ASTRONOT

Answer to Big Company

RFP for the Low-cost CubeSat Constellation for Global IoT Connectivity

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II. Introduction

AstroNot SA is proud to submit this technical proposal for a low-cost CubeSat constellation providing global IoT connectivity. This document outlines our technical approach, leveraging cutting-edge technologies, proven subsystems, and innovative designs to deliver a robust solution tailored to meet the specific requirements of your project.

Our solution has been designed with a focus on optimizing global coverage, ensuring long-term reliability, and minimizing environmental impact. Through the use of advanced materials, high-efficiency components, and a modular architecture, our proposed constellation not only meets but exceeds industry standards for performance and sustainability. This technical proposal highlights our constellation architecture, subsystem design, and operational strategies, ensuring a seamless deployment and reliable service for IoT applications worldwide.

III. Architecture

1. Mission Analysis

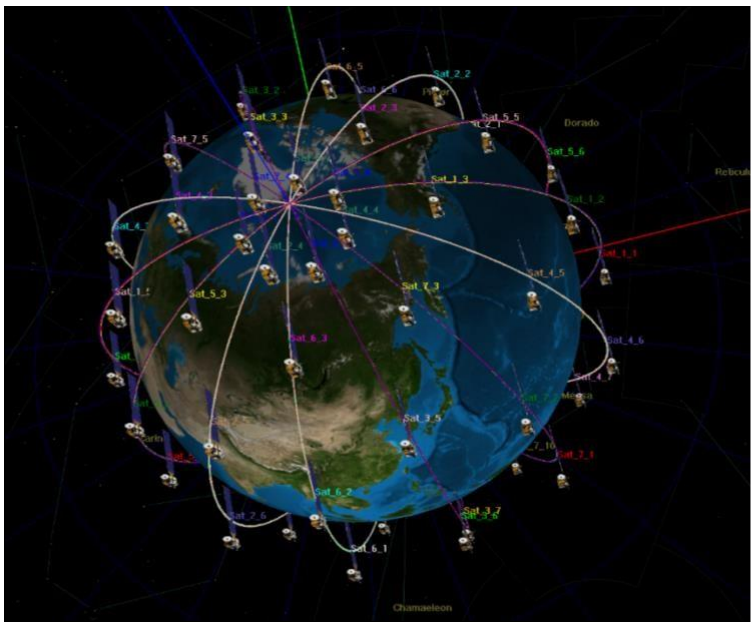

Figure 1: Constellation design

The proposed IoT satellite constellation is designed with a focus on optimized coverage, sustainability, and compliance with orbital debris mitigation guidelines. Our analysis identified a polar constellation with 70 satellites arranged in 7 orbital planes at an altitude of 600 km and an inclination of 87°. This configuration offers comprehensive coverage while maintaining an efficient revisit time for IoT connectivity worldwide.

Positioning the constellation at a 600 km altitude allows for an average revisit time of approximately 8 minutes and 6 seconds, meeting the low-latency requirements of IoT applications that demand frequent data collection. The configuration includes orbital planes spaced 51.3° apart, each containing 10 satellites with a true anomaly separation of 36°, ensuring comprehensive global coverage with minimal gaps. At this altitude, each satellite covers a ground radius of 2 586 km, with sufficient overlap to maintain continuous coverage over densely populated areas and critical IoT zones.

Altitude (km)	600
Number of satellites	70
Number of orbital planes	7

Inclination (°)	87
Space between orbital planes (°)	51,3
Anomaly separation (°)	36
Satellite coverage (km)	2586
Revisit time	*8 min 6 s*

