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Proposal and Review of a Ground Sensor Terminal (GST) Design for Environmental Data Collection and LoRa-Based CubeSat Missions

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Abstract

With the surge of CubeSats in the academic and scientific world, establishing a purpose for its mission is very important. Due to its versatility, various technologies can be embedded into these satellites to compose missions, such as cameras, sensors, or just communications modules. This paper focuses on the design of a Ground Sensor Terminal (GST) for the CubeSat store & forward mission CIMATÉLITE-1. Its main objective is to collect environmental data from crop fields and send these to the satellite. By reviewing previous projects' literature and identifying solutions, opportunities, and challenges, an insightful analysis was conducted to guide the conceptual development of the system architecture. The key components, such as sensor integration, power management, and data handling, were thoroughly evaluated to enhance the performance and reliability of the system. The framework obtained by this study will emphasize the necessary trade-offs and considerations required for a successful application in a CubeSat mission, leading to the implementation of said GST in the near future.

1 Introduction

Small satellite projects have become increasingly present in the technology world. Usually used in LEO (Low Earth Orbit), there are already more than 2,300 missions in this niche, predominantly scientific and educational [1].

Usually, these missions use a type of nanosatellite called "CubeSat", a standard for development, establishing characteristics such as size, mass, and an overall design for its structure [4]. The main reason for this model to be developed is to facilitate frequent and affordable access to space [2], without the several limitations that bigger satellite missions have. This makes it possible to carry out missions in several areas, such as meteorology, photography and space research, communication, and geolocation.

However, for CubeSats to be launched, it is first necessary to designate a mission. One example of this is to monitor regions that do not yet have access to electricity or internet on the planet. Monitoring remote locations is extremely important for mapping natural resources and conducting studies on the geographic characteristics of a given area [3], resulting in feasibility analyses of installing solar or wind power plants in the territory under study, for instance.

To monitor land in remote environments, it is essential to create a Ground Sensor Terminal (GST) to store and transmit the collected data via satellite. These platforms need to be self-sufficient and able to withstand the local climate. The data transmitted by these platforms is captured during missions and then sent to another location for analysis.

This article aims to create a self-sufficient GST for collecting environmental data from a specific location and transmitting it to a CubeSat, which will transmit the data for analysis onward. This platform will form an integral part of the CIMATÉLITE-1 mission, a Store & Forward (S&F) mission focused on studying the climate of Northeastern backlands.

The data collection focal point is to measure variables of interest for the study of crop fields at the Senai CIMATEC Sertão campus and monitor the status of local cultivations. The data can also be utilized as a way to confirm that the region is carbon-free, to create predictive meteorological models, and to observe climate changes over time.

2 Literature Review

Before developing concepts, a literature review of similar stations was carried out to identify technologies, opportunities, and learnings that may be relevant to the project.

2.1 Application of Small Satellites for Low-Cost Remote Data Using LoRa Transmitters

One of the most notable works in this sort of project was conducted by (Lepcha et al., 2021), which was associated with the BIRDS-2 Constellation. More specifically this work, the GST for the BHUTAN-1 satellite was developed, which aims to collect environmental data and transmit it to the CubeSat.

The main feature of this station resides in its low cost and robustness. Due to the use of LoRa technology and mostly low-power components, energy consumption is considerably small, and it allows the usage of smaller batteries and solar panels. Even though the system can only last for 9 hours without sunlight, the trade-off for more compact and cheaper designs is notable. Figure 1 shows the developed design.

Choosing simpler components and a more robust composition allows the GST to operate in harsher environments without depending on other infrastructures to be installed. Focusing on Off-the-Shelf products to build the GST significantly reduces manufacturing costs, making the system viable for large-scale deployment in areas without traditional communication infrastructure.

