LATIN AMERICAN CUBESAT WORKSHOP
SALVADOR, BR
OCTOBER 2024

Systems Engineering of a Brazilian Amazon Imaging CubeSat Constellation: FritzSAT Mission

Damylle C. X. Donati*[1], Henrique M. Lehmkuhl[1], Ludmila Kopko[1], Thiago C. Carreiro[1], and Talita Sauter Possamai[1]

[1]Department of Aerospace Engineering, Federal University of Santa Catarina
damylle.donati@gmail.com, henrique.lehmkuhl@gmail.com, ludmila.kopko@gmail.com, thiagocelestinocarr@gmail.com, talita.possamai@ufsc.br

Abstract

The FritzSAT mission aims to develop a constellation of nanosatellites dedicated to imaging the Brazilian Amazon, addressing the strategic importance of the region and the growing demand for precise environmental data. Despite the presence of existing monitoring systems, significant gaps persist in coverage, revisit frequency, and, notably, the autonomy of private companies in acquiring environmental data. This lack of autonomy hampers these companies' ability to effectively meet their operational and strategic needs, resulting in a dependency on external data sources and limiting innovation in the sector. This study details the initial phase of systems engineering for the FritzSAT mission, and was structured into four key stages: analyzing the environmental monitoring scenario in the Amazon, identifying and analyzing stakeholders, defining mission goals and objectives, and estimating potential system configurations. The scenario analysis involved a comprehensive evaluation of the primary entities responsible for monitoring the Amazon, their data requirements, and relevant data suppliers. A subsequent feasibility analysis of the proposed configurations led to the identification of a constellation of nanosatellites with segmented missions and the definition of operational concepts and system interfaces. This structured framework serves as a guide for the ongoing development of the project, providing a solid foundation for the subsequent phases of the FritzSAT mission, which aims to enhance the autonomy and effectiveness of environmental monitoring efforts in the Brazilian Amazon.

*Corresponding author:damylle.donati@gmail.com

1 Introduction

The deployment of satellites has been a crucial factor in the advancement of environmental monitoring, particularly in regions with high ecological significance, such as the Amazon. Notable satellite systems such as the Landsat series [1] [2] [3] [4], Sentinel-2, and MODIS [5] [6] [7] have played a pivotal role in providing high-resolution imagery and crucial data for hydrological studies, deforestation monitoring, and forest fire detection. To illustrate, the long-term time series data provided by Landsat has been invaluable in monitoring deforestation trends, while the multispectral imaging capabilities of Sentinel-2 [7] have facilitated the assessment of vegetation health. Similarly, the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites has enabled the detection of active fires, providing near-real-time information that is crucial for disaster response. Notwithstanding the invaluable contributions of these large satellite systems, they frequently encounter challenges pertaining to revisit times, spatial resolution, and the capacity to capture localized, rapidly changing events.

The advent of nanosatellite constellations, driven by the new space movement, offers a transformative approach to overcoming these limitations. The deployment of numerous, cost-effective satellites allows for more frequent and targeted monitoring of specific regions [8] [9] [10] [11] [12]. Private sector initiatives are at the vanguard of this innovation, propelling the frontiers of what is feasible in environmental surveillance. The FritzSAT project, inspired by this new space paradigm, proposes a constellation of nanosatellites dedicated to addressing critical environmental monitoring needs in the Amazon.

The FritzSat Project is defined as a hypothetical space mission to monitor the Brazilian Amazon territory. The project is motivated by the training of human resources at the Laboratory of Applications and Research in Space (LARS) of the Federal University of Santa Catarina, Joinville campus (UFSC-CTJ) in relation to the mission design process and space systems engineering. It envisages the eventual contracting of the laboratory to build a design solution for environmental data acquisition for post-processing resale. The objective of this work is to delineate the phases of systems engineering that have been undertaken in order to define the mission, objectives, requirements, and principal systems that comprise the project.

The project was devised in response to the need for an effective monitoring system for the Brazilian Amazon territory. It was initiated with a comprehensive survey of the current monitoring landscape, encompassing the prevailing methodologies, data requirements, equipment requirements, and data suppliers. In light of this understanding, two principal conclusions informed the design of the mission: the gap to be filled and the mission constraints directly associated with the scenario.

2 Scenario Analysis

2.1 Deforestation monitoring

Monitoring deforestation in Brazil is essential for preserving its diverse biomes—Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampas—amid pressures from agriculture, livestock farming, and logging. Satellite technologies, such as PRODES, DETER, and TerraClass [13], are critical tools for tracking land use, deforestation, and vegetation regeneration. By utilizing high-resolution images from satellites like Landsat, CBERS, and Sentinel, these systems assess environmental impacts and identify illegal activities. Despite this, challenges such as cloud cover and resolution limits can hinder image clarity. To improve accuracy, additional tools like high-resolution satellites, drones, and LIDAR systems are employed, and continuous temporal analysis helps uncover seasonal patterns.

2.2 Fire monitoring

Monitoring forest fires in Brazil is crucial for safeguarding vulnerable biomes like the Amazon, Cerrado, and Pantanal, which are prone to both natural and human-induced fires, such as those caused by agricultural burning. This monitoring relies on advanced technologies, including satellites, thermal sensors, unmanned aerial vehicles (UAVs), and real-time alert systems. The National Institute for Space Research (INPE) is central to this effort, employing systems like QUEIMADAS and INPE Fire [13] to deliver detailed information on hotspot locations and fire intensity.

