	1
2017-01-01 00:12:30	2017-01-01 00:24:16	23:42:12	1	23:59:33	1	-	1	-	1	2016-12-31 23:44:05	2017-01-01 00:05:33	23:46:03	23:59:13	1	-	-	1			10	23:49:03	1	23:59:03	1	15	-	1	-	1

Figure 5.13: Observation scheduling - Part 2: Extract of the observation scheduling for BRITE-Austria for four days: to calculate the optimal observation start and stop times, several the blue and bright green highlighted columns on the far left of the upper screenshot indicate the overall visibility windows for the two target fields (in this case Cassiopeia and Orion). Taking into account the constraints for observations (see lower screenshot: green area = SAA, blue area = penumbra/eclipse, red area = contact windows with the ground station in Graz) as well as the planned observation time and time offset, the script start and stop times are calculated.

5.1.6 Time-Tagged Commands (TTCs) Generation

While the generated TTC scripts state the relative time offsets between the commands needed for performing the observation cycle, the correspondent absolute time stamps calculated during the scheduling process for starting and stopping the scripts are derived. Using these time stamps Time Tagged Commands (TTCs) are generated, which can be then uploaded to the spacecraft.

Although the primary purpose of TTC scripts and commands is to perform nominal scientific operations, any satellite command can be time-tagged. This feature is extremely useful for the execution of procedures exceeding available contact times, as well as for recovery and maintenance purposes. As an example, nadir tracking is performed using a script on-board and respective time stamps for execution.

The spacecraft autonomy would allow observation scheduling for very long periods of time, but the observation scheduling and TTC upload for automatic execution on the BRITE-Austria spacecraft is still performed on nearly a weekly basis. This strategy is pursued for taking into consideration changes of the satellite position in orbit in the observation scheduling process by using up-to-date Two Line Elements (TLEs) as well as the pointing performance of the observation data sets upon consultation with the scientific coordinator.

5.1.7 Upload of Files and Commands

The TTC scripts are manually pre-positioned in the Persistent Flash File System (PFFS) on the satellite's HKC, which is responsible for implementing the time-tagged queue. The scripts and the corresponding TTCs are uploaded using the *Queued Time Tag Uploader* module.

The setup file indicating the scientific observation parameters is uploaded directly to the IOBC. Due to the ring buffer structure on this computer, the setup file is copied internally on a regular basis by TTC to avoid overwriting.

5.1.8 Analysis of Satellite Performance

After several observation trials, the satellite performance has to be analysed and checked, if the desired stability and performance is met. The telemetry and SDRs are downloaded and further analysed regarding:

- Three-axis pointing performance
- BRITE-Austria health status
- Scientific output of the first observation attempts.

More information on the performance analysis during the first years in-orbit is given in Chapter 6.

5.1.9 Nominal Operations

In case a stable configuration is found, nominal operations can start. Otherwise it would be necessary to restart the whole procedure. Nominal operations include the manual analysis of the performance and the satellite's health on a daily basis and the observation scheduling, generation of new commands and respective upload on a weekly basis.

5.2 Satellite Setup and Control

Once a stable configuration is found, nominal operations can start. The following steps are involved and carried out for the satellite:

- Planning of the observations at a specific target and scheduling the start and stop timestamps
- Generation of TTCs and manual upload to the satellite on a weekly basis
- Performance and health check of the satellite on a daily basis
- Manual intervention in case of attitude control loss, power events or any other non-optimal behaviour, using emergency and contingency procedures

Nominal satellite operations of BRITE-Austria is mainly performed automated by ground segment modules mainly developed by UTIAS/SFL and adapted for the BRITE mission. The MUX master (at the MCC) commands the MUX station (at the ground station) to establish contact according to the tracking information. After the acquisition of signal and establishing of the contact, several software modules start interacting with the satellite from the MCC.

The *BRITE-Snapshot* software autonomously requests a ”snapshot” of the core telemetry values on-board. Next to the software state, the core telemetry values including currents, voltages, and temperatures of the subsystems, the current attitude mode and state, as well as detailed telemetry of the scientific payload is requested. For each telemetry value validity conditions and acceptable limits are defined, which are highlighted in case of anomalies.

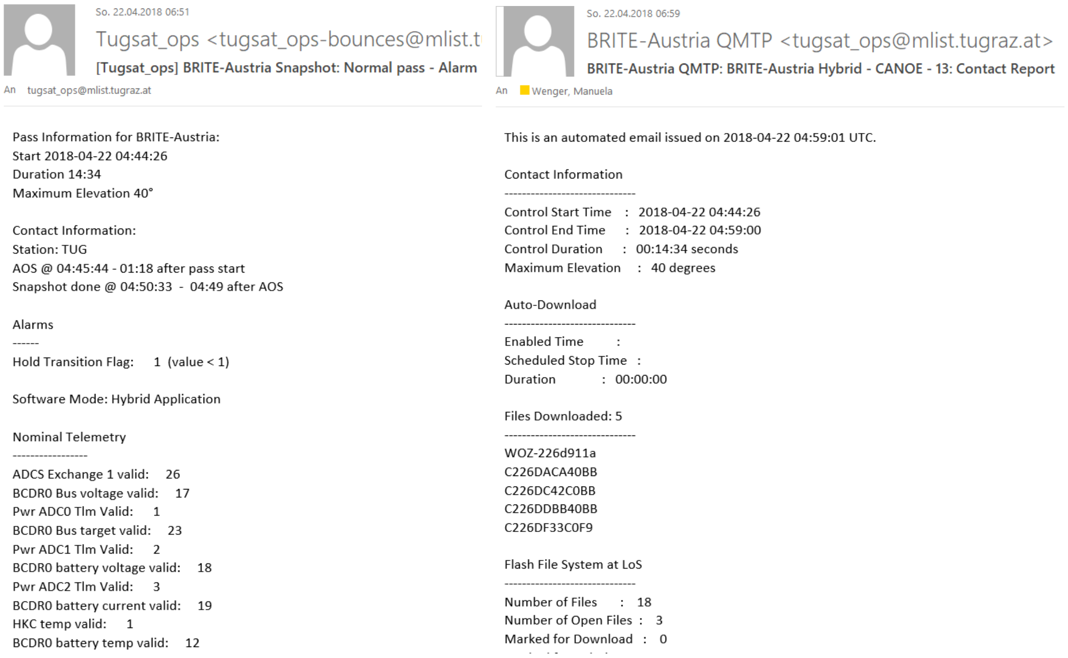
The software is capable of generating automatic reports, indicating the pass information, software states and switches, the telemetry received and any alarm condition. These reports are forwarded via email to the operators, to keep them informed on the state of the satellite.

Next to the telemetry snapshot, two other software modules can autonomously interact with the spacecraft's OBCs: the module *BRITE Queued Mass Transfer Program (BRITE QMTP)* reads out the current mass memory state of the HKC, the module *BRITE Generic Mass Transfer Program (BRITE GMTP)* reads out the current state of the IOBC.

Both software modules are also capable of generating reports, indicating the current file and script listing on the OBC, the state of the files, the list of downloaded files during the contact, and additional statistics on the file read process. These reports are also automatically forwarded to the operators at the end of a pass (Figure 5.14).

In addition, the TTCs can be pre-loaded into the command queue of the *Queued Time Tag Uploader (QTTU)* module, which can be configured to automatically upload the TTCs during a pass.

In case manual intervention is needed, the software module *GNB Control* is used to interact with the OBCs, upload manual commands, and load the necessary configurations and software (see Section 5.5).



So. 22.04.2018 06:51

Tugsat_ops <tugsat_ops-bounces@mlist.t

[Tugsat_ops] BRITE-Austria Snapshot: Normal pass - Alarm

An tugsat_ops@mlist.tugraz.at

```
Pass Information for BRITE-Austria:
Start 2018-04-22 04:44:26
Duration 14:34
Maximum Elevation 40°

Contact Information:
Station: TUG
AOS @ 04:45:44 - 01:18 after pass start
Snapshot done @ 04:50:33  -  04:49 after AOS

Alarms
------
Hold Transition Flag:    1  (value < 1)

Software Mode: Hybrid Application

Nominal Telemetry
-----------------
ADCS Exchange 1 valid:    26
BCDR0 Bus voltage valid:    17
Pwr ADC0 Tlm Valid:    1
BCDR0 Bus target valid:    23
Pwr ADC1 Tlm Valid:    2
BCDR0 battery voltage valid:    18
Pwr ADC2 Tlm Valid:    3
BCDR0 battery current valid:    19
HKC temp valid:    1
BCDR0 battery temp valid:    12
```

So. 22.04.2018 06:59

BRITE-Austria QMTP <tugsat_ops@mlist.tugraz.at>

BRITE-Austria QMTP: BRITE-Austria Hybrid - CANOE - 13: Contact Report

An Wenger, Manuela

```
This is an automated email issued on 2018-04-22 04:59:01 UTC.

Contact Information
------------------------------
Control Start Time   :  2018-04-22 04:44:26
Control End Time     :  2018-04-22 04:59:00
Control Duration     :  00:14:34 seconds
Maximum Elevation    :  40 degrees

Auto-Download
------------------------------
Enabled Time        :
Scheduled Stop Time  :
Duration          :  00:00:00

Files Downloaded: 5
------------------------------
WOZ-226d911a
C226DACA40BB
C226DC42C0BB
C226DDBB40BB
C226DF33C0F9

Flash File System at LoS
------------------------------
Number of Files      :  18
Number of Open Files :  3
Marked for Download  :  0
```

Figure 5.14: Email reports: At the end of the pass, the operators receive status emails of the BRITE software modules Snapshot, QMTP and GMTP (excerpts of a Snapshot and QMTP status mail are depicted.

The following figures show the software modules used for operating BRITE-Austria during a pass.

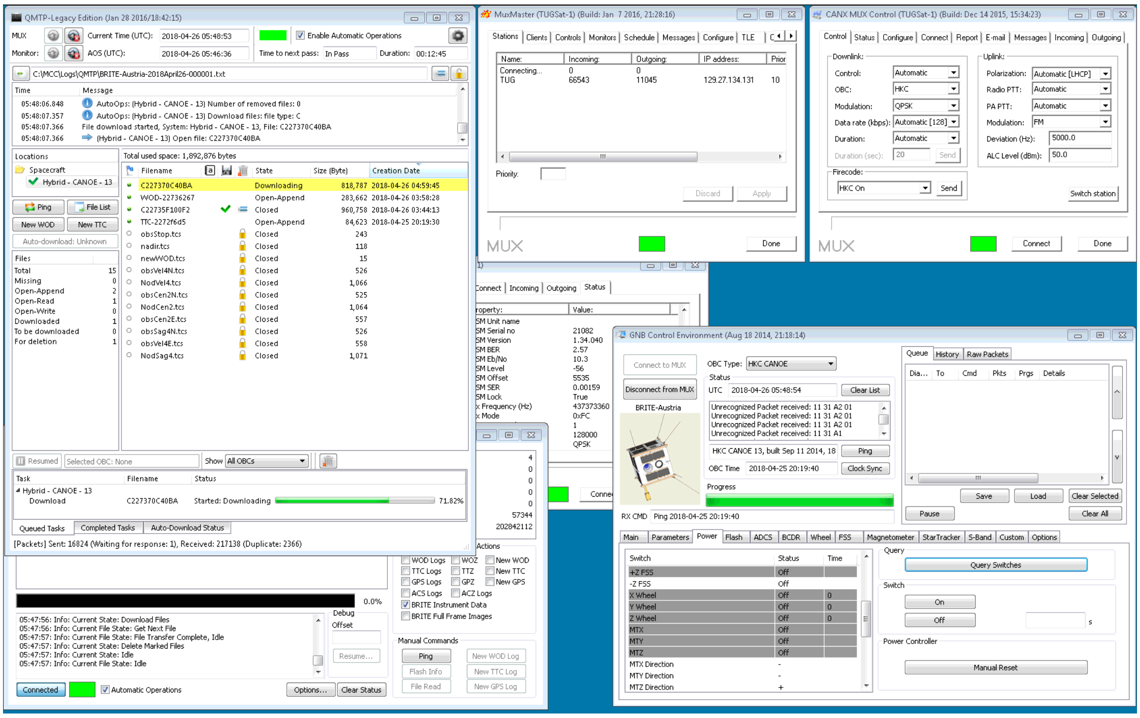


Figure 5.15: Mission control PC1: This screen shows the software modules (QMTP and GMTP, far left) to check the OBCs' state and files, the MUX communication suite (centre) and the GNB Control software for manual intervention (bottom right).

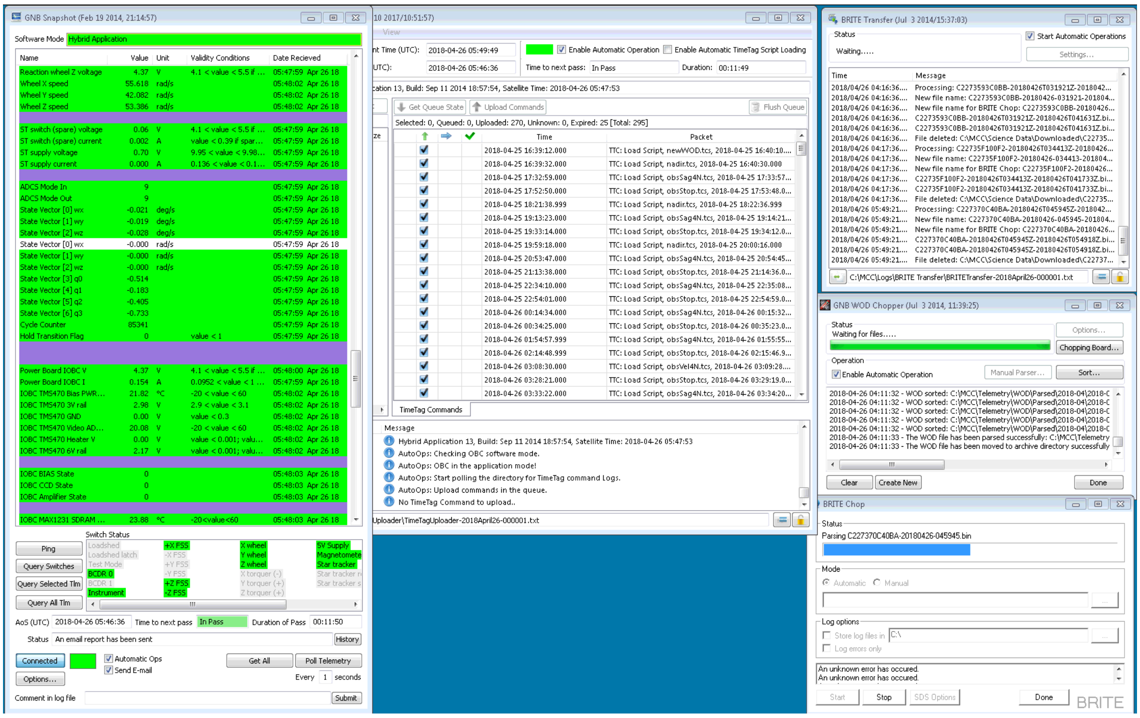
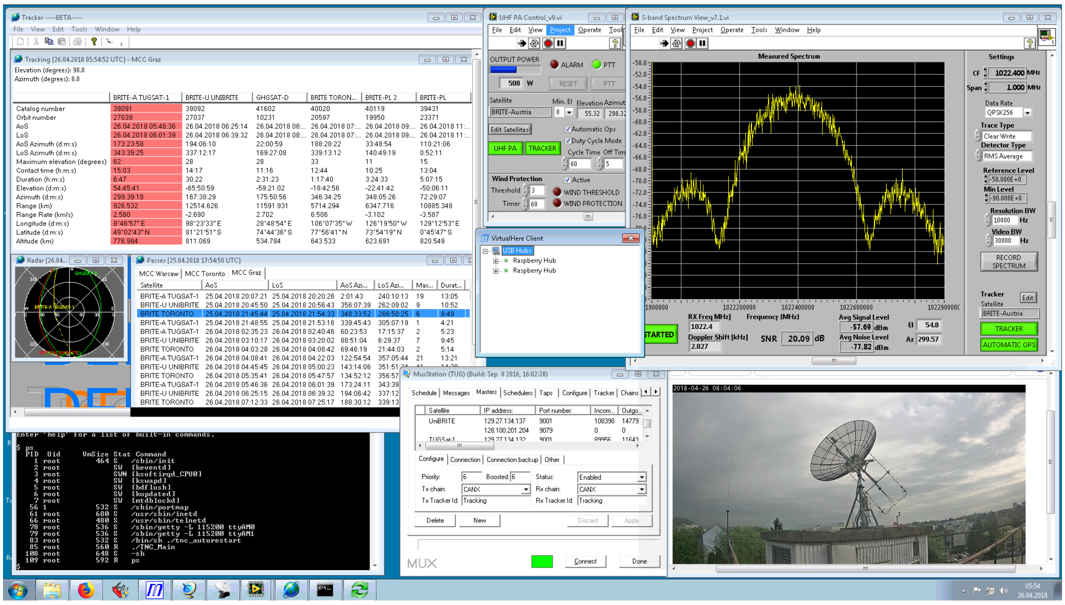


Figure 5.16: Mission control PC2: BRITE-Snapshot provides a brief status of the satellite's health and telemetry values (left). QTTU is used for TTC upload (centre), and the modules on the right are used for integrity checks and data dissemination.

Besides, the ground station in Graz is also configured to operate automatically. The software *Tracker* [22] requests the latest TLEs of BRITE-Austria from NORAD via SpaceTrack [44], calculates the orbit and schedules the respective passes. Based on the information retrieved from Tracker, the ground station controls the rotators and automatically establishes contact with the satellite when in view [45]. The NORAD ID of the spacecraft is compared to the contact information of the software, to avoid interference with other spacecrafts in case of misconfiguration.

The uplink chain is constantly monitored, and in case of malfunction or heavy wind loads is automatically deactivated. In case heavy wind loads are detected, the rotators additionally move the antenna to a parking position to minimize the risk of damage. In this case, alarm reports are generated and forwarded to the operators via email. The received signal in the downlink is also continuously monitored and analysed, as the downlink rate can be changed according to the link quality in real-time, which maximises the data throughput [46].

Figure 5.17 shows the ground station PC, indicating the software modules used.



Tracking [26.04.2018 05:54:52 UTC] - MCC Graz

Elevation (degrees): 90.0
Azimuth (degrees): 0.0

	BRITE-A TUGSAT-1	BRITE-U UNIBRITE	GHGSAT-D	BRITE TORON...	BRITE-PL 2	BRITE-PL
Catalog number	39091	39092	41602	40020	40119	39431
Orbit number	27039	27037	10231	20597	19950	23371
AoS	26.04.2018 05:46:36	26.04.2018 06:25:14	26.04.2018 08:...	26.04.2018 07:...	26.04.2018 09:...	26.04.2018 11:...
LoS	26.04.2018 06:01:39	26.04.2018 06:39:32	26.04.2018 08:...	26.04.2018 07:...	26.04.2018 09:...	26.04.2018 11:...
AoS Azimuth (d:m:s)	173:23:58	194:06:10	22:00:59	188:28:22	33:48:54	110:21:06
LoS Azimuth (d:m:s)	343:39:25	337:12:17	169:27:08	339:13:12	140:49:19	0:52:11
Maximum elevation (degrees)	62	28	28	33	11	15
Contact time (h:m:s)	15:03	14:17	11:16	12:44	10:25	13:04
Duration (h:m:s)	6:47	30:22	2:31:23	1:17:40	3:24:33	5:07:15
Elevation (d:m:s)	54:45:41	-65:50:59	-59:21:02	-18:42:56	-22:41:42	-50:06:11
Azimuth (d:m:s)	299:39:18	167:38:29	175:50:56	346:34:25	348:05:26	72:29:07
Range (km)	926.532	12514.626	11591.931	5714.294	6347.716	10885.348
Range Rate (km/s)	2.580	-2.690	2.702	6.506	-3.102	-3.587
Longitude (d:m:s)	9°46'57" E	98°23'33" E	28°48'54" E	106°07'35" W	126°19'50" W	129°12'53" E
Latitude (d:m:s)	49°02'43" N	81°21'51" S	74°44'36" S	77°56'41" N	73°54'19" N	0°45'47" S
Altitude (km)	776.984	811.069	534.784	643.533	623.691	820.549

Passes [25.04.2018 17:54:50 UTC]

MCC Warsaw | MCC Toronto | MCC Graz

Satellite	AoS	LoS	AoS Azi...	LoS Azi...	Max...	Durat...
BRITE-A TUGSAT-1	25.04.2018 20:07:21	25.04.2018 20:20:26	2:01:43	240:10:13	19	13:05
BRITE-U UNIBRITE	25.04.2018 20:45:50	25.04.2018 20:56:43	356:07:39	262:09:02	9	10:52
BRITE TORONTO	25.04.2018 21:45:44	25.04.2018 21:54:33	348:33:52	266:50:25	6	8:49
BRITE-A TUGSAT-1	25.04.2018 21:48:55	25.04.2018 21:53:16	339:45:43	305:07:19	1	4:21
BRITE-A TUGSAT-1	26.04.2018 02:35:23	26.04.2018 02:40:46	60:23:53	17:15:37	2	5:23
BRITE-U UNIBRITE	26.04.2018 03:10:17	26.04.2018 03:20:02	88:51:04	6:29:37	7	9:45
BRITE TORONTO	26.04.2018 04:03:28	26.04.2018 04:08:42	69:46:19	21:44:03	2	5:14
BRITE-A TUGSAT-1	26.04.2018 04:08:41	26.04.2018 04:22:03	122:54:54	357:05:44	21	13:21
BRITE-U UNIBRITE	26.04.2018 04:45:45	26.04.2018 05:00:23	143:14:06	351:51		
BRITE TORONTO	26.04.2018 05:35:41	26.04.2018 05:47:57	134:52:12	356:57		
BRITE-A TUGSAT-1	26.04.2018 05:46:36	26.04.2018 06:01:39	173:24:11	343:39		
BRITE-U UNIBRITE	26.04.2018 06:25:15	26.04.2018 06:39:32	194:06:42	337:12		
BRITE TORONTO	26.04.2018 07:12:33	26.04.2018 07:25:17	188:30:12	339:13		

```
Enter 'help' for a list of built-in commands.

$ ps
  PID  Uid     VmSize Stat Command
    1 root        464 S   /sbin/init
    2 root            SW  [keventd]
    3 root            SWN [ksoftirqd_CPU0]
    4 root            SW  [kswapd]
    5 root            SW  [bdflush]
    6 root            SW  [kupdated]
    7 root            SW  [mtdblockd]
   56 1           532 S   /sbin/portmap
   61 root        680 S   /usr/sbin/inetd
   66 root        480 S   /usr/sbin/telnetd
   78 root        536 S   /sbin/getty -L 115200 ttyAM0
   79 root        536 S   /sbin/getty -L 115200 ttyAM1
   83 root        532 S   /bin/sh ./tnc_autorestart
   85 root        560 R   ./TNC_Main
  108 root        648 S   -sh
  109 root        592 R   ps
$
```

OUTPUT POWER 508 W
Satellite: BRITE-Austria
Min. El: 0
Elevation: 55.32
Azimuth: 298.32
☑ Automatic Ops
☑ Duty Cycle Mode
Cycle Time: 60
Off Time: 5
Wind Protection
☑ Active
Threshold: 3
Timer: 60
WIND THRESHOLD
WIND PROTECTION

Settings
CF: 1022.400 MHz
Span: 1.000 MHz
Data Rate: QPSK256
Trace Type: Clear Write
Detector Type: RMS Average
Reference Level: -50.000E+0
Min Level: -90.000E+0
Resolution BW: 10000 Hz
Video BW: 30000 Hz
Tracker Satellite: BRITE-Austria

RX Freq [MHz]: 1022.4
Doppler Shift [kHz]: 2.827
SNR: 20.09 dB
Avg Signal Level: -57.69 dBm
Avg Noise Level: -77.82 dBm
El: 54.8
Az: 299.57

MuxStation (TUG) (Build: Sep 8 2016, 16:02:28)

Schedule | Messages | Masters | Schedulers | Taps | Configure | Tracker | Chains

Satellite	IP address:	Port number:	Incom...	Outgo...
UniBRITE	129.27.134.137	9001	108398	14779
	128.100.201.204	9079	0	0
TUGSat-1	129.27.134.132	9001	89956	11643

Configure | Connection | Connection backup | Other

Priority: 6
Boosted: 6
Status: Enabled
Tx chain: CANX
Rx chain: CANX
Tx Tracker Id: Tracking
Rx Tracker Id: Tracking

2018-04-26 08:04:06

Figure 5.17: Ground station PC: According to the pass information from Tracker (upper left), the communication chains are activated, the signal is received (upper right) as the antenna tower is tracking BRITE-Austria (lower right).

5.3 Health Status and Performance Evaluation

Although *BRITE-Snapshot* provides a brief snapshot of the current satellite's health at the beginning of a pass, a confirmation on the health state during a whole orbit can only be gained after analysis of the whole orbit data (WOD) and time tagged command logs.

The spacecraft automatically collects all telemetry values on-board at a predefined interval (typically every 60-180 s). These values are stored in the WOD files and can be visualised by using *BRITE TLMView*.

In case time-tagged commands are used, TTC logs are automatically recorded. The logs indicate the following information and can be viewed via the *QTTU*:

- The original TTCs as uploaded including the corresponding time stamp for execution
- The spacecraft's response to each individual command (acknowledgement or negative acknowledgement), including the actual time stamp of execution
- If applicable, the value requested by command (e.g. the startracker replies to tuning commands)

To analyse the performance of the ADCS system in detail, an ACS log can be recorded. However, as the ACS log collects the respective telemetry every second, large data amounts are accumulated, therefore they are not suitable for nominal operations, but for debugging and target attempts. A dedicated *ACS log reader* allows to visualise the telemetry values for better analysis of the performance.

5.4 Data Integrity Checks and Dissemination Strategy

During the download of all the raw data files, the ground software automatically performs integrity checks with checksums and retrieval of missing packets, also allowing partial file downloading. Only after complete download and successful integrity check, a raw data file is parsed and forwarded to the respective repository/the mission control centre in charge. The raw data files are then processed depending on their type:

- The raw binary Whole Orbit Data files, comprising the telemetry values collected on-board the satellite, are parsed, combined in groups and translated to Comma Separated Value (CSV) files. These files can then be viewed in *BRITE TLMView* and the health state and spacecraft performance is analysed.
- The science data records (SDRs) are split up in their individual raster images and converted into a Flexible Image Transport System (FITS) file, which is a very common format used for image data. The files can be viewed using *BRITE Preview* for a quick assessment.

The latter are then mirrored to a scientific repository via FTP for further analysis by the scientific coordinator. The science data extraction steps and their respective data products are depicted in Figure 5.18.

The local file repository at the MCC of BRITE-Austria is periodically synchronised with the IKS/TUGraz server repository network drive on a nearly daily basis. All satellite data (raw and parsed), scripts and TTCs, as well as all ground segment logs and software are archived on the IKS/TUGraz servers and are accessible for the BRITE-Austria operators for further processing and analysis.

The science data (including raw and parsed data, as well as processed data products) are in addition stored on an FTP at UTIAS/SFL and after first analysis of the scientific coordinator, the data is forwarded to the BRITE Mission Data Archive (MDA) at the Copernicus Astronomical Centre (CAC) in Warsaw (where all data of all five satellites is stored). In addition, mirror sites for the archive are available at the University of Vienna and University of Montreal.

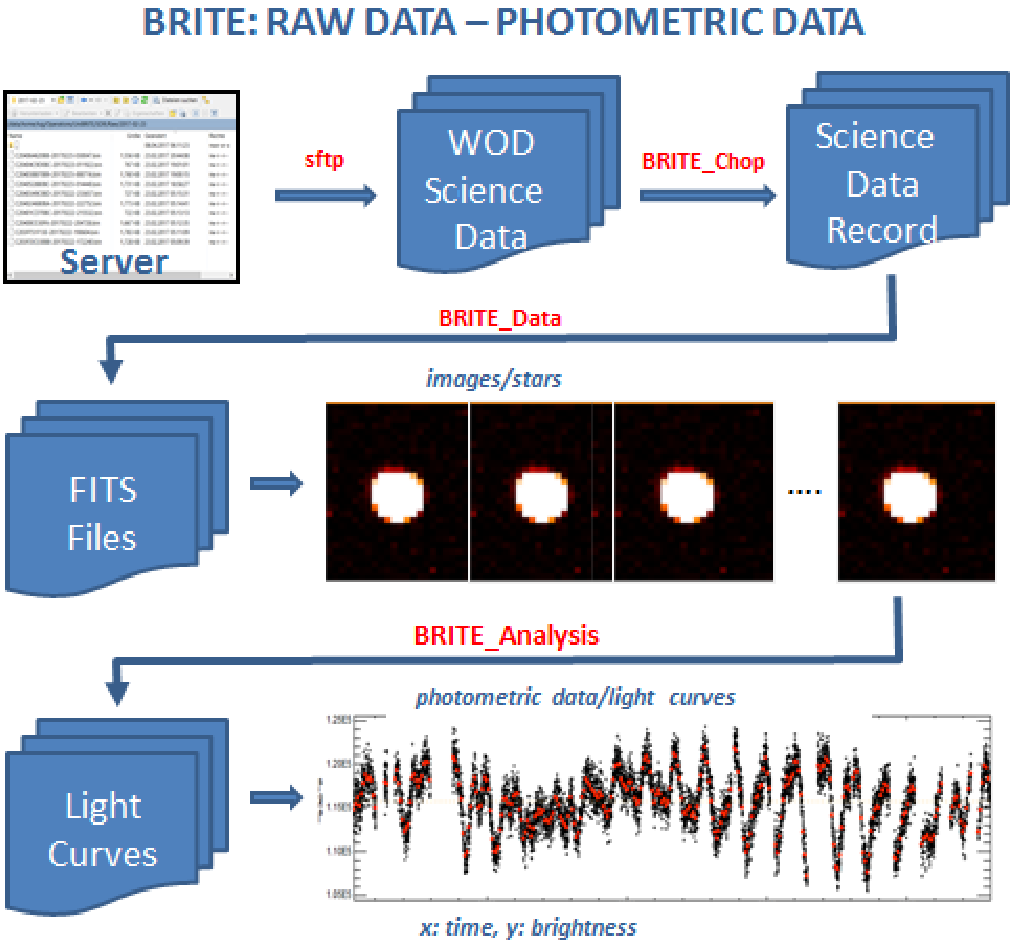


Figure 5.18: Science data extraction: The steps during data extraction and the respective data products are shown [48].

5.5 Operations Support Processes

A manual intervention of the operations is mostly performed for routine maintenance tasks of the spacecraft, as well as in case of non-optimal behaviour occurs. For these tasks, scripted procedures were defined and are available to speed up the process and avoid mistakes or omission of commands during manual interventions. Scripted procedures are available for several purposes:

- Satellite startup scripts
- Recovery scripts (for subsystems or the entire spacecraft)
- Contingency scripts (e.g. for readouts or memory dumps)
- Configuration scripts (e.g. housekeeping parameters, TLE and target quaternion, special ACS settings)

In addition, scripted procedures for automation of the ground station, mission planning, and documentation tasks are used. These procedures include:

- Automated compilation of various status reports
- Miscellaneous automation tasks such as TLE retrieval; processing and email forwarding of pass logs/reports.

To define the approach and course of actions to be taken in case of anomalies in the behaviour of the satellite and the Graz ground station, contingency and recovery procedures were elaborated during the AIT phase of the satellite, and the setup of the ground station. During the commissioning and early operations phase, these procedures were continously refined to cope with the experience gained in-orbit and the actual behaviour of the spacecraft.

The general strategy, how to approach such anomalies, is to verify the correct functionality and configuration of the ground station itself, before taking any critical actions on the spacecraft. The experience showed, that e.g. in case no contact with the satellite is established, or the communication link is not stable, the issue usually was found on the stations/ground segment side. The procedures cover the most common issues, that may occur during operations of the BRITE-Austria satellite or the ground station, and a respective set of in-pass and post-pass corrective actions are defined.

Although the operators receive the email notifications about the BRITE-Austria health status including pass information, the operators need remote access to the ground station and MCC to intervene in case any anomaly or problem occurs. Therefore, remote access for operators was established. The operators can remotely log in to the MCC and ground station PCs via mobile devices or PC using a secured connection. Although this feature is not meant for nominal operations, this tool allows to provide the operators full control over the ground station in case needed. In addition, this tool is also helpful in case of support or training, as viewers or operators from other project partners can be granted remote access too.

Chapter 6

Performance of BRITE-Austria in Orbit

During its first five years in orbit, BRITE-Austria has successfully fulfilled its mission requirements. The goals of the BRITE-Austria project were not only achieved, but are also significantly beyond the expectations in quantity and quality.

At the end of April 2018 BRITE-Austria has already

- traveled more than 1230 million kilometres in over 27000 orbits
- performed 21 observation campaigns, observing over 160 individual stars
- collected over 700000 science datasets
- produced over 20 GB raw data

In the first part of this chapter a performance evaluation of the star field observations over the first 5 years in orbit is given, including a light curve consisting of individual image samples gathered by BRITE-Austria.

In addition, the performance degradation of the CCD detector is analysed and described, the implemented countermeasures however can be found in Chapter 7

The second part of this chapter deals with the analysis and verification of the spacecraft's health status and its performance during the nominal mission phase.

The performance figures of the ground station involved can be found in ”Ground Station Engineering and Operations of Nanosatellite Missions” [24].

6.1 Scientific Performance of Star Field Exposures

BRITE-Austria has successfully conducted 19 observation campaigns, and two campaigns are currently ongoing. Table 6.1 gives more details about the observation campaigns, stating the star fields observed, the start and end dates, the number of observation days and stars observed. The numbering of the fields was defined by BEST and is applicable to all the BRITE satellites.

Field		**Start**	**End**	**Days**	**# Stars**
1	Orion-I_2013	2013-12-01	2014-03-18	108	15
2	Centaurus-I_2014	2014-03-25	2014-08-18	147	30
5	Perseus-I_2014	2014-09-02	2015-02-18	170	21
6	Orion-II_2014*	2014-09-24	2015-03-17	175	22
7	VelPup-I_2014	2014-12-11	2015-05-28	169	28
8	Scorpius-I_2015**	2015-02-22	2015-08-31	185	8
9	Cygnus-II_2015	2015-06-01	2015-11-25	178	7
10	CasCep-I_2015	2015-08-27	2015-10-23	58	12
12	Orion-III_2015	2015-12-12	2016-02-15	66	13
12b	VelPup-II_2015	2015-12-20	2016-01-30	42	12
13	CruCar-I_2016	2016-02-04	2016-05-27	114	19
14	Sagittarius-II_2016	2016-04-21	2016-09-13	146	12
17	Cassiopeia-I_2016	2016-08-07	2016-12-31	147	13
20	Orion-IV_2016	2016-09-12	2017-03-06	176	16
24	Carina-I_2017	2017-01-11	2017-02-10	31	12
23	VelPup-III_2017	2017-02-14	2017-04-27	73	11
25	Sagittarius-III_2017	2017-03-24	17.09.2017	178	12
30	Cassiopeia-II_2017	2017-08-07	15.01.2018	162	7
32	Orion-V_2017	2017-09-15	08.03.2018	174	16
34	VelPup-IV_2018	2018-01-17	ongoing		11
36	Sagittarius-IV_2018	2018-03-21	ongoing		12

Table 6.1: Stars observed by BRITE-Austria: BRITE-Austria has performed 21 observation campaigns.
* 15 stars are same as in Orion-I field / ** 2 stars are same as in Centaurus field

Since end 2015 parallel observations of even two fields per orbit were investigated to increase the overall science output. In fall 2016 this approach actually became a baseline during nominal operations for BRITE-Austria. Due to this strategy almost 35% more stars were observed in the same period as envisaged before according to the requirements.

Figure 6.1 shows an all sky map using a Lambert projection, where the right ascension is seen in the horizontal axis and the declination is plotted on the vertical axis. The observation fields of BRITE-Austria and their location on the sky are highlighted and encircled.

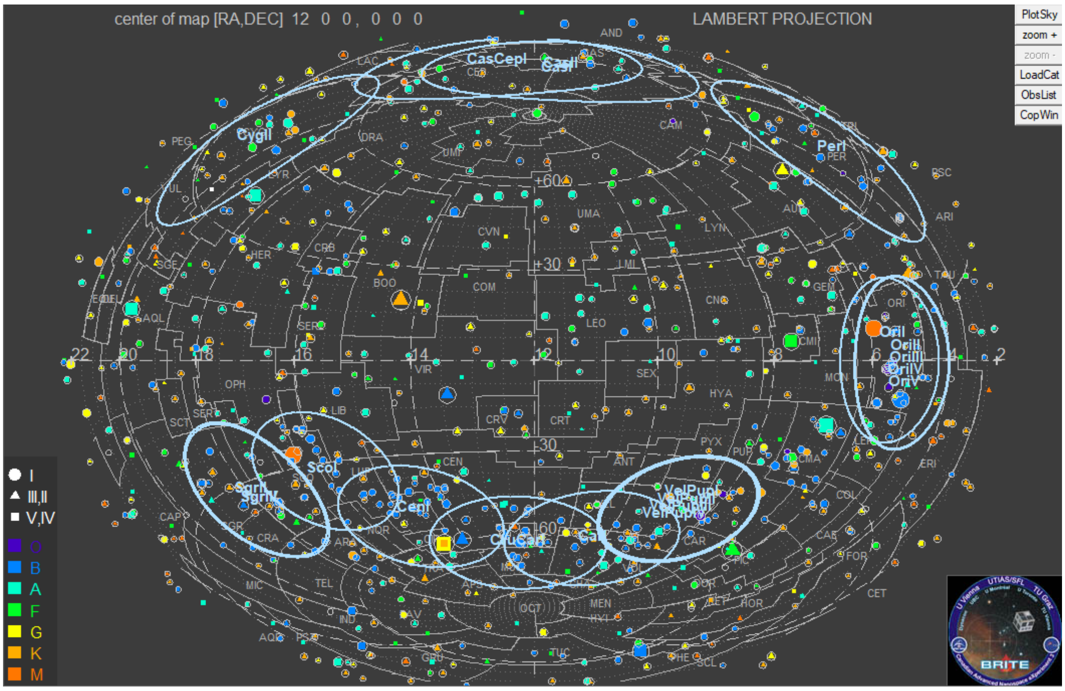


Figure 6.1: BRITE-Austria sky map: The BRITE-Austria observation fields are depicted on the sky map.