The study demonstrates that utilizing small satellites equipped with LoRa transmitters pro-

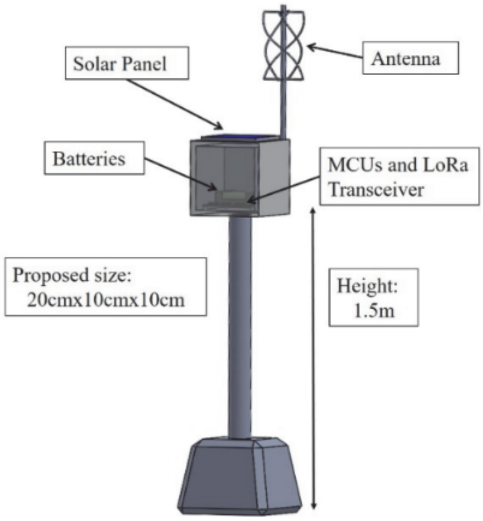

Figure 1: CAD Model of the papers station. [6]

vides an expandable and cost-effective solution for remote data collection. The report outlines areas for further improvement, including enhancing the energy system and performing long-range communication tests, laying the foundation for future advancements in satellite-based remote sensing systems.

2.2 Samanaú.PCD

Samanaú.PCD is a GST standard developed in Brazil whose premises are to build a modular, low-cost, and flexible station for environmental data collection [7]. The platform consists of an intuitive system integration, in which data is collected by a self-sustainable structure, sent by Radio-Frequency (RF) by a low-cost transmitter module, handled, and presented in a WEB platform [8].

The design of the GST can be seen in Figure 2. The structure is fairly compact, given the antenna and rain gauge stay separated from the main framework. Despite that, the platform is still adaptable to other sensors and is IOT-compatible.

Figure 2: Samanaú.PCD node system [7].

Following (Souto, 2017), bringing together all development fronts (GST, WEB, and RF) results in the Samanaú.SAT project, the combination of all those with the increment of a satellite transmitter, represents an S&F Mission.

2.3 Data Collection Platform Design using LEO Satellite-based LoRa for Disaster Management in Indonesia

Despite not being exactly environmental data, the study conducted by (Arifim, et al, 2023) aimed to design a GST for disaster management and detection. By using high-sensitive disaster sensors and detectors, and LoRa technology for satellite communication, it was proposed a data collection platform to boost disaster management in Indonesia, a country that is vulnerable to various natural disasters as a result of its geographical location and characteristics.

It proposes a communication architecture that takes advantage of the LoRa capabilities exploring two different scenarios: in urban areas, which already have more options for data uplink, and in rural areas, where satellite communication must be integrated into the GST.

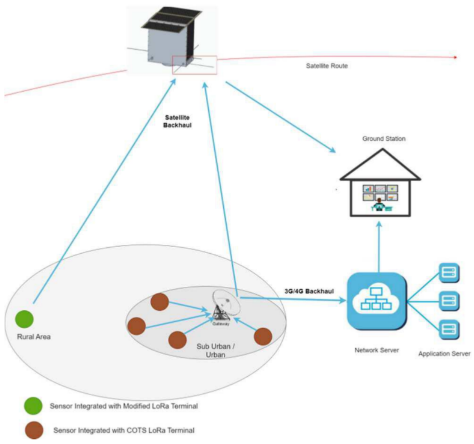

Figure 3: Communication architecture used for disaster management [10].

In this project, LoRa technology is used in uplink and local communication, highlighted in Figure 4. Urban areas take advantage of gateways, using both satellite and terrestrial backhauls to send data to a ground station. However, in rural regions, an adaptation is needed so that the data can be sent to its destination by LEO satellites since some of these areas have more restricted access to technology, electricity, and the internet.

And even for LEO communication, LoRa has proven to be an effective way to transmit data. This technology has been compelling for the CubeSat community for a while and papers such as [11] and [12] have shown its efficiency for such applications. Despite only showing simulation results, the paper analyzes the configurable LoRa transmission, searching for the one that has the best link budget at various elevation variations [9]. This characteristic is unique to this protocol and makes it noticeably adaptable to different contexts and missions.