The data collected covers hotspot locations, flame intensity, affected area, and meteorological conditions—such as temperature, humidity, and wind speed—that influence fire spread. Satellite images from the Terra and Aqua satellites, equipped with the MODIS sensor, are crucial for tracking large-scale fires, with updates ranging from a few hours to a few days for near real-time monitoring. High-resolution systems like GOES offer continuous surveillance of risk areas. Challenges include cloud cover obstructing fire detection and the need for rapid response, especially during droughts. To enhance accuracy, drones with thermal cameras and LIDAR systems can map burnt areas and assess damage. Integrating meteorological data and fire propagation models is essential for predicting fire behavior and guiding firefighting efforts. Continuous analysis and coordination are key to effective monitoring and response.

2.3 Hydrological monitoring

Hydrological monitoring in Brazil is crucial for maintaining ecosystem health and ensuring the availability of water resources for consumption, irrigation, and energy production. Given the country's numerous river basins, including the Amazon, São Francisco, and Paraná, precise tracking of rivers, lakes, and reservoirs is essential for predicting floods and droughts and maintaining water quality. This monitoring employs a range of technologies, such as hydrometric stations, water level sensors, satellite imagery, and mathematical models, with the National Water and Sanitation Agency (ANA) and the National Institute for Space Research (INPE) playing key roles.

The monitored data includes river levels, flow rates, rainfall, evaporation, water quality, and soil moisture. Hydrometric stations provide real-time or periodic measurements, while water level sensors, rain gauges, and quality probes contribute essential data. Satellites like Sentinel-1 and Landsat offer radar and optical imagery that help analyze flooded areas, track changes in water surfaces, and detect hydrological anomalies. This data is integrated into geographic information systems (GIS) and hydrological models to forecast extreme events such as floods and droughts. Nonetheless, challenges include difficulties in accessing remote areas, maintaining equipment, and the limitations of data resolution for capturing short-duration or small-scale events. The increasing use of drones, remote sensors, and Internet of Things (IoT) technologies is helping to address these issues.

2.4 Scenario's constraints and possible payloads

The implementation of environmental monitoring in Brazil is constrained by a number of technical limitations, which can be quantified in terms of cloud cover, spatial resolution, and satellite revisit time. Cloud cover in the Amazon, for instance, can reach up to 80% during the rainy season [13], which significantly constrains the acquisition of clear images, particularly in regions where continuous monitoring is crucial. To address this issue, satellites equipped with radar sensors, such as Sentinel-1, which can penetrate cloud cover, are employed. However, these satellites offer a spatial resolution that can range between 5 and 20 meters [7]. While this resolution is sufficient for the detection of large-scale deforestation or fires, it may prove inadequate for the identification of smaller events or subtle changes in the landscape.

Moreover, the spatial resolution of the most commonly utilized optical satellites, such as Landsat and CBERS, ranges from 10 to 30 meters, enabling the detection of extensive affected regions but potentially lacking the capacity to capture finer details. Furthermore, the revisit time of the satellites, defined as the interval between consecutive passes over the same area, represents another significant limitation. Concerning Landsat, the revisit time is 16 days, whereas Sentinel-2 [7] has a revisit time of approximately 5 days. This interval may prove inadequate for the rapid detection of changes or the prompt response to rapidly evolving events such as forest fires or flash floods. To circumvent this limitation, the integration of data from multiple satellites and the deployment of complementary technologies, such as drones with high temporal and spatial resolution, are becoming increasingly crucial to ensure effective and responsive monitoring.

To efficiently monitor deforestation, forest fires and hydrological conditions, a mission must be equipped with the following types of sensors and instruments:

1. High-resolution optical camera: Capture detailed images of the Earth's surface for monitoring deforestation, flooded areas, and identifying changes in the landscape. Resolution: 10 to 30 meters, or better;

2. Synthetic Aperture Radar (SAR) sensor: Capturing images through clouds and in low light conditions, essential for monitoring in tropical areas and at night. Resolution: 5 to 20 meters;

3. Thermal sensor: Detects hotspots, allowing identification of forest fires and areas with anomalous temperatures. Resolution: 100 meters or less, with high thermal sensitivity;

4. Multispectral radiometer: Collects data in multiple bands of the electromagnetic spectrum to analyze vegetation, water quality and detect environmental changes. Spectrum: Visible, near infrared (NIR) and mid infrared (MIR);

5. Spatial rain gauge: Precipitation measurement, crucial for monitoring the hydrolog-

ical cycle and predicting floods. Technology: Precipitation radar and microwave radiometry;

6. Radar altimeter: Precise measurement of the elevation of the water surface in rivers and lakes, for hydrological monitoring. Vertical resolution: Centimeter;

7. Imaging spectroradiometer: Detailed analysis of water quality and detection of pollutants or nutrients in water bodies. Spectrum: Includes ultraviolet (UV) and mid-infrared (MIR) bands;

8. GNSS (Global Navigation Satellite System) receiver: Provides precise location data, necessary for georeferencing observations and correcting altimetric data;

9. Real-time data communication system: Immediate transmission of data to ground stations, crucial for monitoring and rapid response to forest fires and floods;

10. On-board processing unit: Preliminary processing of collected data, including image compression and real-time anomaly detection, to optimize the use of bandwidth and speed up the transmission of relevant data;

11. Power Supply subsystem: CubeSats with demanding payloads typically require 10-20% of their total volume and weight for power systems (solar panels, batteries, regulators).

To facilitate a comprehensive understanding of satellite equipment requirements, two tables are presented. Tab. 1 provides a comparative analysis of various camera models utilized in satellite applications. This table details the resolution, volume, and mass of different camera types, ranging from high-resolution models such as the WorldView-3 to compact miniaturized CubeSat cameras. The comparison elucidates the trade-offs between high-resolution imaging capabilities and the constraints of size and weight, which are critical for selecting suitable cameras for satellite missions.