Table 1: Orbital parameters

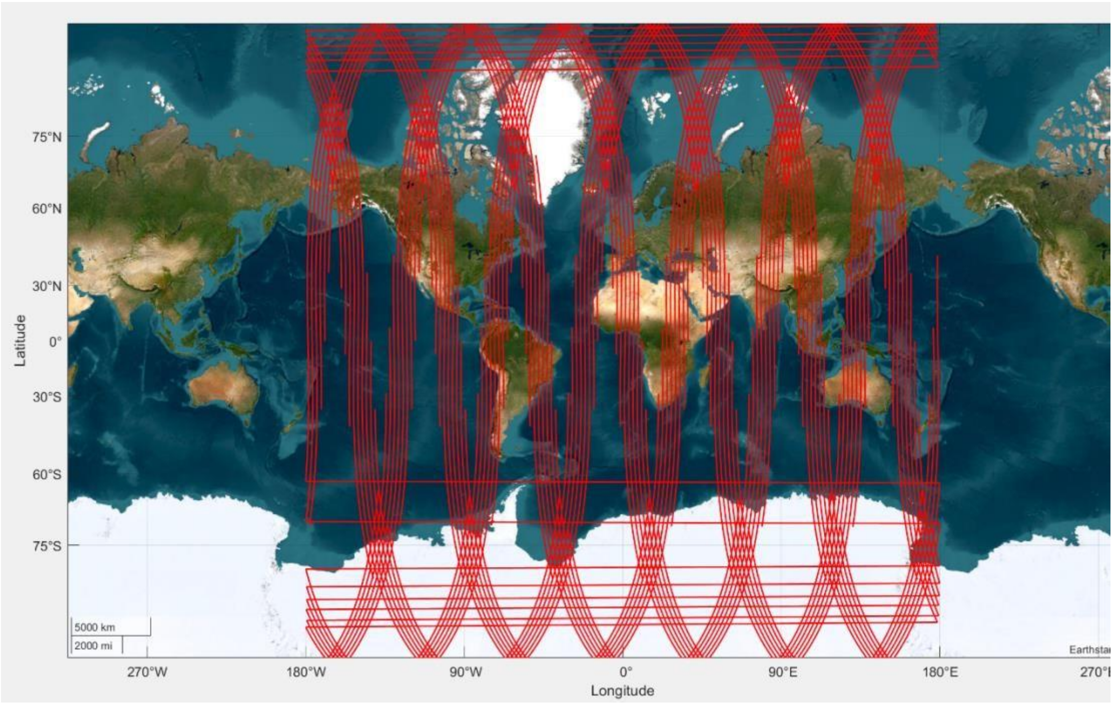

Figure 2: Orbital design

The proposed orbital design includes access to ground stations located at strategic high-latitude locations, enhancing communication with satellites as they pass over key regions. Coverage simulations, verified through our MATLAB-based orbital tracking code and GMAT simulation. To ensure the constellation's reliability, we plan to manufacture an additional 10% of satellites as spares. This approach allows for prompt replacement of any malfunctioning units, maintaining consistent service quality.

The constellation is designed with scalability in mind to handle increased data demands efficiently. In areas with high data traffic, multiple satellites can work together to cover the region, ensuring seamless service. The large number of satellites, combined with a strategically distributed ground segment in key areas of interest, enables the constellation to manage extraordinary data flows. This architecture ensures flexibility and reliability, adapting to varying user needs without compromising performance.

2. CubeSat Architecture

The proposed CubeSat is a 3U platform with a total mass of 2,53 kg, specifically designed to meet the demands of a low-cost and efficient IoT constellation. The compact 3U form factor ensures ease of integration into all type of launch vehicles. Subsystems within the CubeSat are arranged in a modular configuration, allowing for straightforward assembly, testing, and potential upgrades. The satellite's internal design maximizes thermal dissipation, minimizes interference between systems, and ensures a stable operational environment for all components.