3 Methodology

This work's methodology focuses on the conceptual development of a self-sufficient and robust Ground Sensor Terminal (GST) for environmental data collection and transmission, aligned with the CIMATÉLITE-1 mission, which aims to monitor the climate of the Northeastern backlands.

This research is an explanatory literature review and case studies of Google, Google Academic, and IEEE Xplore periodical articles. It aims to assist in choosing embedded devices to apply in Ground Sensor Terminal design for LoRa CubeSat missions and environmental data collection, performing analysis to simplify the equipment's choice.

4 Results

After studies were conducted reviewing other designs, and given the project requirements that need to be met, the design proposed to de GST follows the diagram presented in Figure 4.

The application will consist of an embedded device to process the data collected and sensors to measure data from the environment described, such as temperature, humidity, wind direction, wind speed, carbon dioxide, and rainfall sensors. The local display interface is a project requirement that will be used to display helpful data to passersby locally, like farmers who want to see the humidity of the soil, and for maintenance operators in the future.

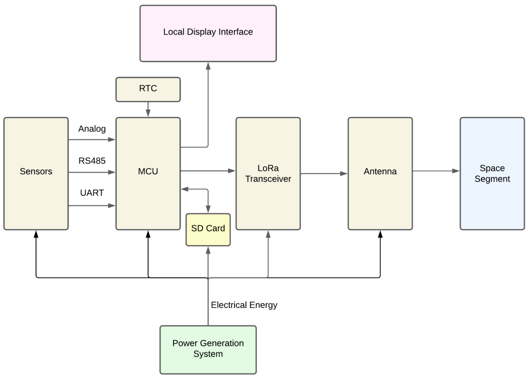

Figure 4: Diagram of proposed design.

Unfortunately, just one GST is not enough to cover a big area, and one of the requirements is to cover various crop fields in a region of approximately 600 hectares. The solution is a GST network comprised of one master GST, responsible for satellite communication, and various support GSTs, that will only collect data and send it to the master. This scenario is shown in Figure 5.

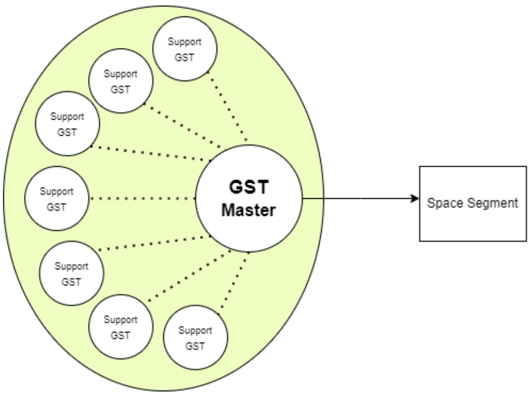

Figure 5: Diagram representing the proposed GST network.

Given this scenario, the master GST must be able to send all the data packets to the satellite. Since the communication uses LoRa technology, the radio data rate can be calculated as per Equation 1.

$$R_b = SF \cdot \frac{BW}{2^{SF}} \cdot \frac{4}{(4 + CR)} \tag{1}$$

With CIMATÉLITE-1 Mission parameters, a data rate can be obtained. The bandwidth "BW is $125kHz$, the spreading factor "SF" is 10, and the coding rate $"CR"$ is 4. This results in a data rate "R_b" of approximately 610 bits/s. As seen in Figure 6, the maximum packet size for the CIMATÉLITE-1 protocol is 256 bits, in one second the radio can send 2,4 packets to the satellite. It is noteworthy to mention that the protocol is an adaptation of the KITSUNE-1 format present in [13], with the addition of two extra bytes: One for the address of the data start register (STG ADDR), and another with the total number of registers (N of REG).

Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9	Byte 10	Byte 11	Byte 12	Byte 13	Byte 14	Byte 15
0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x01	0x00
GST ID		DATA TYPE	TIME				STG ADDR	N of REG	SENSOR DATA (6 bytes)						CHECK SUM

Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8	Byte 9	Byte 10	Byte 11	...	Byte 29	Byte 30	Byte 31
0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x01	0x00
GST ID		DATA TYPE	TIME				STG ADDR	N of REG	SENSOR DATA (22 bytes)						CHECK SUM

Figure 6: Communication Protocol for CIMATÉLITE-1 Mission.

On the other hand, the Power Generation System is composed of a solar panel, batteries, and a charge controller. The specifications of these components were obtained after a Power Budget for the system was made. The key moment where power is needed is during transmission, by powering the radio.

Aiming to lower the power consumption of the GST, two strategies were incorporated: a

10-minute work cycle and a switch activation for the radio. Figure 7 depicts how the loop will be divided. In short, for the most part, the system will be in an "Idle Mode", where the MCU will be in low-power mode and all components besides the LoRa radio will be turned off. During the "Read Mode", sensors will be turned on, making a measurement, and the data packet for the respective read will be created and stored in both the radio buffer for transmission and in an inner SD card.

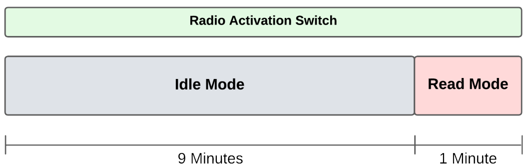

Figure 7: Cycle of the systems work schedule.

The radio activation switch is a logic created in the MCU that will make the radio emit a transmission pulse every few seconds. Since the successful transmission with the satellite can be detected by the radio module, a stack logic can be used to queue data packets and serve as a buffer.

Finally, a comparison between embedded devices and sensors will be conducted to identify the optimal solution for the application, prioritizing maximum efficiency, cost-effectiveness, and high performance. To effectively compare embedded devices, it is essential to establish clear evaluation metrics, including architecture analysis, processor speed, memory capacity, integrated peripherals, programming language compatibility, and robustness. For sensors, key parameters encompass measurement range, precision, latency, communication interface, and sensitivity.

4.1 Embedded Device

Four embedded devices were evaluated: the Arduino Uno, STM32, ESP32, and BeagleBone Black. The Arduino Uno, an 8-bit microcontroller with 16 MHz processing, 2 KB RAM, and 32 KB Flash memory, includes USART, SPI, GPIO, and I2C. It is low-cost and beginner-friendly, ideal for low-complexity projects [14].

The STM32 offers an 80 MHz 32-bit processor, 1 MB Flash, and 128 KB RAM, with I2C, Bluetooth, WiFi, USART, USB, GPIO, and SPI interfaces. Programmed in C/C++ with STMCubeIDE, it is widely used in industrial applications[15].

The ESP32, a 160 MHz dual-core processor with 520 KB internal RAM and 16 MB Flash support, has WiFi and Bluetooth and supports C/C++ and MicroPython. Known for low power consumption, it is commonly used in IoT[16].

The BeagleBone Black, with a 1 GHz ARM Cortex-A8 and 512 MB DRAM, supports Linux, Python, and C/C++, making it highly robust for advanced projects. It offers I2C, SPI, UART, USB, and Ethernet interfaces [17].

Table 1: Comparison of Microcontrollers

Device	Processor	Clock Speed	Flash Memory	RAM	Interfaces	Programming Languages
Arduino Uno	8-bit	16 MHz	32 KB	2 KB	USART, SPI, GPIO, I2C	C++
STM32	32-bit	80 MHz	1 MB	128 KB	I2C, Bluetooth, WiFi, USART, USB, GPIO, SPI	C/C++
ESP32	32-bit dual-core	160 MHz	16 MB (external)	520 KB	GPIO, SPI, I2C, I2S, UART, WiFi, Bluetooth	C/C++, MicroPython
BeagleBone Black	32-bit ARM Cortex-A8	1 GHz	4 GB	512 MB	I2C, SPI, UART, USB, Ethernet	C/C++, Python

The comparative results can be seen in table 1. Although the BeagleBone Black offers superior processing power and memory, the STM32 was chosen due to its cost-effectiveness and better applicability for the target project. The STM32 provides a balanced combination of performance, features, and flexibility, making it more suitable for the project's requirements while staying within budget constraints.