In addition, Tab. 2 summarizes the mass, volume, and CubeSat Units (U) required for each type of satellite equipment, including optical cameras, radar sensors, thermal sensors, and other essential components. This table provides a total for the combined payload, offering insights into the overall space and weight requirements necessary for accommodating all instruments on a satellite.

Given the constraints outlined in the tables, it becomes evident that a single spaceborne system encompassing all required functions is not feasible due to its substantial size and the corresponding financial investment. The integration of diverse instruments—such as high-resolution optical cameras, radar sensors, thermal sensors, and other critical components—within a single satellite exceeds the typical size and weight limits of current satellite platforms. Consequently, at this stage of the project, a strategic decision must be made between two primary options: reducing the number of functions to fit within a single satellite or disaggregating the system into multiple smaller satellites.

Alternatively, the project could consider leveraging existing legacy systems that already cover some of the required functions, thereby reducing the need for a fully integrated new system. Another approach could involve integrating satellite platforms with other remote sensing technologies such as Data Collection Plataforms (DCPs) or Unmanned Aerial Ve-

Table 1: Comparison of camera models for satellite applications

Camera Model	Resolution	Volume (m^3)	Mass (kg)	Suitability
WorldView-3	31 cm (panchromatic), 1.24 m (multispectral)	0.5	150	High resolution but large
Landsat-8 OLI	30 m (multispectral), 15 m (panchromatic)	0.3	50	Good resolution, relatively compact
Miniaturized CubeSat Camera	Up to 3 m	0.05	10-20	Compact and suitable for CubeSats

Table 2: Comparison of satellite equipments

Equipment	Mass (kg)	Volume (m^3)	Number of U
High-resolution optical camera	50	0.2	200
Synthetic Aperture Radar (SAR) sensor	150	0.4	400
Thermal sensor	30	0.1	100
Multispectral radiometer	40	0.15	150
Spaceborne rain gauge	100	0.3	300
Radar altimeter	50	0.15	150
Imaging spectroradiometer	60	0.2	200
GNSS receiver	10	0.05	50
Real-time data communication system	20	0.1	100
Onboard processing unit	25	0.08	80
Power supply subsystem	75	0.15	150
Total	**673**	**1.73**	**1780**

hicles (UAVs), which could provide complementary data and enhance the overall system capabilities. Additionally, combining multiple smaller satellites in a constellation, each focused on specific functions, could offer a modular and scalable solution. Each of these alternatives presents distinct advantages and challenges related to cost, integration complexity, and mission objectives, requiring careful evaluation to align with the project's overall goals.

In order to gain insight into the present situation and the underlying dynamics, it is crucial to identify the key stakeholders who exert influence and are affected by these circumstances. A stakeholder analysis provides a comprehensive examination of the interactions and interests of the parties involved, elucidating their respective functions, motivations, and roles in the development and implementation of the discussed strategies. This understanding is fundamental to ensuring that the proposed actions are aligned with the expectations and needs of the different groups, thereby guaranteeing the effectiveness of the initiatives and minimizing potential conflicts.

3 Stakeholders' Analysis

A stakeholder is defined as an actor who participates in a project and holds a vested interest in its outcome. In other words, they have expectations and needs related to the results obtained from the implementation of the project in question. Stakeholders may include direct and third-party suppliers, contracting clients or end users, as well as consultants and service providers whose work has an impact on the development of the project.

In the context of the FritzSat mission, it is postulated that UFSC, via LARS, will be contracted to develop an imaging data acquisition mission with the objective of monitoring the Brazilian Amazon territory. The project is predicated on the interest of a private company in reselling environmental data to prospective users/customers of the company, subsequent to the processing and treatment of the data packages obtained by the systems. The Brazillian government has been incorporated into the project as a regulator and a source of financial support, given that the majority of funding is anticipated to originate from calls for proposals issued by the Brazilian government's Ministry of Science, Technology and Information (MCTI). Figure 1 illustrates the connections and the principal interests and products provided by these key stakeholders in the form of a rich picture.

While the primary interest of secondary customers is in the final mission data, the contracting company also places importance on the training of human resources to enable the independent operation of the space system following the conclusion of the project. The University of Santa Catarina (UFSC) is identified as a supplier, contributing to the advancement of space research, technology, and innovation through the training of students and educators, as well as the promotion of local industrial growth. The Brazilian government serves as a facilitator and regulator, ensuring compliance with established guidelines and standards. The National Institute for Space Research (INPE) comprises two divisions: one responsible for qualification testing and the other for operating a possible Ground Station for communication and control of space missions. Private companies act as customers, interested in developing their own acquisition systems and utilizing imaging data for commercial purposes. Their involvement stimulates economic growth and innovation in the space sector.

The primary financial supporters of the mission are the Ministry of Science, Technology, and Innovation (MCTI) and other government entities, which provide crucial backing for the advancement of national technology. Additionally, the objective is to utilize media projection as a means of showcasing the country's technological achievements. Government funding is of critical importance in enabling long-term research and large-scale projects, thus ensuring the sustainability of space initiatives.

The ultimate beneficiaries of the mission are the secondary customers and users who utilize the data and images obtained. Such data is employed in a variety of applications, including border monitoring, vegetation analysis, terrain assessment, and meteorology. The availability of both processed and unprocessed data allows for a wide range of potential applications, including academic research, commercial endeavors, and government initiatives. It is of the utmost importance that the needs of these beneficiaries are met in order to ensure the success of the mission and the practical significance of the technologies developed.