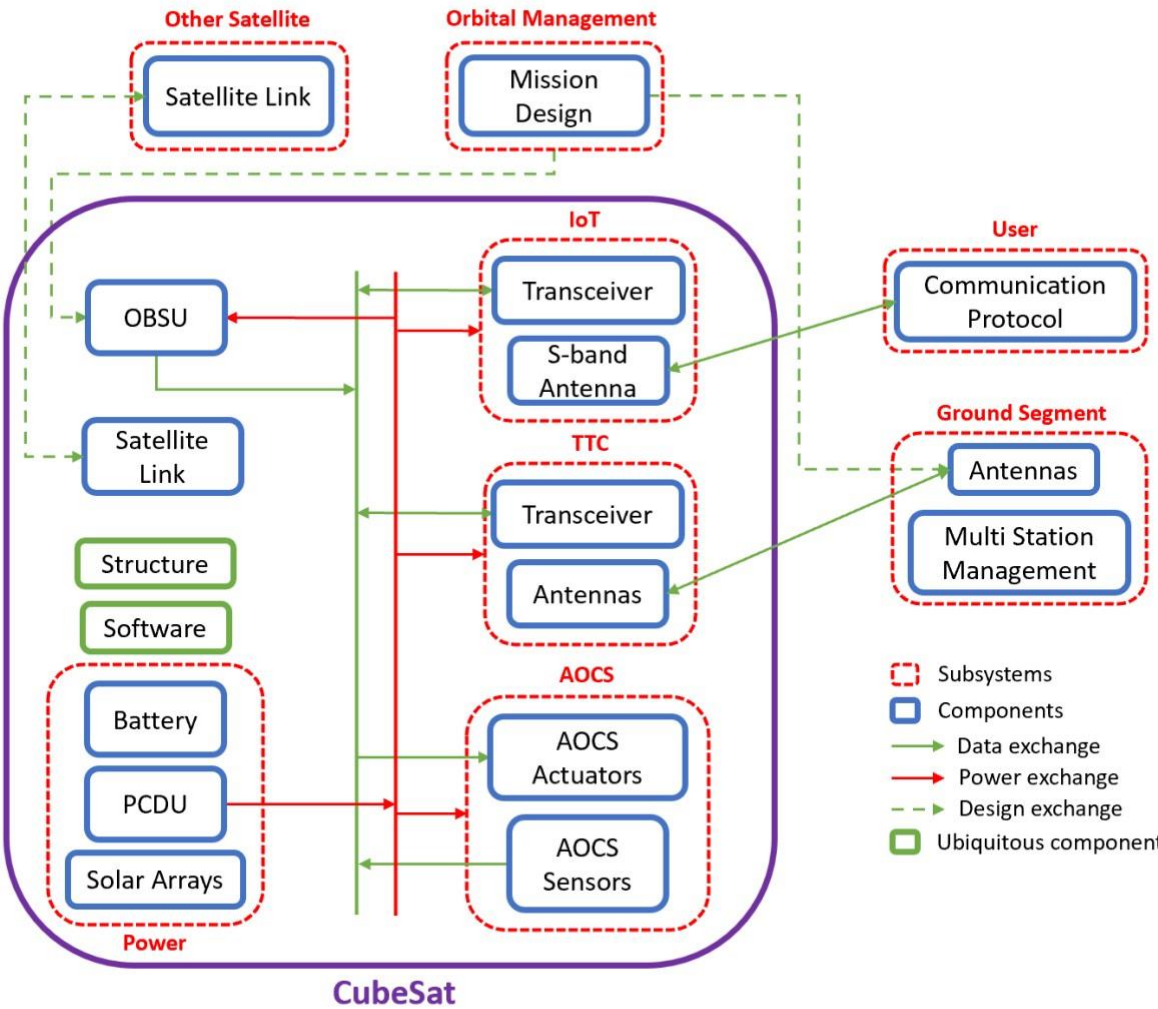

Figure 3: CubeSat Architecture

The following CATIA renderings illustrate the detailed 3D model of the satellite, showcasing the compact 3U architecture and the arrangement of critical subsystems. These visuals highlight the efficient integration of components such as the deployable solar panels, antennas, and structural elements.

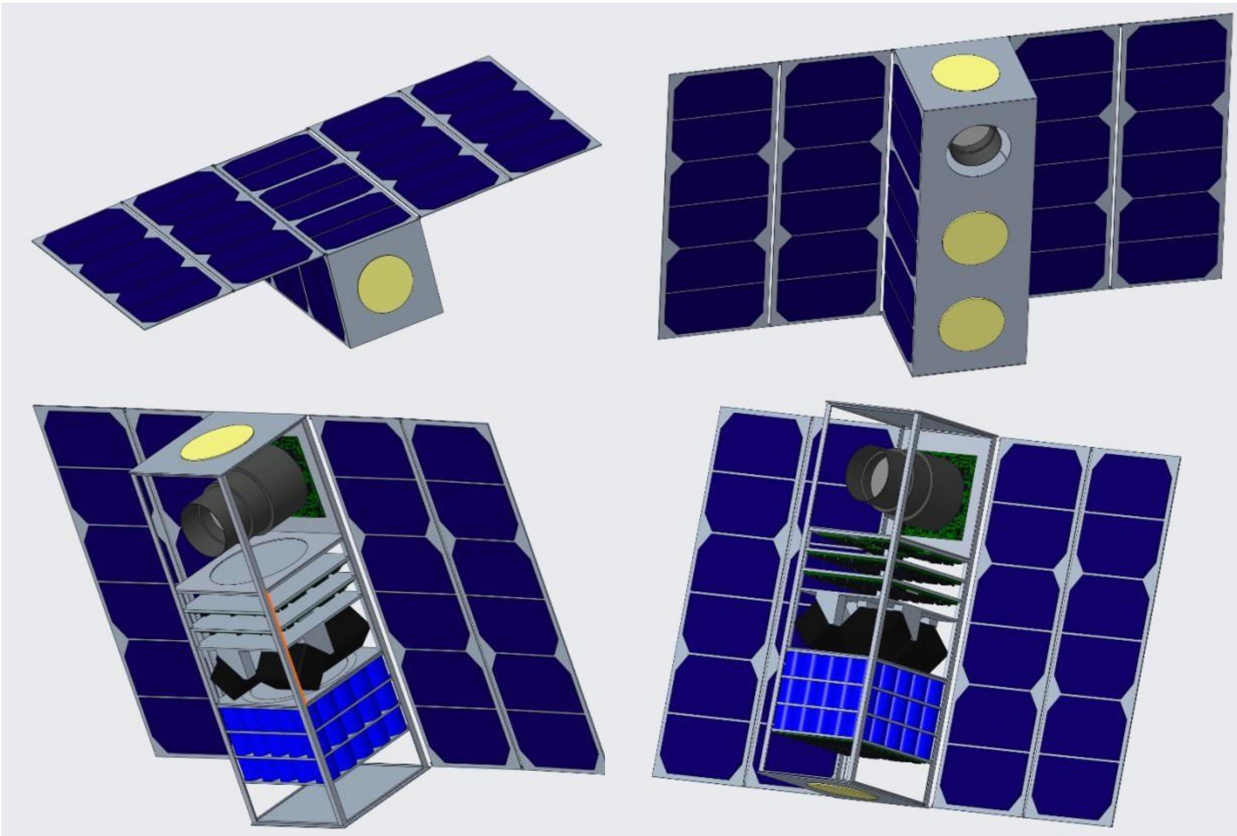

Figure 4: CAD Design

3. Sub-systems detail

a) Onboard Computer

To support the processing and management needs of our IoT constellation, we have selected the OBC from EnduroSat. This OBC is specifically engineered for LEO missions and offers high performance.