4.2 Temperature Sensor

Five temperature sensors were evaluated: the DHT11, DHT22, SEN-11050, and CS215-L.

Starting with the DHT11, it operates within a temperature range of 0°C to 50°C, providing an accuracy of ±2°C and a latency of 2 seconds. Due to its low sensitivity, it is best suited for controlled environments. In contrast, the DHT22 covers a wider range of -40°C to 80°C and offers a higher accuracy of ±1°C, with a latency of less than 5 seconds. While its sensitivity is moderate, it remains suitable for basic applications.

The SEN-11050 has a temperature range of -55°C to 125°C and an accuracy of ±0.5°C, demonstrating superior sensitivity, making it ideal for industrial monitoring. Lastly, the CS215-L, which operates between -40°C and 70°C with a latency of just 1 millisecond, boasts an accuracy of ±0.4°C. Equipped with SDI-12 communication, it is particularly well-suited for high-precision data collection in critical environments.

Table 2: Comparison of Temperature Sensors

Sensor	Temperature Range	Accuracy	Latency	Communication Interface	Sensitivity
DHT11	0°C to 50°C	±2°C	2 s	One-wire digital	Low
DHT22	-40°C to 80°C	±1°C	5 s	One-wire digital	Low
SEN-11050	-55°C to 125°C	±0.5°C	N/A	Single-wire	High
CS215-L	-40°C to 70°C	±0.4°C	1 ms	SDI-12	High

After evaluating the data above, as seen in Table 2, it is possible to identify that the sensor with the highest accuracy, sensitivity, and lowest latency is the CS215-L, all of them have ideal temperature ranges for the application, which would be between 0°C and 40°C, approximately, and the communication interface is the same in most cases, except for the CS215-L, which has a different interface.

4.3 Humidity Sensor

To collect humidity data as accurately as possible, four sensors were selected for the project: the T9501, CS215-L, DHT11, and DHT22. The T9501 sensor transmits data using the MODBUS communication protocol. It has a sensitivity of 0.01% relative humidity (RH) and offers a humidity range of 0 to 95% RH, with an accuracy of ±2.0% RH (20–80% RH) and ±3.5% RH (0–20% and 80–100%). The sensor's latency is 100 seconds, providing a rapid response when capturing data[21].

The CS215-L sensor has a sensitivity of 0.03% RH and a wider humidity range of -20°C to +60°C, with an accuracy of ±4.0% RH (0–100% RH) and ±2% RH (10–90%), with latency of 20 seconds [20]. The DHT11, with a humidity range of 20 to 80% RH and an accuracy of ±5.0% RH, has a latency of 15 seconds [18]. Lastly, the DHT22 sensor operates within a humidity range of 0 to 100% RH and provides an accuracy of ±2.0% RH, with a latency of approximately 15 seconds[18].

Table 3: Comparison of Humidity Sensors

Sensor	Communication Protocol	Sensitivity (% RH)	Humidity Range (% RH)	Accuracy (% RH)	Latency (s)
T9501	MODBUS	0.01	0 - 95	±2.0 to ±3.5	100
CS215-L	N/A	0.03	0 - 100	±2.0 to ±4.0	20
DHT11	N/A	N/A	20 - 80	±5.0	15
DHT22	N/A	N/A	0 - 100	±2.0	15

By comparing each sensor with the help of Table 3, the T9501 sensor was chosen for its exceptional accuracy and sensitivity over the others, offering 0.01% RH sensitivity and a wide humidity range of 0 to 95% RH. Its accuracy of ±2.0% RH (20–80% RH) surpasses the other options. It is also noteworthy that thanks to its robustness, often being implemented in industrial applications.