4 Goals and Objectives

Table 3 details the objectives and goals of a mission focused on imaging, highlighting various aspects of environmental monitoring and technological development in Brazil. The goals and objectives are divided into four main categories, each with a specific focus ranging

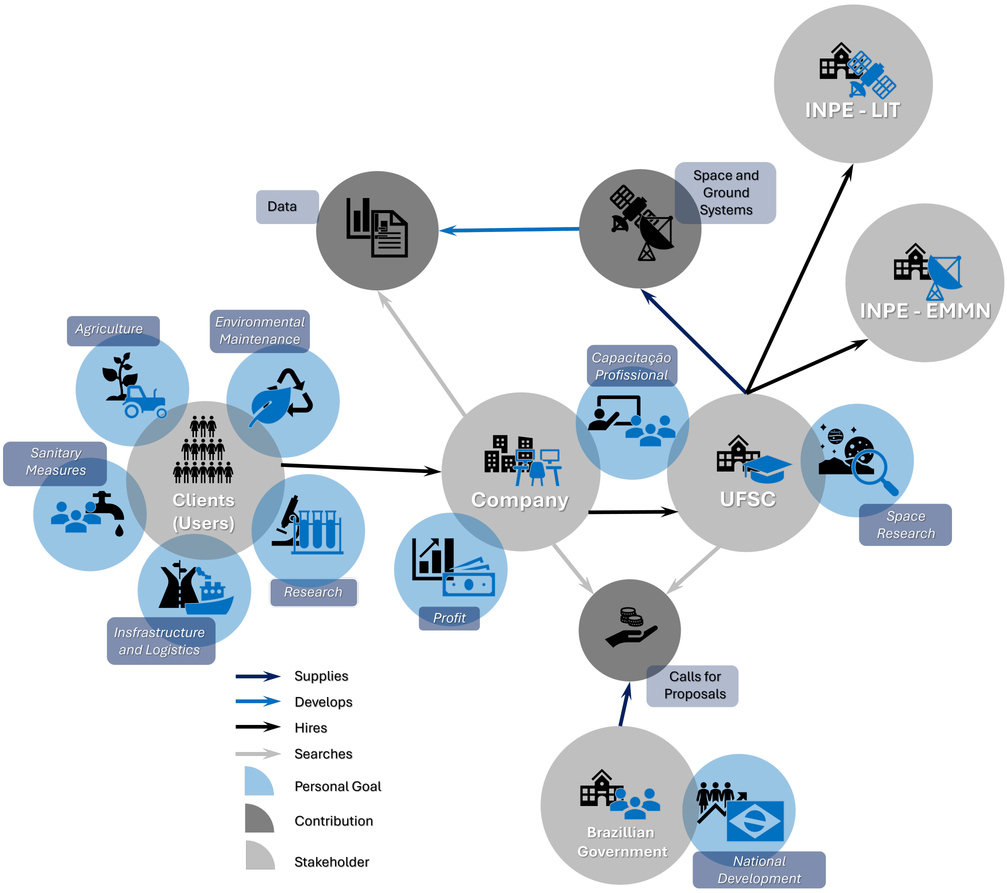

Figure 1: The primary stakeholders involved in the project and the nature of their connections.

from data acquisition to national technology development.

The first goal focuses on obtaining critical data to monitor the Brazilian Amazon. The associated objectives include acquiring data necessary for identifying deforestation, fires, monitoring livestock, vegetation, and water resources in the Amazon region.

The second goal is aimed at developing legacy documentation, with a specific objective: to develop a methodology for adapting systems engineering standards for space projects to nanosatellite projects. This objective is crucial to ensure that established knowledge and practices in the space sector can be applied and adjusted to the needs and specifics of nanosatellites. Such adaptation is essential to ensure the effectiveness and sustainability of future missions utilizing this miniature technology, ensuring compliance with quality and safety standards.

The third goal addresses the development of nanosatellite imaging technology in Brazil. Objectives include providing data access to the client, training company staff, and developing national technology in accordance with the

PNAE. This set of objectives emphasizes the importance of not only creating the technology but also ensuring that end-users can utilize it effectively and that national technical capacity is enhanced through training. Alignment with the PNAE indicates a commitment to national strategic guidelines and goals for the space sector.

The fourth goal is similar to the first but focuses on the Santa Catarina territory. Objectives include acquiring data to identify deforestation, fires, monitoring livestock, vegetation, and water resources in the Santa Catarina region. The geographical specificity of this goal highlights the importance of monitoring different biomes and regions of Brazil, recognizing that each area has its own environmental needs and challenges. Expanding the mission to other territories enhances the client's portfolio but adds complexity to mission development, and for this reason, it is considered a **secondary goal**.

4.1 Feasibility Analysis of the Space Mission

In evaluating the feasibility of the proposed space mission with a focus on cost-efficiency and data autonomy, it is essential to explore various approaches, including the use of existing systems, a mix of existing and newly developed systems, large satellites, and constellations of nanosatellites. Each approach presents unique advantages and challenges that impact both cost and the ability to manage and utilize data independently.

1. **Utilization of Existing Systems:** One approach is to rely entirely on existing systems, such as legacy satellites and ground-based infrastructure, to achieve the mission objectives. This approach can significantly reduce development and operational costs, as it leverages proven technologies and infrastructure. Since the mission's primary goal is to acquire and utilize data, utilizing these pre-existing systems can be efficient if they meet the required specifications for data acquisition and processing. However, this approach may be limited by the availability and suitability of these systems, potentially necessitating compromises in mission capabilities or data quality.