Due to the restrictions of the startracker on BRITE-Austria, several bright so-called guiding stars have to be present in the FOV of the startracker. Hence, fields only located in or at least close to the Galactic plane are suitable for observations. However, due to the introduction of parallel observations, a change in observation strategy for the individual satellites was performed. The individual satellites were assigned to the most suitable target fields (in terms of blue or red target stars, as well as the visible magnitude range) and not, as foreseen, all to the same target field. With this strategy the overall science output of the BRITE constellation was increased significantly.

The individual original images obtained by BRITE-Austria are downloaded and stored on a local repository at TU Graz. In near-realtime the data is forwarded to the scientific coordination for further data reduction and processing. The information of the brightness in the images is extracted and plotted over time to give an indication on the oscillations of the star. As example, Figure 6.2 gives the light curve of Eta Centauri.

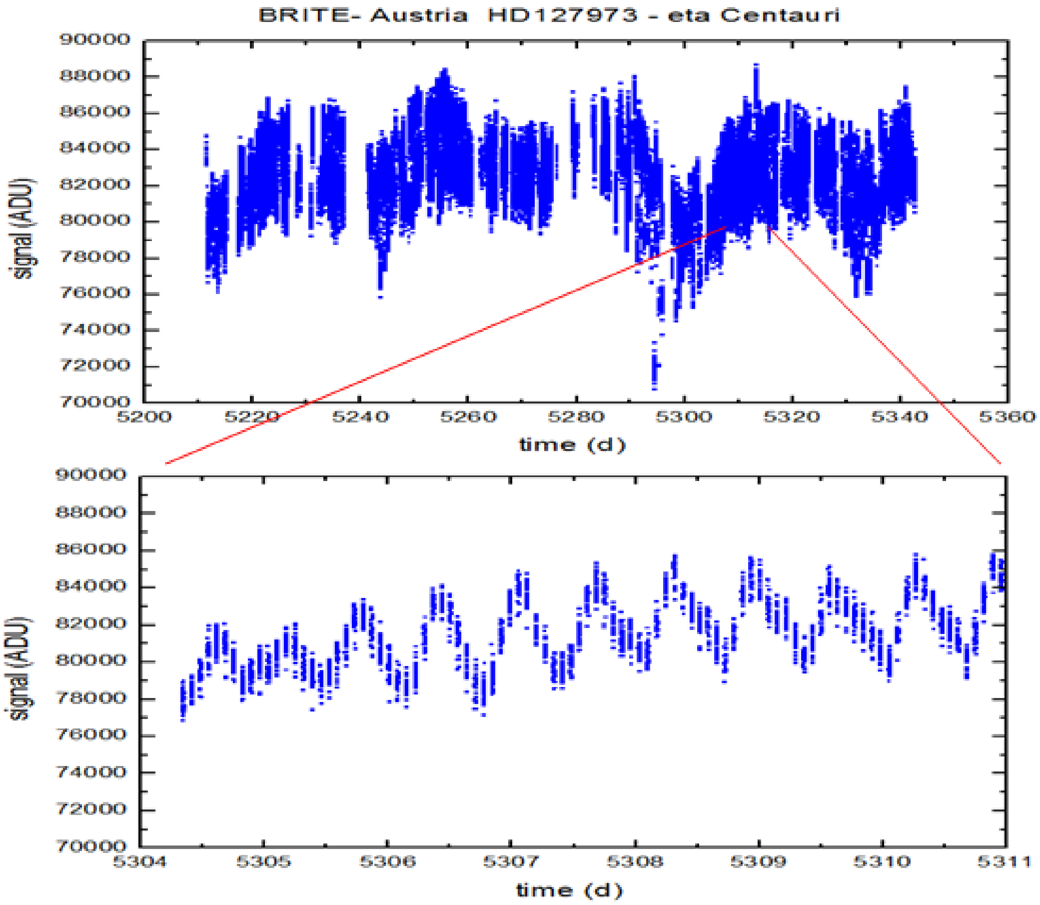


Figure 6.2: Eta Centauri light curve: The picture shows the light curve of Eta Centauri, observed by BRITE-Austria. The individual signal levels of the star observed are depicted [42].

These data sets are then forwarded and further analysed by the scientific community, which has indicated their interest in the proposal phases at an earlier project state.

A full list of the individual observations fields and stars observed by each of the BRITE satellites can be found on the BRITE Wiki page [47]. In addition, a publications list of the results and data analysis based on the observation data of the BRITE satellites can also be found on this page, as the scientific evaluation of the data gathered by BRITE-Austria is outside of scope of this thesis.

Another important performance degradation was discovered already during the early months of the commissioning phase. The first full frame images already showed several artifacts, various pixels and even whole columns with higher dark signals were spread across the CCD.

By analysing the full frame images, which were gathered at the beginning of a new observation campaign, it was found, that the progression rate of the artifacts is at 1.7% per year. A new method was introduced in early 2015 to mitigate this issue, and to ensure the level of high quality data also for the upcoming years. More information on the problem as well as the respective mitigation strategies like chopping can be found in Chapter 7.

6.2 Overall System Behaviour

During the commissioning phase, several challenges had to be faced and solutions provided (see Section 7.2). The telemetry gathered in this time, does not fully represent the operational status of BRITE-Austria.

Therefore, when analysing and verifying the in-orbit behaviour of the satellite, the operational phase starting in December 2013 until May 2018 is investigated.

In principle, two main operational phases have to be distinguished:

- Operations during the eclipse season (typically October to February), where eclipse durations of up to 30 minutes are experienced
- Operations during the rest of the year, when the spacecraft is continuously illuminated by the Sun

To verify the behaviour and the spacecraft's performance, a detailed analysis of the telemetry gathered over the years in a two-year interval is given. As BRITE-Austria is orbiting the Earth about 14 times a day, the optimal plotting size of the analysis diagrams was set to one day.

The analysis of the behaviour in eclipse is depicted by analysing the telemetry values from December 27th of the years 2013, 2015, and 2017.

To check the performance during continuous Sun illumination, as examples, telemetry values from May 1st of the years 2014, 2016, and 2018 are compared.

A comparison of the following telemetry groups was made:

- Battery power analysis (during eclipse)
- General spacecraft power statistics
- Currents generated by the solar panels
- Body rates experienced during CTAP and FTAP
- Temperature analysis of the boards as well as measured on the inside of the panels

6.2.1 Performance during Eclipse

The following paragraphs should give an insight on the satellite's performance in eclipse over the years. As BRITE-Austria is in a sun-synchronous dawn-dusk orbit, the battery is only used during the eclipse season and kept in a full charged state during the remaining months in sunlight.

6.2.1.1 Battery power analysis

The most critical item during the eclipse phase is the battery/BCDR. The temperature of the battery should be kept at a stable level above 10 degrees. The following plots represent the behaviour of the battery over the years.

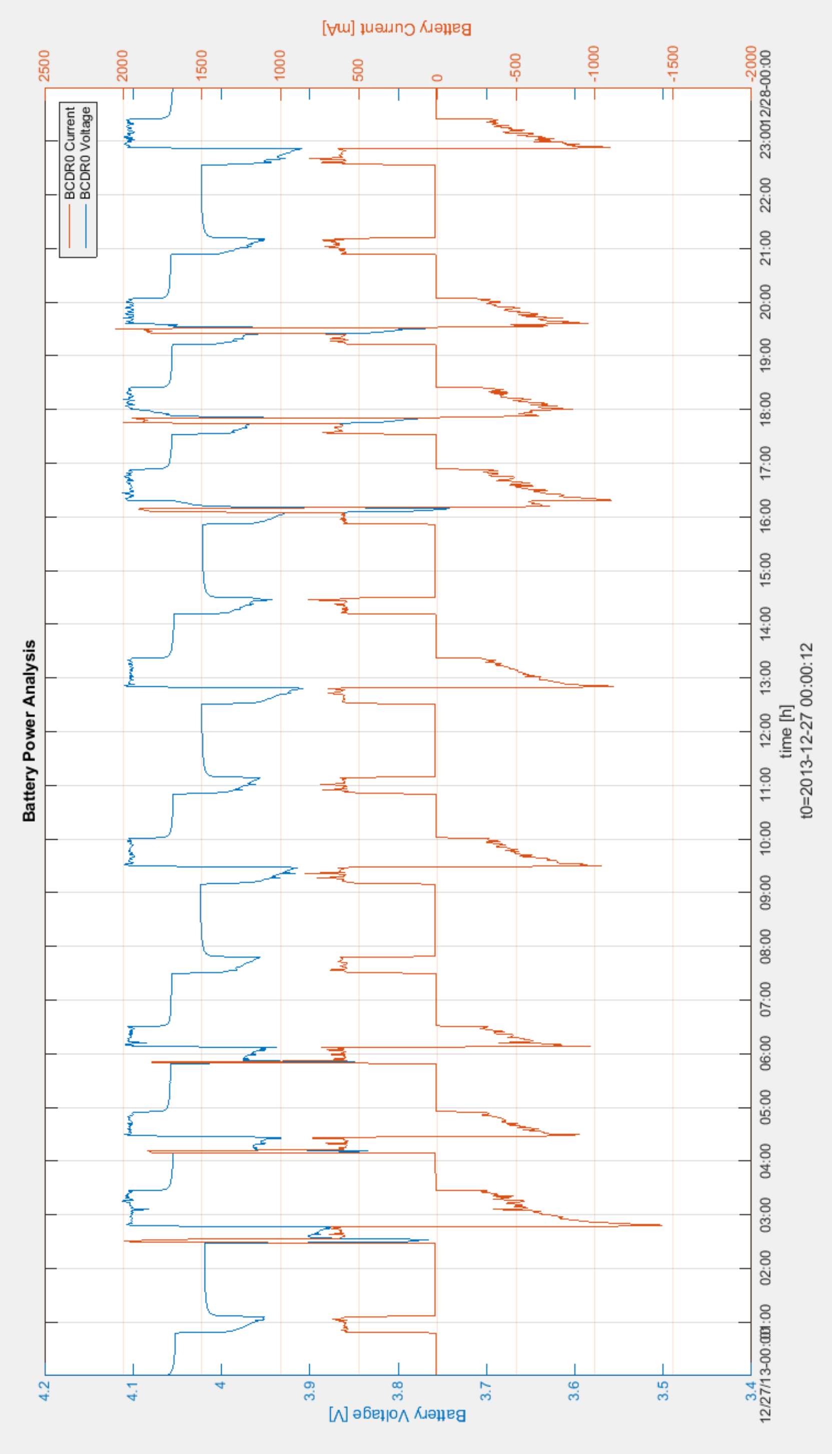


Figure 6.3: Battery behaviour in eclipse in 2013: The battery behaviour from a day in December 2013 is depicted. The blue lines indicate the voltage values, the red lines state the current.

In case the battery voltage drops below 3.95V the battery is put into charging mode and recharged until its full capacity is achieved. In December 2013 observations were not scheduled for each orbit, therefore the battery voltage did not drop under the charge threshold on every orbit. In December 2015, it can be seen that during the orbital maneuvers a higher power demand was observed. In addition, the transmitting power of the S-band downlink during the morning and evening passes can be clearly seen.

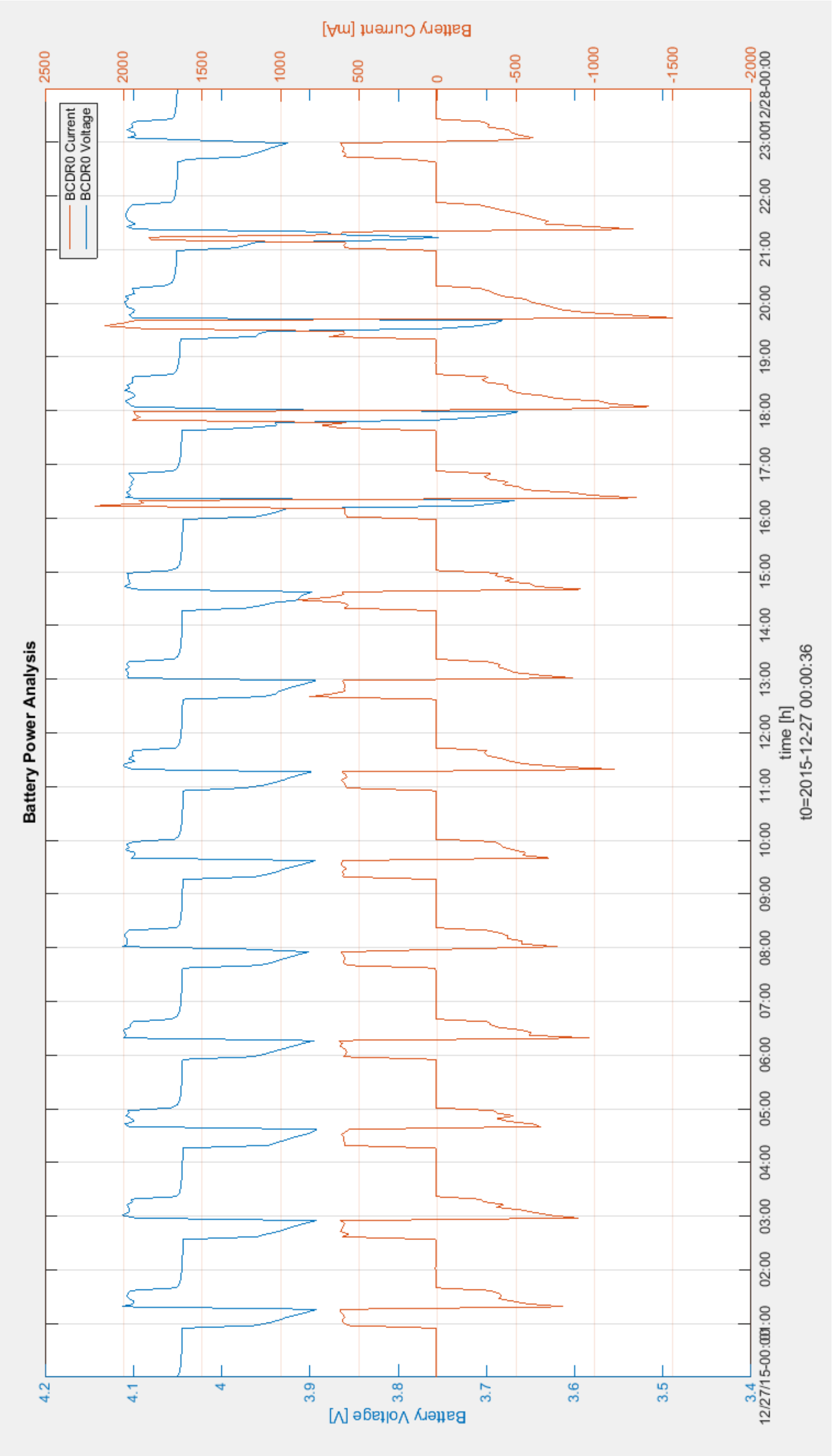


Figure 6.4: Battery behaviour in eclipse in 2015: The battery behaviour from the December 27th in 2015 is depicted.

Given the plots, it can be seen that over the years the battery looses its capacity faster during the eclipse part of the orbit and the regeneration time is getting longer. Although a degradation of the battery is obvious, there are several mitigation strategies for the upcoming years to minimize this impact on the mission, like shortening/avoiding the scientific observations during eclipse or even switching to the redundant battery/BCDR.

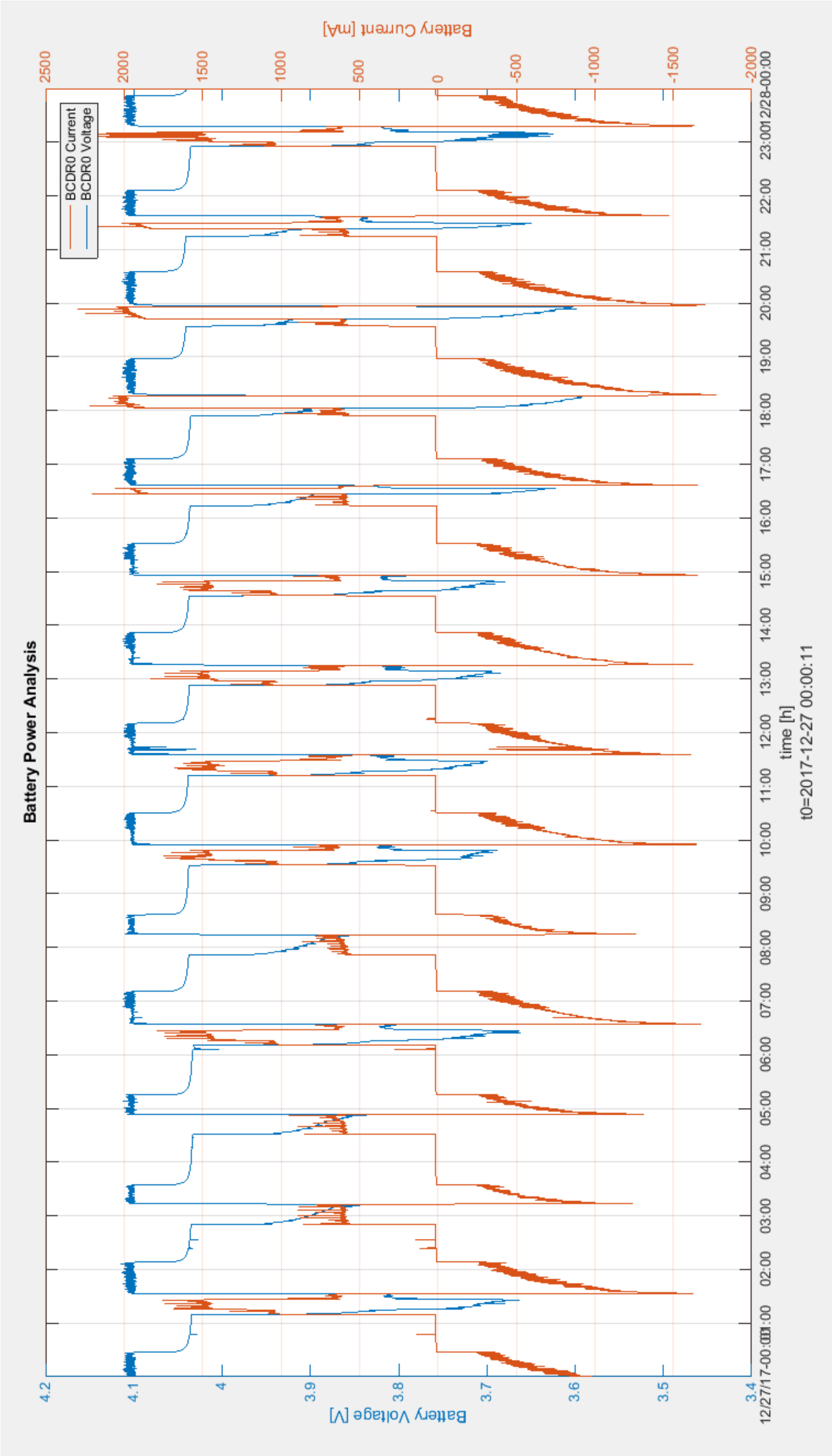


Figure 6.5: Battery behaviour in eclipse in 2017: The battery behaviour from a comparable day in 2017 is depicted.

6.2.1.2 General Spacecraft Power Statistics - Eclipse

As a comparison, the overall power statistics of the spacecraft in the years 2013/2015/2017 are depicted. To charge the battery efficiently, peak-power tracking of the solar cells is used. The behaviour as seen from the battery is also recognisable given the consumed and generated power (solar cells only or in total).

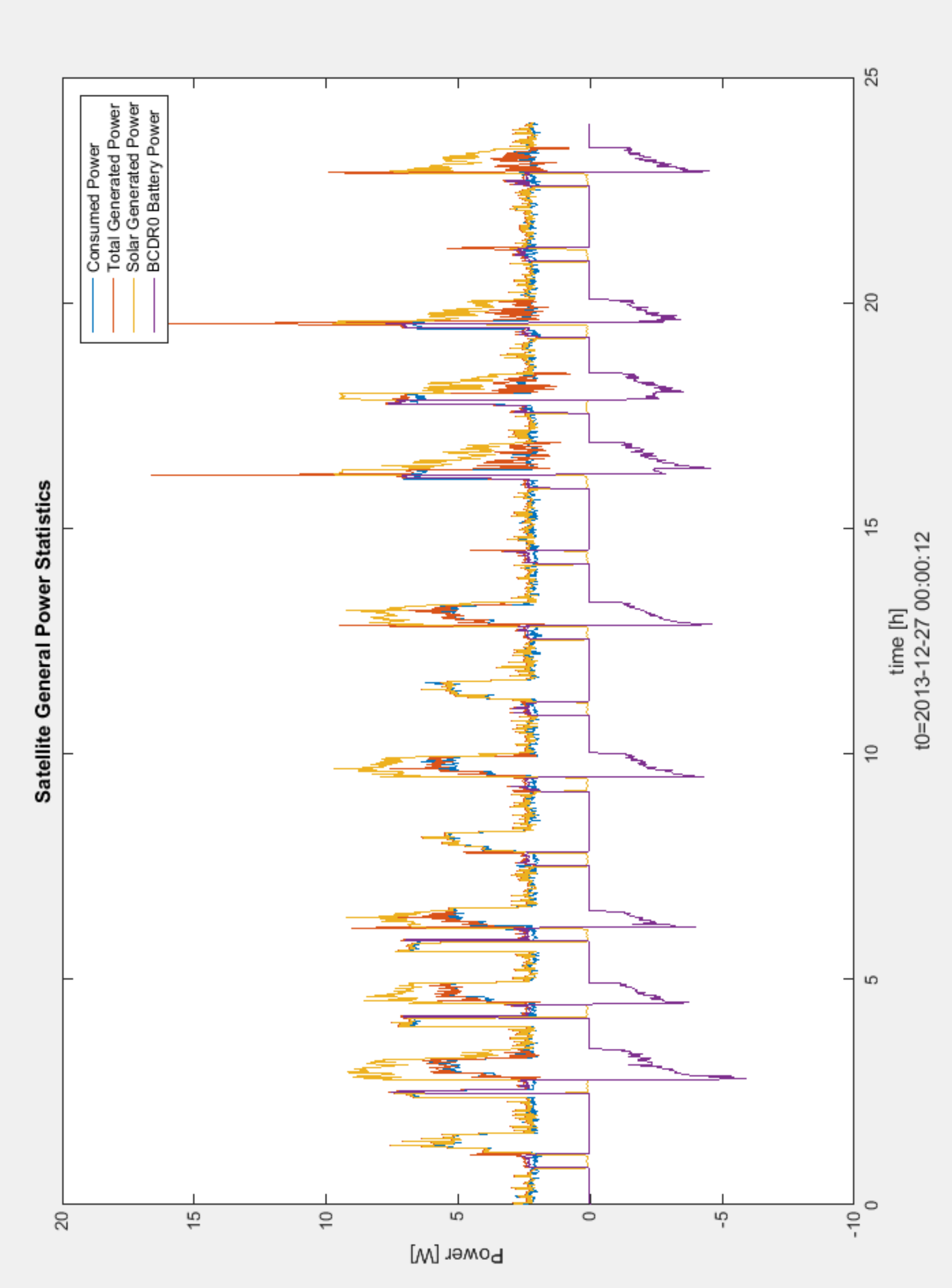


Figure 6.6: Power statistics in eclipse: The plots state the power statistics, from a day in December 2013. The battery power is depicted next to the consumed, and generated power (solar and total).

In the graph below the power statistics of December $27th$ are shown. It can be clearly seen, that the battery is significantly used in case the eclipse overlaps with the observations (nearly every 100 min). The peaks in the total power generation in the evening hours correspond to the ground station contacts and therefore use of the S-band transmitter.

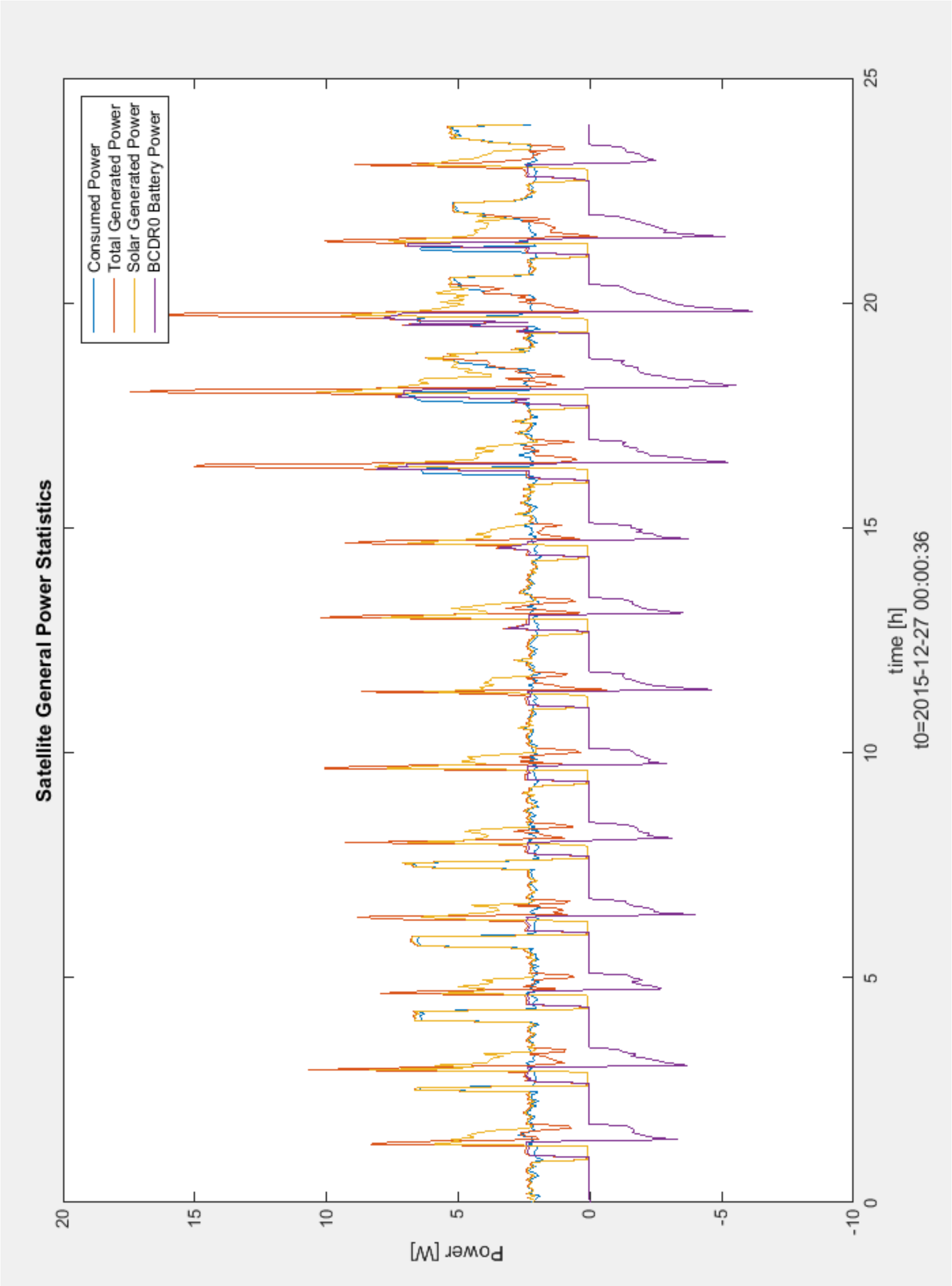


Figure 6.7: Power statistics in eclipse: The plots state the power statistics, collected during the same day in December in 2015.

Given the power statistics in December 2017, it is seen, that the battery charging duration is increasing as well as the discharge depth. To avoid peak power needs, it was decided to perform no observations in case a data download to the Graz ground station is occurring.

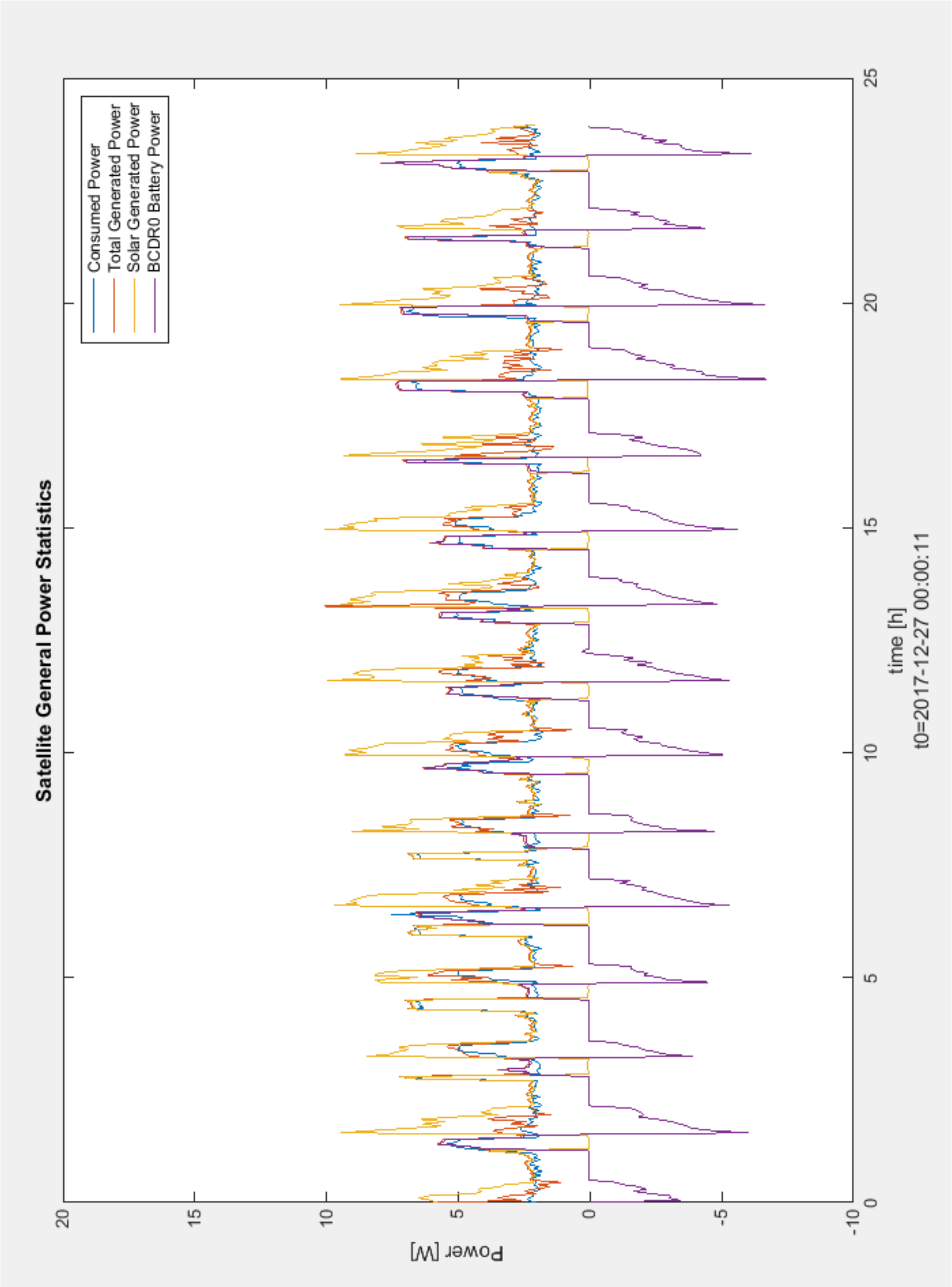


Figure 6.8: Power statistics in eclipse: The plots state the power statistics, collected during the same day in December in 2017.

6.2.1.3 Body Rates experienced during CTAP and FTAP - Eclipse

While the spacecraft is not observing, the attitude is only coarsely stabilised. Over the years no degradation of the attitude performance in coarse pointing, but also in fine-pointing during observations was not noticable.

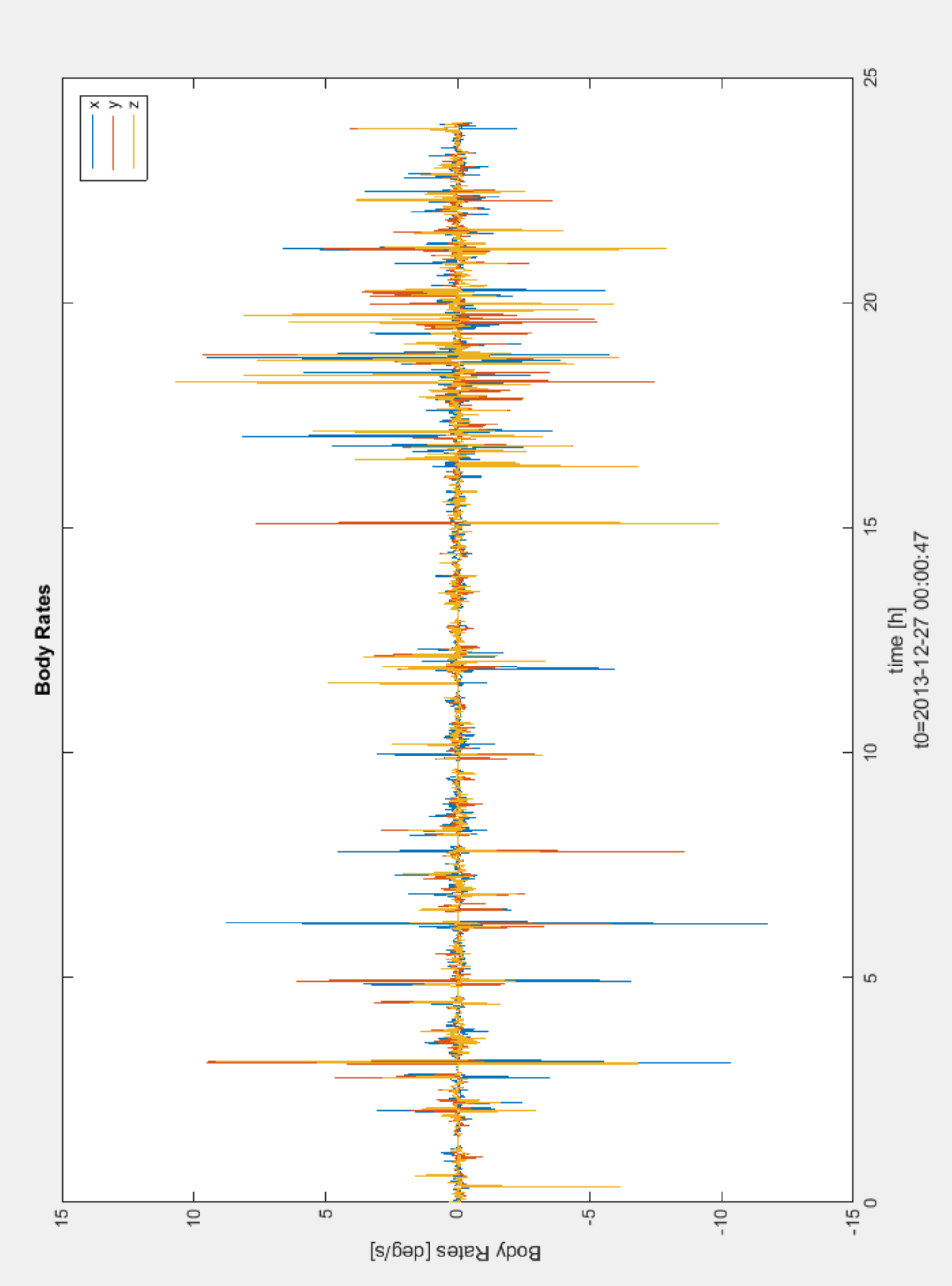


Figure 6.9: Body rates in eclipse: The body rates of the spacecraft on a day in December in 2013 are shown. The three colours represent the body rates in the respective axis.

In this plot it can be seen, that the spacecraft was only coarsely attitude controlled until around 6 p.m., followed by observations (a significant change in body rates for target alignment and for mode change) and nadir tracking for ground station contacts.

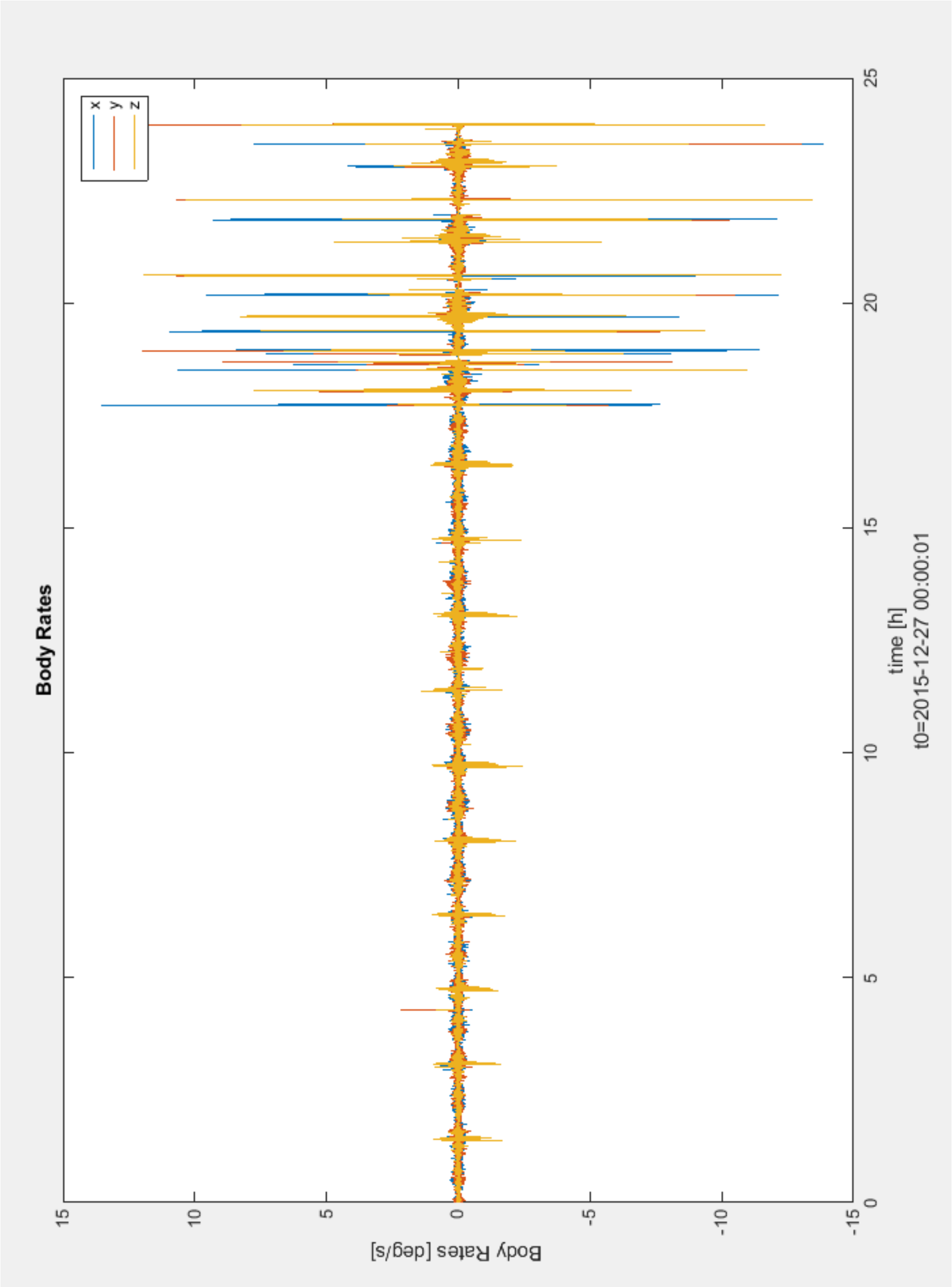


Figure 6.10: Body rates in eclipse: The body rates of the spacecraft on same day in December in 2015 are shown.