It has a powerful processor that can manage complex data handling, communication protocols, and real-time processing. For the IoT constellation, this means the OBC can handle simultaneous connections from up to 1400 users without degrading speed, access or data.

Figure 5: EnduroSat OBC

The EnduroSat OBC is designed with radiation-hardened components that ensure stable operation in space. In addition, the onboard computer integrates both a GNSS and two 3-axis magnetometers for redundancy. This diminishes the reliance on external sensors or additional modules and reduces the complexity of the system. Finally, EnduroSat has very strong experience in aerospace and proposes complete solutions for CubeSats. The EnduroSat Onboard

Computer is a flight-proven system, with over 2500 modules currently operating in orbit, including 150 of our satellites. A hot redundancy is implemented in the CubeSat to improve reliability.

b) Attitude, Orbit, and Control

The Attitude, Orbit, and control (AOCS) is the subsystem in CubeSats that ensures proper orientation and orbit stability. It includes 2 components, sensors (e.g., sun sensors, magnetometers, gyroscopes) to determine attitude, and actuators (e.g., reaction wheels, magnetorquers) for control. The flight software/OBC makes the link between the sensors and the actuators, delivering commands based on control laws, mission status, and needs. The AOCS will then enable precise pointing for payloads, such as cameras or antennas.

The proposed solution for the AOCS is partially contained in the OBC with its two 3-axis magnetometers acting as the sensors, while a system of four reaction wheels acts as the actuators. The pyramidal configuration of the actuators increases robustness, reduces the likelihood of saturation, and provides redundancy.

We use Gomspace's GSW600 Nano Torque reaction wheels, specifically designed for CubeSats. These wheels offer high torque and momentum storage capability, while their compact design is optimized for CubeSat U-form factors, allowing for efficient integration into the satellite. Additionally, their advanced bearing technology ensures extended operational life, even in challenging space environments.

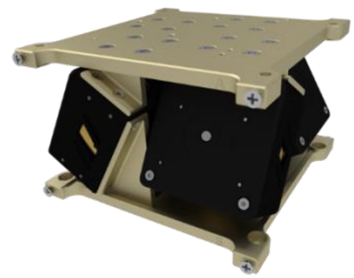

Figure 6: GSW600 reaction Wheels

AstroNot has already implemented these reaction wheels successfully in two previous constellations, with no in-orbit anomalies to date. This proven track record demonstrates their reliability and highlights their capability to meet demanding mission requirements. Combined with our innovative design and software integration, this AOCS solution guarantees optimal performance and long-term mission success.

c) Power

Our power system design ensures a resilient and efficient energy solution for the IoT satellites. Utilizing advanced components from AAC Clyde Space, each with a TRL of 9 and flight-proven for more than 10 years. The design emphasizes efficient power generation, storage, regulation, and distribution, ensuring system resilience even under challenging conditions such as eclipse phases. It operates through three main components: solar arrays for power generation, batteries for energy storage and supply, and a PCDU for power management within the satellite.

The power generation system utilizes high-efficiency deployable and fixed solar arrays from AAC Clyde Space's Photon series. This configuration includes two deployable solar arrays (9U each) and a oneside-fixed solar array (3U) with an efficiency of 30,7%, achieving an average power generation of 27W. This comfortably exceeds the 20W average power requirement for 3U CubeSats. The solar arrays are specifically designed to maximize power output in a compact form, optimizing the power-to-size ratio essential for the constellation.

Figure 7: Deployable solar arrays

Energy storage for each satellite is provided by robust, space-grade batterie of 40 Wh capacity from AAC Clyde Space, specifically chosen to support continuous operation, including during eclipse phases. This batterie offer high cycle life and excellent charge/discharge efficiency, ensuring the satellite mission during his life. The battery system is designed to be robust, with enough reserve to support peak power demands.

The Starbuck Nano Power Conditioning and Distribution Unit (PCDU) from AAC Clyde Space is ensuring stable power regulation and distribution across all subsystems. The Starbuck Nano's advanced features, including overcurrent protection, voltage regulation, and fault isolation, enhance the overall resilience and reliability of the power system, safeguarding each subsystem's power supply even in fluctuating operational conditions. Fully compatible with the chosen solar arrays and battery system, the PCDU is designed to manage power flows effectively, meeting both peak and steady power requirements while optimizing energy efficiency.