4.4 Wind Speed Sensor

To ensure precise wind speed measurement, the SEN0483, S-WSB-M003, and RXW-WCF-900 sensors were selected. The SEN0483 has a range of 0–32.4 m/s with an accuracy of ± 0.3 m/s and transmits data via the MODBUS protocol. It features high measurement accuracy, stability, low-resistance bearings, and strong anti-interference capabilities [22].

The S-WSB-M003 measures wind speeds from 0 to 76 m/s with an accuracy of $\pm 4\%$, providing fast and reliable readings due to its low latency. Sensor parameters are stored internally and automatically transmitted to the logger, minimizing the need for user configuration [23].

As for the RXW-WCF-900, with a range of 0 to 76 m/s and an accuracy of ± 1.1 m/s or $\pm 5\%$, it supports remote installation via its HOBOnet wireless interface, efficiently monitors wind speed, gusts, and direction, transmitting data to the RX3000 station or relaying it through other wireless sensors to the central station. Data is accessed via Onset's cloud-based HOBOlink platform, and the sensor is pre-configured for ease of use [24].

The main differences between these sensors are identified in Table 4.

Table 4: Comparison of Wind Speed Sensors

Sensor	Wind Speed Range	Accuracy	Communication Interface	Features
SEN0483	0 - 32.4 m/s	± 0.3 m/s	MODBUS	High accuracy, low starting wind speed, good stability
S-WSB-M003	0 - 76 m/s	$\pm 4\%$	Smart sensor (auto-config)	Reliable, fast measurements, low latency
RXW-WCF-900	0 - 76 m/s	± 1.1 m/s or $\pm 5\%$	HOBOnet wireless	Sensitive to light winds, records wind speed, gusts, and direction

The SEN0483 was selected for its superior accuracy of ± 0.3 m/s and robust features. It outperforms the S-WSB-M003 and RXW-WCF-900 in precision and stability, with reliable MODBUS data transmission and excellent anti-interference. Its high accuracy and advanced capabilities make it the optimal choice for precise wind speed measurement.

4.5 Wind Direction Sensor

To collect wind direction data as accurately as possible, the SEN0482, EN-024, and the previously mentioned S-WSB-M003 sensors were selected as options for the project. The SEN0482 sensor transmits the information collected via the MODBUS communication protocol, has a measurement range of 16 directions, and has a starting speed of 0.3 m/s [25].

The EN-024 Wind Direction Sensor, made of anodized aluminum and stainless steel, is designed for durability. As far as its specifications are concerned, the operating speed range corresponds to 0 to 160 km/h, the starting speed 0.5 m/s, the 360° operating range, and the operating temperature 10°C to +70°C [26].

Table 5: Comparison of Wind Direction Sensors

Sensor	Measurement Range	Starting Speed	Operating Temperature	Communication Interface
SEN0482	16 directions	0.3 m/s	N/A	MODBUS
EN-024	360°	0.5 m/s	10°C to +70°C	N/A
S-WSB-M003	0 - 76 m/s (for wind speed)	N/A	N/A	Smart sensor (auto-config)

SEN0482 was chosen for its precise 16-direction range, low starting speed of 0.3 m/s, and MODBUS communication. Of the options studied, it was the most suitable one for the project.

4.6 Precipitation Sensor

Precipitation sensors evaluated include the TS221, QMR101, RG13, TB3, TB4, and TB6. The TS221 features a 200 mm collection ring with ±1% accuracy at 50 mm/h and uses analog communication [27].

With a 144 mm/h capacity, ±2% accuracy, and 0.2 mm sensitivity, the QMR101's compact, UV-resistant design makes it ideal for portable setups [28]. The Vaisala RG13 detects every 0.2 mm of rain using a tipping bucket mechanism and offers a large 225 mm collection area [29].