Over the years, it was only noticeable, that due to the degradation of the startracker, a transition from coarse to fine pointing is very dependent on the target field and the locations of the guiding stars and fails more often (every several days, compared to 1-2 weeks in 2015). However, also the number of observations increased over the years, leading to more possible mode drops.

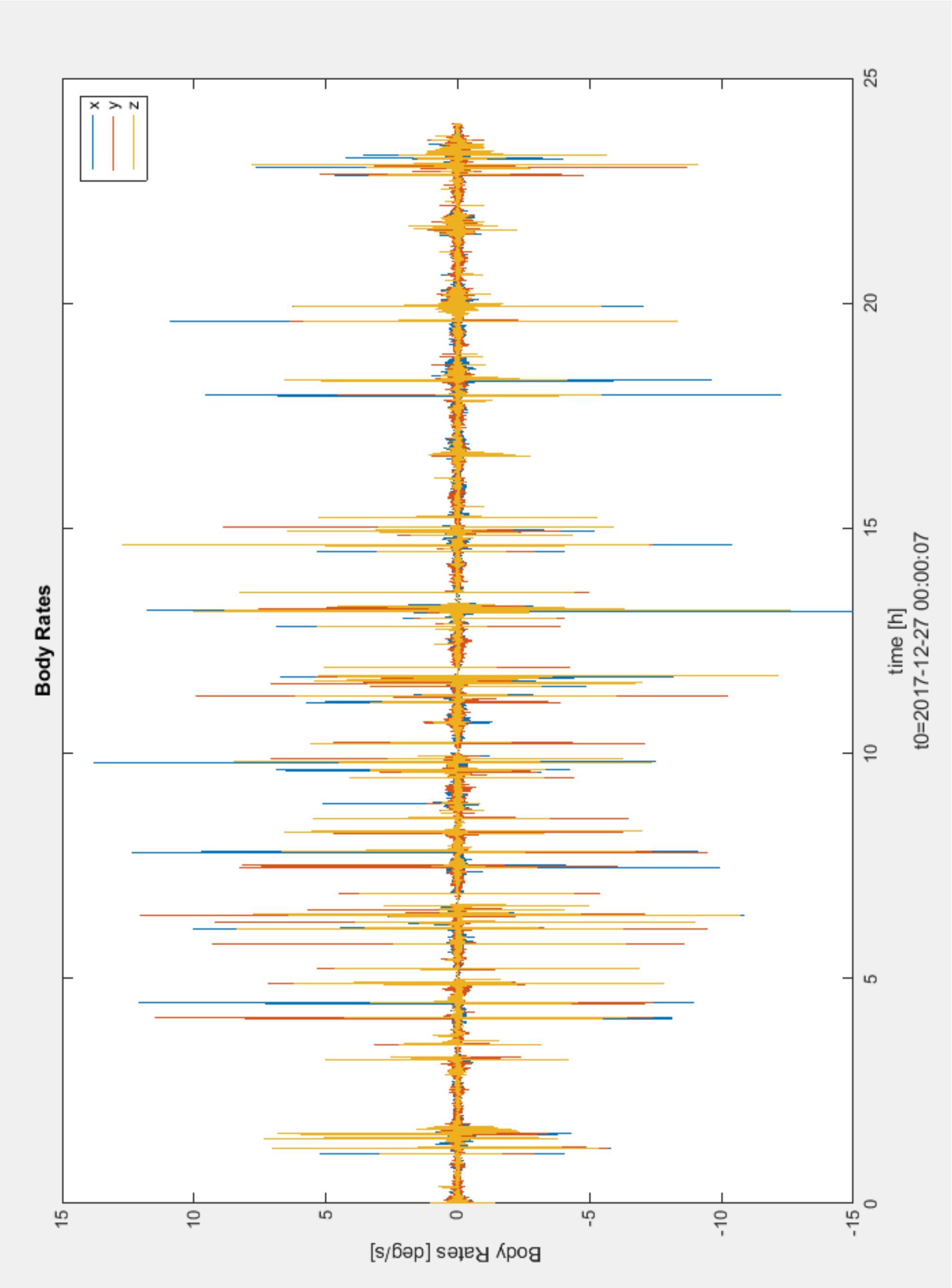


Figure 6.11: Body rates in eclipse: The body rates of the spacecraft on same day in December in 2017 are depicted.

6.2.1.4 Temperature Analysis of the Boards as well as measured on the Inside of the Panels - Eclipse

As the temperatures gradients can be quite challenging during the eclipse phase, the temperatures of the power board (located in the +Z tray) and the UHF receiver (located in the -Z tray) are analysed. These systems are permanently on since the launch and are therefore monitored conscientiously. A temperature gradient of less than 10° C is seen.

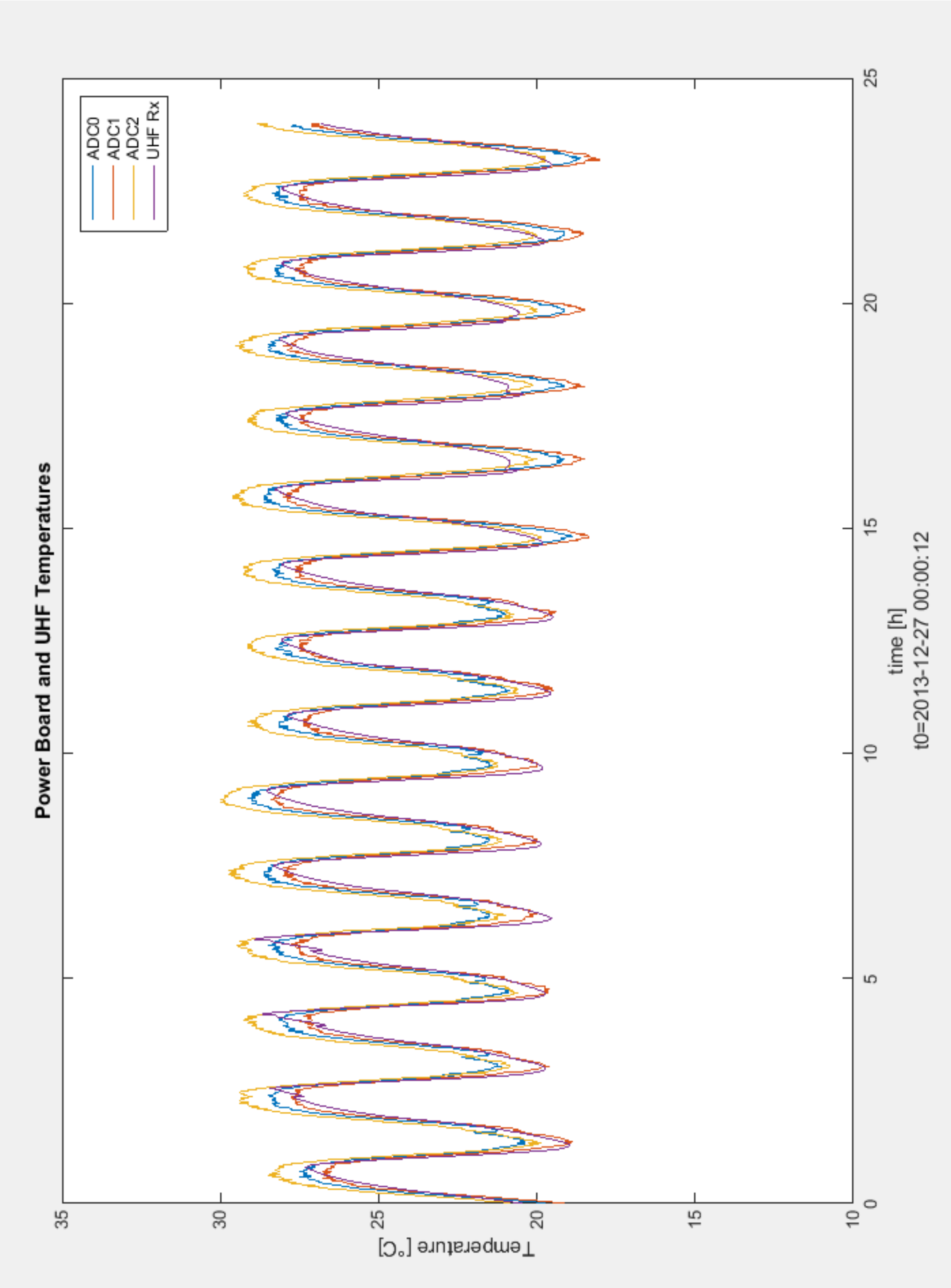


Figure 6.12: Board temperatures in eclipse: The temperatures of the boards on December $27th$ in 2013 are depicted.

Comparing with the body rates in 2015 given in the previous section (Figure 6.10), it can be seen that the orientation of the spacecraft was changed during the evening hours, leading to a different internal thermal distribution.

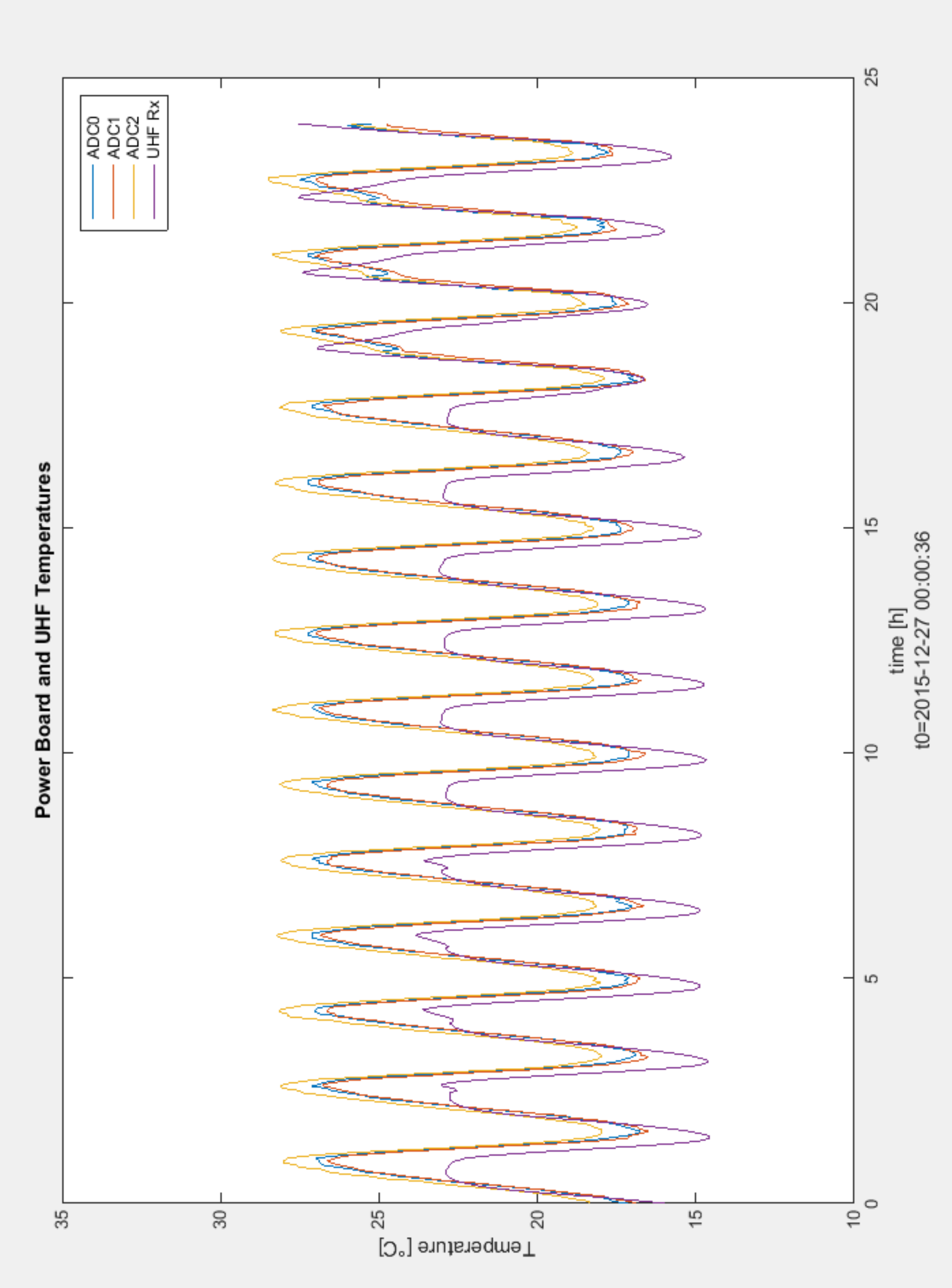


Figure 6.13: Board temperatures in eclipse: The temperatures of the boards on same day in December in 2015 are shown.

As the spacecraft tends to get too cold during eclipse, the spacecraft is re-oriented in case no observations or ground contacts are foreseen. The spacecraft is therefore aligned as such, that three faces are illuminated by the Sun to heat the satellite up.

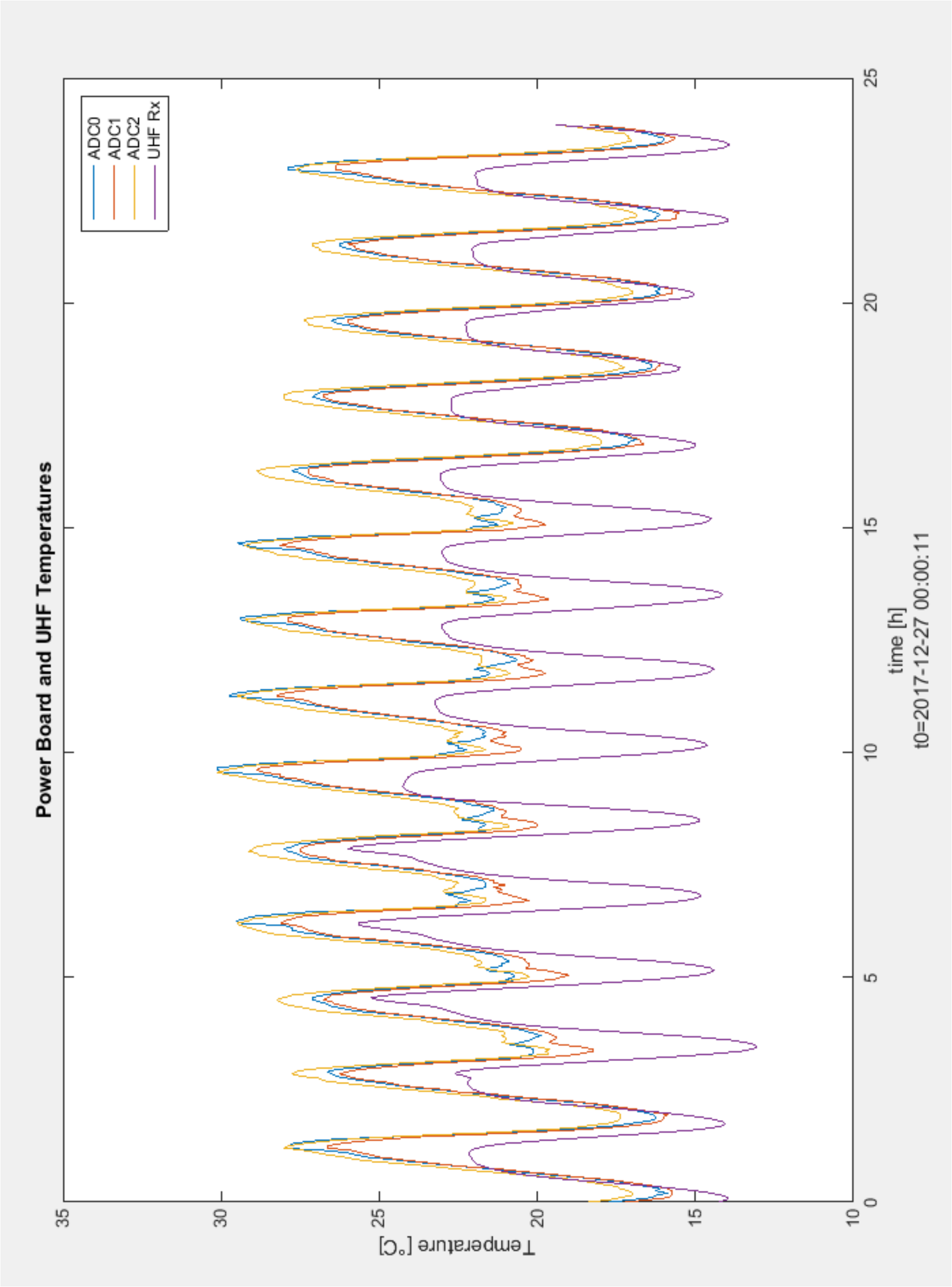


Figure 6.14: Board temperatures in eclipse: The temperatures of the power board as well as the UHF receiver on a day in December in 2017 are depicted for comparison.

As comparison, the temperature values of the sensors on the inner side of the panels are shown. It can be seen that the temperatures during the eclipse phase drop significantly for each panel, but always stay in the positive temperature range.

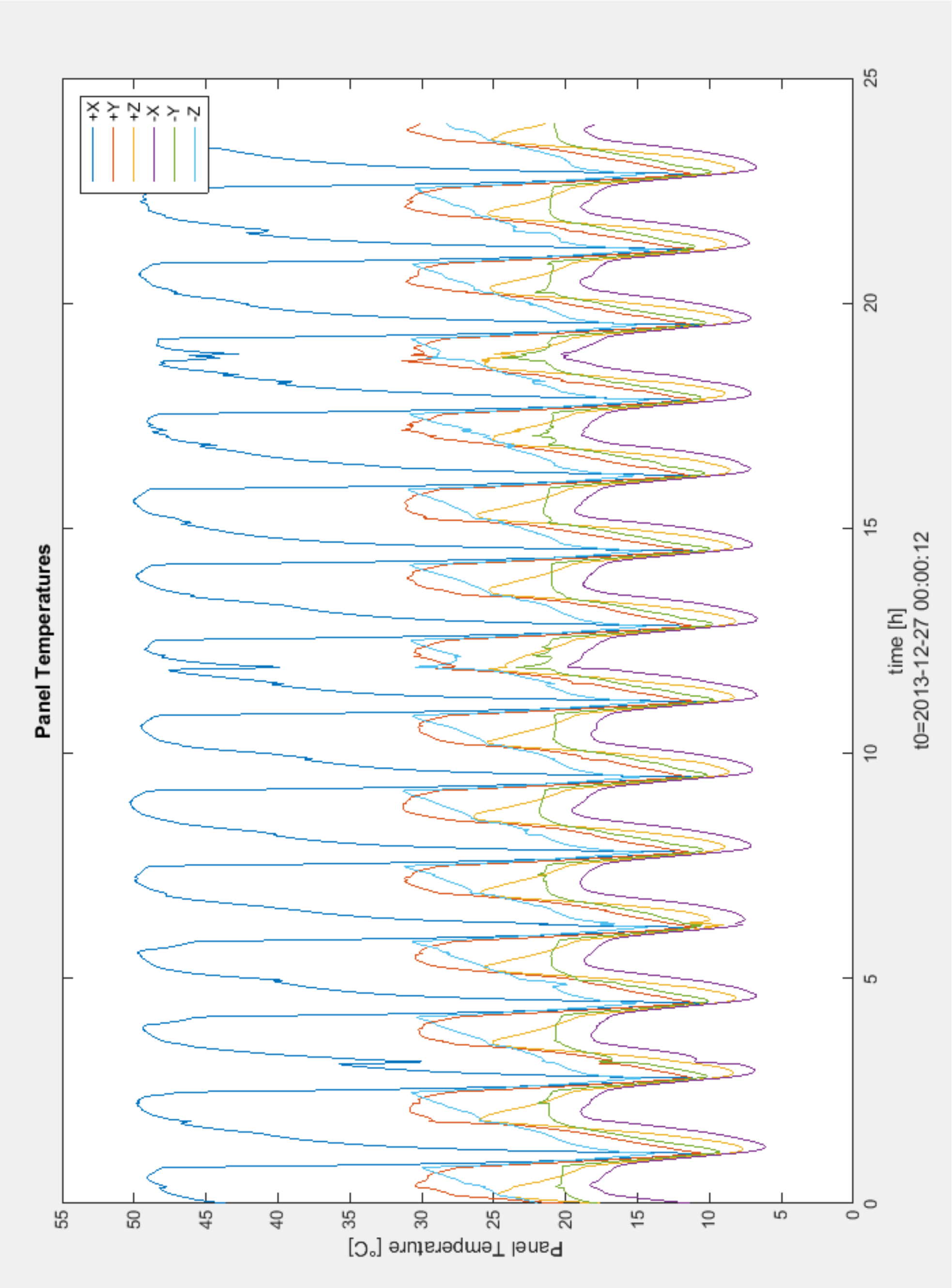


Figure 6.15: Panel temperatures in eclipse: The temperatures of the panels, measured on the inside, on December 27th in 2013 are depicted.

In 2013, the spacecraft was only oriented to a test quaternion, while in 2015 the spacecraft was already pointed to Perseus (for the more uniform illumination on three of the panels), when coarsely attitude controlled. The following plot shows this behaviour.

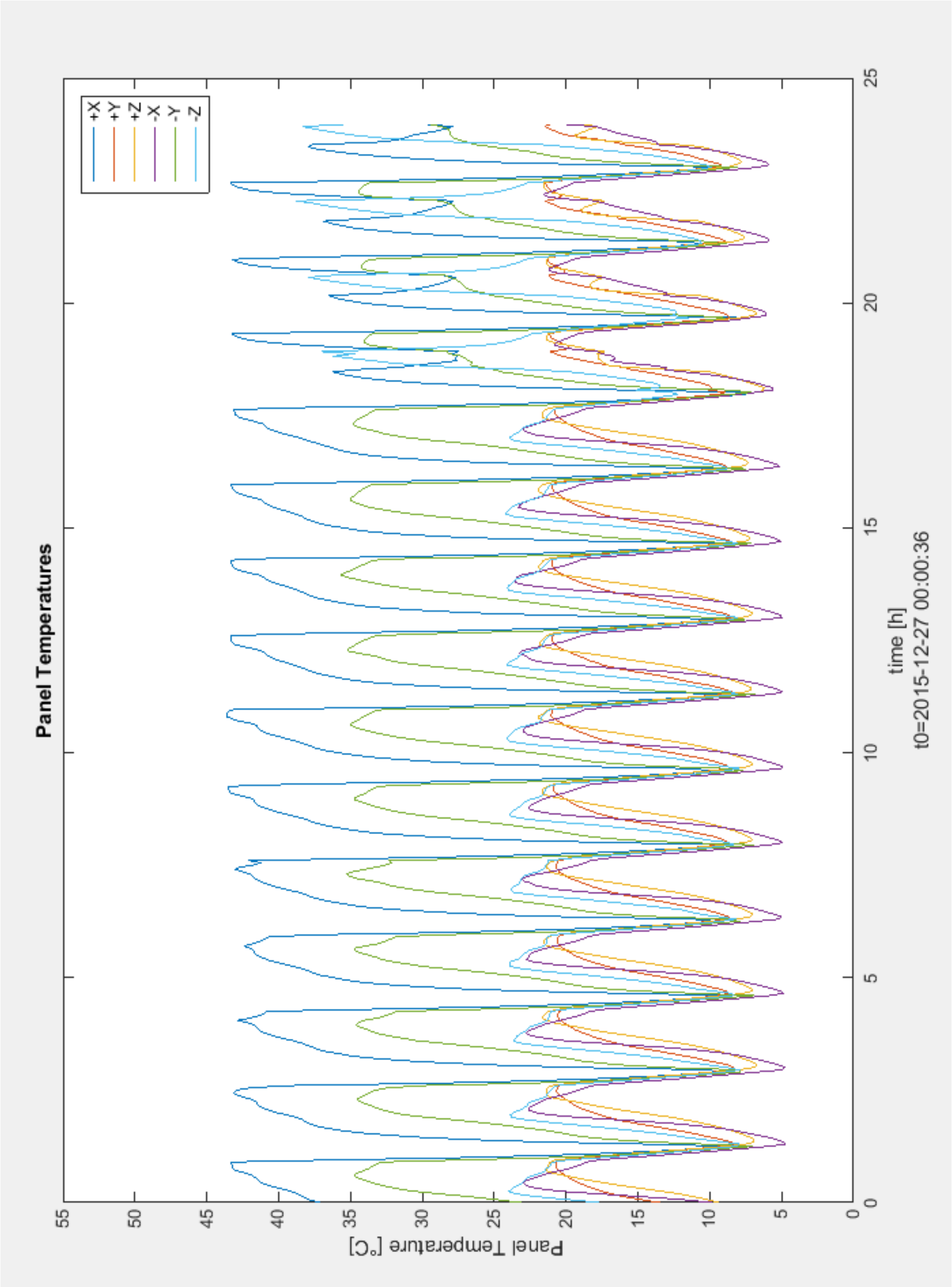


Figure 6.16: Panel temperatures in eclipse: The temperatures of the panels, measured on the inside on a day in December 2015 are shown.

Although the temperatures measured on the inside of the aluminum panel faces significantly drop when entering the eclipse, the overall minimum temperature is still in the positive range.

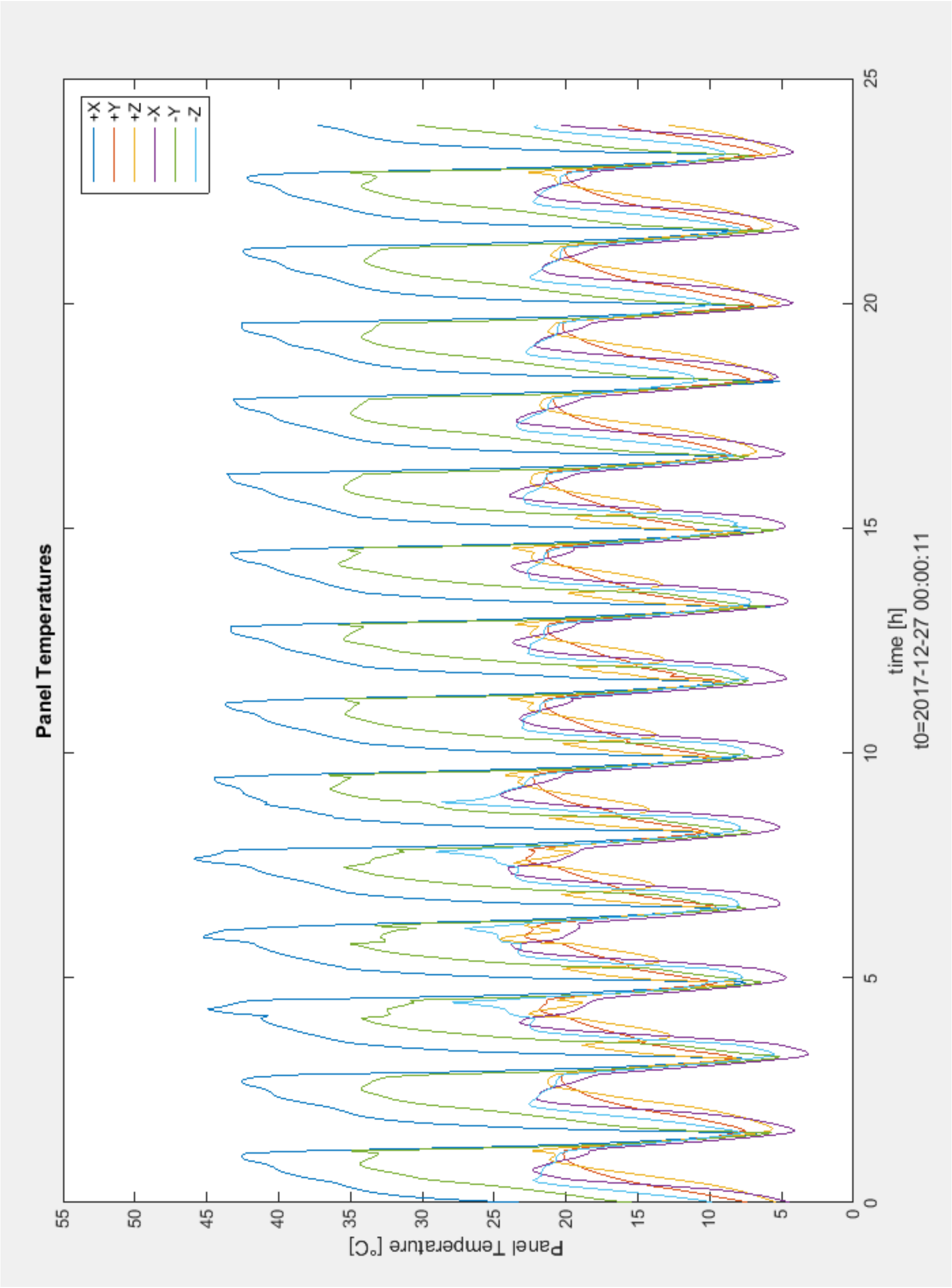


Figure 6.17: Panel temperatures in eclipse: The temperatures of the panels, measured on the inside, on December 27th in 2017 are depicted.

6.2.2 Performance in Continuous Sunlight

The same analysis of the telemetry values is performed for an operational day in May 2014/ 2016/2018. As the battery is typically not used during the non-eclipse phase, the voltage level remains in the predefined range of 4 to 4.2 V.

6.2.2.1 General Spacecraft Power Statistics - Sunlight

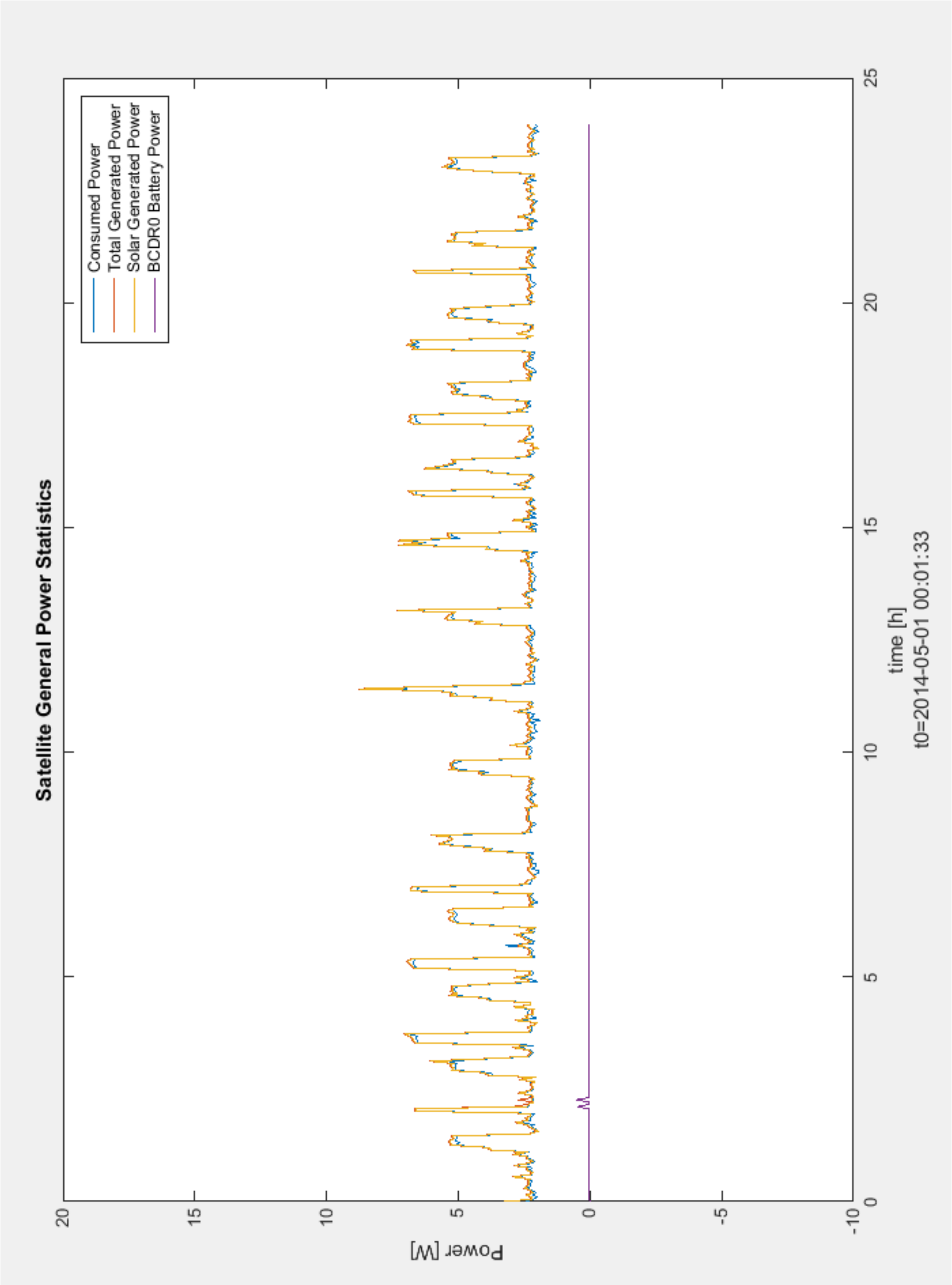


Figure 6.18: Power statistics in sunlight: The power statistics are depicted from May 1^{st} 2014. As the battery is not used during operations in sunlight, the consumed power equals the total generated solar power.

The plots in Figures 6.18 to 6.20 state the overall power statistics of BRITE-Austria during sunlight. It can be seen, that the spacecraft needs around 2 W during coarse pointing and additional power is needed during attitude channge, observations and ground station contacts.

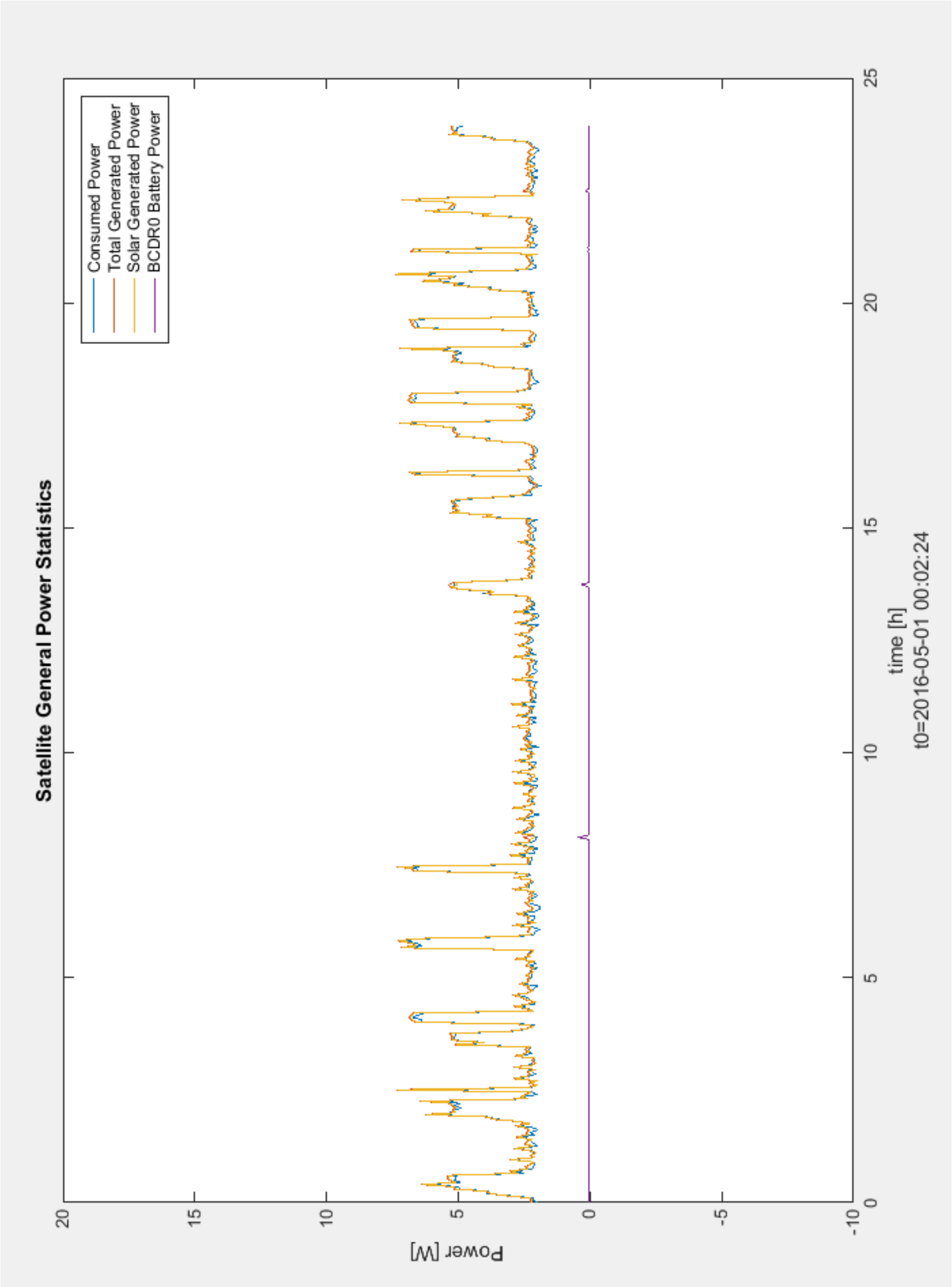


Figure 6.19: Power statistics in sunlight: The power statistics are depicted from May 1^{st} 2016.

When comparing the plots, the overall power demands have not changed over the years.