Figure 8: Starbuck Nano - PCDU

d) Antennas

The TT&C module is mission-critical, ensuring reliable spacecraft management. Based on the mission analysis, each satellite has a minimum of 23 minutes of visibility per orbit with the ground stations to exchange all TT&C data. The satellite generates approximately 1,000 measurement points, each 2 bytes in size, resulting in 16 kbps of data. Additionally, an estimated 100 kbit is allocated for uplinked data. The data budget is summarized in the following table:

Orbit time (s)	5,792
Contact time (s)	1380
Effective window	60%
Contact time with margin (s)	828
Telecommand and Telemetry data (bps)	16000
Command data (b)	100000
Data to transmit (b)	92772000
Compression rate (Huffman-Coding)	50%
Data rate (kbps)	**56.02**

Table 2: Data budget

The TT&C (Telemetry, Tracking, and Command) module incorporates several key design choices. To enable bi-directional communication, a half-duplex link with time sharing was selected to minimize onboard antenna requirements and reduce costs. The system uses flight proven (TRL 9) transceivers and antennas validated by space agencies, ensuring reliability. Filtering is integrated to prevent interference, and data transmission is packet-based for power efficiency. To mitigate the risk of lost packets, the transmission window is limited to 60% of its actual duration, allowing time for retransmissions when necessary.

Data is transmitted over the S-band using a single patch antenna with selectable circular polarization. This design reduces accuracy errors without requiring changes to the satellite's orientation. All transmitted data is secured with AES-256 encryption for enhanced security. The downlink budget is summarized in the following table:

Satellite	Transmit power (dBm)	33
	Transmit antenna gain (dBi)	7
	Transmitter losses (dB)	4
Ground Station	Receive antenna gain (dB)	35
	Receiver losses (dB)	6
	Receiver sensitivity (dBm)	-120
Other	Distance Sat-GS (km)	2560
	Frequency (MHz)	2200
	Other system losses (dB)	3
	FSPL (dB)	167.46
	Downlink margin (dB)	**14.54**

Table 3: Downlink budget

Ground Station	Transmit power (dBm)	40
	Transmit antenna gain (dBi)	55
	Transmitter losses (dB)	6
Satellite	Receive antenna gain (dB)	7
	Receiver losses (dB)	4
	Receiver sensitivity (dBm)	-100
Other	Distance Sat-GS (km)	2560
	Frequency (MHz)	2100
	Other system losses (dB)	3
	FSPL (dB)	167.05
	Uplink margin (dB)	**15.94**

Table 4: Uplink budget

The obtained margins ensure reliable TT&C communication, accommodating variations in system parameters. The selected transceiver supports data rates up to 125 kbps, providing a 55% margin for data rate flexibility. The link budgets are designed to allow adjustments in data rate or frequency if necessary, ensuring adaptability to changing mission requirements.

The IoT communication will be done with a circularly polarized S band antenna and an S band transceiver from GOM space. Both systems are flight proven (TRL 9) and validated by space agencies, ensuring reliability. The transceiver integrates an efficient FPGA module enabling high data rate operations. In addition, the transceiver is modular allowing to encompass all the transceivers for the different communication subsystems (TT&C, ISL) within one module, thus improving weight, cost, and power consumption. Finally, the FPGA being reprogrammable allows uploading software patches on the fly.

e) Structure

To meet the structural requirements, our proposed solution uses a frame built using 3D-printing technology from Anisoprint. The frame is made of continuous carbon fiber called PEEK which is one of the strongest polymers. This material is as resistant as traditional aluminum frames but 50% lighter and quicker to manufacture.

Anisoprint is in collaboration with different actors in the space industry and has multiple aerospace projects in progress involving this technology. This technology is the most promising 3D printed innovation and is under study in multiple projects supported by NASA and ESA.

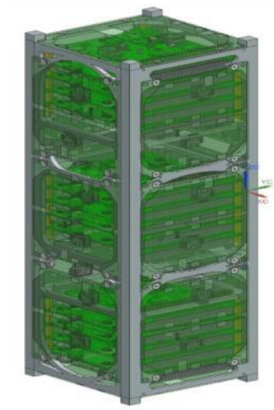

Figure 9: Anisoprint 3U Frame

f) Inter Satellite Link

To enable inter-satellite communication, each satellite is equipped with two circularly polarized S-band antennas (top and bottom). Once data is uploaded to the IoT system, it is relayed through multiple satellites before being downloaded from the destination satellite. An advanced proprietary algorithm developed by AstroNot optimizes the selection of relay satellites to minimize latency. Satellites in the same orbital plane are spaced 4,312 km apart, and data transmission occurs at 2.29 GHz with a 7 dB margin to ensure a secure connection. Each antenna supports both transmission and reception using a time-sharing method.

g) Software

The CubeSat's software is developed using C for core operations and automation. Running on a real-time operating system (RTOS), it ensures efficient management of subsystems such as AOCS, and power. The modular design simplifies updates and supports over-the-air upgrades. Fault detection and recovery (FDR) mechanisms are implemented with redundant routines to maintain operability in case of anomalies. The software is validated through simulations in MATLAB/Simulink and tested using Hardware-in-the-Loop (HIL) setups.