2. **Combination of Existing and Newly Developed Systems:** Another viable approach involves a hybrid solution, integrating both existing systems and newly developed technologies. This strategy allows for leveraging the cost advantages and reliability of existing systems while incorporating new technologies to address specific mission requirements that current systems may not fulfill. For instance, existing satellites could handle broad data collection tasks, while newly developed nanosatellites or advanced payloads could address specialized needs such as high-resolution imaging or specific data types. This mix can provide a balance between cost savings and enhanced mission capabilities but requires careful coordination to ensure compatibility and integration between different systems.

3. **Large Satellites:** Deploying large, high-capability satellites is an alternative that offers extensive data acquisition and processing capabilities. Large satellites typically provide higher resolution sensors and greater onboard processing power, which

Table 3: Mission Goals (G) and Objectives (O)

Goal	Objective
G.1: Acquire imaging data of the Brazilian Amazon	O.1.1: Acquisition of data required for deforestation identification in the Amazon region O.1.2: Acquisition of data required for fire detection in the Amazon region O.1.3: Acquisition of data required for livestock monitoring in the Amazon region O.1.4: Acquisition of data required for vegetation monitoring in the Amazon region O.1.5: Acquisition of data required for hydrological monitoring in the Amazon region
G.2: Develop legacy documentation	O.2.1: Develop methodology for adapting systems engineering standards for space projects to nanosatellite projects
G.3: Develop national nanosatellite imaging technology	O.3.1: Provide data access to the client O.3.2: Staff training O.3.3: Development of national technology according to the PNAE
G.4: Acquire imaging data of the Santa Catarina territory	O.4.1: Acquisition of data required for deforestation identification in the Santa Catarina region O.4.2: Acquisition of data required for fire detection in the Santa Catarina region O.4.3: Acquisition of data required for livestock monitoring in the Santa Catarina region O.4.4: Acquisition of data required for vegetation monitoring in the Santa Catarina region O.4.5: Acquisition of data required for hydrological monitoring in the Santa Catarina region

can enhance data quality and reduce the need for extensive ground-based processing. However, the high cost of development, launch, and maintenance associated with large satellites can be a significant drawback. The financial burden of such an approach may be prohibitive, especially if budget constraints are a major concern.

4. **Constellation of Nanosatellites:** Using a constellation of nanosatellites presents a cost-effective and flexible solution. Nanosatellites are smaller, lighter, and less expensive to build and launch compared to large satellites. Deploying multiple nanosatellites in a constellation allows for a distributed approach to data acquisition, providing broader coverage and more frequent revisits to target areas. This approach can enhance data collection efficiency and resilience, as the failure of a single satellite does not critically impact the mission. However, managing a constellation involves complexity in terms of coordination, data integration, and ensuring consistent communication between satellites. Additionally, the initial setup cost for a constellation may still be substantial, though it generally remains lower than that of a large satellite mission.

The evaluation of these approaches involves two primary metrics: cost-efficiency and data autonomy. Cost-efficiency refers to the overall financial investment required for development, launch, and operation. In contrast, data autonomy assesses the ability of the system to independently acquire, process, and utilize data without excessive reliance on external support.

- **Cost-Efficiency:** Utilizing existing systems provides the lowest cost but may limit mission capabilities. A hybrid approach balances cost and functionality but requires integration efforts. Large satellites, while offering high capabilities, entail high costs. Nanosatellite constellations offer a scalable and cost-effective solution but introduce management complexities.
- **Data Autonomy:** Large satellites and well-integrated existing systems can provide high data autonomy with advanced onboard processing capabilities. Nanosatellite constellations, with their distributed approach, enhance data acquisition frequency and coverage, supporting effective data autonomy if managed well. Hybrid solutions can also offer enhanced autonomy by combining the strengths of existing and new technologies.

In conclusion, the feasibility of the mission, focusing on low cost and data autonomy, is best supported by a constellation of nanosatellites or a hybrid approach that incorporates existing systems with new technologies. These strategies offer a balance of cost-efficiency and operational capability, aligning well with the mission's goals of acquiring and utilizing data independently.

5 Missions Definition

The findings from the preceding study have concluded that a constellation of nanosatellites offers the most effective configuration for achieving the mission objectives. This approach enables specialized focus and enhanced data collection capabilities for distinct environmental monitoring tasks. Consequently, three distinct missions have been defined within the FritzSAT project: FritzSat Ycatu for hydrological monitoring, FritzSat Tatá for forest fire monitoring, and FritzSat Yby for deforestation monitoring. Each nanosatellite within this constellation is equipped with a primary payload tailored to its specific mission. FritzSat Ycatu is outfitted with a Synthetic Aperture Radar (SAR) to capture detailed hydrological data. FritzSat Tatá features a thermal infrared sensor to detect and monitor forest fire hotspots, while FritzSat Yby is equipped with a multispectral camera to assess changes in vegetation and forest cover. This strategic payload allocation ensures that each mission effectively addresses its targeted environmental issue.

Building upon the mission definitions, the subsequent sections will elaborate on the essential system interfaces and operational concepts (ConOps) that underpin the successful execution of the FritzSAT missions. The interface section will detail the interactions between each nanosatellite and its respective monitoring scenario, as well as the communication protocols with ground systems. Additionally, the ConOps section will outline the operational strategies and procedures for each mission, ensuring that the payloads operate effectively and the mission objectives are achieved. These sections provide a comprehensive framework for understanding how the nanosatellites will function and interact throughout their lifecycle.