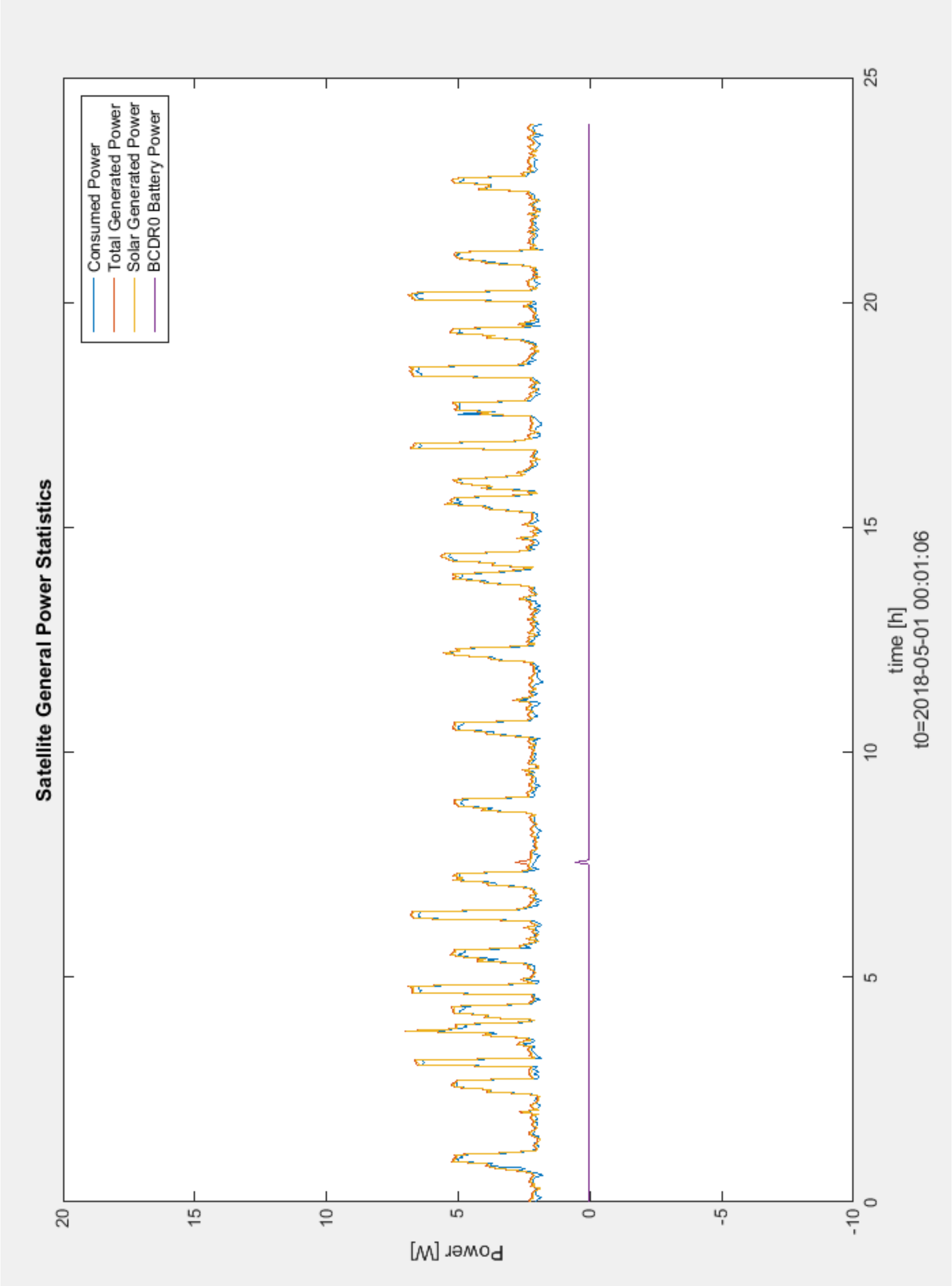


Figure 6.20: Power statistics in sunlight: The power statistics of a respective day in May 2018 are shown.

6.2.2.2 Body Rates experienced during CTAP and FTAP - Sunlight

The attitude behaviour and stabilisation has hardly changed over the years. The body rates shown in the diagrams state the change of attitude in degrees per second in each axis.

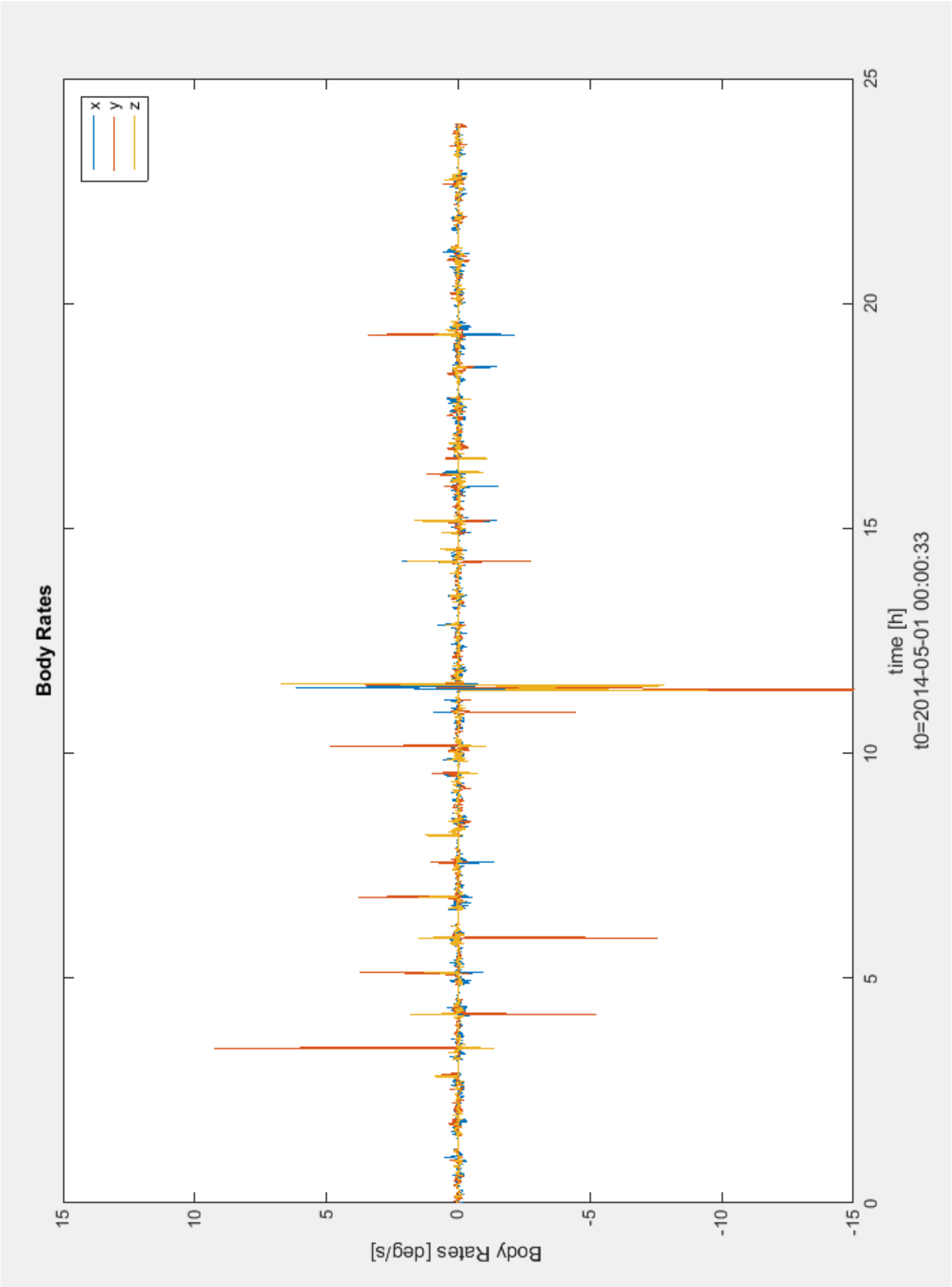


Figure 6.21: Body rates in sunlight: The body rates on a representative day in May 2014 are shown.

The peaks and increase in body rates are due to the attitude change, the decrease of body rates represents a successful mode change from coarse to fine attitude control.

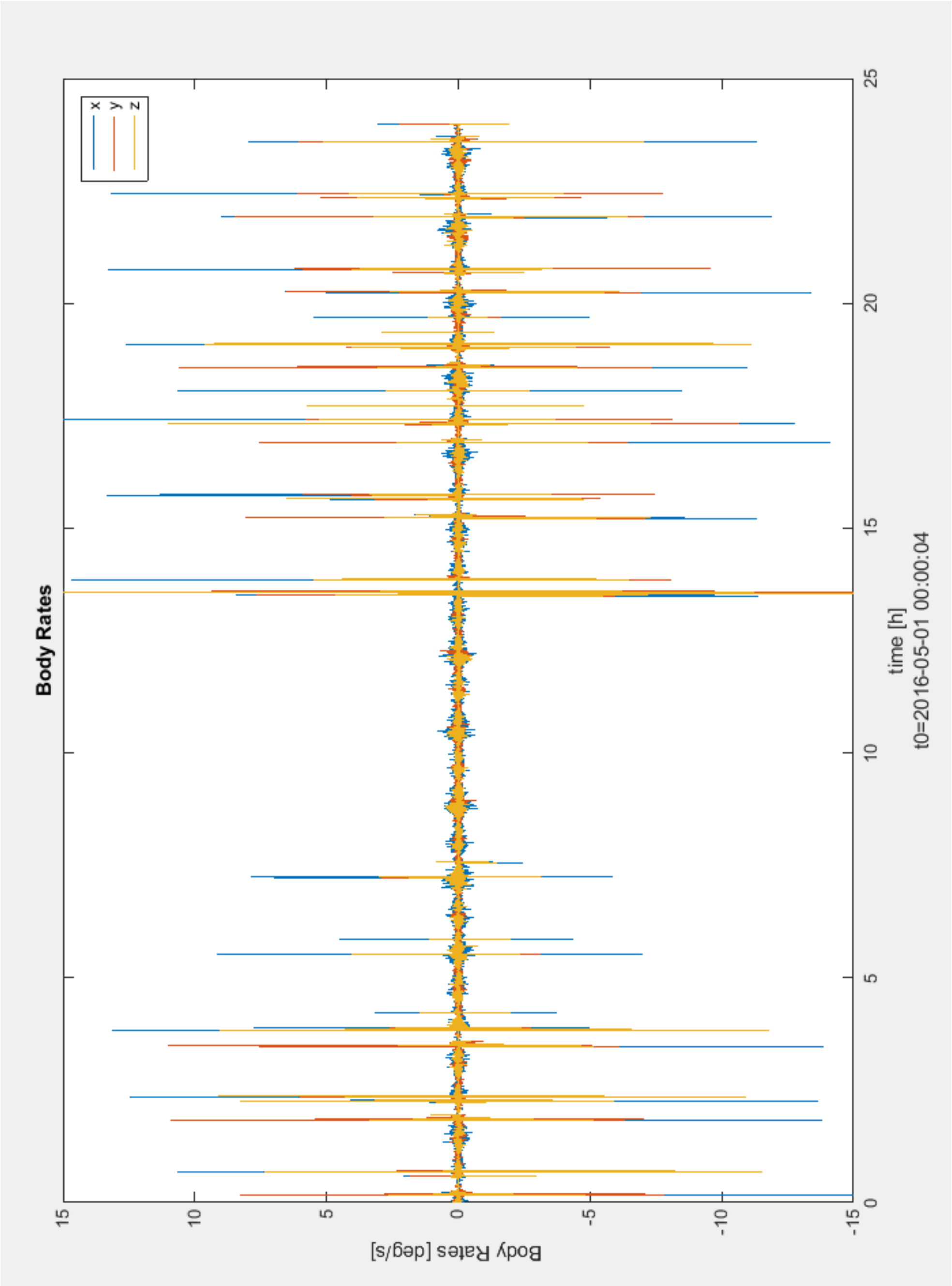


Figure 6.22: Body rates in sunlight: The plots indicate the body rates of the spacecraft on May 1st in 2016.

In case the bodyrates stay high for a period of 15-20 min, a non-successful change in attitude mode occured. When comparing the body rates over the last years, the typical rates in coarse pointing are still in the range of 0.5 deg/sec in each axis.

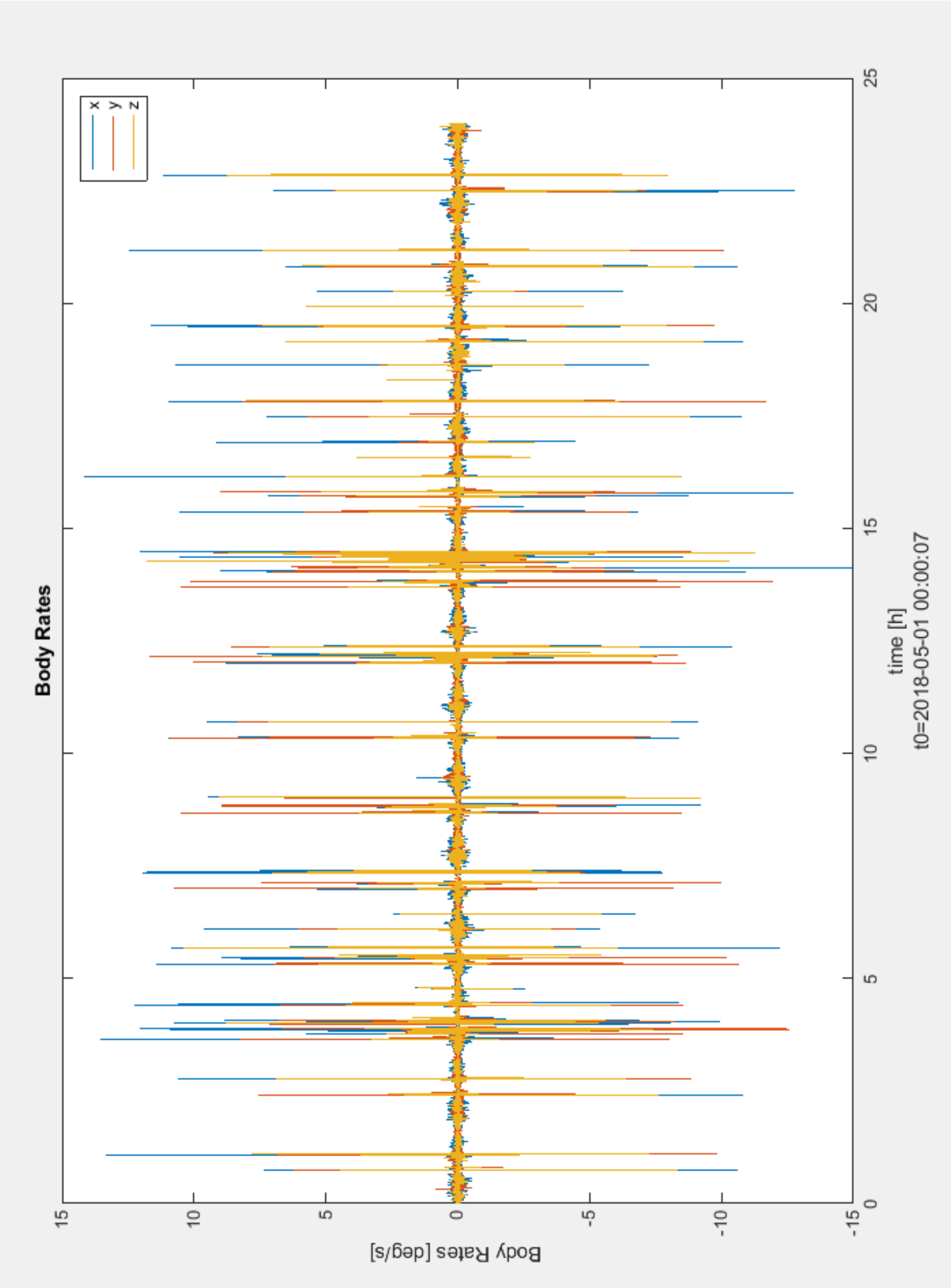


Figure 6.23: Body rates in sunlight: The plots indicate the body rates of the spacecraft on May 1^{st} in 2018.

6.2.2.3 Temperature Analysis of the Boards as well as measured on the Inside of the Panels - Sunlight

When in eclipse the satellite interior might get too cold, during the continuous sunlight phase, the spacecraft gets heated up easily. In May 2014 the temperatures of the power board and the UHF receiver were typically between 25 and 35 °C.

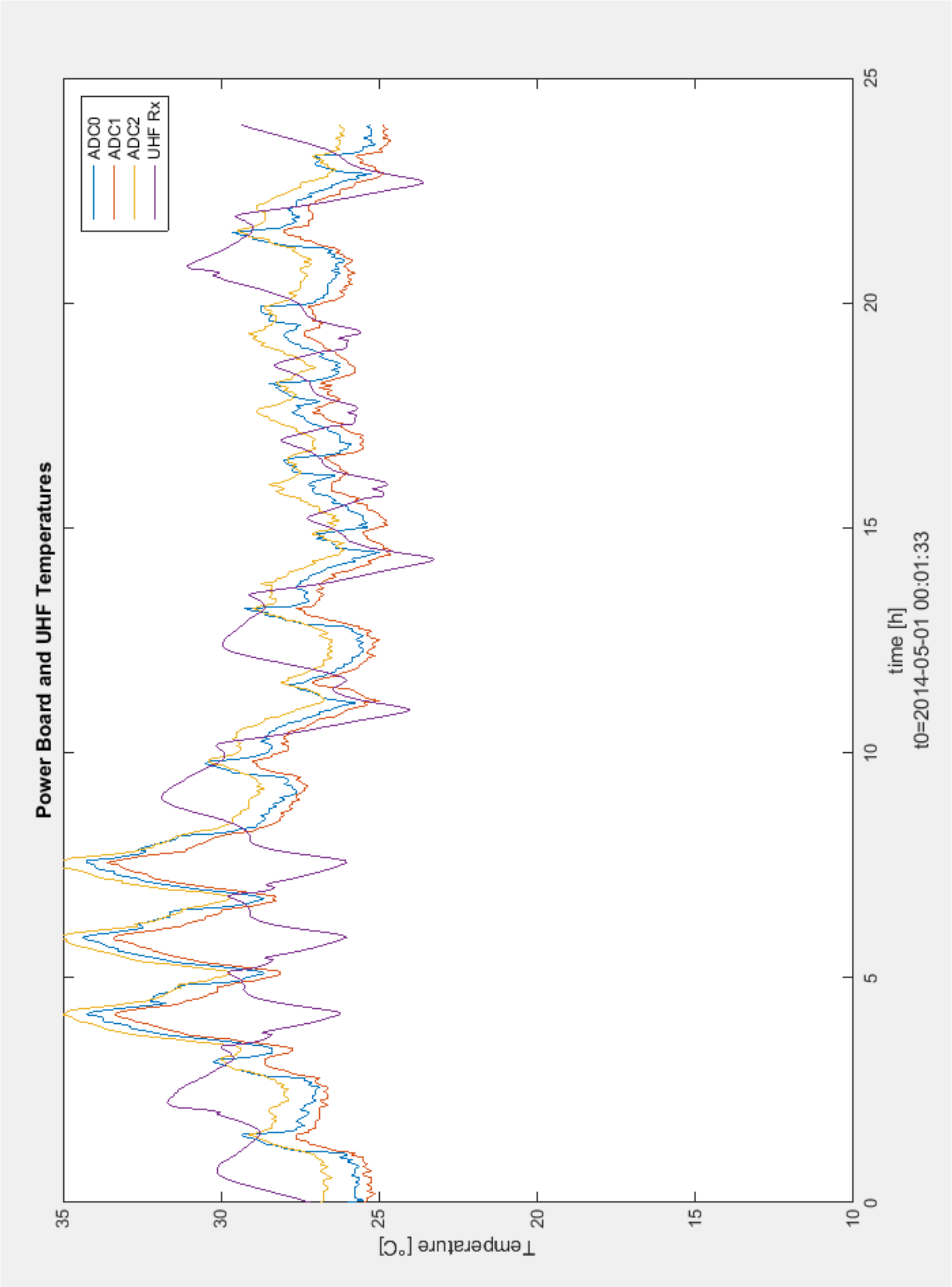


Figure 6.24: Board temperatures in sunlight: The temperatures of the boards on one day in 2014 are depicted.

The countermeasure of reorienting the spacecraft in an anti-Sun direction between observations in 2016 led to a significant decrease in temperature measured on the boards inside by several degrees, as can be seen in the following plot.

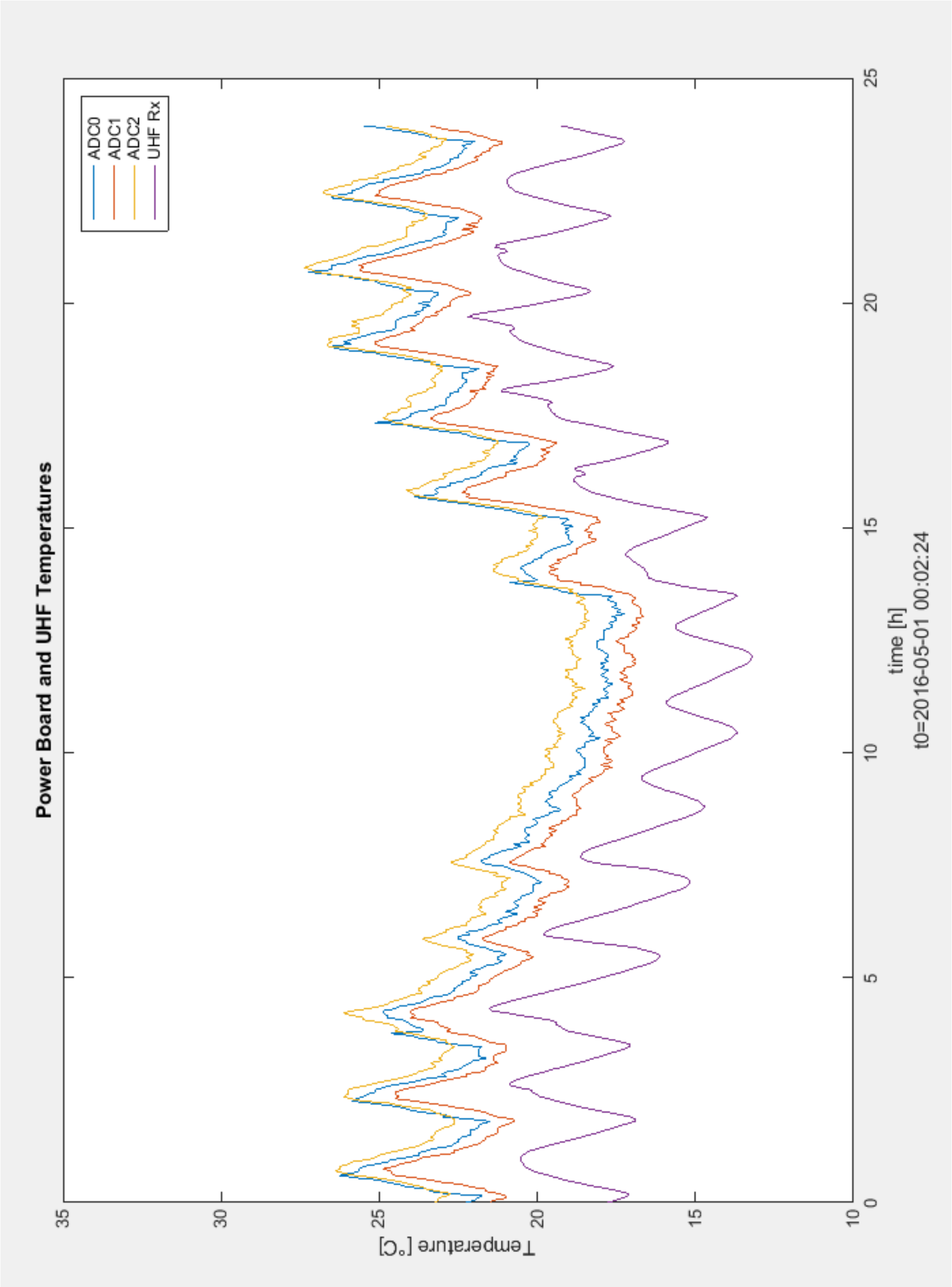


Figure 6.25: Board temperatures in sunlight: The temperatures of the boards are shown for a respective day in May 2016.

When introducing parallel observations, the temperature differences even more decreased during the following years.

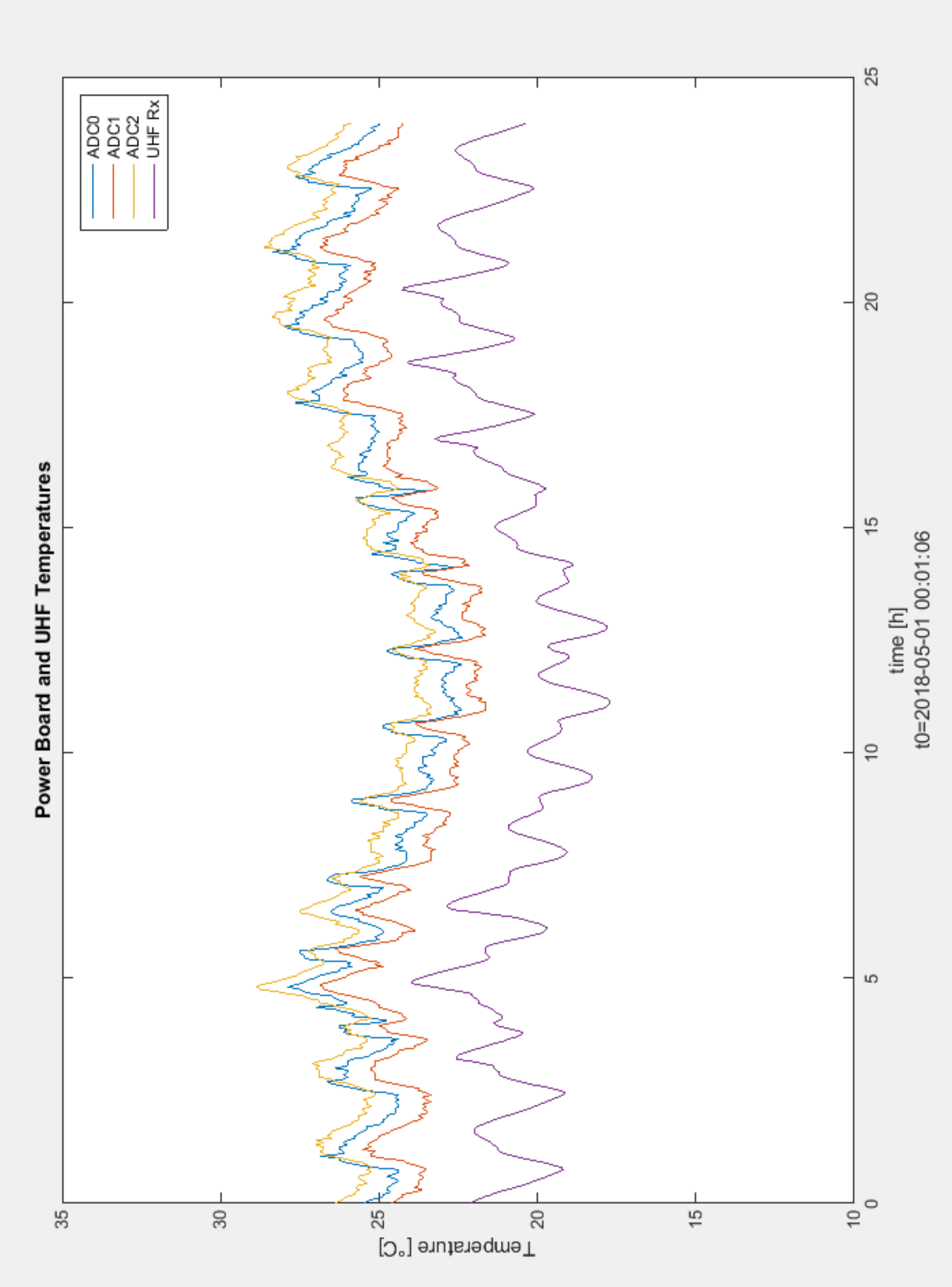


Figure 6.26: Board temperatures in sunlight: The temperatures of the boards on one day in 2018 are depicted.

The same behaviour of temperature reduction can also be seen at the panel temperature telemetry values.

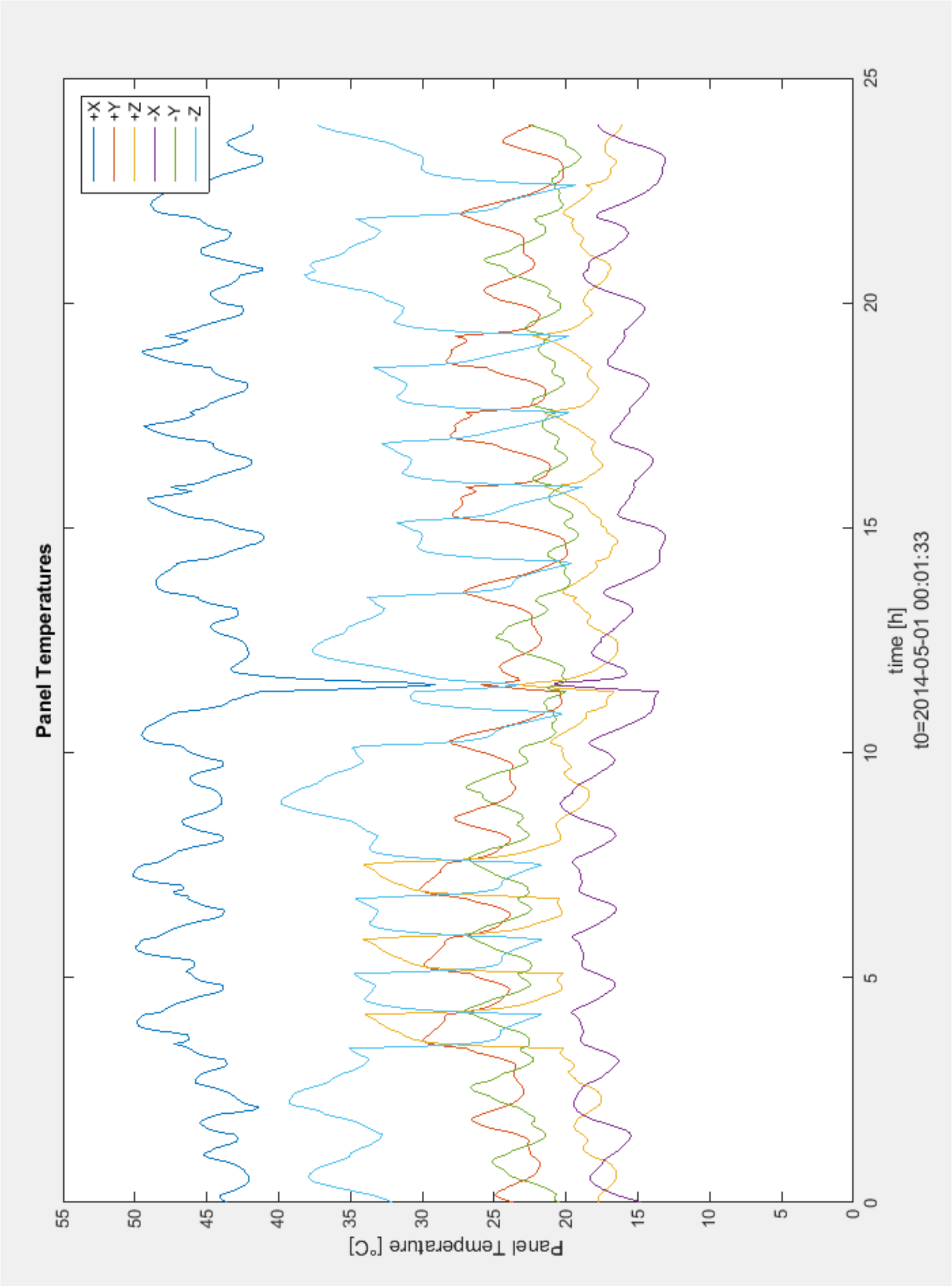


Figure 6.27: Panel temperatures in sunlight: The temperatures of the panels, measured on May 1st 2014 on the inside, are depicted. The spikes in the diagrams correspond to a change in attitude, as seen in 6.21

When changing the attitude due to observations or nadir tracking, the impact on the temperature at the inside of the panels can be seen easily.

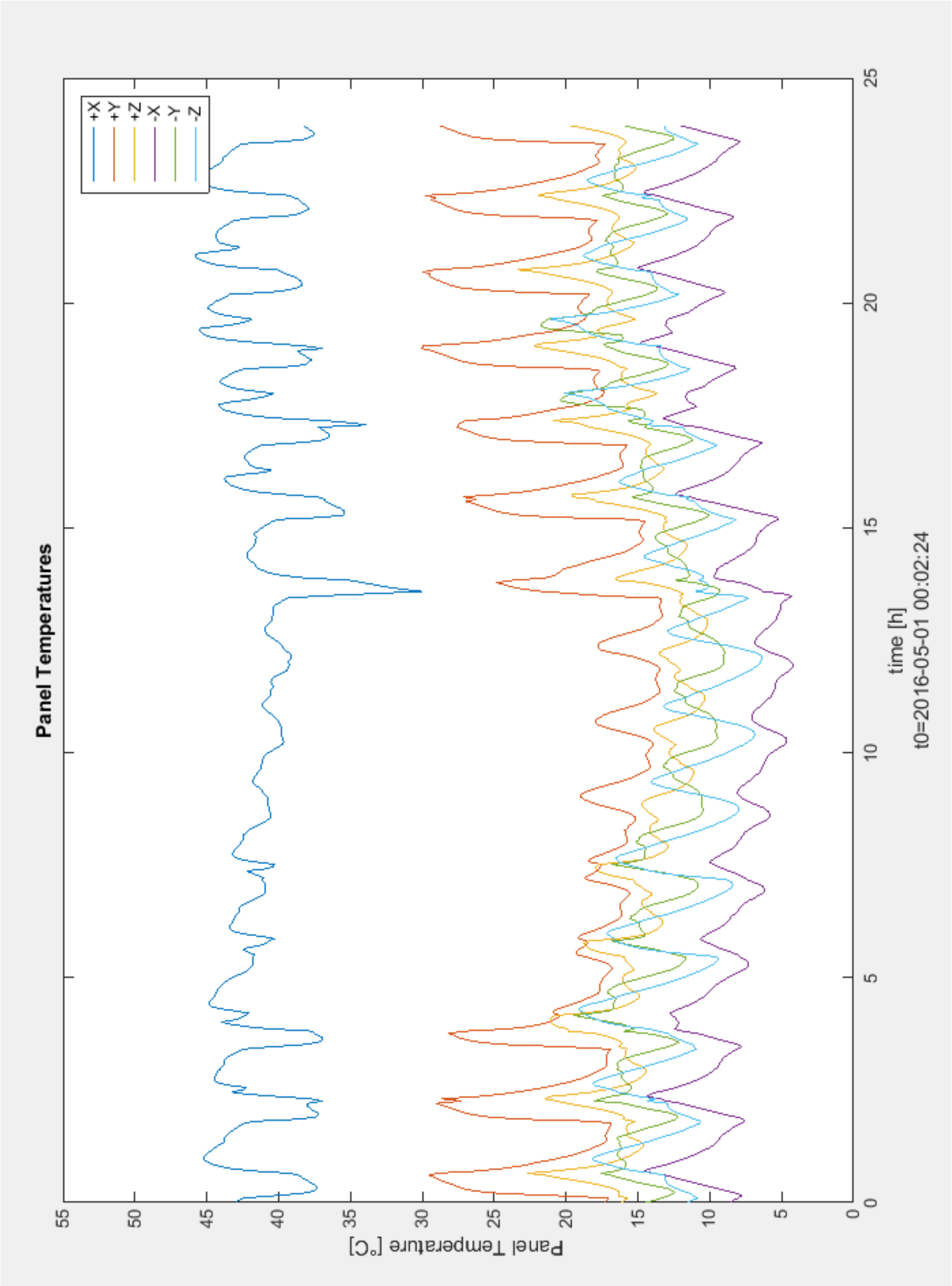


Figure 6.28: Panel temperatures in sunlight: The panel temperatures from inside the spacecraft are depicted for a respective day in May 2016.

Due to the reorientation of the spacecraft to an anti-Sun direction when not observing yields to a significant temperature drop on the -X face (opening of instrument and startracker) as well as on the -Z face (location of UHF receiver).

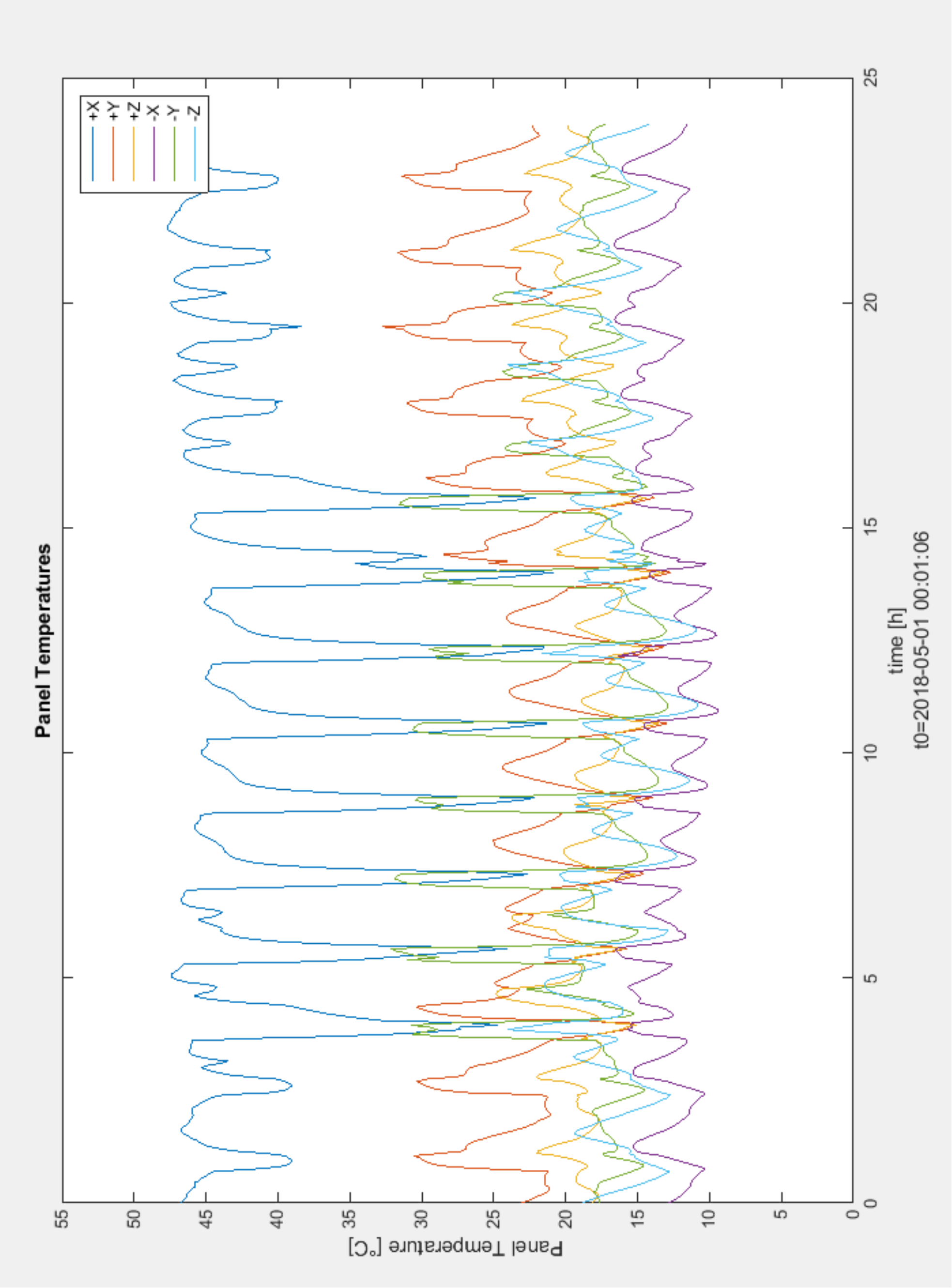


Figure 6.29: Panel temperatures in sunlight: The temperatures of the panels, measured on May 1^{st} 2018 on the inside, are depicted. The spikes in the diagrams correspond to a change in attitude, as seen in 6.23

Chapter 7

Functional Optimisation and Challenges Faced

During operations, the behaviour and performance of the spacecraft and the payload is continuously analysed. Due to these analyses several optimisations of the functionality were introduced over the years. In addition, as the entire spacecraft is degrading, a set of countermeasures in space and on ground were defined and set into place to still guarantee the high level of data quality [43].