The IoT payload software, written in C and Rust, is based on the LoRaWAN protocol with satellite-specific adaptations. It optimizes data transmission using Chirp Spread Spectrum (CSS) and Time Division Multiple Access (TDMA). Dynamic frequency hopping reduces interference, and AES-128 encryption ensures secure data handling.

h) Optional Features

As an optional enhancement, the constellation design includes the possibility of integrating a compact camera (visible spectrum) module on each satellite from Dragonfly aerospace. The camera can generate pictures of 32km swath with 16m of resolution. This addition enables the capture of high-resolution images, which can be processed and transmitted through the IoT network. Potential applications include asset tracking, environmental changes, and agricultural lands, providing users with visual insights alongside IoT data. The camera is designed to operate within the existing power and communication budgets, ensuring minimal impact on the satellite's primary mission.

IV. IoT network management

1. IoT network

The system is specifically configured to use the LoRaWAN protocol, which has been adapted to maximize performance for IoT data transmission in satellite applications. This adaptation enhances the system's ability to support consistent connectivity for numerous devices while keeping power usage efficient and reducing network congestion.

In terms of data rate, bandwidth, and connection capacity, the system has been carefully optimized to meet the operational requirements, with a capacity to deliver 1.4 Mbps across all channels and to support up to 1,400 simultaneous connections, each with a minimum data rate of 1 kbps per user. Operating within the 2400 - 2450 MHz range in S-Band, the system provides 50 MHz of bandwidth. Within this bandwidth, the LoRaWAN standard 125 kHz channel width enables approximately 400 individual channels, ensuring robust accommodation for a high number of simultaneous connections.

Using Chirp Spread Spectrum (CSS) modulation with a spreading factor of 7, each channel can achieve a data rate of about 5.47 kbps, which, after accounting for protocol overhead and margin adjustments, results in a reliable throughput of 3.5 kbps per channel. Additionally, to manage user access and optimize channel usage, we employ Time Division Multiple Access (TDMA) within each frequency channel. TDMA effectively divides the channel into separate time slots for each user, ensuring that the system maintains low latency and high throughput, even with many users. This approach allows the constellation to fully take advantage of LoRaWAN's flexibility and range, while ensuring smooth, efficient IoT communication in real-world conditions.

2. Frequency allocation

Our communication system operates within the worldwide ISM band 2.4GHz and specifically at 2.4 - 2.4835 GHz. This choice allows license-free operation, simplifying regulatory processes, reducing licensing costs, and accelerating deployment timelines compared to licensed bands. Managed by the International Telecommunication Union (ITU), the ISM band is used worldwide and is already trusted in various applications including Wi-Fi, medical implants, automotive radars, and telemetry systems, demonstrating both its reliability and safety for IoT connectivity.

In cases of interference within this band, our system will use frequency hopping techniques, allowing smooth shifts across frequencies, and helping to reduce potential signal disruption. This dynamic adjustment also improves signal security by making transmissions harder to track. Additionally, we have partnered with Group-IB, a well-known cybersecurity firm based in Singapore with which we have previous experience. Group-IB's expertise will provide an extra layer of protection against cybersecurity risks, further securing our IoT communication links.

Operating within the ISM band requires adherence to international emission standards, including specific constraints on transmission power. Our solution is fully compliant with these requirements, following ITU regulations to ensure responsible and sustainable use of the frequency band.

V. Secondary System

1. Ground Control

To manage and control the constellation of 70 polar-orbiting satellites, we propose a virtual ground segment utilizing a network of five strategically distributed, cloud-hosted ground stations. These stations are located in Svalbard (Norway), Punta Arenas (Chile), Colorado Springs (United States), Dongara (Australia), and Hartebeesthoek (South Africa). This geographic distribution ensures global coverage, allowing for frequent contact with each satellite in polar orbit and maximizing tracking and control windows, even in remote regions.