Built for extreme weather, the TB3 measures up to 700 mm/h with ±2% accuracy for 0–250 mm/h and ±3% for 250–500 mm/h [30]. The TB4 adds a RainTrak Undercover system for real-time monitoring and data logging [31]. The TB6 improves upon this with refined components [32].

The SEN0575 provides precise 0.28 mm resolution measurements, operates on 3.3 to 5.5V DC with under 3 mA current, and supports temperatures from -40 to 85°C, offering versatility and compactness [33].

Table 6: Comparison of Precipitation Sensors

Sensor	Collection Diameter	Accuracy	Capacity	Sensitivity	Features
TS221	200 mm	±1% at 50 mm/h	N/A	N/A	Analog input communication
QMR101	N/A	±2%	144 mm/h	0.2 mm	Lightweight, UV-resistant plastic
RG13	225 mm diameter	N/A	Unlimited	0.2 mm	Tipping bucket mechanism, large collection area
TB3	N/A	±2% (0-250 mm/h), ±3% (250-500 mm/h)	700 mm/h	N/A	Suitable for heavy rainfall
TB4	N/A	Similar to TB3	700 mm/h	N/A	Option for RainTrak Undercover system
TB6	Enhanced from TB3/TB4	N/A	700 mm/h	N/A	Improved components

The SEN0575 was chosen for its high resolution of 0.28 mm, versatile I2C/UART output, and robust temperature range. Its combination of precision, adaptability, and compact design makes it a good option for precipitation sensors.

4.7 Final System Considerations

Now, with the sensors defined, a more definitive format system architecture will be as shown in Figure 8.

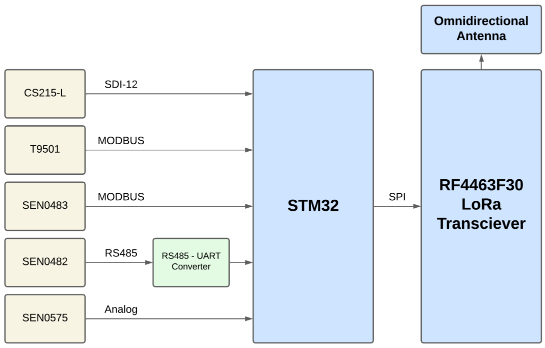

Figure 8: Cycle of the systems work schedule.

The radio module used will be the same as for CIMATÉLITE-1 Mission, the RF4463F30, to allow communication compatibility without needing to add other components to the system.

Since the GST will be only for transmission, there is no need for satellite tracking. An omnidirectional antenna with circular polarization presents as the optimal solution for communication links. With a bigger area of coverage, it ensures that during orbital pass the GST will be able to communicate with the satellite, in accordance with an established link budget done for CIMATÉLITE-1 Mission.

5 Conclusion

In conclusion, this study proposes a comprehensive GST design optimized for LoRa-based CubeSat missions aimed at environmental data collection. Through a thorough literature review of similar projects and a systematic evaluation of critical components such as sensors and communication technologies, this work establishes a robust framework for GST deployment. Key technology choices, such as the use of low-power embedded devices like the STM32 and ESP32, were made to ensure efficient processing and data handling, while the integration of LoRa technology guarantees reliable, long-range communication with CubeSats.

The selection of high-precision sensors emphasizes accuracy and reliability in extreme environmental conditions. The proposed system is designed to be energy-efficient, powered by solar energy with low-power modes, and scalable through a network of support GSTs to cover larger areas, such as the 600-hectare scope outlined in the CIMATÉLITE-1 mission.

This design framework not only meets the technical and operational requirements for the CIMATÉLITE-1 mission but also sets the stage for future advancements in GST systems for CubeSat missions, paving the way for enhanced remote sensing and environmental monitoring capabilities in remote areas.

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