7.1 Optimisation of Scientific Output and Data Quality

To increase the data output and to guarantee the data quality of the scientific observations also in the upcoming years, various improvements have been realised.

7.1.1 Optimisation of the Observation Cycle

As the startracker needs to warm up before the spacecraft can be put into fine pointing, this time duration is shortening the overall observation time. After several trials it was found that the 20 minutes for warmup were not needed, and the time could be reduced down to 3 minutes. In addition, the time needed to change the position and align to a target field could also be decreased from 5 to 3 minutes, allowing longer observation campaigns.

Observations with two setup files
For observations at Centaurus, a special configuration was introduced. Since Alpha and Beta Centauri, the two brightest stars in the field, are orders of magnitude brighter than the other stars in that field of view, two setup files were executed sequentially during one orbit observation.

One dedicated setup file for Alpha and Beta Centauri with a reduced exposure time of only 400 ms was used, and a second setup file with an exposure time of 1000 ms was executed for the rest of the field.

Introduction of a secondary observation field to be performed each orbit
Due to the constraints of SAA, eclipse and ground station passes, a target field might not be able to be observed on each orbit. In addition, observations only last 10-15 minutes, summing up to 20-25 minutes including setup. Therefore, a secondary target field was introduced, to increase the overall data volume, but still keeping the spacecraft power and thermally safe.

7.1.2 Correction of CCD Radiation Effects

The CCDs on the BRITE satellites are effected by the penetration of the protons and electrons during their flight over the poles, and of course their multiple daily passages through the SAA. These penetrations yield to several defects of the CCD:

- **Warm columns** - All pixels along distinct columns have higher signal values compared to unaffected columns. The signal levels are about 100-500 Adjusted Digital Units [ADUs] above nominal background.
- **Hot pixels** - These are isolated pixels and are spread across the entire image. They show consistently signal values above the nominal background, ranging from 100 ADU to saturation at 12000 ADU.
- **Charge Transfer In-efficiency (CTI) domains** - These areas are not randomly spread across the CCD but appear in distinct areas. The defect shows as vertical streaks, like smearing, starting from an pixel with high signal levels (hot pixels or stars).

Figure 7.1 shows the defects on empty areas and star rasters.

With combined efforts among the BRITE partners, strategies to mitigate the impact of radiation damage on the data quality have been developed. During post-processing of the scientific data, the warm columns and hot pixels can be deleted to a large extent. The CTI areas could be diminished by changing the CCD clock speed and increasing the pixel read time from the original 3.5 μs to the maximum recommended value of 20 μs.

Concerning the operational countermeasures, by reorienting the spacecraft (see Section 7.2.1) the CCD is cooled and the hot pixel generation rate was restrained somewhat.

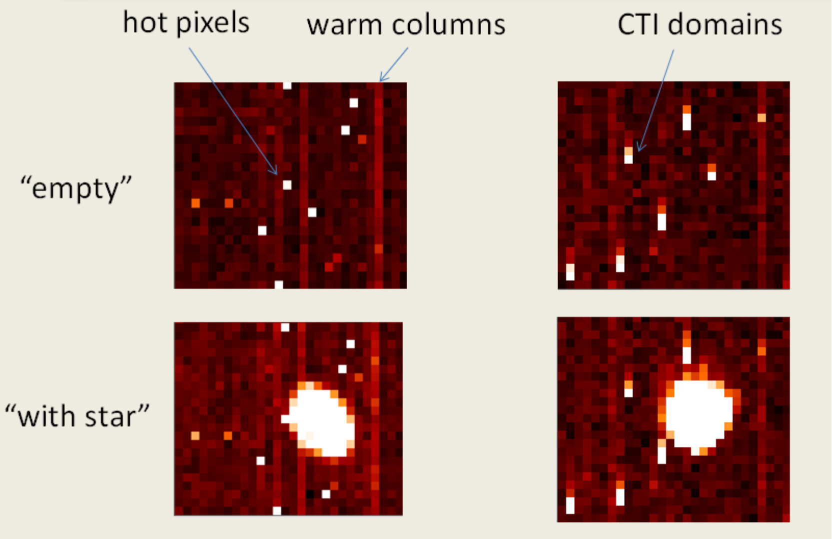


Figure 7.1: CCD defects: The two pictures on the left side who the hot pixels and warm column, whereas the pictures on the right display the CTI effect [43].

To further investigate the CTI domains and keep track of their development, a full frame image is obtained every two months. The exact sequence is first to take an image when pointing towards the bright Earth with several seconds exposure time. Afterwards, the spacecraft is pointed with the instrument to deep space and another exposure with only 40 ms is taken without reading the first image. The charge is still present in the second image and states the exact CTI domains. In addition, a new scheme ”chopping” was introduced.

Chopping

During chopping, the satellite slightly changes its orientation in one axis between two consecutive exposures yielding to a different star position on the CCD. This strategy is used in observational astronomy for decades. Instead of square rasters of 32x32 pixels, rectangular rasters were introduced to enclose the star PSF, independent of its position. Figure 7.2 shows two consecutively collected rasters by BRITE-Austria. These two images are then paired and subtracted, and the background with warm columns, hot pixels and CTI effects is removed without complicated replacement algorithms.

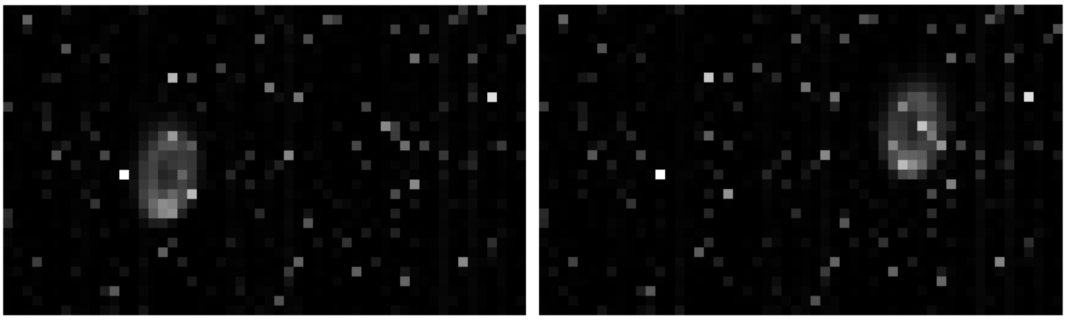
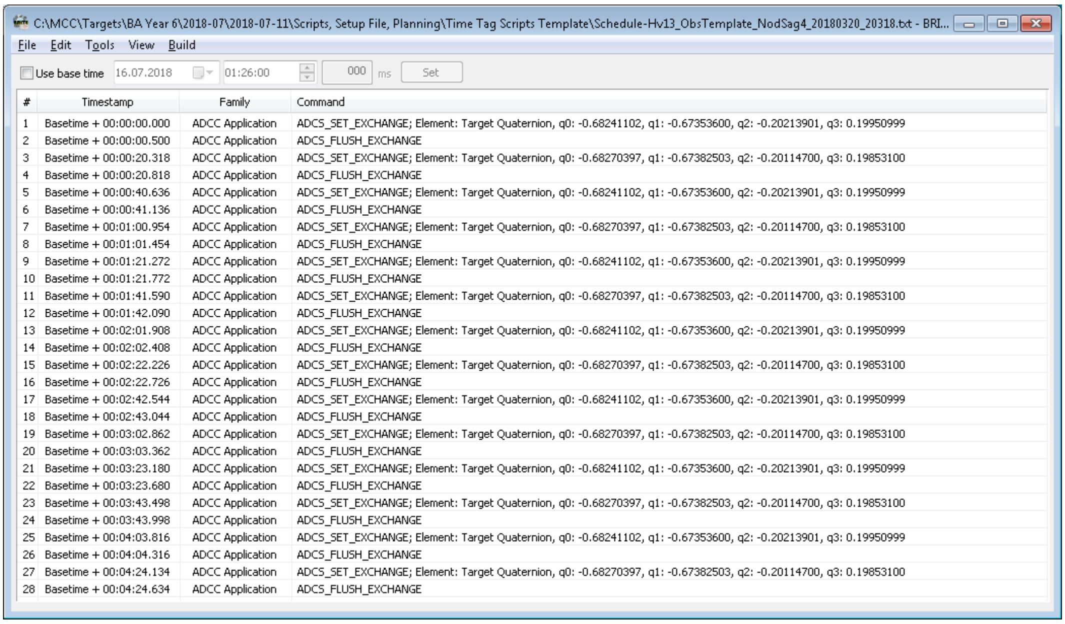


Figure 7.2: Chopping: Two consecutive rasters are collected, the star is seen on different areas of the CCD.

A chopping script was introduced, which slightly changes the target quarternion every 20 sec between two exposures.



☐ Use base time 16.07.2018 01:26:00 000 ms

#	Timestamp	Family	Command
1	Basetime + 00:00:00.000	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
2	Basetime + 00:00:00.500	ADCC Application	ADCS_FLUSH_EXCHANGE
3	Basetime + 00:00:20.318	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
4	Basetime + 00:00:20.818	ADCC Application	ADCS_FLUSH_EXCHANGE
5	Basetime + 00:00:40.636	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
6	Basetime + 00:00:41.136	ADCC Application	ADCS_FLUSH_EXCHANGE
7	Basetime + 00:01:00.954	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
8	Basetime + 00:01:01.454	ADCC Application	ADCS_FLUSH_EXCHANGE
9	Basetime + 00:01:21.272	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
10	Basetime + 00:01:21.772	ADCC Application	ADCS_FLUSH_EXCHANGE
11	Basetime + 00:01:41.590	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
12	Basetime + 00:01:42.090	ADCC Application	ADCS_FLUSH_EXCHANGE
13	Basetime + 00:02:01.908	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
14	Basetime + 00:02:02.408	ADCC Application	ADCS_FLUSH_EXCHANGE
15	Basetime + 00:02:22.226	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
16	Basetime + 00:02:22.726	ADCC Application	ADCS_FLUSH_EXCHANGE
17	Basetime + 00:02:42.544	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
18	Basetime + 00:02:43.044	ADCC Application	ADCS_FLUSH_EXCHANGE
19	Basetime + 00:03:02.862	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
20	Basetime + 00:03:03.362	ADCC Application	ADCS_FLUSH_EXCHANGE
21	Basetime + 00:03:23.180	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
22	Basetime + 00:03:23.680	ADCC Application	ADCS_FLUSH_EXCHANGE
23	Basetime + 00:03:43.498	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
24	Basetime + 00:03:43.998	ADCC Application	ADCS_FLUSH_EXCHANGE
25	Basetime + 00:04:03.816	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68241102, q1: -0.67353600, q2: -0.20213901, q3: 0.19950999
26	Basetime + 00:04:04.316	ADCC Application	ADCS_FLUSH_EXCHANGE
27	Basetime + 00:04:24.134	ADCC Application	ADCS_SET_EXCHANGE; Element: Target Quaternion, q0: -0.68270397, q1: -0.67382503, q2: -0.20114700, q3: 0.19853100
28	Basetime + 00:04:24.634	ADCC Application	ADCS_FLUSH_EXCHANGE

Figure 7.3: Introduction of nodding scripts: Between two consecutive exposures, a slightly change in target quaternion and hence orientation of the spacecraft is introduced.

7.2 Spacecraft and Ground Segment Enhancements

Over the years several issues concerning the BRITE-Austria spacecraft and its subsystems, as well as the ground segment were detected. The following paragraphs give an overview of the issues and problems faced, and state the strategies, solutions and improvements that were made [49][43].

7.2.1 Thermal and Power Subsystem

Thermal stability due to satellite reorientation

As BRITE-Austria is in an SSDD orbit, the satellite only experiences eclipses during 3 months a year, while the satellite is continuously illuminated by the Sun during the remaining time. This special orbit provides very good power conditions, as the batteries are only used during eclipse, keeping the number of charging cycles low and increasing therefore the lifetime.

The disadvantage, however, is that the thermal conditions can be quite challenging. As the spacecraft gets heated up during observations, it was decided to reorient the satellite to a position in anti-Sun direction between observations. Due to the reorientation, the only illuminated and heated face of the satellite is the +X face (hosting eight solar cells). The illuminated cells still generate enough power to sustain the satellite's health and in addition, as the other five panels face deepspace, the satellite inside is cooled down by several degrees.

During eclipse season however, the interior temperature of the spacecraft is decreasing. It was seen that if the temperature inside falls below 10° C, the efficiency of the battery drastically decreases. Therefore, during eclipse season and between observations the satellite is reoriented such, that three faces are illuminated by the Sun, heating up the interior by about 10-15° C. Figure 7.4 shows the battery temperature during eclipse season after reorientation of the satellite. A significant temperature rise can be seen after reorientation, as well as an increase of the overall temperature stability.

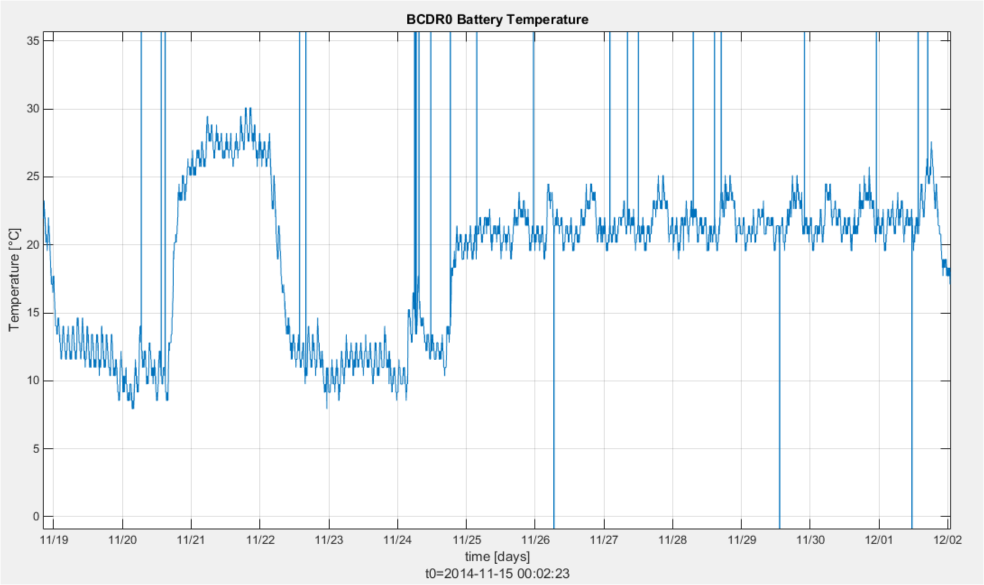


Figure 7.4: Battery temperature: Due to a reorientation of the spacecraft, a significant temperature rise of the BRITE-Austria battery temperature can be seen.

7.2.2 On-board Computer and Data Handling

Hybrid software version

Some weeks after launch, issues with the attitude determination and control OBC of BRITE-Austria occurred, leading to restrictions in the attitude control. Therefore it was necessary to transfer the functionality of the ADCC to the housekeeping computer (HKC) and create an application software that combines the housekeeping and attitude tasks. While the so-called Hybrid CANOE software was developed by UTIAS/SFL in the context of another contract, some functional enhancements concerning ADCS and especially startracker operations have been included in a later step.

Transfer of SDR from IOBC to HKC

After an observation is stopped, the scientific data is stored on the IOBC, where it can be retrieved during the following passes. However, it is not possible to use the maximum download data rate of 256 kbit/s, as the inter-OBC-communication link is restricted to 128 kbit/s. To overcome these shortages, the SDR is transferred from the IOBC to the HKC after the observation was stopped, to use the higher data rate settings in the download.

7.2.3 ADCS Subsystem

In-orbit calibration of the magnetometer

To improve the coarse determination accuracy and reduce the peak error, especially during eclipse, where the magnetic determination is the sole method of attitude information, it was decided to perform an in-orbit calibration of the magnetometer. The BRITE-Austria magnetometer had undergone intense testing and calibration on ground, however the process cannot replicate the exact behaviour as in space.

The calibration process lasted approximately two months, as extensive characterisation and in-orbit testing was performed to find the optimal and most reliable solution out of finally 19 calibration sets.

Adaption of the attitude cycle length

During the first FTAP attempts, the stability of the startracker readings and inclusion into attitude thread was not very reliable. It was found that the envisaged cycle time of 2 seconds for reading the sensors, calculation the torques and controlling the actuators was too short. After several tests and various cycle times, the optimum of 2.5 seconds was defined, as longer cycle times would increase the error in pointing accuracy significantly.

Startracker performance

All optical sensors on-board are sensitive to radiation, the startracker unfortunately is no exception. When an image is taken by the startracker, the image is quartered and the parts are readout sequentially and compared with a database to find the orientation. On BRITE-Austria it seems that a special quarter has increased radiation damage. Unfortunately it is not possible to read out a whole image and download it for further analysis and to localise the damaged area. Therefore, when attempting fine pointing at a new target field, it might be necessary to slightly shift the centre coordinates to find the optimum orientation. Sometimes, even a simple roll of the target field has brought success.

7.2.4 Communications

Since October 2013 BRITE-Austria is affected by strong ground based interference over central Europe in the UHF band, especially between 435 to 438 MHz. The interference signal affects the operations significantly, by impairing the upload of the commands and by limiting the downlink performance, as acknowledgements to the data download transmissions might get lost in the return channel. Figure 7.5 shows the measurements of the interference signal power, compared with the signal power of the ground station. The pulses are partly very strong and even overshoot the power level at the ground station. A detailed analysis of the signal as well as the countermeasures taken is given in [24].

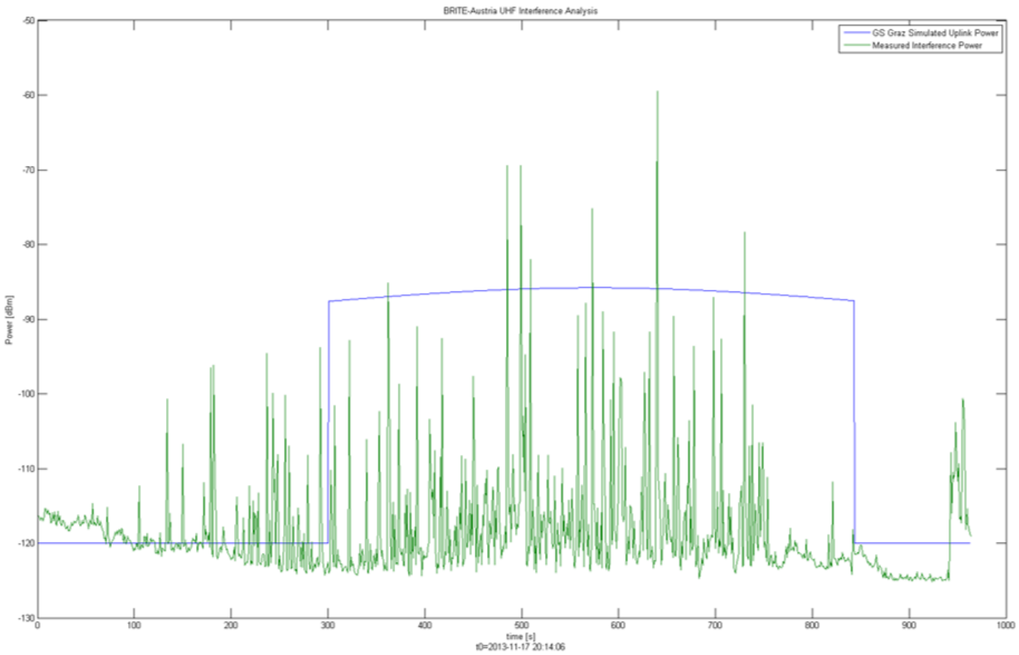


Figure 7.5: UHF interference: The measurements of the interference power in the uplink path (green) are depicted, the blue line represents the simulated power available at the ground station [24].

The origin of the interference is not exactly known, but measurements indicate a location of the source in north-east Europe, where space surveillance radars are located.

Optimization of upload/download strategy

To overcome the issues that arose with the appearance of the UHF interference, the upload and download procedures of telecommand/telemetry and science data had to be revised. The size of the data packets was decreased, as smaller packets are easier to upload. However, additional overhead was introduced. The command upload was re-ordered, and the start-up and contingency scripts were adapted accordingly.

Nadir pointing

Shortly before a pass over the ground station in Graz the spacecraft is reoriented to Nadir. This is performed to optimise the orientation of the satellite's antennas with respect to the ground station and to increase the downlink signal stability for the use of higher data rates and increase of throughput. The drawback however is, that no scientific observations can take place during a ground station pass.

7.2.5 Ground Segment

Ground segment virtualisation

To allow separation of the hardware interfaces from the ground station software and mission control software, virtual machines were introduced as additional abstraction layer. A concept for the BRITE-Austria ground station at IKS/TUGraz was elaborated and the following hierarchy was realised:

- Virtual machines for mission control and operation, hosting the ground segment software of the specific satellites.
- A virtual machine for ground station control, implementing the software to access and monitor the ground station hardware

Ground station enhancements

Due to the UHF interference, upgrades in the uplink path of the ground station were performed:

- A configuration of two UHF antennas (instead of one) was installed,
- The power amplifier was upgraded from 500 W to 1000 W

This upgrade was conducted in March 2014 and increased the ground station's EIRP by +5dB.

In January 2015 an upgrade of the antenna rotators was performed. The original rotators had a pointing precision of ±3° each. While these offsets were negligible for the UHF uplink performance (the antenna has a half power beamwidth of 28°), the downlink performance is affected, as the half power beamwidth of the S-band antenna is only 3.13°. Hence, the decision was made to replace this rotators with a new configuration providing pointing precisions of down to 0.1°.

Besides, remote access for the operators has been established to allow them to intervening in case any anomaly was reported.

Chapter 8

Lessons Learned

Since 2007 the author has been the responsible systems engineer for the BRITE-Austria satellite and has been operating the satellite since its launch in February 2013. Next to this activity, other space missions including two Phase A studies have been conducted at the Institute with her participation.

This section gives an overview on the main lessons learned during the conduction of space missions. In addition, an insight in the programmatic and managerial aspects is given, followed by an overview of regulatory issues, that had to be adressed during the execution of the BRITE mission. More information on the supporting disciplines can be found in Appendix C.

8.1 Challenges during the Design Process

The main design phases were already concluded in 2007, when the author joined the BRITE-Austria project in the role as systems engineer. Therefore, the focus was laid on the establishment of the first test procedures and adaptation to the various test facilities. In addition, the requirements had to be monitored and analysed thoroughly.

The frequency coordination was an intense and time-consuming process, as BRITE-Austria was the first Austrian space object and no preknowledge on how to conduct the coordination was available (more information on this matter can be found in Section 8.5.4).

Concerning the other projects, which have been or are currently conducted at the IKS/TUGraz, a major lesson learned was that at design start, a mission design hosting only the necessary entities to satisfy the mission objectives shall be provided. The requirements shall be defined as such to state the minimal demands to make the mission successful, no so-called nice-to-have requirements shall be specified.

Adding various additional functionality or payloads is still possible, but only if a significant gain to the mission objective is achieved or other valuable insight is gained (e.g. flight heritage). In addition, the resources regarding costs, time and human power have to be taken into account and analysed in the first stages of the project.

8.2 Experiences during Assembly, Integration and Testing

The verification strategy has to be defined early in the project. As not all test facilities might be available at the organisation, the tests have to be conducted at other premises. It is advisable to plan such test campaigns early in advance, and search for several suitable test facilities, as schedule conflicts might easily occur. It has to be kept in mind, that this strategy involves additional human resources and can have a huge financial impact.

The time which is dedicated to the testing itself is almost negligible compared to the time necessary for test planning, setup, documentation and post-processing of results. More human resources shall be planned for the conduction of the AIT phase to lighten the overall workload. The following table states the time needed during the execution of the various environmental tests of BRITE-Austria.

Test	**Preparation**	**Test Duration**	**Post Test Analysis**
Vibration	7	7	5
TVAC	15	7	5
EMC	5	3	5
Open-field	5	2	5
ADCS	8	10	5

Table 8.1: Test duration: The time which is needed to conduct the test is nearly negligible compared to the time needed for planning, setup, documentation, and post-processing of test data. The durations in days of the time spent for the environmental tests of BRITE-Austria is listed [50].

There are and will be points during testing, where it seems that nothing is working. To avoid panicking, a set of dedicated questions, a so-called ”TUGSat-1 Guide to the Galaxy”, was created, based on the novel *The Hitchhiker's Guide to the Galaxy ®* by Douglas Adams.

In case some units or functions are not working properly at a first attempt, it was found that most of the problems can be solved by simply checking various configurations or setups and answering the following questions:

1. Is it plugged in?
2. Is it turned on?
3. Is the address / COM-port right?
4. Is it on frequency / is the baud rate right?
5. Is the wiring correct?
6. Is the latest version of software/driver used?

8.3 Lessons Learned during Launch Campaign and Operations

The launch campaign is a challenging and interesting phase. It is vital to prepare the launch campaign early in advance. The final checkout procedures for verification of the spacecraft's health shortly before launch can be prepared already during the AIT phase.

Besides, lots of organisational issues have to be resolved in advance, to ensure a smooth execution of the campaign. These preparations include:

- The compilation of packing lists, indicating the flight system, GSE, tools and cleanroom garments needed.
- The organisation of the transport taking into account customs
- The take out of insurances, for the transport and the human resources involved

The next most memorable moment was the launch followed by the first contact with the BRITE-Austria spacecraft. The upside was, that the LEOP and commissioning procedures were prepared way in advance and the tasks to be performed were trained before, because in that moment the excitement is overwhelming.

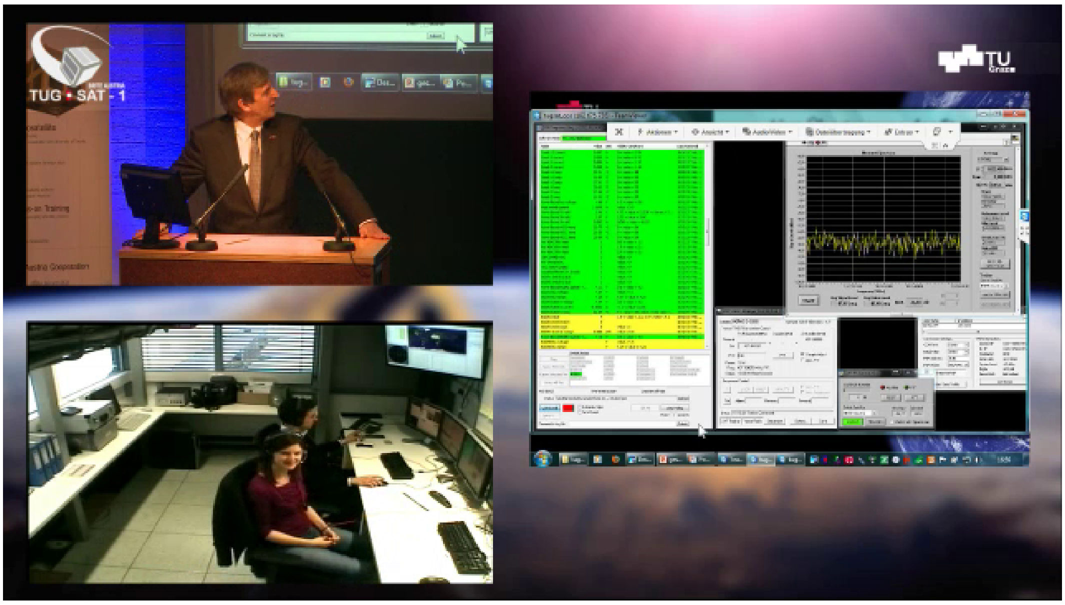


Figure 8.1: First contact: Impressions of the first contact with BRITE-Austria established during the first overflight over Graz

Depending on the final orbit of the spacecraft, the times for operating the satellite can be quite challenging. In the case of the BRITE-Austria mission, the overflights over Graz usually occur between 3:00 and 8:00 in the morning and 16:30 and 21:30 in the evening (UTC).

During nominal operations, where the manual interactions are limited, the last morning passes and early evening passes are monitored daily. However, during the commissioning phase, the operation of the satellite during each pass is very valuable and might be necessary. As these time frames were beyond the normal working hours, a dedicated arrangement with the university and the work council was found to ensure insurance and labour protection.

Since 2016, the IKS/TUGraz is also responsible for operating the UniBRITE spacecraft. Therefore, the planning of observations and analysis of the spacecraft health is performed for two BRITE satellites in parallel. In addition, the ground segment is monitored thoroughly, as the parallel observations lead to faster degradation of the hardware used.

The cooperation of the operation teams, especially in sharing the experience and knowledge gained and also the ground station, is a vital factor in the success of the mission. Figure 8.2 shows the ground station in Graz while performing a pass with BRITE-Toronto.

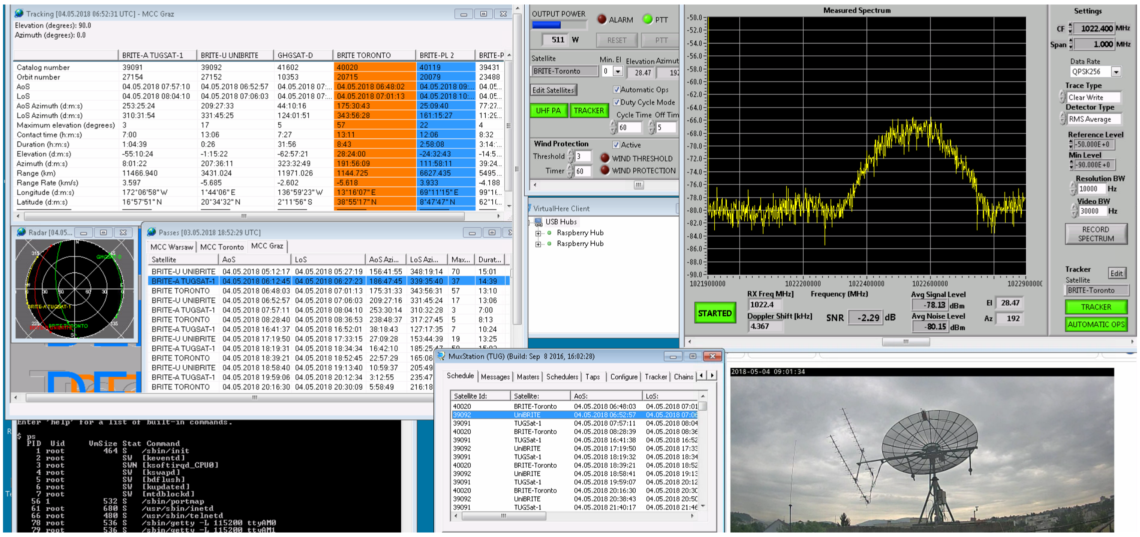


Figure 8.2: Pass with BRITE-Toronto using the Graz ground station: Due to the distributed ground segment concept, a dedicated Master MCC can connect to various ground stations. In this case, a pass with the BRITE-Toronto satellite was established using the ground station in Graz due to maintenance work at the ground station in Toronto. The ground station control modules are shown, depicting the actual signal received from BRITE-Toronto. The ground station in Graz just acts as relay station, all the communication and control is handled via the BRITE-Toronto MCC located at Toronto/Canada.

Although the successful testing and prosperous operation of the spacecraft in orbit is of utmost importance, the chance to work in space missions and the experience and memories gained during the life phases of the mission are remarkable.

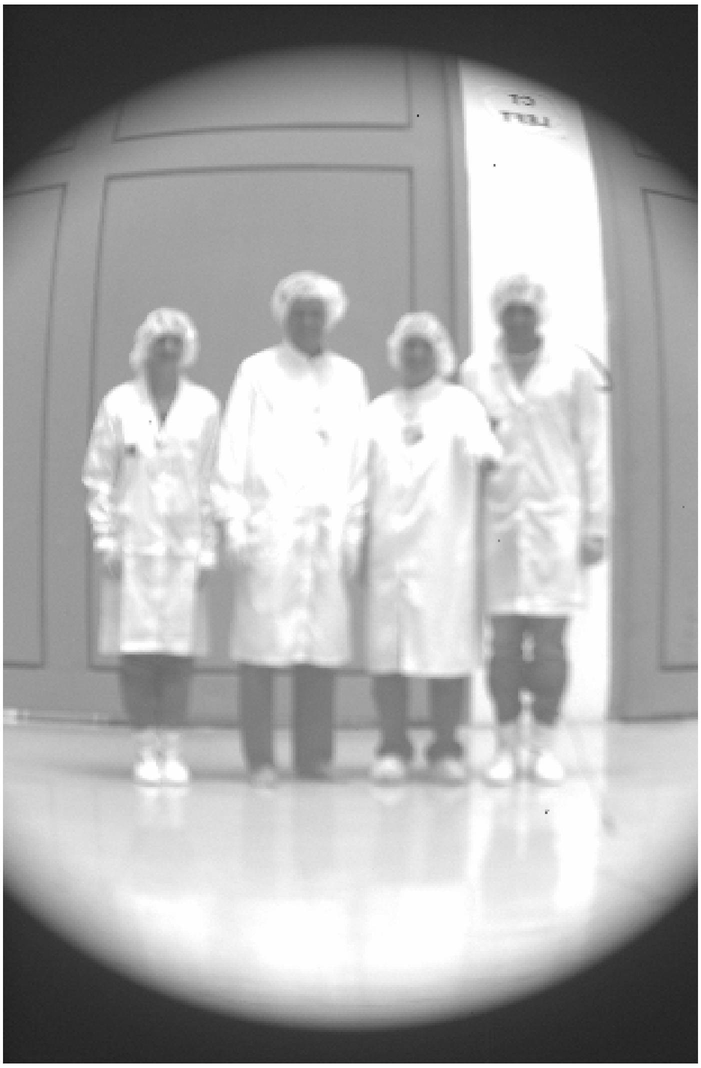


Figure 8.3: BRITE stars: The last image taken on ground by the instrument was conducted during the launch campaign.

8.4 Programmatic and Managerial Challenges

During the conduction of the BRITE mission and other small space studies, several challenges and difficulties occured, which had to be solved in either way. Regarding the programmatic and managerial aspects some insights can be shared:

Funding and reporting strategy:
The BRITE-Austria project was funded by the Austrian Research Promotion Agency (FFG) in the framework of the Austrian Space Applications Programme (ASAP). The first contract (ASAP3) covered the whole design, manufacture and testing phase. However, due to launch delays and excessive testing, and of course the upcoming mission phases and preparations involved, additional proposals had to be prepared nearly every year.

The proposals were granted and ensured the cashflow over the years. The drawback however was, that a lot of overhead was created due to proposal and report writing. A common solution between both entities would be advantageous to lower the complexity (e.g. in documentation or reporting period), as it binds a lot of human resources.

Although funding was provided, lots of in-kind contribution from participating institutions, in form of additional human resources or test facilities, were needed to ensure the project success.

Documentation strategy:
The documentation strategy in the BRITE-Austria project was divided into external reporting to the funding agency, and internal documentation. The project documents for internal use comprised the following:

- Design and requirements documents for the mission and the overall system
- Design and requirements documents for each subsystem and the ground segment
- Product tree and compliance matrix
- Test plans, procedures and reports on the tests on each level (unit, flatsat, system and environmental)
- Assembly procedures and logbooks
- Launch preparation documents
- Procedures for commissioning, operations, and contingency including status reports

In the new projects OPSSAT and PRETTY - that are currently conducted at the IKS/TUGraz - the IOD (In-Orbit Demonstration) CubeSat Tailoring standard [51] was adapted (see also Section C.1.1) and the documentation according to the requirements prepared.

Communication strategy:
Since the early project phase, bi-weekly telecons are held between the systems engineers of the BRITE satellites, the operators and the BEST members. During these telecons the progress of each satellite is reported, managerial aspects on the coordination and responsibilities of different activities are discussed, and the status of on-going publications is given [27].

On the technical level, all the e-mail correspondence between the specialists of both organisations was sent in copy to the BRITE-Austria systems engineer and the program manager and technical lead at UTIAS/SFL. Concerning ground segment issues, the ground station engineer and operations directer was involved. All scientific matters were coordinated by the BRITE-Austria payload scientist.

The general communication strategy was the use of e-mail, as the documentation is simplified. In urgent cases, telecons were held, and the systems engineer was always kept in the loop.

As part of the technology transfer, mentoring visits from experts of UTIAS/SFL took place during critical mission phases, e.g. laydown of solar cells, flatsat test support, flight assembly of the spacecraft, vibration testing and launch preparations.

Human resources:
Several people shall be familiar with the entire satellite system. It is advisable to involve a core team early in the project phase and during the unit- and flatsat-level testing phase. The experience gained in these phases helps significantly in the upcoming AIT phase and of course during operations, as the people get a feel for the spacecraft and can easier interpret the reasons for a variety of issues.

Besides, especially environmental testing can be very intense regarding time pressure and effort. The more people are familiar with the system, the more time can be saved during the test preparation and training.