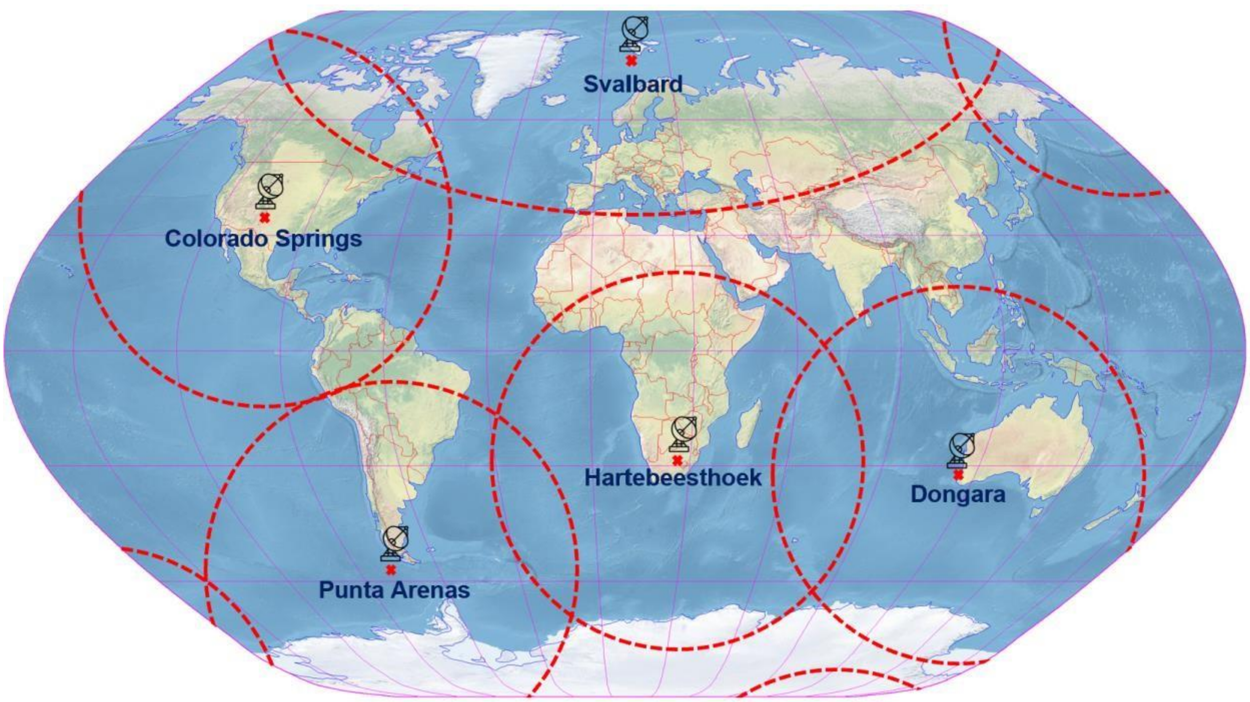

Figure 10: Antennas localization

Each station is equipped with S-band and X-band antennas dedicated to telemetry, tracking, and control (TT&C) functions, providing a multi-satellite infrastructure that enables simultaneous connections with multiple satellites.

This virtual ground segment was selected for its flexibility and cost-effectiveness. Unlike a physical infrastructure, a virtual ground segment eliminates upfront construction costs and significantly reduces ongoing maintenance expenses. Furthermore, it allows the mission to scale responsively. The network currently consists of five stations, but additional stations can be integrated seamlessly if the constellation expands, ensuring service continuity without infrastructure constraints. By choosing a virtual ground segment, we maximize network coverage and availability while maintaining cost control and providing operational flexibility that can support future constellation growth. The choice of a cloud-based virtual ground segment enhances redundancy and ensures data security and backup at each contact point. Builtin maintenance capabilities and high availability provided by cloud vendors offer additional resilience for operational demands. To design our system, we are collaborating with Skynopy, a company specializing in virtual ground segment solutions, offering a network of 15 available stations.

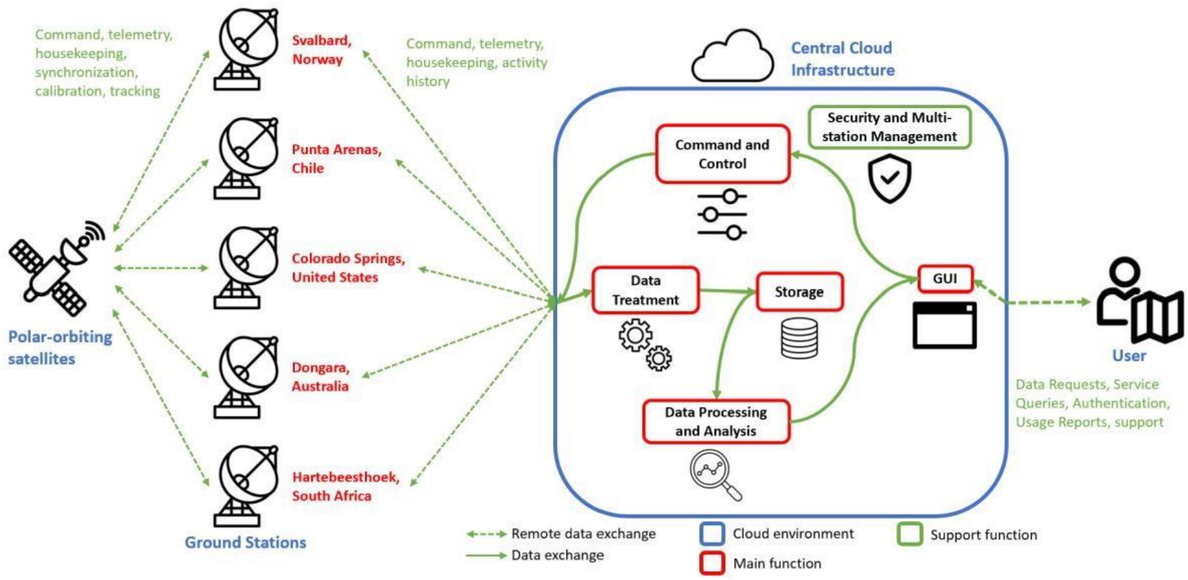

Figure 11: Virtual ground segment architecture

This diagram illustrates the operation of the virtual ground segment, where the cloud facilitates communication between the operations team and various ground stations.