5.1 Interfaces

The interfaces of the systems that comprise the space mission must be defined to understand their relationships and identify the requirements for effective communication. From the perspective of the components:

- **FritzSat Ycatu - Hydrological Monitoring Mission**
  - **Space System $\rightleftharpoons$ Monitoring Scenario:**
    - **Primary Payload:** Synthetic Aperture Radar (SAR)
    - **Data Types:** Radar images capturing soil moisture, water levels, and flood areas.
    - **Transmission Mechanisms:** SAR data is processed onboard to extract key hydrological indicators, reducing the data volume before transmission.
    - **Transmission Requirements:** Data is transmitted via X-band for high-rate downlink to ensure timely delivery to ground stations. UHF/VHF links are used for telemetry and command operations.
  - **Space System $\rightleftharpoons$ Ground System:**
    - **Data Types:** Processed radar images and telemetry data.
    - **Transmission Mechanisms:** Data is transmitted using X-band for radar images and UHF/VHF for telemetry and control. Ground stations receive the data and integrate it into hydrological models.
    - **Transmission Requirements:** Reliable and continuous communication to ensure real-time monitoring and immediate analysis of hydrological events.

- **FritzSat Yby - Deforestation Monitoring Mission**
  - **Space System ⇌ Monitoring Scenario:**
    - **Primary Payload:** Multispectral Camera
    - **Data Types:** Multispectral images capturing vegetation indices and forest cover changes.
    - **Transmission Mechanisms:** Onboard processing to detect changes in vegetation indices and reduce data volume.
    - **Transmission Requirements:** Data is transmitted via S-band or X-band, with a focus on maintaining high image quality and frequent updates.
  - **Space System ⇌ Ground System:**
    - **Data Types:** Multispectral images and telemetry data.
    - **Transmission Mechanisms:** Data is transmitted using S-band or X-band for multispectral images and UHF/VHF for telemetry and control. Ground stations analyze the data to assess deforestation rates.
    - **Transmission Requirements:** High-frequency data transmission to ensure continuous monitoring and rapid detection of deforestation activities.
- **FritzSat Tatá - Forest Fire Monitoring Mission**
  - **Space System ⇌ Monitoring Scenario:**
    - **Primary Payload:** Thermal Sensor (Infrared)
    - **Data Types:** Thermal images capturing fire hotspots and temperature anomalies.
    - **Transmission Mechanisms:** Onboard processing prioritizes data associated with detected fire events for immediate transmission.
    - **Transmission Requirements:** Low-latency transmission via X-band to ensure rapid response capabilities. UHF/VHF links are used for telemetry and control.
  - **Space System ⇌ Ground System:**
    - **Data Types:** High-resolution thermal images and telemetry data.
    - **Transmission Mechanisms:** Data is transmitted using X-band for thermal images and UHF/VHF for telemetry and control. Ground stations use this data to generate real-time alerts for firefighting teams.
    - **Transmission Requirements:** Ultra-low latency and high reliability to support immediate detection and response to forest fire events.

5.2 Concepts of Operation

Concepts of Operation (ConOps) are structured narratives that describe how a system, such as a nanosatellite mission, will be employed to meet its objectives. ConOps provide a detailed understanding of the mission from the perspective of end-users and stakeholders, outlining how the system will function throughout its lifecycle. The application and understanding of ConOps are crucial because they ensure that all parties involved have a shared vision of the system's goals, operational scenarios, and constraints. This shared understanding is essential for aligning the technical design with the mission's intended purpose, facilitating effective communication, and supporting decision-making processes across the project lifecycle.

- **FritzSat Ycatu - Hydrological Monitoring Mission**
  - **Objective:** To monitor hydrological variables such as soil moisture, water levels, and flood areas using Synthetic Aperture Radar (SAR).
  - **Operation Concept:**
    - **Data Collection:** The SAR payload operates in a specific mode (broadband or narrowband) depending on the monitoring objective, capturing radar images of the Earth's surface.
    - **Data Processing:** Onboard processing is conducted to reduce raw data volume, focusing on extracting key hydrological indicators before transmitting to the ground.
    - **Data Transmission:** Processed data is transmitted via X-band to ground stations, with UHF/VHF links used for telemetry and control.
    - **Data Analysis:** Ground stations receive the data, which is further analyzed and integrated into hydrological models, providing real-time insights into water levels, soil moisture, and potential flood zones.
- **FritzSat Yby - Deforestation Monitoring Mission**
  - **Objective:** To monitor changes in forest cover and detect deforestation activities using a Multispectral Camera.
  - **Operation Concept:**
    - **Data Collection:** The multispectral camera captures images in various bands (visible, NIR, SWIR) at regular intervals, allowing for continuous monitoring of forested areas.
    - **Data Processing:** Onboard processing reduces the data load by focusing on detecting changes in vegetation indices, which are critical for identifying deforestation.
    - **Data Transmission:** Multispectral images, along with metadata, are transmitted to ground stations using S-band or X-band communication links.
    - **Data Analysis:** Ground stations analyze the data to assess changes in forest cover, providing actionable intelligence for environmental protection agencies and policymakers.