8.5 Regulatory Framework

The regulatory framework is quite a complex area and involves several parties. Early support from legal experts, national entities and the local space agency helps significantly.

The following subsections mainly describe the experience and know-how gained during the BRITE-Austria project, unless otherwise stated.

8.5.1 Space Law

Several space missions and even human spaceflight missions have been carried out with Austrian technologies and experiments. Austria is also one of five nations that had ratified all the international space treaties, but till recently did not have a national space law. Due to the launch of BRITE-Austria in 2013 however, Austria has become a launching state, being responsibly for any damage caused by the operation of the spacecraft. This incident was used to introduce the "Austrian Federal Law on the Authorisation of Space Activities and the Establishment of a National Registry (Austrian Outer Space Act)" in December 2011, which consists of the following 17 paragraphs [52]:

1. Scope of application
2. Definitions
3. Authorisation
4. Conditions for authorisation
5. Mitigation of space debris
6. Modification or termination of the space activity
7. Revocation and modification of the authorisation
8. Transfer
9. Registry
10. Registration and information
11. Recourse
12. Regulation
13. Supervision and competent authorities
14. Sanctions
15. Transitional provision
16. Linguistic equal treatment
17. Implementation

8.5.2 Satellite Registration

To trace and monitor the status of the objects in outer space, a register containing the orbital parameters and specifications of the objects has to be installed. As Austria did not have such a registry, a decision whether to register the spacecraft in an existing register (e.g. as a flight object in the Austrian aeronautical registry) or create a dedicated registry for space objects. After the launch of the Austrian space law, two paragraphs (§9/§10) define the register, the responsibilities of the state and users/operators, as well as the information needed about the space object.

In Austria the Federal Ministry for Transport, Innovation and Technology is responsible for maintaining such a register for space objects. All objects, for which Austria is considered as a launch state, are subject to the jurisdiction and control of the State of Austria. A preliminary version of the main characteristics of BRITE-Austria and its envisaged orbital parameters have already been submitted to the Ministry after the successful launch negotiations.

Immediately after launch the actual parameters were delivered, a summary of the information provided is given in Table 8.2.

As the State of Austria has ratified the conventions of the United Nations (UN), it was obliged to provide information upon launch of the BRITE-Austria spacecraft also to the UN. Therefore, the relevant information was forwarded by the Federal Minister for Transport, Innovation and Technology via the Federal Minister for European and International Affairs to the Secretary-General of the UN.

Item	Parameter		Answer
1	Name of launching State		Republic of Austria
2	Appropriate designation of the space object	Experimental satellite	BRITE-A TUGSAT-1
		ITU designation	BRITE
3	Date and territory or location of launch		25.02.2013, 12:31 UTC Sriharikota, India, Satish Dhawan Space Centre
4	Main orbital parameters (preliminary)	Nodal period	100.33 min
		Inclination	98.6291°
		Apogee	780.92 km
		Perigee	766.79 km
5	General function of the space object		Astronomy mission (investigation of the brightness variations of massive luminous stars with a three-axis stabilised nanosatellite)
6	Manufacturer of the space object		Graz University of Technology
7	Owner and operator of the space object		Graz University of Technology
8	Additional information		-

Table 8.2: Satellite registration: Information of BRITE-Austria that was provided to the Ministry and then forwarded to the UN. [52] (ITU - International Telecommunication Union)

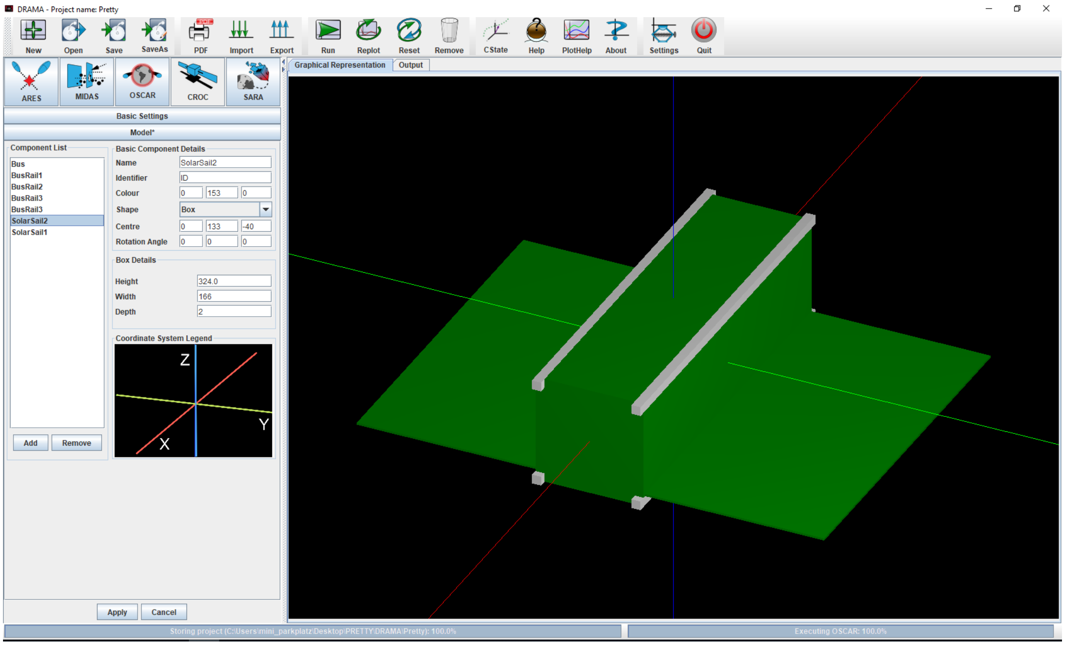
8.5.3 Space Debris Mitigation

Professor Dr. rer. nat. Hans-Peter Röser, from the Institute of Space Systems, University of Stuttgart has performed a study concerning the end-of-life scenario for the BRITE-Austria satellite. Given the launch altitude of about 800 km, the spacecraft will re-enter the atmosphere in 100-400 years, depending on the solar activity. Although this timeframe exceeds significantly the proposed 25 years for re-entry by the UN, the spacecraft was allowed to be launched in this orbit as the launch contract was already signed before the guidelines came into force.

For the new nanosatellite projects OPS-SAT and PRETTY, the ESA tool DRAMA (Debris Risk Assessment and Mitigation Analysis) [53] was used to calculate the cross-sections of the spacecraft and re-entry scenarios according to the space debris mitigation guidelines.

The figures show the 3D model of the PRETTY spacecraft with deployed solar panels for the cross-section calculations, followed by the best case / worst case lifetime results in a SSO with LTDN 06:00 and an altitude of 592 km (which represents the upper limit to ensure the 25 years timeframe of re-entry).

In addition, in the projects OPSSAT and PRETTY a Space Debris Mitigation Document (SDMD) had to be provided to ESA as part of the Preliminary and Critical Design Review (PDR/CDR) data package, indicating the compliance with the space debris guidelines as well as stating a battery break-up analysis.



Component List
- Bus
- BusRail1
- BusRail2
- BusRail3
- BusRail3
- SolarSail2
- SolarSail1

Basic Component Details

Name	SolarSail2		
Identifier	ID		
Colour	0	153	0
Shape	Box		
Centre	0	133	-40
Rotation Angle	0	0	0

Box Details

Height	324.0
Width	166
Depth	2

Storing project (C:\Users\mini_parkplatz\Desktop\PRETTY\DRAMA\Pretty): 100.0%

Executing OSCAR: 100.0%

Figure 8.4: Cross-section calculations of PRETTY: Full deployed CROC (Cross Section of Complex Bodies) model in the ESA-DRAMA environment is shown.

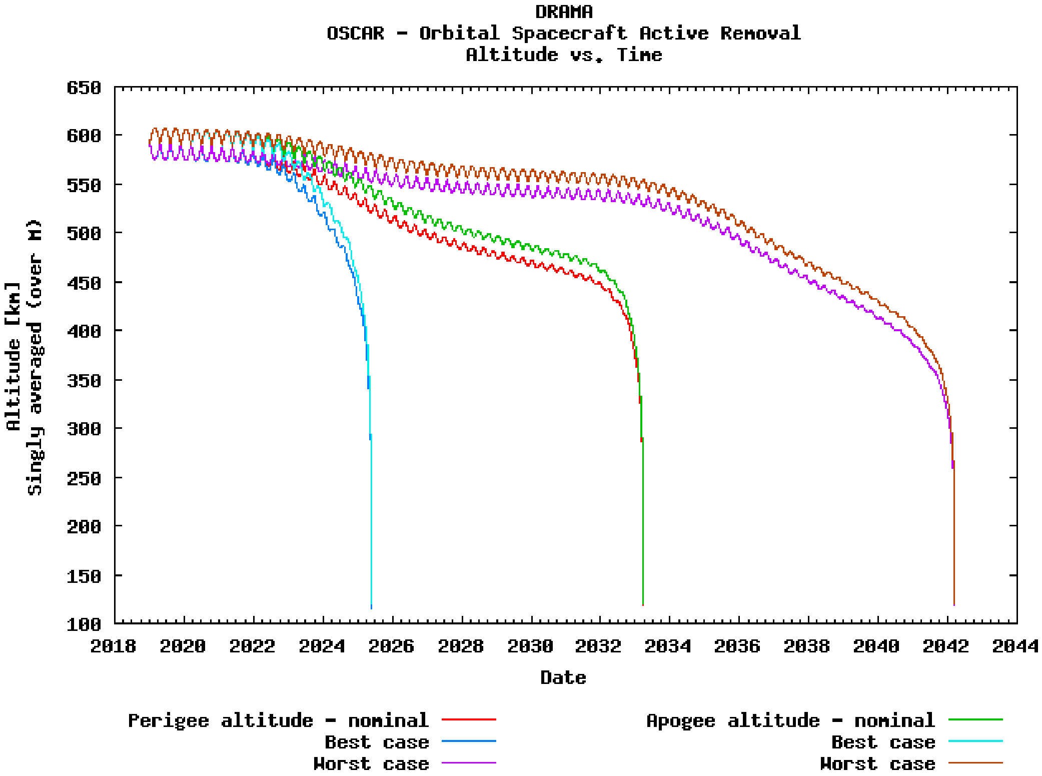


Figure 8.5: Lifetime results of PRETTY: The best case and worst case lifetime results in a SSO with LTDN 06:00 and an altitude of 592 km using OSCAR (Orbital Spacecraft Active Removal) were calculated.

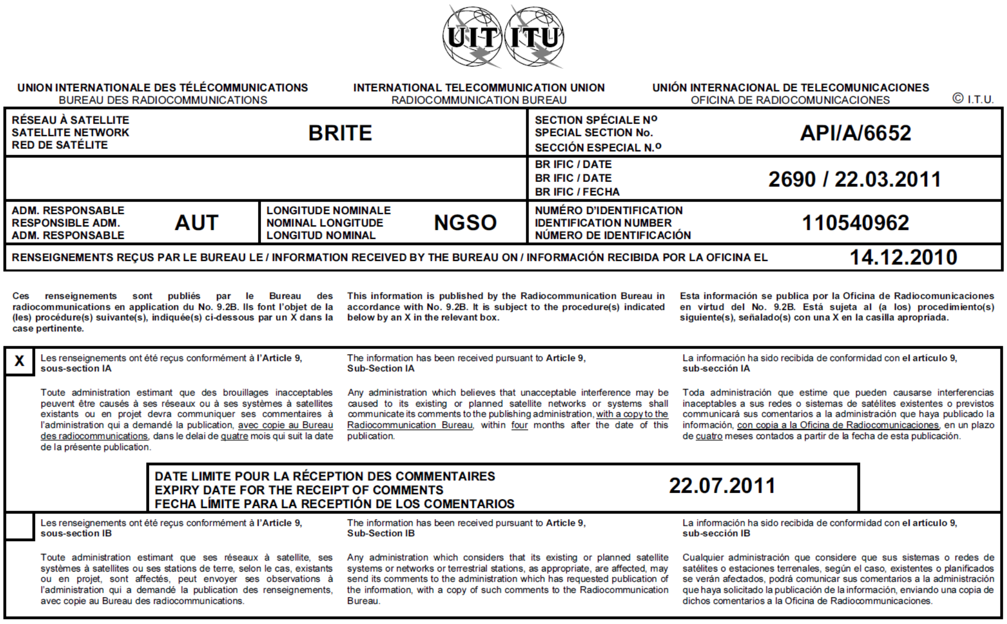
8.5.4 Frequency Coordination

BRITE-Austria is using both amateur frequencies (in the UHF and VHF band) as well as coordinated frequency bands (the Space Research Services [SRS] Space-to-Earth band, 2200 - 2290 MHz in the S-band). Therefore both frequency organisations - ITU and IARU - were involved in the frequency coordination process.

8.5.4.1 International Telecommunication Union (ITU)

As both Austrian BRITEs - BRITE-Austria and UniBRITE - use the same receive and transmit frequencies, it was decided to combine them and register them as a Non-Geostationary Satellite Orbit (NGSO) ”BRITE” satellite network at the ITU - Space Services Department. An additional aspect was also the fact that an administration could apply for a cost reduction for one filing per year.

The process already started in 2010, when the Advanced Publication Information (API) was transmitted formally via the Austria Frequency Office to the ITU and published in March 2011.



UIT ITU

UNION INTERNATIONALE DES TÉLÉCOMMUNICATIONS
BUREAU DES RADIOCOMMUNICATIONS

INTERNATIONAL TELECOMMUNICATION UNION
RADIOCOMMUNICATION BUREAU

UNIÓN INTERNACIONAL DE TELECOMUNICACIONES
OFICINA DE RADIOCOMUNICACIONES

© I.T.U.

RÉSEAU À SATELLITE **SATELLITE NETWORK** **RED DE SATÉLITE**	**BRITE**	**SECTION SPÉCIALE Nº** **SPECIAL SECTION No.** **SECCIÓN ESPECIAL N.º**	**API/A/6652**
		BR IFIC / DATE **BR IFIC / DATE** **BR IFIC / FECHA**	**2690 / 22.03.2011**
ADM. RESPONSABLE **RESPONSIBLE ADM.** **ADM. RESPONSABLE** **AUT**	**LONGITUDE NOMINALE** **NOMINAL LONGITUDE** **LONGITUD NOMINAL** **NGSO**	**NUMÉRO D'IDENTIFICATION** **IDENTIFICATION NUMBER** **NÚMERO DE IDENTIFICACIÓN**	**110540962**

RENSEIGNEMENTS REÇUS PAR LE BUREAU LE / INFORMATION RECEIVED BY THE BUREAU ON / INFORMACIÓN RECIBIDA POR LA OFICINA EL **14.12.2010**

Ces renseignements sont publiés par le Bureau des radiocommunications en application du No. 9.2B. Ils font l'objet de la (les) procédure(s) suivante(s), indiquée(s) ci-dessous par un X dans la case pertinente.

This information is published by the Radiocommunication Bureau in accordance with No. 9.2B. It is subject to the procedure(s) indicated below by an X in the relevant box.

Esta información se publica por la Oficina de Radiocomunicaciones en virtud del No. 9.2B. Está sujeta al (a los) procedimiento(s) siguiente(s), señalado(s) con una X en la casilla apropriada.

☒ Les renseignements ont été reçus conformément à **l'Article 9, sous-section IA**

Toute administration estimant que des brouillages inacceptables peuvent être causés à ses réseaux ou à ses systèmes à satellites existants ou en projet devra communiquer ses commentaires à l'administration qui a demandé la publication, avec copie au Bureau des radiocommunications, dans le delai de quatre mois qui suit la date de la présente publication.

The information has been received pursuant to **Article 9, Sub-Section IA**

Any administration which believes that unacceptable interference may be caused to its existing or planned satellite networks or systems shall communicate its comments to the publishing administration, with a copy to the Radiocommunication Bureau, within four months after the date of this publication.

La información ha sido recibida de conformidad con **el artículo 9, sub-sección IA**

Toda administración que estime que pueden causarse interferencias inaceptables a sus redes o sistemas de satélites existentes o previstos comunicará sus comentarios a la administración que haya publicado la información, con copia a la Oficina de Radiocomunicaciones, en un plazo de cuatro meses contados a partir de la fecha de esta publicación.

DATE LIMITE POUR LA RÉCEPTION DES COMMENTAIRES
EXPIRY DATE FOR THE RECEIPT OF COMMENTS
FECHA LÍMITE PARA LA RECEPTIÓN DE LOS COMENTARIOS
22.07.2011

☐ Les renseignements ont été reçus conformément à **l'Article 9, sous-section IB**

Toute administration estimant que ses réseaux à satellite, ses systèmes à satellites ou ses stations de terre, selon le cas, existants ou en projet, sont affectés, peut envoyer ses observations à l'administration qui a demandé la publication des renseignements, avec copie au Bureau des radiocommunications.

The information has been received pursuant to **Article 9, Sub-Section IB**

Any administration which considers that its existing or planned satellite systems or networks or terrestrial stations, as appropriate, are affected, may send its comments to the administration which has requested publication of the information, with a copy of such comments to the Radiocommunication Bureau.

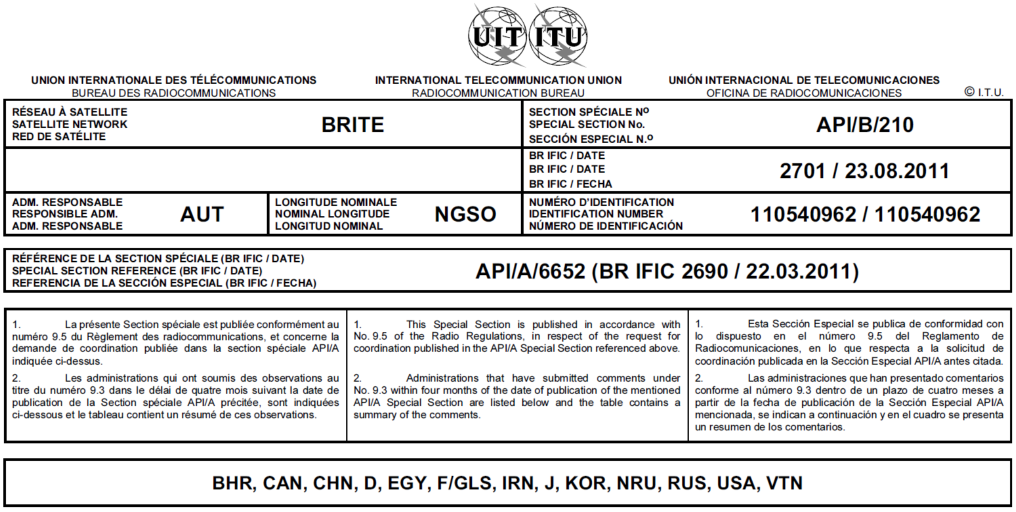
La información ha sido recibida de conformidad con **el artículo 9, sub-sección IB**

Cualquier administración que considere que sus sistemas o redes de satélites o estaciones terrenales, según el caso, existentes o planificados se verán afectados, podrá comunicar sus comentarios a la administración que haya solicitado la publicación de la información, enviando una copia de dichos comentarios a la Oficina de Radiocomunicaciones.

Figure 8.6: Advanced publication information for the BRITE network: The first page of the official API of the BRITE network is shown.

As it already was planned to eventually use the BRITE ground station network with stations in Toronto/Canada and Warsaw/Poland, the service area during the coordination process was already extended to these two countries.

After the official four months appeal time, several administrations from other countries had concerns on the planned frequency allocation. The ITU published another API add-on summarizing the comments and concerns of the respective administrations in August 2011:



UNION INTERNATIONALE DES TÉLÉCOMMUNICATIONS
BUREAU DES RADIOCOMMUNICATIONS

INTERNATIONAL TELECOMMUNICATION UNION
RADIOCOMMUNICATION BUREAU

UNIÓN INTERNACIONAL DE TELECOMUNICACIONES
OFICINA DE RADIOCOMUNICACIONES

© I.T.U.

RÉSEAU À SATELLITE SATELLITE NETWORK RED DE SATÉLITE	BRITE			SECTION SPÉCIALE Nº SPECIAL SECTION No. SECCIÓN ESPECIAL N.º	API/B/210
				BR IFIC / DATE BR IFIC / DATE BR IFIC / FECHA	2701 / 23.08.2011
ADM. RESPONSABLE RESPONSIBLE ADM. ADM. RESPONSABLE	AUT	LONGITUDE NOMINALE NOMINAL LONGITUDE LONGITUD NOMINAL	NGSO	NUMÉRO D'IDENTIFICATION IDENTIFICATION NUMBER NÚMERO DE IDENTIFICACIÓN	110540962 / 110540962

RÉFÉRENCE DE LA SECTION SPÉCIALE (BR IFIC / DATE) SPECIAL SECTION REFERENCE (BR IFIC / DATE) REFERENCIA DE LA SECCIÓN ESPECIAL (BR IFIC / FECHA)	API/A/6652 (BR IFIC 2690 / 22.03.2011)

1. La présente Section spéciale est publiée conformément au numéro 9.5 du Règlement des radiocommunications, et concerne la demande de coordination publiée dans la section spéciale API/A indiquée ci-dessus. 2. Les administrations qui ont soumis des observations au titre du numéro 9.3 dans le délai de quatre mois suivant la date de publication de la Section spéciale API/A précitée, sont indiquées ci-dessous et le tableau contient un résumé de ces observations.	1. This Special Section is published in accordance with No. 9.5 of the Radio Regulations, in respect of the request for coordination published in the API/A Special Section referenced above. 2. Administrations that have submitted comments under No. 9.3 within four months of the date of publication of the mentioned API/A Special Section are listed below and the table contains a summary of the comments.	1. Esta Sección Especial se publica de conformidad con lo dispuesto en el número 9.5 del Reglamento de Radiocomunicaciones, en lo que respecta a la solicitud de coordinación publicada en la Sección Especial API/A antes citada. 2. Las administraciones que han presentado comentarios conforme al número 9.3 dentro de un plazo de cuatro meses a partir de la fecha de publicación de la Sección Especial API/A mencionada, se indican a continuación y en el cuadro se presenta un resumen de los comentarios.

BHR, CAN, CHN, D, EGY, F/GLS, IRN, J, KOR, NRU, RUS, USA, VTN

Figure 8.7: Comments of other administrations: Several comments were received upon the frequency API of the BRITE-network concerning either the excluding territory or possible interference to existing terrestrial and/or space services (page 1 of the Special Section).

These requests of the listed countries had to be officially answered via the Austrian Frequency Bureau and any missing information or data had to be provided. It has to be noted, although the SRS frequency band is assigned to Space-to-Earth links by the ITU, parts of the band can be allocated to national terrestrial services too. In Austria, for example, part of the spectrum is reserved for non-civil terrestrial services. Many requests concerning interference issues could be mitigated by specifying the transmitting times in the downlink, as the transmitter on-board is only activated after reception of a dedicated ground command via the respective ground station, and is only active during the contact itself and hence the service area specified.

Once all the necessary information was given, the final notification request could officially be filed through ITU in September 2012. Shortly after launch in February 2013, an official statement of the Austrian Frequency Office was sent to ITU for ”Bringing-into-use” the frequencies.

As the frequencies of the BRITE satellite network were only valid and secured for five years, a proposal for extension of frequency use was submitted in autumn 2017.

8.5.4.2 International Amateur Radio Union (IARU)

Although both Austrian spacecraft were treated as a network via the ITU, the frequency coordination requests via the IARU had been prepared individually for each spacecraft.

Since 2007 an official amateur radio club named ”Radioclub for Communication and Wave Propagation (RCCW)” was reactivated at the IKS/TUGraz. The ground station for future operations of the BRITE-Austria satellite at Graz was registered under the call sign OE6XUG.

At least one operator per shift during the commissioning and operations phase of the Austrian satellites is in possession of an amateur radio license, and is therefore allowed to perform communication with the spacecraft. During the preparation of the coordination requests, the intense contact with the national amateur radio society in Austria Österreichischer Versuchssenderverband (OEVSV) was very advantageous and helpful.

8.5.5 Ground Station Licensing

Prior to launch the ground station on the premises of the Graz University of Technology was registered at the national telecommunication department for operation of the BRITE-Austria satellite and at a subsequent date also for operation of UniBRITE. As the BRITE mission is purely scientific and used for research, the registration of the ground station was free of charge.

8.5.6 Insurances

The persons involved in the BRITE mission were covered by the employer's (Graz University of Technology) liability insurance during the execution of the research activities worldwide.

The BRITE spacecraft was insured during all transport activities (between the IKS/TUGraz and test facilities, as well as to the launch site) up to the amount of the replacement value.

The launch of BRITE-Austria was not insured. The decision of non-insuring the launch was made in coordination with the funding agency FFG and was justified by the following rationales:

- **Insurance costs:** As the costs of securing the launch can be up to 30-40% of the overall project costs, the funding would have been highly unlikely.
- **Success rate of selected launcher:** The Indian PSLV rocket had 18 successful launches in a row prior to the launch of BRITE-Austria, and was therefore considered as a low risk factor.

It has to be kept in mind however, that due to domestic legislation the launching state might share the risk of personal and material damage with the satellite's operator, requiring the operator to provide a liability insurance of predefined value.

8.5.7 Export Control

The only item on BRITE-Austria, that was export controlled, was the startracker. The startracker was purchased from a company from the United States and hence was International Traffic in Arms Regulation (ITAR) controlled. The fact that the startracker already had heritage, and the specifications and performance needed for achieving the mission objectives were ideal. Hence, the decision on taking the ITAR controlled one was made.

Such critical decision however might have impact on the selection of launchers, as it is highly dependable on the current trade relations between the USA and possible launching states like Russia, China, and India.

Chapter 9

Conclusion and Achievements

The BRITE-Constellation is the world's first nanosatellite constellation dedicated to astronomy and currently the only operational mission in the fundamental physics discipline of asteroseismology.

The BRITE-Austria mission impressively demonstrates that demanding scientific tasks can be performed with small and inexpensive nanosatellite platforms. Industry, Space Agencies and research organizations are embracing this fairly new technology as a means for low-cost in-orbit validation and demonstration.

As the nanosatellite BRITE-Austria is currently in its sixth year in orbit, it is probably one of the longest operating nanosatellites in space, performing continuous observations while delivering astronomical data with outstanding quality.

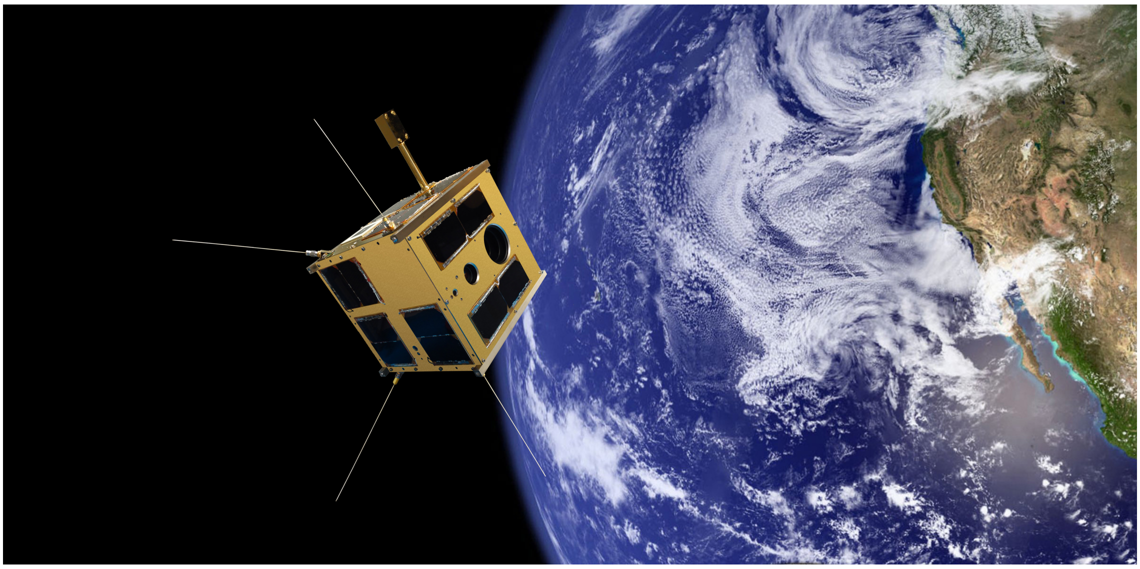


Figure 9.1: Artist's impression of BRITE-Austria/TUGSAT-1 in space: The first Austrian satellite BRITE-Austria/TUGSAT-1 is already in its sixth year in orbit (Image Courtesy: TUGraz).

High Scientific Output and Quality

Since the launch in February 2013, followed by a commissioning and optimisation phase, more than 20 GByte of high-quality science data were obtained by BRITE-Austria. Although the mission was designed for a two year lifetime, the spacecraft is currently in its sixth year in orbit, delivering excellent scientific data.

This achievement was only possible due to the continuous analysis of the spacecraft's performance and behaviour, and the introduction of improvements and functional optimisations.

Concerning the increase in scientific output and quality, a comparison between the original assumptions and requirements to the actual achieved performance figures is given:

Scientific Parameter	**First Assumptions**	**Actual Values**	**Consequences**
Number of setup files	1	2	stars with significant magnitude gap in one field during one observation could be observed in parallel
Number of targets per orbit	1	2	increase of scientific data amount taken into account not-usable orbits due to other constraints (nadir tracking during ground station contacts / SAA / eclipse)
Number of stars in one field	15	up to 30	increase of overall data return
Observation time per orbit	up to 15 min	up to 30 min	increase in data return
Continuous observation of one field	up to 100 days	up to 178 days	optimisation of mission planning strategy and optimising the exclusion zones of the startracker
Instrument sensitivity	Visual magnitude = +3.5	Visual magnitude = +4.5	number of possible targets has increased

Table 9.1: Assumptions versus scientific achievements: A comparison between original assumptions to actual achieved performance values is given.

Mission Operations for Science Missions

Due to the challenges in operating a nanosatellite and furthermore performing scientific observations, special focus has to be laid on the mission planning and operations.

During the operational lifetime of BRITE-Austria, several technical issues occurred, which were described in Chapter 6. The following list should give a summary of the main challenges and the respective countermeasures and optimisations, which were taken into account in the mission planning and operations.

- **In-orbit calibration of magnetometer** to enhance the overall coarse determination of the ADCS subsystem
- Introduction of **Hybrid software version** to combine all the spacecraft's functionality on one OBC
- Correction of **CCD radiation effects** by reducing the overall temperature of the spacecraft inside and introducing a chopping procedure
- Analysis of weak **startracker performance** and definition of constraints in observation
- Introducing **satellite re-orientation** to avoid overheating of the spacecraft in sunlight and too cold temperatures during the eclipse season
- Optimisation of **upload and download strategy** to overcome the shortages introduced by the UHF interference in the uplink path
- Introduction of **nadir pointing** during ground station contacts that provides a stable downlink and allows the use of higher data rates up to 256kbps using QPSK
- **Upgrade of ground station** by adding a second UHF antenna. by increasing the power amplifier output from 500 to 1000 W and by installing more precise rotators

The mission planning of scientific missions is a critical task, as the behaviour of the payloads and various subsystems (e.g. ADCS) can only be verified in orbit. Such a mission has not been flown before and operations is not really comparable to bigger missions dedicated to astrophysics like Hubble, as no service or alterations can be performed.

A continuous monitoring and analysis was and still has to be performed to maximise the quality and amount of scientific data output and to keep or even increase the functionality and overall performance in attitude control and instrument sensitivity over the years.

Achievements versus Requirements

Given the high performance of BRITE-Austria in orbit, it has exceeded many mission requirements. A comparison of the achieved results and the requirements is given in the following table:

	Requirements	**Achievements**
Pointing accuracy	90 arcsec RMS	70 arcsec RMS
Startracker warm-up (increase of overall useable observation window and shorten time for high-power demands)	20 min	3 min
Instrument sensitivity (# of possible targets)	Visual magnitude = +3.5	Visual magnitude = +4.5
Science data return	2 MB / day	15 MB / day (16,3 MB including telemetry)
Downlink data rate and modulation	32 kbit/s (BPSK)	256 kbit/s (QPSK)
Mission lifetime	2 years	6 years and on-going

Table 9.2: Comparison between systems requirements and actual achieved results: The values listed can be directly connected to the mission success of BRITE-Austria.

To summarise, this thesis gave an insight in

- the conduction and design of advanced nanosatellite missions and comparing them to conventional state-of-the-art spacecraft missions
- the system engineering aspect including the essential AIT activities
- the launch and early operations tasks as well as
- the successful and mission planning and operation including verification and optimisation of a nanosatellite way beyond its envisaged lifetime.

Furthermore, this thesis provided an innovative guideline and professional approach on how projects in the field of ”New Space” can be designed and executed, while ensuring and enhancing the required quality.

Appendix A

Mission Architecture and Design

The following chapter should give an insight in the space mission life cycle and the respective phases. An overview of different mission architectures is described, concluding with a the design recommendation as used in this thesis, and a description of the disciplines and elements involved.

A.1 The Space Mission Life Cycle

As any program or project, a space mission life cycle is formed by a sequence of interrelated tasks or phases, which typically are [13]:

- **Concept exploration**, the study phase and initial definition of the space mission and its components
- **Detailed development**, the design phase and definition of the components involved
- **Production and deployment**, the manufacturing of the ground and space segment and launch of the spacecraft
- **Operations and support**, the daily operation of the space segment including maintenance and contingency up to its end-of-life scenario

These phases may be named and structured differently depending on the standards used. The graph in Figure A.1 depicts the phases as defined by the European Space Agency, respectively the European Cooperation for Space Standardization (ECSS), indicating also the reviews during the space mission life cycle.

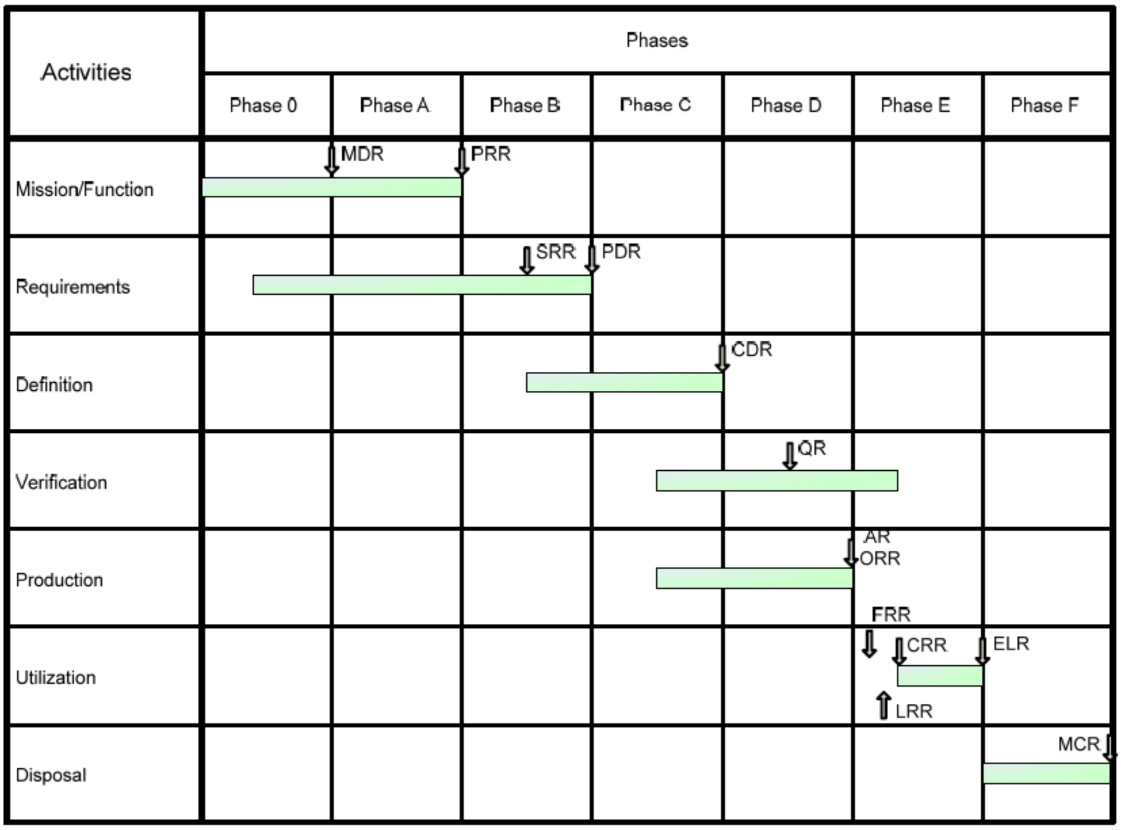


Figure A.1: Space mission life cycle: During the lifecycle of a space mission, seven phases are passed through, each dedicated to specific activities [14].
(MDR - Mission Definition Review, PRR - Preliminary Requirements Review, SRR - System Requirements Review, PDR - Preliminary Design Review, CDR - Critical Design Review, QR - Qualification Review, AR - Acceptance Review, ORR - Operational Readiness Review, FRR - Flight Readiness Review, CRR - Commissioning Result Review, LRR - Launch Readiness Review, ELR - End-of-Life Review, MCR - Mission Close-out Review)

During the Phases 0, A, and B several tasks have to be performed [14]:

- Define and elaborate the functional and technical requirements of the system
- Design and identify a system concept, which complies with the mission objectives, taking into account any programmatic and technical constraints
- Identify all activities and resources needed, to develop the space and ground segments of a project (see Section A.2 and A.3)
- Assess the programmatic and technical risks and initiate the first pre-development activities.

The Phases C and D comprise the activities to be performed, to develop, manufacture and qualify the space and ground segments.

During the Phase E, focus is laid on the following activities:

- All tasks involved in order to launch and commission the space segment
- Utilisation and maintenance of the space segment, as well as the associated ground segment.

Phase F comprises all activities, which need to be performed to safely dispose all products launched into space as well as the ground segment.

Each phase starts with an kick-off event and ends with the successful completion of a review, where the respective output of the phase has to be assessed and checked for fulfillment before proceeding to the next phase. These reviews are useful to keep track and identify early problems or schedule slips on the one hand, but also to communicate the project status to the customer or consumer on the other hand.

A.2 Mission Architecture

Given the space mission life cycle, the first step in any design process is to start with a mission goal or objective, and decomposite the idea into meaningful components [54].

In the development of the concept and architecture of a mission, various systems and elements are involved which are interlinked. Each spaceflight mission can be divided roughly into architectural elements, which form the core of a mission. Depending on the mission itself and the organisations involved, the elements may vary, but have to be considered in either way. There are different views in defining such a mission.

Wertz-Larson [13] propose a division into architectural elements, which forms a mission concept:

- Mission objective or subject
- Payload
- Spacecraft bus or platform
- Orbit and constellation
- Launcher
- Ground segment
- Command, control, and communications architecture
- Mission operations

The ECSS standards, however propose a division into physical segments [14]:

- Space segment - divided into spacecraft bus and payloads (can also consist of several spacecraft)
- Ground segment - divided into mission control, ground stations, communications network, and payload data management
- Launch segment - divided into launcher and launch facilities

- User segment

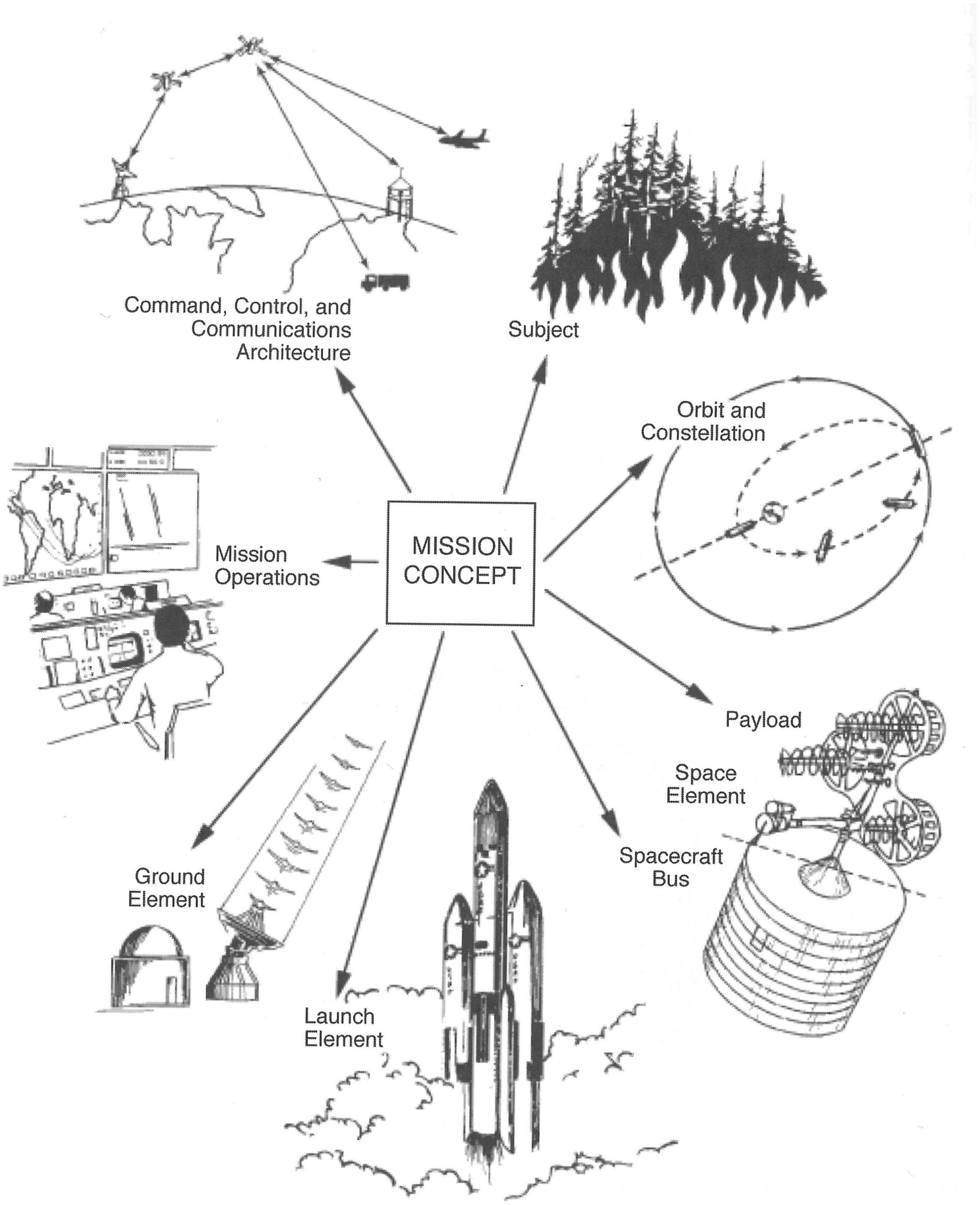


Figure A.2: Elements of a mission: Each space mission mainly consists of the elements depicted, according to Wertz-Larson. [13]

A.3 Designing a Mission

The mission architecture and design as it is described within this thesis is a combination of both philosophies, as the ground segment defined in ECSS is more representing the user interface by distinguishing between mission control and payload data management. The next subsections describe the following mission elements in more detail, the focus in addition is laid on the application on small satellite projects (Figure A.3):

1. Mission Objective
2. Space Segment
3. Orbit and Constellation
4. Launch Segment
5. Ground Segment
6. Mission Operations
7. User Segment

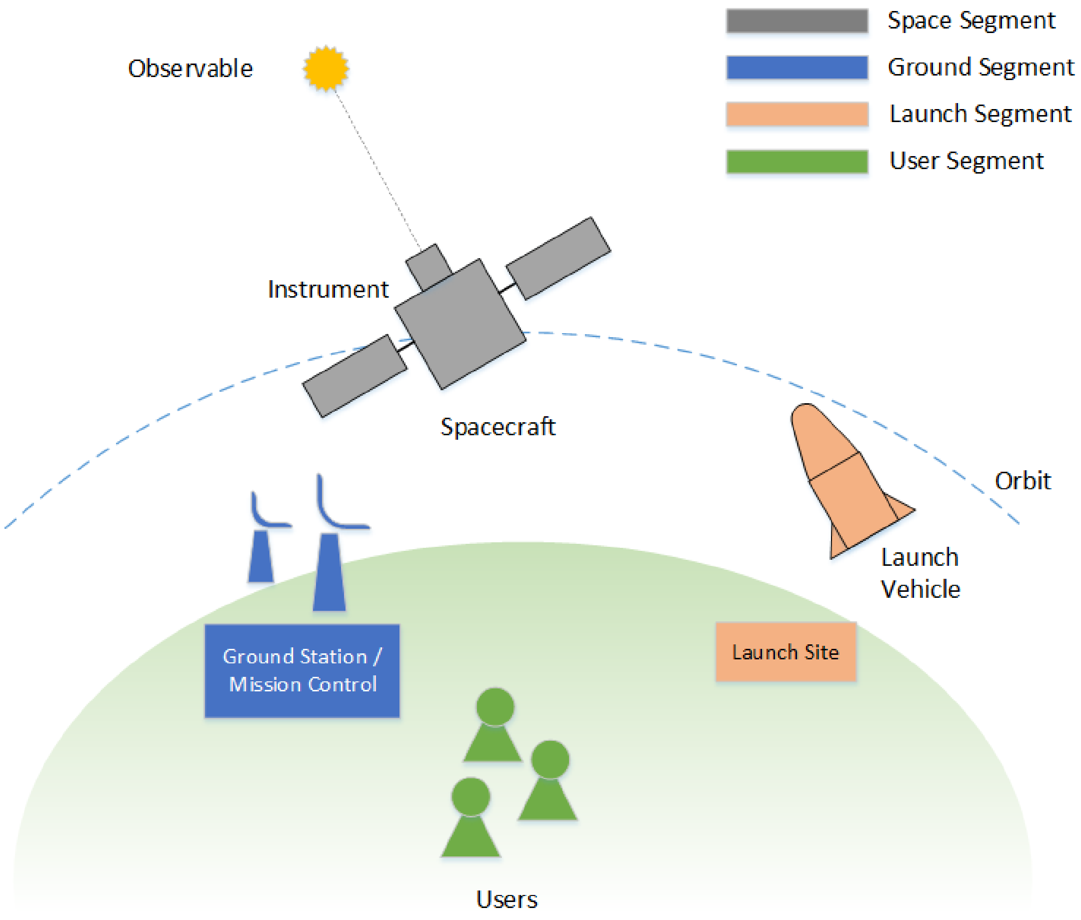


Figure A.3: Mission design: The elements of a small satellites space mission, as described throughout the thesis.

A.3.1 Mission Objectives

The mission objective or mission goal states the reason or the use of the spaceflight mission, the subject, value and beneficial effect of the mission. Unlike requirements, which give quantitative values and expressions to specific functionalities and performances, objectives are broad statements that declare what the mission must fulfill to be useful and productive.

A space mission might have several objectives, mainly divided into

- the **primary objective** and mission goal, which states the reason for the mission and the subject or observable to be observed, and
- the **secondary objective**(s).

Secondary objectives can be, for example, additional data products that can be gained with the already planned equipment, or even new subsystems/payloads. There might also be non-technical, social, political, or cultural objectives, which also have to be considered.

A.3.2 Space Segment

The space segment is the key element in realising the mission objective. It can consist of one or a constellation of spacecraft, whereas the spacecraft can be a probe, a satellite or a even a station. When talking about satellites, the space segment can mainly be divided into the payload and the spacecraft bus.

A.3.2.1 Payload

The payload represents the mission specific instruments that are used to obtain the data and results to fulfill the mission objectives. The payload is the key driver for the overall spacecraft bus requirements and design. Depending on the mission, different types of payloads may be realised, e.g. scientific instruments, research instruments, transponders for communication applications or indeed a combination of several sensors and experiments.

A.3.2.2 Spacecraft Bus

The spacecraft bus incorporates all subsystems that enable the basic functionality of the spacecraft and ensure the correct execution of the payload and hence achieving the mission objective(s). Typically a spacecraft (independent of the size) consists of the following subsystems next to the payload:

- **Mechanical subsystem (MEC)**
  The mechanical structure houses all subsystems, provides strength and stiffness, and ensures survival during transportation, launch and in orbit. It can be distinguished between primary (carries all the major loads), secondary (e.g. panels, booms, mechanisms) and tertiary structures (e.g. individual radiation housings).

- **Thermal control (THM)**
  The thermal subsystem ensures that subsystems are kept within their specified temperatures. Excessive heat is typically radiated to space, and by the use of thermal tapes or coatings on the outside faces of the spacecraft an optimal thermal budget can be achieved. Depending on the orbit and spacecraft design active thermal heating/cooling elements might be installed for sensitive devices (e.g. batteries or sensors).

- **Guidance, Navigation and Control (GNC) or Attitude Determination and (Orbit) Control System (ADCS/AOCS)**
  Attitude control is used to maintain and control the satellite's attitude and orientation, navigation control is needed to maintain and control the orbit/trajectory. Determination of the attitude is achieved by the use of sensors (e.g. magnetometer, sun sensors, star-tracker, horizon detectors). Attitude control is performed with actuators (e.g. gyros, magnetorquers, reaction wheels, propulsion systems).

- **Power (PWR)**
  The tasks of the power subsystem are the generation and storage of electrical power, as well as the distribution to the individual subsystems. Small satellites use solar cells for power generation. Batteries are used to store excessive power for eclipse phases (Earth's shadow) or high power demands.

- **On-board Data Handling (OBDH)**
  The on-board data handling subsystem handles ground commands and forwards them to the respective subsystem. Besides, it monitors the satellite's health state by collecting housekeeping telemetry. The subsystem consists of on-board computers (OBCs) (hardware) and on-board software.

- **Communications (COM) or Telemetry, Tracking and Command (TT&C)**
  The communications subsystem is responsible for receiving ground commands or new flight software from Earth, as well as transmitting housekeeping and payload data to Earth. Therefore, the subsystem comprises at least a receiver and transmitter unit including cables, amplifiers and antennas.

- **Propulsion**
  A propulsion system is used for navigation control. Small satellites are often designed to be more or less orbit independent, therefore propulsion systems are rarely used on such platforms. However, investigations are on-going to miniaturise the propulsion equipment for further use in station-keeping, orbital maneuvering, or deorbiting at the end-of-life. An example of a nanosatellite mission was the CanX-4/CanX-5 formation flying mission [55].

A spacecraft does not need to host all of these subsystems. It also depends on the mission objective and the possible reduction of risk and complexity, which subsystems are finally implemented (e.g. the need of a propulsion system).

A.3.3 Orbit and Constellation

The orbit states the path or trajectory of the spacecraft. In most cases the mission objectives determine the range of possible orbits or state the orbit boundaries. It has to be kept in mind that small satellites often have to rely on piggyback launches. Therefore, a trade-off of the target orbit has to be performed already in the early design phase, to allow flexibility during launch negotiations.

The orbit selection is very critical, next to the influence on programmatic decisions - like lifetime, launch costs, treaties - it can also affect several other areas:

- The payload design and its performance (e.g. spatial or temporal resolution, coverage areas)
- The spacecraft design (e.g. sunlight versus eclipse ratio impacts on power and thermal budget)
- The design and performance of the payload and sensors due to the radiation environment
- The ground station coverage and its impact on the communication and OBDH subsystem

A.3.3.1 Definition of an Orbit

To define an orbit around a body, six parameters are needed. This set of orbital elements is also known as the set of Keplerian elements [56]. In 1543 Copernicus published his theory of the heliocentric system with the planets moving around the Sun on circular orbits. Based on the observation data of the planet Mars, Johannes Kepler however discovered that the Sun could not be in the centre of the Mars orbit. As Mars changed its velocity with the distance from the Sun, he found, that circular orbits could not explain this behaviour and assumed that a mysterious force must radiate from the Sun.

The findings were certified by Newton's law of universal gravitation in 1686. Isaac Newton presumed that the natural laws experienced on Earth are also applicable to celestial bodies. Hence he concluded that Kepler's so-called mysterious force might be the gravitational force, which couples the planets with the Sun.

The second law of motion states that two bodies attract each other with a specific force F, which is directly proportional to the product of the individual masses m_1 and m_2, and inversely proportional to the square of the distance r between their centres. G is defined as the universal gravitational constant, with a numerical value of $6.672 \cdot 10^{-11} \left[m^3 \; kg^{-1} \; s^2\right]$:

$$F = G \cdot \frac{m_1 \cdot m_2}{r^2} \quad [N] \tag{A.1}$$

To describe the motion of a planet around the Sun, the findings were compiled in three scientific laws, also known as the Kepler's laws of planetary motion (see Table A.1).

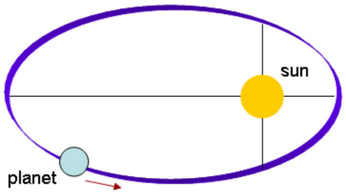
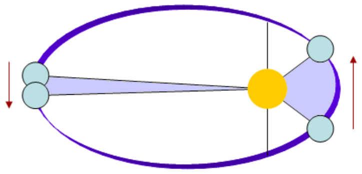
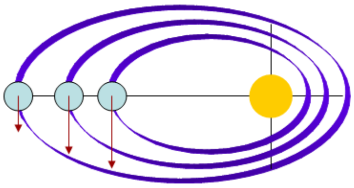
First Law	**Second Law**	**Third Law**
The orbits of the planets are ellipses with the Sun in one focus.	A line joining a planet to the Sun sweeps out equal areas in equal times.	The squares of the orbital periods of planets are directly proportional to the cubes of the semi-major axis of the orbits.
		

Table A.1: Kepler's laws of planetary motion [56]

Given these laws, six parameters are needed to define a Keplerian orbit around a body. This set of orbital elements is also known as the set of Keplerian elements:

- Semi-major axis (a)
- Eccentricity (e)
- Inclination (i)
- Right ascension of ascending node (Ω)
- Argument of perigee (ω)
- Mean anomaly at epoch (M0).

The semi-major axis and the eccentricity define the shape of the ellipse. The eccentricity is a measure of the deviation of a circle and is defined between 0 (circular) and 1. The nearer at 1, the smaller and longer is the ellipse.

To define the orientation of the ellipse in the Earth-Centred Inertial Coordinate System (ECI), three angles are used [56]:

- Inclination (i) states the angle of intersection between the orbital plane of the ellipse and the equatorial plane. It is counted positively from 0° to 180° in forward direction. An inclination of more than 90° means, that the satellite moves in opposite direction to the Earth's rotation
- The Right Ascension of the Ascending Node (RAAN) (Ω) gives the angle between the direction of the vernal equinox (Υ) and the direction of the ascending node. The latter states the point where the satellite crosses the equatorial plane on its way from south to north. It can take values from 0° to 360°.
- The Argument of Perigee (ω) defines the location of the ellipse itself in its plane. This angle is defined as the angle between the direction of the ascending node and the direction of the perigee (point on ellipse nearest to Earth). It can take values from 0° to 360° in forward direction.

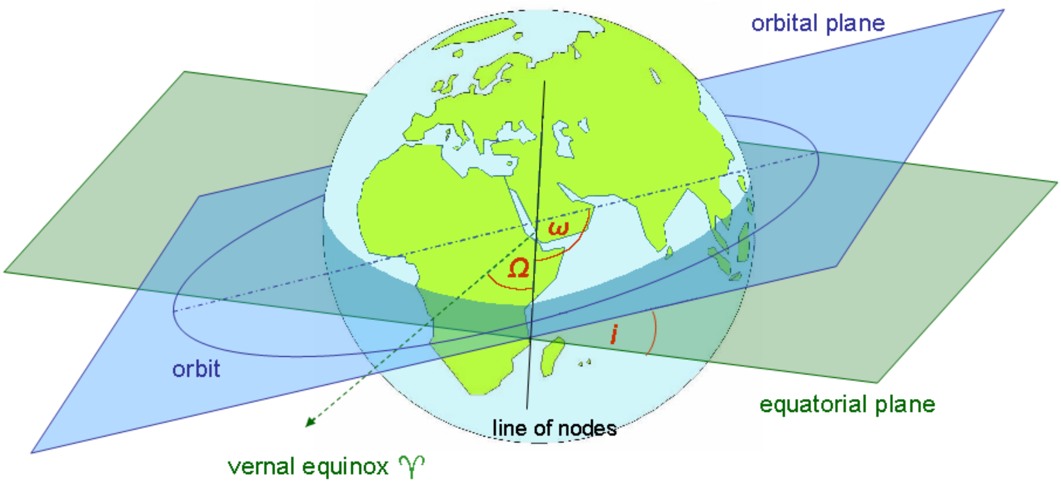


Figure A.4: Location of the orbit in space: The location of the orbital ellipse compared to the ECI coordinate system can be described with three angles. [56]

The last Keplerian element is comprised by two values: the epoch T0, the point in time where all these values are valid or were observed, and the mean anomaly. The Mean Anomaly does not correspond to an angle between any physical objects. It is mainly one of three angular parameters, historically known as ”anomalies”, that define a position of an object along its orbit. The other two are the true anomaly (ν) and the eccentric anomaly (E).

Once these orbital elements are known for a specific object, its position can be calculated forward and backwards in time. However, due to orbital perturbations (e.g. solar radiation pressure, atmospheric drag, attraction of third bodies, inhomogeneity of the gravitational field), the elements change over time [57].

A.3.3.2 Types of Orbits

According to their orbital altitude and main characteristics, different types of orbits are defined.

- **LEO** - Low Earth Orbit
- **MEO** - Medium Earth Orbit
- **GEO** - Geosynchronous Earth Orbit
- **HEO** - High-elliptical Earth Orbit

The following tables gives the respective specifications.

	LEO	MEO	GEO	HEO
Altitude (km)	400 - 1000	6000 - 25000	35786	500 - 36000
Inclination (°)	0 - 99	miscellaneous	0	63,44
Orbital period	90 - 100 min	5 - 12 h	24 h	12 h
Typical contact time per pass	8 - 15 min	2 - 4 h	24 h	11 h
Typical applications	miscellaneous	GNSS, Communication	Communication, Remote Sensing	Communication

Table A.2: Definition of Earth orbits: Inclination states the angle between the orbital plane and the equatorial plane. Orbital period gives the time a spacecraft needs to travel around the Earth. [58]

The orbits can also be divided according to their function [58]:

- **Ejection orbit** - The orbit, where the spacecraft will be placed after separation from the launch vehicle.
- **Initial parking orbit** - The orbit, where the spacecraft will be temporarily ”parked” before transferring it to its final mission orbit.
- **Transfer orbit** - The orbit used to put the satellite from its parking orbit into its final mission orbit, also called Hohmann-transfers.
- **Final mission orbit** - The orbit, where the satellite can fulfill its mission objective(s).
- **Graveyard orbit** - The orbit, where the GEO satellites will be placed after its end-of life, it is about 100 km higher than the geosynchronous orbit.

A.3.3.3 Satellite Constellations

Several satellite applications have high demands on the revisit times, spatial or temporal resolution of data, which often one single spacecraft cannot provide. Constellations of satellites however can acquire more data for a specific purpose, by either using different sensors and observing the same target, or increase the spatial and temporal resolution.

Although the use of more satellites might decrease the overall risk and manufacturing costs per unit (in case the same design is used), the overall complexity of the system increases. The ground segment has to provide the tracking capabilities, as well as the storage, processing, and distribution capacities. In addition, the effort for mission operations increases significantly.

A.3.4 Launch Segment

The launch segment is the transportation system, which brings the satellite into its designated orbit. It can mainly be divided into:

- **Launch vehicle** - the rocket including all stages and the payload fairing
- **Launch facilities** - The launch pad, integration facilities for the rocket and the payloads, ground support equipment, and mission control centre

Concerning the launch strategy there are three different approaches: a single launch, a separated launch (for constellations) or a piggy-back launch. Typically small satellites act as secondary payloads during a launch. These so-called piggy-back launches have the advantage of relatively low launching costs, as the primary payload's institution bears the large part of the overall rocket costs. However, the primary payload also dictates the target orbit and even sometimes the launch date, the consequences resulting due to these changes have to be taken into account in the early project phases.

The selection of the launch system can also have implications on the design, assembly, integration, and test (AIT) of the spacecraft and its deployment mechanism:

- The environmental conditions (humidity, thermal, vibration, electromagnetic interferences) during integration at the launch site and during launch
- The mass and volume requirements of the launcher concerning the flight system (spacecraft and deployer)
- The various interfaces between launcher and flight system (mechanical, electrical, thermal, power, data)

A.3.5 Ground Segment

The ground segment is an essential part of every space mission, including small satellite missions. The main difference between the ground segments of small satellite missions compared to larger missions is the complexity and the budget constraints.

A.3.5.1 Communications Architecture

The communication architecture describes how the communication between spacecraft and ground looks like. The interconnection between the communication systems on-board and mission elements is defined. The communication architecture can make use of different frequency bands, each dedicated to different communication applications, e.g. telecommand via the Ulta High Frequency (UHF)-band, housekeeping telemetry via S-band and instrumentation/scientific data via X-band.

An important aspect in this matter is the selection and coordination of frequency bands (see also Section C.2). In addition, a distinction concerning the data distribution can be made: point-to-point architecture, where telecommands, telemetry and data is directly exchanged between the spacecraft and the ground station or broadcasting architecture (directly or via relay satellite).

A.3.5.2 Ground Station(s)

The ground station hosts all transmitting and receiving equipment for the communication with the spacecraft. It usually consists of two major units:

- **Outdoor unit**
  - Antenna(s) including feeds for transmitting and receiving
  - Pointing mechanisms or rotator control
- **Indoor unit**
  - Transmitting equipment including frequency generator, modulator and power amplifier
  - Receiving equipment including demodulator
  - Satellite tracking unit for the rotators
  - Software for prediction of satellite's location and frequency/Doppler shift corrections
  - Computer for telecommand encoding and telemetry decoding

When planning a small satellite mission, an important consideration is whether to use a single ground station or a ground station network [23]. As small satellites typically operate in LEO, the contact times of about 10-15 minutes per pass over one station are limited. A network would be desirable to increase the availability and introduce redundancy, e.g. in case of ground station breakdown. As a drawback however, the complexity in terms of scheduling and interfacing is increased, leading to higher costs and human resources.

Furthermore, a decision has to be made either to establish an own ground station or to use existing stations or networks. An own ground station can be customized to fulfill the mission needs, it provides full control and autonomy over the whole mission duration and might be used even for upcoming missions. This solution however requires a lot of resources in terms of time, human power, and money to develop, test and maintain such a station.

Using already existing infrastructure and buy excess capacity from existing ground stations would save time and reduce the overall mission complexity. However, the interoperability has to be guaranteed and the mission has to be compatible with the standards and interfaces used at the ground station. In addition, as the station is probably shared among different space missions, the availability may be limited and increasing the access time is a significant cost factor.

A.3.5.3 Mission Control Centre

The mission control centre (MCC) is the place where the mission operations are planned and executed. The task is to monitor and control the spacecraft, by establishing the communication to the spacecraft via the ground station or ground station network.

Depending on the necessity in the mission, the mission control centre can be divided into a spacecraft control centre and a payload control centre. Nevertheless, the mission control centre mainly comprises of the following components:

- **Telecommand and telemetry system**
- **Archiving system** - for local storage of telecommand sequences and telemetry values, and payload data
- **Post-analysis system** - for the historical analysis and evaluation of mission data
- **Mission planning system**

A.3.5.4 Data Archiving, Processing and Dissemination

Space missions often generate various data products which can address different end users. Therefore, a data archiving, processing and dissemination strategy has to be formulated, which defines the necessary facilities for the archiving and dissemination of data products.

A.3.6 Mission Operations

Mission operations will be executed via the mission control centre and comprise the following tasks:

- **Mission planning**- e.g. planning of ground station usage and pass scheduling, preparation of command files and planning of activities
- **Operation of the space segment** - e.g. execution of scientific measurements or observations
- **Contingency and recovery** - e.g. analysis and management of on-board resources, maintenance and contingency tasks
- **Training of operators**

The in-orbit lifetime of a spacecraft can also be divided into four main phases. Respectively each phase is dedicated to specific tasks:

- **Launch and Early Operations Period (LEOP)**
  This phase represents the first 24-48 hours after the ejection from the launch vehicle. Small satellites usually are powered off during launch. After ejection from its deployment housing and deactivation of the reed switches, the power lines to the solar cells are typically enabled, allowing the satellite to generate energy. In addition, deployment of antennas and/or solar panels might occur.

The operations control centre on ground tries to track and make contact with the satellite during its first overflights/passes over the ground station. The tasks are to turn on the spacecraft's COM and OBDH system and verify the health status of the satellite, especially verify the positive and correct power conditions and thermal behaviour.

- **Commissioning phase**
  Before starting with the actual operations phase, the individual subsystems on-board and their capabilities have to be validated through pre-defined tests and procedures. Therefore, this phase is very intense and requires a significant number of operators and subsystem experts, who can assist in case that non-optimal behaviours occur. The main tasks to be carried out during commissioning are:

  - Verifying the behaviour of the satellite bus systems
  - Detumbling the satellite
  - Pointing mode check
  - Calibration activities (e.g of attitude sensors)
  - Payload checkout and calibration

  Depending on the complexity of the overall system, the commissioning phase may last between weeks up to several months, and therefore should be taken into account in the project schedule. After successful completion of this phase, the spacecraft's operation will be transferred to the operations team or the customer and daily operations may start.

- **Operations phase**
  The operations phase defines the daily operation of the satellite and involves the ground and space segment. The execution of the payload measurements has to be planned, scripts prepared and the data gathered has to be analysed accordingly. The communication between ground and spacecraft has to be planned and maintained.
  Next to nominal operations, malfunctions or exceptional states can occur and will require human resources to interact. Contingency and recovery procedures have to be prepared in advance to enable the operators to intervene and act accordingly. Operations planning needs to take this into account, as the application of shift work or just ensuring short response time of stand-by operators can have a severe cost impact. Therefore, a trade-off between ground segment automation and human interaction has to be made to find the optimal balance.

- **End-of-life phase**
  At the end of the operational lifetime measures have to be taken to avoid the creation of space debris (see Section C.2). During the design of the mission, disposal considerations and decommissioning strategies already have to be taken into account [59]. In case the satellite's orbit is low enough, atmospheric drag can slow the spacecraft down constantly, forcing it to finally re-enter the atmosphere where it should be ensured the spacecraft burns up completely or re-enters in a controlled way.

There is also the possibility to equip the satellites with a propulsion system, like small electric thrusters, change the orbit and decrease the time to re-enter. However, this would increase the complexity of the mission and spacecraft design. Other experiments implementing drag-creating devices, like deployable solar sails or booms, are investigated and have already been tested in-orbit.

A.3.7 User Segment

The users of a mission have an interest in the execution of the space mission and its mission objectives. Depending on their interest and social role, users form part of the following categories:

- Scientific users
- Private users
- Third-party providers e.g. weather service
- Industrial users
- Agencies and administrations
- Military
- Universities and educational entities

The requirements stated by the individual user groups have to be taken into account in the conduction of the mission.

Appendix B

Systems Engineering Approach

Systems engineering is an interdisciplinary approach transforming the technical requirements into an operable system, with respect to the constraints and boundaries.

This chapter should provide more insight in the design, integration and verification processes and methods commonly used in small space missions.

B.1 System Design

Given the requirements and constraints, the individual elements, subsystems and components have to be designed. While a system or element describes a complex arrangement of various subsystems, a subsystem is defined as entirety of the components (complete functional unit), parts and materials, needed to form a functional subsystem. The process of system design is not straight-forward, but rather spirally, as several iterations have to be performed before the design is finalised. The harsh space environment has many implications on the on-board hardware and software, as well as on the material selection and processes, which have to be taken into account:

- Various materials are outgassing in a near-vacuum environment, leading to changes in the material properties and induce risk of stress, corrosion, and aching.
- The thermal transfer in space is critical, and the temperature range for the optimal functionality of the subsystems must be guaranteed.
- The experienced radiation due to plasma, solar and cosmic rays can influence or even damage components or subsystems. Critical units must be therefore shielded and protected, or radiation hard parts selected.

The entire bus or subsystems can either be purchased by third parties, or every subsystem can be built in-house. It is a trade-off between schedule, risk, facilities, and capabilities and is also dependable on the funding environment, the customer and the philosophy of the organisations involved.

The tasks of a systems engineer in the system design phase are diverse and comprise at least the following activities [54]:

- Maintenance of product tree, which defines all units and products to be delivered, and their relations to each other
- Maintenance of budgets, such as mass, power, link, data etc.
- Assessment of AIT and operations impact on the system's design
- Definition and control of a reliability and redundancy concept
- Control of analysis and test data, that show the design meets the requirements

B.2 System Integration

The system integration defines the process of connecting and assembling the subsystems and components to one spacecraft or space segment.

A typical integration process comprises the following features [58]:

- The developments of the subsystems including the payload are completed.
- All GSE and tools for integration are available in the dedicated integration room.
- All steps including tests that need to be performed during the integration phase are defined and summarised in a document (e.g. integration log book). There are two aspects, that have to be taken into account when defining the integration sequence: the functionality and the access possibility of a unit.
- The integration process is split into parts, each of which is considered finished after a verification has occured.
- All steps and tests performed are documented.

B.2.1 Integration and Testing Facilities

The assembly and integration of a spacecraft occurs in an integration room with clearly defined environmental specifications, such as temperature range, relative humidity, clean room class.

The clean room class for example states the number of particles greater than 0.5 μm per ft^3. It depends on the individual space mission if a cleanroom is needed for assembly. This would be the case if e.g. sensitive optical sensors are used. Otherwise an ElectroStatic Discharge (ESD) protected laboratory with typical environmental specification (20 °C +/- 5 °C, relative humidity 50%) would be sufficient.

During and/or after the integration, according to the testing philosophy (see Section B.3), access to various testing facilities has to be provided including:

- Thermal (vacuum) chambers
- Vibration table
- Anechoic chambers
- Electromagnetic compatibility testing facility
- Ground station for compatibility tests

B.2.2 Ground Support Equipment (GSE)

During the assembly, integration and testing (AIT) phase various auxiliary units are needed as support on ground. Different types of so-called ground support equipment can be:

- **Mechanical Ground Support Equipment (MGSE)**
  Supports and allows secure handling, storage and transport of the spacecraft units.
- **Electrical Ground Support Equipment (EGSE)**
  Used for testing and stimulating all electromechnanic and electronic components (e.g. power supplies, interface boards, battery load, signal analyser).
- **Optical Ground Support Equipment (OGSE)**
  Used for the stimulation, calibration, exposure and data recording of optical sensors or instruments.
- **Radio Frequency (RF) equipment**
  Supports the analyses of the communication chain, or simulates the ground segment during testing of the spacecraft.
- **Transport container**
  This container shall ensure the secure transport of the space segment to the launch site. It is equipped with humidity sensors/absorbers, shock sensors/absorbers and is hermetically sealed. It might also be nitrogen-purged if needed.

All GSE used have to be suitable and verified for the envisaged purpose and employment.

B.3 System Verification

The term verification states the proof that a spacecraft fulfills the requirements, corresponds to the qualified concept and is able to fulfill the mission objectives [58][26].

Verification occurs in consecutive phases of the spacecraft's lifecycle, which are defined as following:

- **Qualification** - The goal is to demonstrate, that the design fulfills all requirements including margins. The object must correspond to a flight standard (QM, FM or PFM - see model philosophy next subsection). The proof is gained by applying higher test specification as during acceptance testing on longer and numerous test campaigns.
- **Acceptance** - The objective is to demonstrate, that the unit does not have any defects due to manufacturing or integration, and that it is ready for deployment. The test levels applied are slightly higher than the expected loads.
- **Verification prior launch** - The evidence is provided by test and analysis, that the spacecraft is suitable for the launch and further in-orbit operation.
- **Verification in-orbit** - The goal is to demonstrate, that the spacecraft or subsystem is suitable for the deployment in the space environment (e.g. the performance of the ADCS system on ground is not directly transferable to a zero-g environment).
- **Verification post-landing** - After the mission, dedicated functionalities and the condition of the system are checked to spot any consequences due to in-orbit anomalies (only applies to re-entry systems).

B.3.1 Verification Strategy and Model Philosophy

The verification on a unit, subsystem or spacecraft is performed using one of the four methods:

- **Review by design** - by validating data or proven concept reports, technical description or plans, that unambiguously show that the requirements were fulfilled
- **Inspection** - the visual proof of the physical properties of the unit (e.g. documented by protocols or photos)
- **Analysis** - by evaluating the properties of the unit with accepted techniques (e.g. methodical, statistical, qualitative, by simulation)
- **Test** - by measuring the properties or functions of the unit under simulated environmental conditions, which might also include qualitative analysis

The system verification control matrix, or compliance matrix, is used to identify the individual verification methods and tracks the verification status with respect to the requirements during the project lifecycle.

The verification might not be performed on the flight model itself, different models can be used during the AIT process of a space mission, depending on the model philosophy defined. The number and sort of models to be used on different levels (unit, subsystem, system) for verification shall be optimised concerning risk, schedule, cost and verification extent. An overview of the most common models is given below:

- **Development Model (DM)** - the model is used to proof the feasibility of a concept. While it represents dedicated functionalities of a the future flight unit, the volume, interfaces or form factor might be different.
- **Engineering Model (EM)** - the model is used to qualify the functionality of a system, including the main specifications and reliability.
- **Qualification Model (QM)** - represents the flight design of a unit or subsystem and is tested on qualification level.
- **Proto-Flight Model (PFM)** - the model is used for qualification of the design and for flight.
- **Flight Model (FM)** - the model is used for flight, only tested on acceptance level.

B.3.2 Test Philosophy and Environmental Testing

To sustain the harsh environmental conditions experienced during launch and in space, the spacecraft and its subsystems must be tested and qualified before launch. The requirements of the tests to be performed during the test campaign depends on several aspects: the mission itself, the selection of the launcher, was well as the lifetime and orbit of the spacecraft.

A test plan has to be developed, which defines the tests to be performed on each level (unit, subsystem, system). Functional tests are performed to proof the correct behaviour and functionality of the Device under Test (DUT), that might include:

- Hardware and software tests
- Interface testing
- Behaviour and performance investigations of the DUT (e.g. ADCS subsystem)
- Deployment tests of antennas, solar arrays or deployment mechanism
- Communication tests

Next to functional tests of the systems, so-called environmental tests have to be performed. During these tests, the DUT is subject to the environmental conditions as they occur during launch or in-orbit. The most important, but not exclusive, environmental conditions are:

- **Structural conditions** - static, dynamic and aerodynamic loads, vibration and shock
- **Thermal conditions** - vacuum, internal and external thermal sources and drains
- **Electromagnetical conditions** - self-induced or natural high-energy magnetic fields
- **Radiation conditions** - space radiation, Earth near radiation regions like South Atlantic Anomaly or polar areas, or radiation belts
- other conditions like micro-gravity, plasma, interplanetary space.

Depending on the test plan and philosophy, functional tests have to be performed after, and sometimes even before and during the conduction of the environmental test.

Appendix C

Support Disciplines

During the conduction of a space mission, several programmatical and managerial aspects have to be considered. In addition, the regulatory framework might have a significant impact on the mission design.

C.1 Project Management

Although this thesis focuses more on the technical definition and realisation of a space mission, the field of project management still plays an import role in its successful implementation.

A project manager should have an insight in various fields of knowledge [58]:

- **Methodical competence**
  - Risk management
  - Schedule management
  - Cost management
  - Procurement management
- **Social competence**
  - Communication strategy and management
  - Team structure and human resources management
- **Technical competence**
  - Documentation strategy
  - Product and quality assurance (PA/QA)

Some of the competences (especially the documentation and PA/QA competences) might be transferred to the systems engineer, who supports and complements the project manager.

C.1.1 Documentation Strategy and Product and Quality Assurance

The document strategy is a very critical decision, a trade-off between necessary documentation and organisation/costumer requirements have to be negotiated, without binding to many human resources. The ECSS standard suite (Figure C.1) give a good insight in the various space disciplines and state the requirements and documentation.