- **FritzSat Tatá - Forest Fire Monitoring Mission**
  - **Objective:** To detect and monitor wildfires using a Thermal Sensor (Infrared).
  - **Operation Concept:**
    * **Data Collection:** The thermal sensor continuously scans for infrared radiation indicative of fire hotspots, with a focus on rapid detection of temperature anomalies.
    * **Data Processing:** Onboard processing includes automatic identification of potential fire events, prioritizing data for immediate transmission.
    * **Data Transmission:** High-resolution thermal data is transmitted via X-band, with a priority on low latency to enable real-time response. UHF/VHF links are used for telemetry and control.
    * **Data Analysis:** Ground stations receive and process the data, generating alerts for firefighting teams and providing real-time maps of active fire zones.
- **Joint Operation Concept (Constellation-Wide)**
  - **Objective:** To maximize the overall effectiveness of the constellation in monitoring the Brazilian Amazon across multiple domains (hydrological, deforestation, and fire monitoring) without inter-satellite communication.
  - **Operation Concept:**
    * **Data Collection:** Each satellite operates independently, collecting data specific to its mission (SAR, multispectral, or thermal).
    * **Data Scheduling:** Ground stations manage data collection schedules for each satellite, ensuring coverage optimization across different monitoring needs.
    * **Data Transmission:** Each satellite transmits its data to the ground independently, with scheduling to avoid conflicts and ensure that all data is captured and processed in a timely manner.
    * **Data Integration:** Ground stations integrate data from all satellites, providing a comprehensive view of environmental conditions across the Amazon, which is then shared with relevant stakeholders.
- **General Operation Concept (Lifecycle of the Constellation)**
  - **Conception:** Initial assessment of environmental monitoring needs, leading to the decision to deploy a nanosatellite constellation focusing on hydrological monitoring, deforestation, and fire detection.
  - **Design:** Detailed design of the satellites, including payload selec-

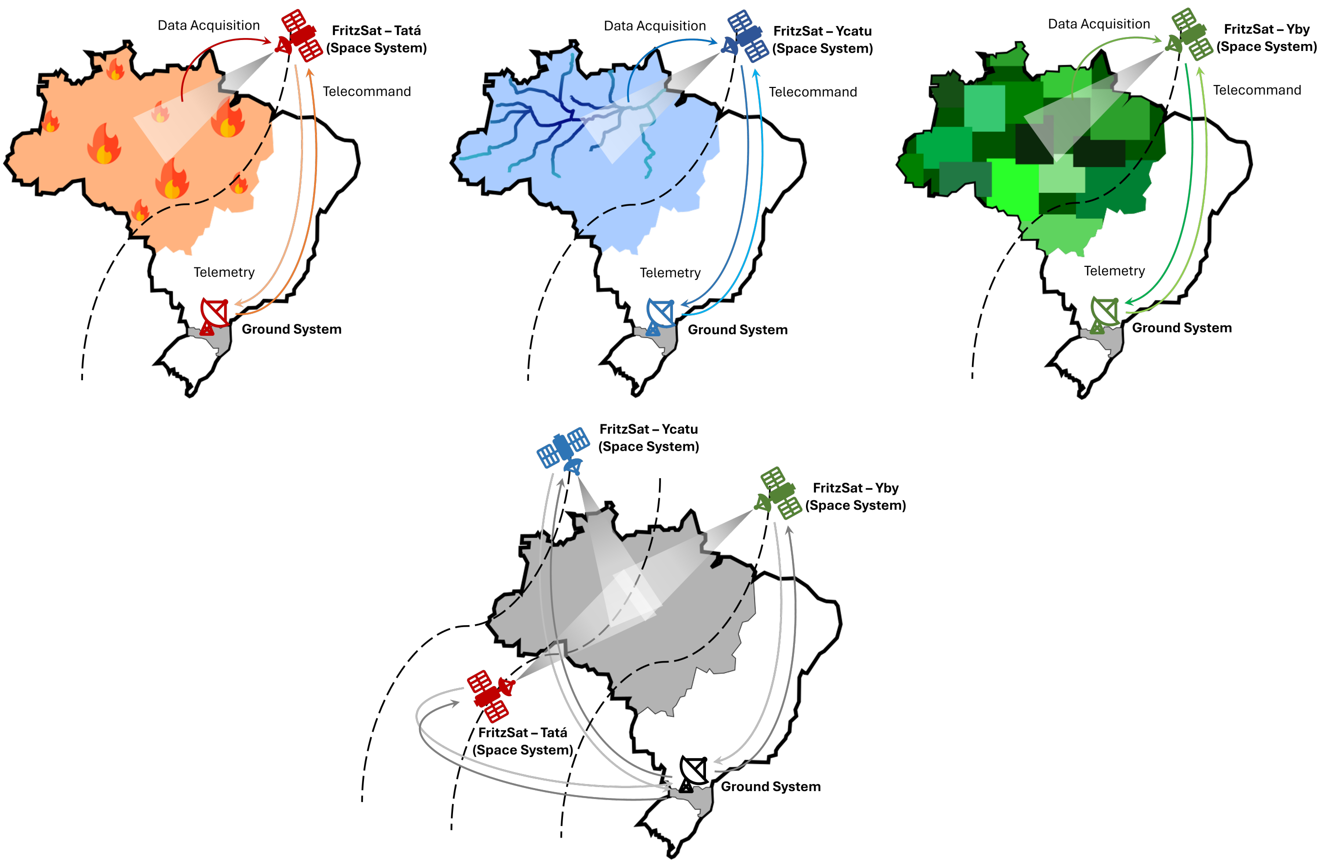

Figure 2: Concepts of operation for the three main missions (above) and the general concept of operation (below).

tion (SAR, multispectral camera, thermal sensor) and system interfaces. Mission concepts and data requirements are established during this phase.

- **Manufacturing:** Construction and testing of the nanosatellites, ensuring that each meets the specifications necessary for its intended mission. This phase includes payload integration and system validation.
- **Launch:** Deployment of the constellation into orbit, ensuring that each satellite reaches its designated position. Launch procedures include final system checks and initial calibration.
- **Commissioning:** Post-launch testing and calibration of each satellite, including payload operation and data transmission validation. Ground stations begin receiving and analyzing initial data.
- **Operation:** The constellation enters full operation, with each satellite carrying out its mission as

planned. Ground stations manage the schedule and integrate data from all satellites to provide continuous monitoring.

– **Decommissioning and Disposal:** At the end of the mission's life, satellites are decommissioned. Procedures are followed to ensure safe disposal, minimizing space debris and ensuring compliance with international guidelines.