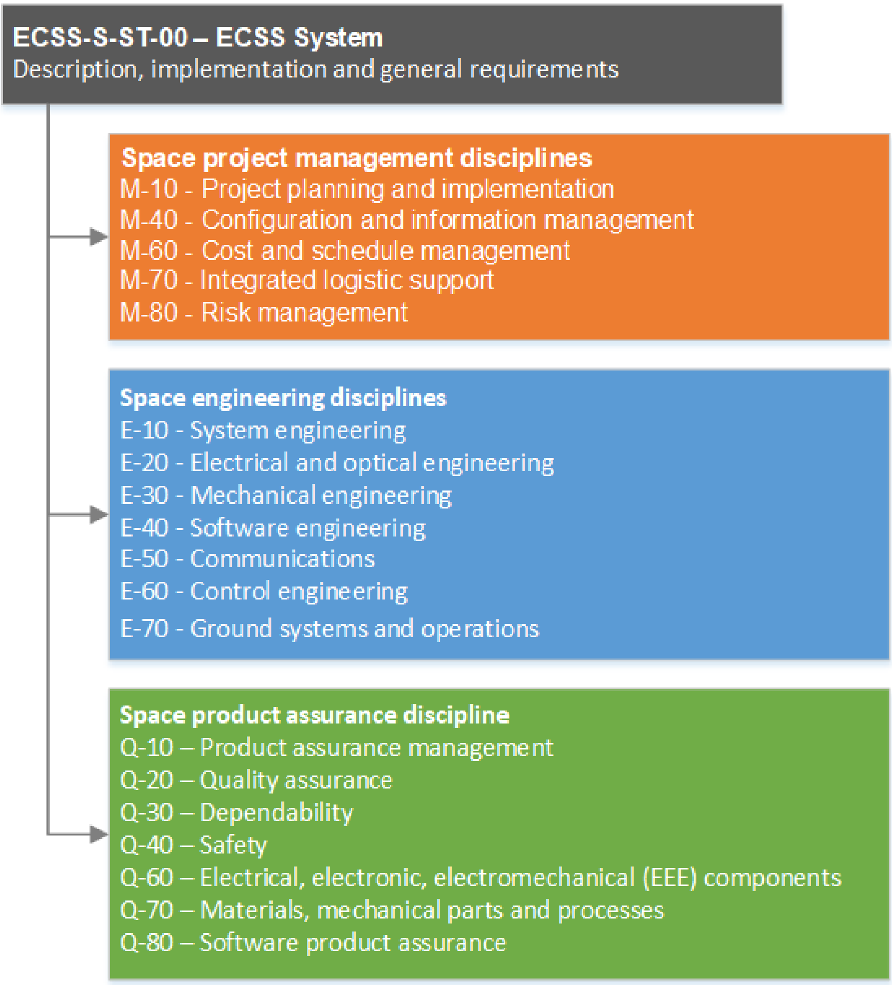


Figure C.1: ECSS standards: The diagram gives an overview of the ECSS standard suite. [60]

However, the full standard is way out of scope for small satellite missions. For this case the European Space Agency (ESA) created the IOD (In-Orbit Demonstration) CubeSat Tailoring standard [51], which tries to state a good consent between the ESA requirements and a small satellite/CubeSat mission. It gives an overview of the ECSS engineering standards and declares, whether a standard is applicable, a guideline or even not applicable and a higher risk is accepted.

In addition, a light version of the product and quality assurance requirements [61] was formulated, to cope with the extensive use of Commercial Off-The-Shelf (COTS) components and higher risk tolerances.

Besides, a list of documents was defined (IOD CubeSat Document Requirements Definition [62]), which should be prepared during the course of space mission. At the Preliminary Design Review, the following documents are of main interest:

- **Mission Requirements Document (MRD)** - specifies the mission requirements/constraints, and states the high level payload user requirements
- **Mission Analysis Report (MAR)** - describes the mission design and mission planning
- **System Requirements Document (SRD)** - specifies the system requirements, for the spacecraft bus, the payload and the ground segment
- **System Design Report (SDR)** - provides a technical description of the mission, the spacecraft system and ground segment, including all interfaces and system budgets.
- **Environmental Design Specification (EDS)** - defines the launch and space environment the spacecraft will be encountering and gives the implications on the spacecraft and subsystem design
- **Space Debris Mitigation Report (SDMR)** - shows the compliance of space debris avoidance
- **Product Assurance Plan (PAP)** - defines the product assurance and safety disciplines and states the resources, requirements and responsibilities
- **Space-to-ground Interface Control Document (SGICD)** - defines the interfaces between the space segment and the ground segment
- **Satellite Mechanical Analysis Report** - describes the spacecraft's mass properties, structural analysis set-up, assumptions, and analysis results in relation to the relevant requirements
- **Satellite Thermal Analysis Report** - describes the thermal analysis set-up, assumptions, and analysis results in relation to the relevant requirements
- **Satellite AOCS Analysis Report** - describes the AOCS analysis set-up, assumptions, and analysis results in relation to the relevant requirements
- **COTS User Manuals** - describes the Commercial Off-The-Shelf (COTS) products to be used in the satellite design baseline
- **System Development Plan (SDP)** - defines the detailed activities to be performed on new developed units
- **Platform-Payload Interface Control Document (PPICD)** - defines the interfaces between payload(s) and spacecraft bus

- **Declared Lists for parts, materials and processes (DLs)** - states a list of all types of electrical components, mechanical parts and materials needed for the envisaged design for all system-level models

During the later phases, various additional documents might be valuable:

- **Satellite Assembly, Integration and Verification (AIV) Plan** - defines and controls the AIT activities associated with the flight system (issued at the Critical Design Review [CDR])
- **Safety Data Package** - demonstrates the compliance with the launch safety requirements (issued at CDR)
- **System Verification Control Matrix** - identifies the verification methods to track the verification status with respect to requirements during the project lifecycle (issued at CDR)
- **Test Procedures** - establishes objectives, organisation, setup and constraints of verification tests. To establish the procedures/success criteria used in verification tests and the requirements to be verified (issued at CDR)
- **Test Reports** - describes the results of the verification tests at all levels against the specified requirements (issued at CDR)
- **Satellite Integration Logbook** - records the actual events of the satellite integration process (issued at Flight Acceptance Review [FAR])
- **Mission Operations Plan (MOP)** - defines the full plan of activities during the mission operations phase, from launch until end-of-life scenario, covering nominal and contingency procedures (issued at FAR)
- **Mission Operations Status Reports** - regulary reports on the health status of the platform and payload in orbit and the progress with respect to the Mission Operations Plan (issued at the Post-Flight Review [PFR])
- **Post-flight Analysis Report** - summarises the results of the mission based on the data acquired, and describes the lessons learned (issued at PFR)

In addition, in case needed, other documents might be of importance or required by the costumer or funding agency:

- Non-Conformance Reports (NCRs) - states the non-conformances of the system with respect to requirements in terms of nature, root cause, and corrective actions
- Request For Deviations (RFDs) - requests departures from an approved configuration baseline
- Request For Waivers (RFWs) - requests waivers for established requirements.

C.2 Regulatory Aspects

When starting and defining a space mission, the regulatory framework has to be considered already in the early phases of the project. National and international entities are involved in the lifetime of a space mission.

C.2.1 Space Law

Space law imposes several rights and obligations all parties involved in space activities need to be aware of. These rights and obligations can have international and national law aspects [63][64].

On an international level, space law is defined by the five United Nations (UN) Treaties as well as the United Nations Principles on space law. Especially the articles of the Outer Space Treaty and the Liability Convention are of major legal concern for satellite operators, as they define the jurisdiction, ownership and most important the liability concerning any damage caused by the spacecraft [65].

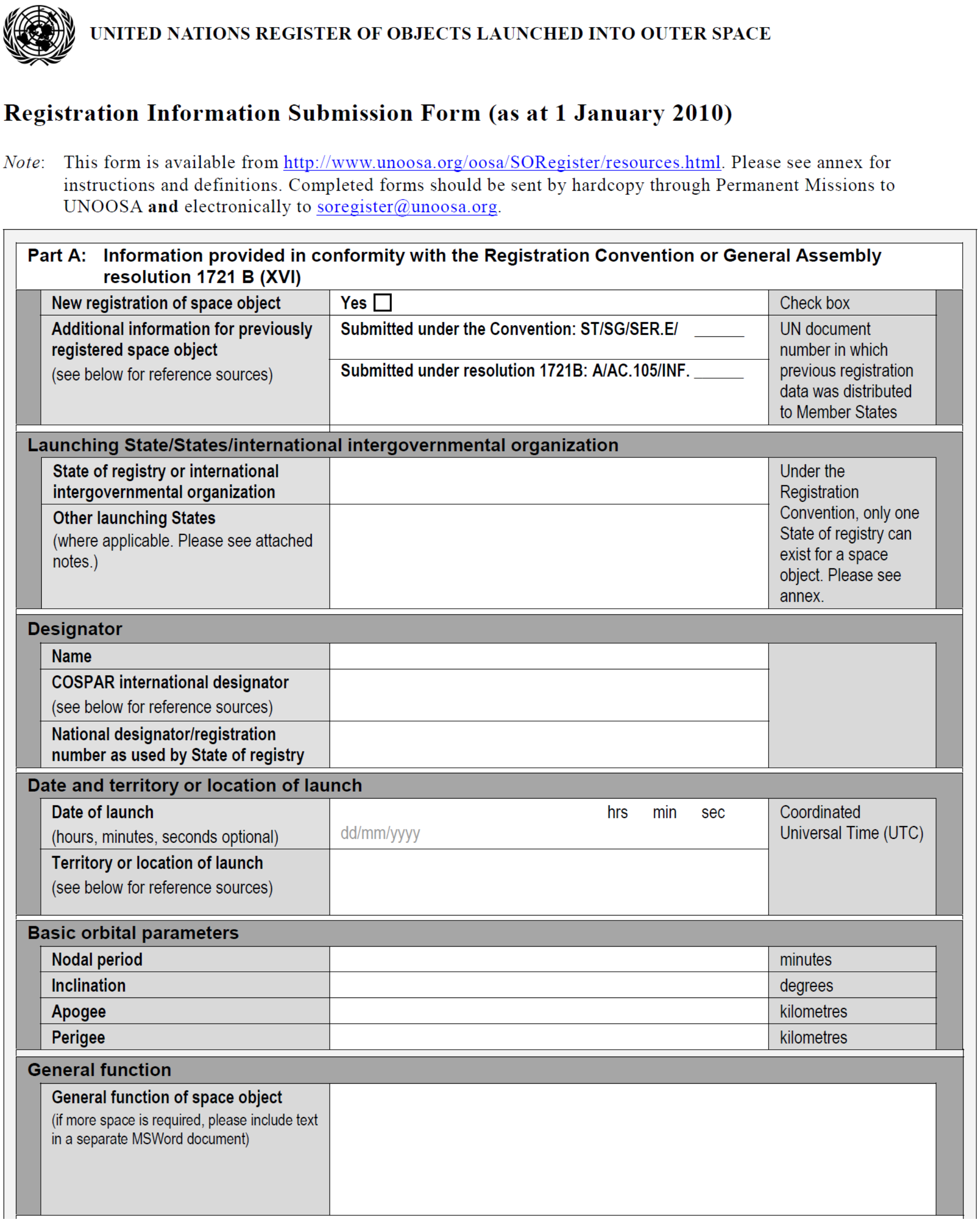
On a national level, each domestic legal system treats the space law differently. When defining a space mission, it is advisable to check whether the state is party to these treaties and if any national law concerning space activities is in force.

The United Nations Office for Outer Space Affairs (UNOOSA) provide a national space law database on their website, stating the existing national legislation of the individual states [66]. In case no entry in the database concerning the state in question can be found, contacting the national Ministry or Agency for space law is advised.

C.2.2 Satellite Registration

The Registration Convention of the United Nations requires that in case a state launches a satellite into Earth orbit or beyond, relevant information shall be provided by the State of registry to the Secretary-General of the United Nations. Upon launch of the spacecraft, the national competent authority of the State of registry provides the filled in registration form (see excerpt in Figure C.2) to the Secretary-General trough a Diplomatic Mission accredited to the United Nations [67].

In case the State of registry is not party of the Registration Convention, it can voluntarily provide the relevant information to the UN.



UNITED NATIONS REGISTER OF OBJECTS LAUNCHED INTO OUTER SPACE

Registration Information Submission Form (as at 1 January 2010)

Note: This form is available from http://www.unoosa.org/oosa/SORegister/resources.html. Please see annex for instructions and definitions. Completed forms should be sent by hardcopy through Permanent Missions to UNOOSA **and** electronically to soregister@unoosa.org.

Part A: Information provided in conformity with the Registration Convention or General Assembly resolution 1721 B (XVI)

New registration of space object	**Yes** ☐	Check box
Additional information for previously registered space object (see below for reference sources)	**Submitted under the Convention: ST/SG/SER.E/** ______ **Submitted under resolution 1721B: A/AC.105/INF.** ______	UN document number in which previous registration data was distributed to Member States

Launching State/States/international intergovernmental organization

State of registry or international intergovernmental organization		Under the Registration Convention, only one State of registry can exist for a space object. Please see annex.
Other launching States (where applicable. Please see attached notes.)		

Designator

Name		
COSPAR international designator (see below for reference sources)		
National designator/registration number as used by State of registry		

Date and territory or location of launch

Date of launch (hours, minutes, seconds optional)	hrs min sec dd/mm/yyyy	Coordinated Universal Time (UTC)
Territory or location of launch (see below for reference sources)		

Basic orbital parameters

Nodal period		minutes
Inclination		degrees
Apogee		kilometres
Perigee		kilometres

General function

General function of space object (if more space is required, please include text in a separate MSWord document)	

Figure C.2: Registration form of objects launched into outer space: Basic information on the spacecraft launched into outer space has to be provided upon launch by the state of registry to the United Nations (page 1 of the form). [68]

C.2.3 Space Debris Mitigation

As the number of human-made objects in the Earth orbit is steadily increasing, the risk of collision in orbit or other influences on the orbital environment or public on ground have to be mitigated.

The United Nations has therefore released the ”Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space” [65].

The guidelines stated should be considered in the mission planning, the design and manufacturing phases, as well as operational phases (launch, nominal operations and disposal) of a spacecraft and launch vehicle stages. A total of seven guidelines were defined:

1. Limit debris released during nominal spacecraft/orbital stages operations
2. Minimize the potential for break-ups during operational phases
3. Limit the probability of accidental collision in orbit
4. Avoid intentional destruction and other harmful activities
5. Minimize the potential for post-mission break-ups resulting from stored energy
6. Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission
7. Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission

Although these guidelines are not legally binding under international law, they may be incorporated in domestic law and get legally binding.

Based on these guidelines, the second edition of the International Organization of Standardization (ISO) 24113 ”Space Systems - Space Debris Mitigation Requirements” [69] was issued in May 2011 as international standard. It establishes a set of requirements for design and operations to minimise the impact on the orbital environment by space operations. Shortly afterwards, the European Coordination on Space Standarisation (ECSS) has adopted this standard as the ECSS-U-AS-10C standard [70], which represents ”the standard” for the technical requirements on space debris mitigation for all ESA projects.

ESA also provides a comprehensive tool called DRAMA (Debris Risk Assessment and Mitigation Analysis) to allow the compliance analysis of a mission with the space debris mitigation standards by providing these calculations [53]:

- Debris and meteoroid impact flux levels (at user-defined size regimes)
- Collision avoidance manoeuvre frequencies for a given spacecraft and a project-specific accepted risk level
- Re-orbit and de-orbit fuel requirements for a given initial orbit and disposal scenario
- Geometric cross-section computations
- Re-entry survival predictions for a given object of user-defined components
- The associated risk on ground at the resulting impact ground swath

C.2.4 Frequency Coordination

An important mission decision is the choice of frequency bands. The frequency bands and their usage are defined and coordinated via the International Telecommunication Union (ITU). There are no dedicated frequency band assignments for the use on small satellites. Applying for a frequency via the ITU can be a quite complex, definitely time-consuming and also cost-intensive process. Therefore, small satellite missions often rely on amateur radio frequency bands only, as the coordination process is simplified, and it is carried out by the International Amateur Radio Union (IARU). The drawback however is, that the application range is very limited. Amateur radio bands can only be used for non-commercial purposes or for experimenting new technologies. Other disadvantages include the limited allowed RF power and usable bandwidths, as well as the non exclusive frequency usage, exposing mission operations success to potential radio interference risks [71].

C.2.4.1 International Telecommunication Union (ITU)

Concerning the frequency coordination via the ITU [72], any official correspondence has to occur via the national frequency bureau or office, no direct contact between the ITU and spacecraft operators is allowed.

The coordination process is quite time-consuming and has to be planned for in the early design phase. In addition, the frequency filing is not free of charge, although it is possible to apply for cost recovery for satellite networks under special circumstances. The coordination process starts with the filing of the Advanced Publication Information (API), where the following information on each of the communication beams planned to be used on the spacecraft has to be published:

- Class of station (dedication of the space station)
- Nature of service (e.g. if the station is open for public correspondence or exclusively to operational traffic of the service concerned)
- Service area (which territories and hence administrations might be involved in the operation of the spacecraft)
- Period of validity and information on the applying administration
- Specifications of the beam (e.g. frequency range, bandwidth, max/min power density and max/min peak power)
- Associated Earth station, its class, coordinates and specifications
- Radiation patterns of the on-board antenna(s) and respective Earth station

After the successful submission, the ITU officially publishes the API. The administrations of the member states have then the possibility to comment and appeal on the filing in case interference might occur to their terrestrial or space services. These comments are then summarized by the ITU and forwarded to the applicant, who has to formally respond to each of the requests by providing explanations or additional information. In case all the requests have been successfully covered, a notification can be filed. Once the coordination process is completed, the frequency usage is granted to the applying administration/state. All ITU members are then obliged to respect the usage of this frequency as allocated. Upon launch of the spacecraft or satellite network an official ”bringing-into-use” statement including the actual orbital parameters of the respective spacecraft or satellite network has to be submitted to ITU. The satellite operator retains the right of using the frequencies throughout the applied period of validity of the spacecraft. If the lifetime of the spacecraft is extended, a formal request of frequency extension has to be submitted.

C.2.4.2 International Amateur Radio Union (IARU)

In case any amateur radio frequency is involved, an amateur satellite frequency coordination request has to be submitted to the IARU [73]. The information to be provided is similar to the one for ITU, except that more information on the spacecraft itself including telecommand and telemetry structure and link budgets have to be submitted. It is advisable to contact the national radio amateur society and include them during the coordination process.

C.2.5 Ground Station Licensing

Although the spacecraft, its frequencies and the envisaged ground station have been notified to the ITU, the ground station itself has to be registered and a license from the national frequency bureau has to be obtained. Depending on the national legislation, different information has to be provided to the local authorities, that might include:

- Description of the spacecraft to be operated including the orbital parameters
- Frequencies and bandwidths used
- Location and coordinates of the ground station
- Description of receiving and transmitting equipment of the ground station
- Antenna diagrams

C.2.6 Insurances

The insurance sector offers several possibilities for insuring space missions. It is up to the satellite's owner or operator, if technical, transport or commercial risks are covered by an insurance or by own reserves, especially the following decisions whether to effect an insurance or not have to be made:

- Insurance of persons involved during the overall execution of the project
- Insurance of persons involved during test campaigns and/or launch campaign outside of the employer's premises
- Insurance of the spacecraft and GSE during the AIT phase
- Insurance of the spacecraft and GSE during transport to/from test facilities and to the launch site
- Insurance of the launch (liability insurances might be necessary due to national legislation)

C.2.7 Export Regulations

It is important to be aware of any technology transfer limitations in the early phases of the project. These limitations and export control constraints have to be considered in the design phase, to avoid technological obstacles and possible impacts on schedule and costs.

When using technological units or equipment from e.g. the United States, these units might fall under the very restrictive export control legislation of the International Traffic in Arms Regulation (ITAR), imposing possible problems in the further export to e.g. launching states.

Abbreviations, Acronyms and Symbols

A

ACS	Attitude Control System
ADCC	Attitude Determination and Control Computer
ADCS	Attitude Determination and Control System
ADU	Adjusted Digital Value
AGB	Asymptotic Giant Branch
AIS	Automated Identification System
AIT	Assembly, Integration and Testing
AIV	Assembly, Integration and Verification
AOCS	Attitude determination and Orbit Control System
API	Advanced Publication Information
AR	Acceptance Review
ASAP	Austrian Space Applications Programme

B

BCDR	Battery Charge and Discharge Regulator
BEST	BRITE Executive Science Team
BIAST	BRITE International Advisory Science Team
BIST	Built-In Self Test
BMVIT	Bundesministerium für Verkehr, Innovation und Technologie
BPSK	Binary Phase Shift Keying
BRITE	BRIght Target Explorer

C

CAC	Copernicus Astronomical Centre
CANOE	Canadian Advanced Nanospace Operating Environment
CCD	Charge Coupled Device
CDR	Critical Design Review

CNES	Centre National d'Etudes Spatiales
COM	Communication subsystem
COTS	Commercial Off The Shelf
CROC	Cross Section of Complex Bodies
CRR	Commissioning Result Review
CSV	Comma Separated Value
CTAP	Coarse Three-Axis Pointing
CTI	Charge Transfer Inefficiency
D	
DEC	Declination
DL	Declared Lists
DLA	Dual Launch Adapter
DM	Development Model
DRAMA	Debris Risk Assessment and Mitigation Analysis
DUT	Device Under Test
E	
EBD	Equipment Bay Deck
ECI	Earth-Centered Inertial Coordinate System
ECSS	European Coordination on Space Standarisation
EDS	Environmental Design Specification
EGSE	Electrical Ground Support Equipment
EIRP	Effective Isotropic Radiated Power
EKF	Extended Kalman filter
ELR	End-of-Life Review
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESA	European Space Agency
ESD	ElectroStatic Discharge
ESOC	European Space Operations Centre
F	
FAR	Flight Acceptance Review
FFG	Forschungs Förderungs Gesellschaft
FITS	Flexible Image Transport System
FLP	First Launch Pad

FM	Flight Model
FOV	Field Of View
FRR	Flight Readiness Review
FTAP	Fine Three-Axis Pointing
FTP	File Transfer Protocol
G	
GBOT	BRITE-Constellation Ground-Based Observing Team
GENSO	Global Educational Network for Satellite Operations
GEO	Geosynchronous Earth Orbit
GMTP	Generic Mass Transfer Program
GNB	Generic Nanosatellite Bus
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSE	Ground Support Equipment
GSS	Ground Segment Software
GSTP	General Support Technology Programme
G/T	Figure of Merit
H	
HDLC	High-Level Data Link Control
HEO	High-elliptical Earth Orbit
HKC	Housekeeping Computer
I	
I^2c	Inter-Integrated Circuit
IARU	International Amateur Radio Union
ICD	Interface Control Document
IKS	Institute of Communication Networks and Satellite Communications
IOBC	Instrument On Board Computer
IOD	In-Orbit Demonstrator
IP	Internet Protocol
ISO	International Organization of Standardization
ISRO	Indian Space Research Organisation
ITAR	International Traffic in Arms Regulation
ITU	International Telecommunication Union

L	
LEO	Low Earth Orbit
LEOP	Launch and Early Operations Period
LFFT	Long Form Functional Test
LNA	Low Noise Amplifier
LRR	Launch Readiness Review
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
M	
MAR	Mission Analysis Report
MB	Mega Byte
MCC	Mission Control Centre
MCR	Mission Close-out Review
MDA	MacDonald, Dettwiler and Associates
MDA	Mission Data Archive
MDR	Mission Definition Review
MEC	Mechanical subsystem
MEO	Medium Earth Orbit
MGSE	Mechanical Ground Support Equipment
MRD	Mission Requirements Document
MOP	Mission Operations Plan
MOST	Microvariability and Oscillations of STars
MSCI	Microsat Systems Canada Incorporated
MST	Mobility Service Tower
MUX	BRITE Multiplexer
N	
NCR	Non-Conformance Reports
NGSO	Non-Geostationary Satellite Orbit
NLS	Nanosatellite Launch Service
NORAD	North American Aerospace Defense Command
NSP	Nanosatellite Protocol
O	
OASYS	On-orbit Attitude SYStem software
OBC	On Board Computer

OBDH	On-board Data Handling subsystem
OEVSV	Österreichischer Versuchssenderverband
OGSE	Optical Ground Support Equipment
ORR	Operational Readiness Review
OSCAR	Orbital Spacecraft Active Removal
P	
PA/QA	Product Assurance / Quality Assurance
PAP	Product Assurance Plan
PC	Personal Computer
PDR	Preliminary Design Review
PFFS	Persistent Flash File System
PFM	Proto-Flight Model
PFR	Post-Flight Review
PPICD	Platform-Payload Interface Control Document
PRR	Preliminary Requirements Review
PSF	Point Spread Function
PSLV	Polar Satellite Launch Vehicle
PWR	Power subsystem
Q	
QB50	International Network of 50 double and triple CubeSats
QM	Qualification Model
QMTP	Queued Mass Transfer Program
QPSK	Quadrature Phase Shift Keying
QR	Qualification Review
QTTU	Queued Time Tag Uploader
R	
RA	Right Ascension
RAAN	Right Ascension of Ascending Node
RBF	Remove Before Flight
RCCW	Radioclub for Communication and Wave Propagation
RF	Radio Frequency
RFD	Request For Deviation
RFW	Request For Waiver
RTV	Room Temperature Vulcanizer
RX	Receive

S

SAA	South Atlantic Anomaly
SDGC	Science Data Generation Code
SDP	System Development Plan
SDR	Science Data Record
SDR	Software Defined Radio
SDMR	Space Debris Mitigation Report
SDSC	Satish Dhawan Space Centre
SFL	Space Flight Laboratory
SFFT	Short Form Functional Test
SGICD	Space-to-ground Interface Control Document
SRAM	Static Random-Access Memory
SRC	Space Research Centre of the Polish Academy of Sciences
SRD	System Requirements Document
SRR	System Requirements Review
SRS	Space Research Services
SP	Satellite Processing building
SPI	Serial Peripheral Interface
SSO	Sun-Synchronous Orbit
SSDD	Sun-Synchronous Dawn Dusk orbit
SSNM	Sun-Synchronous Noon-Midnight orbit
SSTL	Surrey Satellite Technologies Limited
STK	Systems Tool Kit

T

TCP	Transmit Control Protocol
THM	Thermal subsystem
TLE	Two Line Element
TNC	Terminal Node Controller
TT&C	Telemetry Tracking and Command
TTC	Time Tagged Command
TUGraz	Graz University of Technology
TUV	Vienna University of Technology
TVAC	Thermal Vacuum
TX	Transmit

U

UART	Universal Asynchronous Receiver Transmitter
UHF	Ultra High Frequency
UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs
UTC	Universal Time Coordinate
UTIAS	University of Toronto Institute for Aerospace Studies
UV	University of Vienna
UV	UltraViolet

V

VHF	Very High Frequency
VPN	Virtual Private Network

W

WOD	Whole Orbit Data

X

XPOD	eXperimental Push Out Deployer

Symbols

a	Semi-major Axis
e	Eccentricity
E	Eccentric Anomaly
F	Force
G	Gravitational constant
i	Inclination
$M0$	Mean Anomaly
m_1	Mass of body 1
m_2	Mass of body 2
r	Distance
$T0$	Epoch
ν	True Anomaly
Ω	Right Ascension of Ascending Node
ω	Argument of Perigee
♈	Vernal Equinox

Units

AWG	American Wire Gauge
bps	bits per second
mag	visual magnitude
MB	MegaByte
N	Newton
ppm	parts per million
VDC	Volts Of Direct Current

Bibliography

[1] Unterberger, M. et al. - *New telemetry system design for future nanosatellite missions*. Proceedings of the 61^{st} International Astronautical Congress 2010, Paper IAC-10.B2.6.9, Prague, Czech Republic (2010)

[2] Alonsoperez, V. et al - *Go SSP - Guidebook on Small Satellite Programs - Final Report*. International Space University, Publications / Library, Illkirch-Graffenstaden, France (2011)

[3] Gunter's Space Page - *Flying Laptop*. `http://space.skyrocket.de/doc_sdat/flying-laptop.htm`. (2018)

[4] Universidad del Valle de Guatemala, Faculty of Engineering and Research Institute - *CubeSat Project*. `http://uvg.edu.gt/ingenieria/mecanica/actividades/CubeSat/index_en.html#d2` (2018)

[5] Alonsoperez, V. et al - *Go SSP - Guidebook on Small Satellite Programs - Presentation*. International Space University, SSP11 Graz, Austria (2011)

[6] BRITE-Constellation Web Page, `http://www.brite-constellation.at` (2018)

[7] IKS/TU Graz - ”TUGSAT-1/BRITE-Austria Web Portal”, `http://www.tugsat.at` (2018)

[8] Analytical Graphics Inc., ”Systems Tool Kit”, `https://www.agi.com/products/engineering-tools` (2018)

[9] Austrian Research Promotion Agency, ”ASAP - Austrian Space Applications Programme”, `https://www.ffg.at/programme/asap` (2018)

[10] Koudelka, O. et al. - *TUGSAT-1/BRITE-AUSTRIA - The first Austrian nanosatellite*. Acta Astronautica 64, Page 1144-1149, Elsevier Ltd. (2009)

[11] Romano, P., Unterberger, M. and Bergmann, M. - *Small Satellite Program Guide, Chapter 9: BRITE-Austria/TUGSAT-1: First Austrian Nanosatellite - Case Study*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[12] Larson, W.J. et al - *Applied Space Systems Engineering*. Space Technology Series, The McGraw-Hill Companies, USA (2009)

[13] Wertz, J.R. and Larson, W. J. - *Space Mission Analysis and Design, Third Edition*. Space Technology Library, Microcosm Press and Springer, Hawthorne and New York, USA (2010)

[14] European Cooperation for Space Standardization (ECSS) - *ECSS-M-ST-10C Rev.1 - Space project management - Project planning and implementation*. Noordwijk, The Netherlands (2009)

[15] Weiss, W. W. et al. - *BRITE-Constellation: Nanosatellites for Precision Photometry of Bright Stars*. Proceedings of the International Astronomical Union Sysmposium, Volume 301, pp. 67-68 (2014)

[16] Unterberger, M. et al. - *BRITE Austria Operations Phase IIB - ASAP5 - Final Report*. Graz University of Technology, Austria (2009)

[17] Unterberger, M. et al. - *BRITE-Austria - ASAP3 Final Report*. Graz University of Technology, Austria (2011)

[18] Unterberger, M. - *BRITE-Austria - Detailed Design Document*. Graz University of Technology, Austria (2009)

[19] Unterberger, M. and Romano, P. - *Small Satellite Program Guide, Chapter 9.5: Launching Arrangement and Configuration*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[20] Indian Space Research Organisation - *PSLV-C20/Saral Gallery*, `https://www.isro.gov.in/pslv-c20-saral/pslv-c20-saral-gallery`

[21] Unterberger, M. et al. - *Experience in Commissioning and Operations of the BRITE-Austria Nanosatellite Mission*. Proceedings of the 64^{th} International Astronautical Congress 2013, Paper IAC-13,B6.2,9, Bejing, China (2013)

[22] Sumus Technology Limited - ”SUMUS Tracker Web Page”, `http://www.stltracker.com/` (2018)

[23] Romano, P. et al. - *BRITE-Austria Ground Segment and Distributed Operations Concept*. Proceedings of the 63^{rd} International Astronautical Congress 2012, Paper IAC-12-B4.3.9, Neaples, Italy (2012)

[24] Romano, P. - *Ground Station Engineering and Operations of Nanosatellite Missions*. Doctoral Thesis, Graz University of Technology, Austria (2015)

[25] Bergmann, M. - *Small Satellite Program Guide, Chapter 9.1: Contextual Analysis, Motivation, and Benefits of the BRITE-Austria Mission - Why was the Project Started?*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[26] European Cooperation for Space Standardization (ECSS) - *ECSS-E-ST-10C Rev.1 - Space engineering - System engineering general requirements*. Noordwijk, The Netherlands (2017)

[27] Romano, P., and Unterberger, M. - *Small Satellite Program Guide, Chapter 9.2: Programmatic and Managerial Considerations - How Was the Project Carried Out*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[28] Grant, C. - *BRITE Assembly, Integration, and Test (AIT) Plan*. Space Flight Laboratory, University of Toronto, Canada (2009)

[29] Unterberger, M. and Romano, P. - *BRITE-Austria - ASAP3 Flight Readiness Report*. Graz University of Technology, Austria (2011)

[30] Unterberger, M. and Romano, P. - *BRITE-Austria - ASAP3 Qualification Test Report*. Graz University of Technology, Austria (2011)

[31] Metzger, R. et al. - *BRITE-Austria - Vibration Test Report*. SGS Munich and Graz University of Technology, Austria (2011)

[32] Unterberger, M. and Romano, P. - *BRITE-Austria - Thermal Vacuum Test, Procedure & Results*. Graz University of Technology, Austria (2011)

[33] BRITE-PL - ”First Polish Scientific Satellite Web page”, `http://www.brite-pl.pl/index_en.html` (2018)

[34] Unterberger, M. and Romano, P. - *BRITE-Austria - Electromagnetic Compatibility Test, Procedure & Results*. Graz University of Technology, Austria (2011)

[35] Unterberger, M., Romano, P., and Kuschnig, R. - *BRITE-Austria - Open Field Test, Procedure & Results*. Graz University of Technology, Austria (2011)

[36] Unterberger, M. and Romano, P. - *BRITE-Austria - Attitude Determination and Control System Test Report*. Graz University of Technology, Austria (2013)

[37] UTIAS/SFL - ”Low-Cost Launch Services”, `https://www.utias-sfl.net/?page_id=233` (2018)

[38] Unterberger, M. and Romano, P. - *BRITE-Austria Integration Report*. Graz University of Technology, Austria (2013)

[39] Unterberger, M. and Romano, P. - *BRITE-Austria - ASAP4 Launch Contract - Final Report*. Graz University of Technology, Austria (2013)

[40] Romano, P. - *Small Satellite Program Guide, Chapter 9.6: Mission Operations*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[41] Unterberger, M. and Romano, P. - *BRITE-Austria - ASAP7 WP03-Report Satellite Commissioning*. Graz University of Technology (2013)

[42] Romano, P., Unterberger, M. and Kuschnig, R. - *BRITE-Austria - ASAP9 Spacecraft Performance Report - 1st year*. Graz University of Technology, Austria (2014)

[43] Unterberger, M., Romano, P. and Kuschnig, R. - *BRITE-Austria - ASAP9 Spacecraft Performance Report - 2nd year*. Graz University of Technology, Austria (2016)

[44] "Space Track Web Page", `https://www.space-track.org` (2018)

[45] Unterberger, M. and Romano, P. - *BRITE-Austria - ASAP7 WP04-Report Satellite Operations*. Graz University of Technology (2013)

[46] Romano, P. et al. - *BRITE-Austria Mission Operations Phase - First Results and Lessons Learned*. Proceedings of the 65th IAF Congress 2014, Paper IAC-14-B6.3.2, Toronto, Canada (2014)

[47] BRITE Executive Science Team - "BRITE Photometry Wiki" - , `http://brite.craq-astro.ca/doku.php` (2018)

[48] Kuschnig, R., Romano, P. and Unterberger, M. - *BRITE-OPS - ASAP12 Final Report*. Graz University of Technology, Austria (2017)

[49] Romano, P., Unterberger, M. and Kuschnig, R. - *BRITE-Austria - ASAP7 WP02-Report Attitude and Payload Performance, Calibration and Optimization*. Graz University of Technology, Austria (2014)

[50] Unterberger, M. and Romano, P. - *Small Satellite Program Guide, Chapter 9.4: Mission and Spacecraft Concept*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[51] European Space Agency - ESTEC/TEB - *Tailored ECSS Engineering Standards for In-Orbit Demonstration CubeSat Projects - TEC-SY/128/2013/SPD/RW, Issue 1, Revision 3*. European Space Agency, Noordwijk/The Netherlands. (2016)

[52] Austrian Federal Law on the Authorisation of Space Activities and the Establishment of a National Registry (Austrian Outer Space Act) `http://www.spacelaw.at/wp-content/uploads/2015/11/Austrian-Outer-Space-Act-DE-EN.pdf` (2018)

[53] European Space Agency - Space Debris User Portal, `https://sdup.esoc.esa.int/web/csdtf/home` (2018)

[54] Aguirre, M. R. - *Introduction to Space Systems. Design and Synthesis*. Space Technology Library, Springer, New York, USA (2013)

[55] UTIAS/SFL - "CanX-4 and CanX-5 Formation Flying Mission Web Page", `https://www.utias-sfl.net/?p=2154` (2018)

[56] Unterberger, M. - *Simulation of Data Throughput of a LEO Satellite System*. Master Thesis, Graz University of Technology, Austria (2007)

[57] Montenbruck, O. and Gill, E. - *Satellite Orbits. Models, Methods, Applications*. Springer Verlag, Berlin/Heidelberg, D (2005)

[58] Ley, W. and Wittmann, K. and Hallmann, W. - *Handbuch der Raumfahrttechnik, 3. Auflage*. Carl Hanser Verlag, München, D (2008)

[59] Klinkrad, H. - *Space Debris - Models and Risk Analysis*. Springer Verlag and Praxis Publishing Limited, Chichester, UK (2006)

[60] European Cooperation for Space Standardization (ECSS) - *ECSS-S-ST-00C - ECSS system - Description, implementation and general requirements*. Noordwijk, The Netherlands (2008)

[61] European Space Agency - ESTEC/TEB - *Product and Quality Assurance Requirements for In-Orbit Demonstration CubeSat Projects - TEC-SY/129/2013/SPD/RW, Issue 1, Revision 2*. European Space Agency, Noordwijk/The Netherlands. (2016)

[62] European Space Agency - ESTEC/TEB - *IOD CubeSat Document Requirements Definition - TEC-SY/127/2013/DRD/RW, Issue 1, Revision 2*. European Space Agency, Noordwijk/The Netherlands. (2016)

[63] Soucek, A. - *Space Law Essentials. Vol 1 Textbook*. Linde Verlag Ges.m.b.H, Wien, AUT (2015)

[64] Rinner, A. et al. - *Space Law Essentials. Vol 2 Casebook*. Linde Verlag Ges.m.b.H, Wien, AUT (2015)

[65] United Nations Office of Outer Space Affairs - International Space Law: United Nations Instruments, `http://www.unoosa.org/res/oosadoc/data/documents/2017/stspace/stspace61rev_2_0_html/V1605998-ENGLISH.pdf` (2017)

[66] United Nations Office for Outer Space Affairs, `http://www.unoosa.org/oosa/en/ourwork/spacelaw/index.html` (2018)

[67] Committee on the Peaceful Uses of Outer Space - Guidance on Space Object Registration and Frequency Management for Small and Very Small Satellites, `http://www.unoosa.org/pdf/limited/c2/AC105_C2_2015_CRP17E.pdf` (2018)

[68] United Nations Office of Outer Space Affairs - United Nations Register of Objects launched into Outer Space - Registry Submission Form, `http://www.unoosa.org/res/oosadoc/data/documents/2008/unoosaregfrm/unoosaregfrm1_0_html/UNOOSA-REG-FRM-01E.pdf` (2018)

[69] International Standard ISO 24113:2011(E), Second Edition - *Space systems - Space debris mitigation requirements* (2011)

[70] European Cooperation for Space Standardization (ECSS) - *ECSS-U-AS-10C - Adoption Notice of ISO 24113: Space systems - Space debris mitigation requirements*. Noordwijk, The Netherlands (2012)

[71] Unterberger, M. - *Small Satellite Program Guide, Chapter 9.3: Regulatory Framework*. Small Satellite Program Guide, pp. 200-250. Space Technology Series, Space Technology Library, First ed., (2014)

[72] ITU International Telecommunications Web Pag, `http://www.itu.int` (2018)

[73] IARU International Radio Amateur Union Web Page, `http://www.iaru.org/satellite.html` (2018)