Figure 2 provides a graphical approach to better understand the operation concepts described above.

6 Conclusion

The FritzSAT nanosatellite missions, which include FritzSat Ycatu for hydrological monitoring, FritzSat Yby for deforestation monitoring, and FritzSat Tatá for forest fire monitoring, represent a significant advancement in autonomous environmental observation. This study provides a comprehensive account of the mission development process, from the initial analysis of the Amazon's monitoring requirements to the integration of specialized payloads and the formulation of comprehensive operational concepts. The missions are designed to address gaps in current monitoring capabilities, thereby enhancing the autonomy of data acquisition, particularly for private entities.

The study emphasized the necessity of establishing unambiguous system interfaces between the space systems and both the monitoring scenario and ground systems. The selected payloads—a synthetic aperture radar (SAR), a multispectral camera, and a thermal sensor—were chosen based on their capacity to fulfill specific mission objectives. A comprehensive operational concept was devised, encompassing data types, transmission mechanisms, and requirements, to guarantee effective communication and data utilization throughout the mission lifecycle.

In conclusion, the FritzSAT missions offer a robust framework for enhancing environmental monitoring in the Amazon. The comprehensive approach to system design, stakeholder analysis, and mission planning ensures that these nanosatellites will make a significant contribution to addressing critical environmental issues. The insights derived from this study will inform the various stages of the missions, thereby facilitating the sustainable management and expeditious response to environmental changes.

References

[1] A. Bocharov, A. G. Kostianoy, and S. A. Lebedev, "Assessment of the accuracy of determining the caspian sea surface temperature by landsat-5, -7 satellites based on the measurements of drifters," *Ecologica Montenegrina*, 2024. [Online]. Available: https://api.semanticscholar.org/CorpusID:271563609

[2] A. Byrne, D. Lomeo, W. Owoko, C. M. Aura, K. Nyakeya, C. O. Odoli, J. Mugo, C. Barongo, J. Kiplagat, N. M. Mwirigi, S. Avery, M. A. Chadwick, K. Norris, and E. J. Tebbs, "Laqua: a landsat water quality retrieval tool for east african lakes," *Remote Sensing*, vol. 16, 2024. [Online]. Available: https://api.semanticscholar.org/CorpusID:271809574

[3] J. Chen, Y. Wang, J. Wang, Y. Zhang, Y. Xu, O. Yang, R. Zhang, J. Wang, Z. Wang, F. Lu, and Z. Hu, "The performance of landsat-8 and landsat-9 data for water body extraction based on various water indices: A comparative analysis," *Remote Sensing*, vol. 16, no. 11, 2024. [Online]. Available: https://api.semanticscholar.org/CorpusID:270196288

[4] D. T. Gök, D. Scherler, H. Wulf, and D. T. Gök, "Land surface temperature trends derived from landsat imagery in the swiss alps," *EGUsphere*, vol. 2024, pp. 1–29, 2024. [Online]. Available: https://egusphere.copernicus.org/preprints/2024/egusphere-2024-1228/

[5] H. Talebi, S. Samadianfard, and H. Çıtakoğlu, "Estimating reference evapotranspiration in an arid region using a modis sensor and machine learning algorithms," *Advanced Engineering Days*, 2024.

[6] F. Jalal and A. S. Mahdi, "Detection of dust storms using modis reflection mode," *Iraqi Journal of Science*, 2024.

[7] Z. Faraji, A. Kaviani, and L. Khosravi, "Downscaling the modis land surface temperature using a trapezoidal concept applied to the modis and sentinel 2 images," *Environmental Monitoring and Assessment*, 2024.

[8] A. Schwarzenberg-Czerny, W. Weiss, A. Moffat, R. E. Zee, S. Rucinski, S. Mochnacki, J. Matthews, M. Breger, R. Kuschnig, O. Koudelka, P. Orleanski, A. Pamyatnykh, A. Pigulski, and C. Grant, "The brite nanosatellite constellation mission," in *38th COSPAR Scientific Assembly*, 2010.

[9] A. A. Spiridonov, V. Baranova, V. A. Saetchnikov, and D. Ushakov, "The regional nanosatellite constellation modelling formation by a piggyback launch from different spaceports," *Journal of the Belarusian State University. Physics*, 2022. [Online]. Available: https://api.semanticscholar.org/CorpusID:250198254

[10] R. Rose, C. S. Ruf, and H. Seki, "Ocean altimetry and wind applications of a gnss nanosatellite constellation," in *Asia-Pacific Environmental Remote Sensing*, 2012. [Online]. Available: https://api.semanticscholar.org/CorpusID:38919388

[11] I. S. Molina, L. M. Rodríguez, D. G. Díez, M. S. Anfres, J. M. Diaz, and J. J. A. Delgado, "Mission analysis of nanosatellite constellations with opensatkit," in *4th Symposium on Space Educational Activities*, 2022. [Online]. Available: https://api.semanticscholar.org/CorpusID:251117621

[12] K. Kwapien, P. Lasota, M. Kedzierski, and P. Walczykowski, "Design and performance analysis of a constellation of nanosatellites to monitor water quality in the southern catchment of the baltic sea," *Sensors*, vol. 23, 2023. [Online]. Available: https://api.semanticscholar.org/CorpusID:259530655

[13] National Institute of Space Research (INPE), "Monitoramento da cobertura

florestal da amazônia por satélites: sistemas prodes, deter, degrad e queimadas 2007-2008," INPE, São José dos Campos, Tech. Rep., 2008. [Online]. Available: http://www.obt.inpe.br/prodes/metodologia.pdf