2. User Interface

We have chosen to subcontract the development and maintenance of a smartphone and computer application to connect individual users to the IoT constellation system. This application will offer intuitive features such as device integration, real-time monitoring, data visualization, and alert notifications (extreme conditions monitoring). It will facilitate seamless communication between users and the satellite network, enabling efficient data transmission and reception. By providing a straightforward interface, the application will ensure that non-technical users can effectively manage and interact with their IoT devices, thereby enhancing the overall user experience and accessibility of satellite based IoT services.

VI. Environment

1. End of Life

To adhere to international space debris mitigation guidelines, our approach is structured to minimize potential debris and ensure responsible end-of-life (EOL) for the constellation. In alignment with standards set forth by the Inter-Agency Space Debris Coordination Committee (IADC) and ISO 24113:2019, the proposed strategy ensures that each satellite deorbits within 25 years, contributing to sustainable space operations and minimizing collision risks in low Earth orbit (LEO).

Our plan focuses on a passive deorbitation approach, using atmospheric drag for natural orbital decay. At the end of each satellite's mission, we will orient the satellite to maximize its drag area, speeding up deorbitation and ensuring reentry within the 25-year limit, as recommended by IADC and ISO 24113. This passive method eliminates the need for propulsion systems, following best practices for small satellites.

Along with controlled reentry, passive EOL deactivation procedures will ensure that each satellite remains inactive after its mission. Battery power will be fully discharged, and circuits will be isolated to prevent accidental explosions. All antennas will also be permanently deactivated to avoid any signal interference. This ensures that each satellite enters a safe, dormant state upon mission completion, reducing any further orbital risks.

2. Debris mitigation

The satellites are designed with a modular, durable structure that reduces the chance of in-orbit fragmentation. Each satellite component is carefully chosen to endure the space environment, minimizing the risk of structural failure or damage over time. This design not only improves mission reliability but also helps prevent the potential generation of debris from component degradation or detachment.

To ensure total disintegration upon reentry, all structural and component materials are chosen for their thermal resistance and capacity to burn up in the atmosphere. Key materials include:

- Structural Components: Made from aluminum, titanium, and carbon composites, ensuring complete disintegration at reentry temperatures.
- Printed Circuit Boards (PCBs): Composed of FR-4 material, which effectively burns up in atmospheric reentry.
- Solar Panels: Constructed with amorphous silicon, thin-film, and polycrystalline cells, which are fully consumed upon reentry.
- Antenna Materials: Fabricated from copper, aluminum, and conductive polymers, chosen specifically for their ability to disintegrate upon atmospheric entry.

3. Constellation Resilience

The satellites are not equipped with active collision-avoidance systems, in case of loosing a satellite due to a collision event, the design of the constellation still ensures reliable coverage. With a revisit time of just 8 minutes, the constellation offers enough redundancy to keep providing continuous service, even if one satellite becomes non-operational. This guarantees mission continuity without affecting operational goals or safety.

VII. Maintainability and Availability

AstroNot ensures continuous post-deployment monitoring of the constellation, with real-time tracking of key parameters for each CubeSat. This includes orbital data (altitude, position, velocity, etc.), payload data transmission, and software health. Regular software updates will be deployed to address bugs and maintain compatibility with evolving mission requirements, ensuring the longevity of the constellation.

1. Anomaly Detection and Troubleshooting

If an anomaly is detected, a systematic troubleshooting process will identify and resolve the issue efficiently. Telemetry analysis from the ground station provides initial insights to pinpoint the faulty subsystem. On average, moderate issues are resolved within 1 day.

2. Software and Hardware Issues

For software-related anomalies, solutions can typically be implemented remotely. This includes rebooting the onboard computer or deploying patch updates. The diagnosis, root cause analysis, and patch deployment are usually completed within 2 days, resulting in a 3-day Mean Time to Repair (MTTR).

In the case of hardware-related failures that impact constellation performance, replacement CubeSats will be deployed to restore full operational capacity. The process, from identifying the need for a replacement to the satellite's launch, is designed to be completed within 2.5 months. Despite this, the constellation is designed with built-in redundancy, ensuring continuous operation even in the event of multiple satellite failures. Coverage gaps are minimized by leveraging overlapping footprints of remaining satellites.

AstroNot's CubeSats are engineered for high reliability, with an estimated MTBF of approximately 15 months. This, combined with rapid troubleshooting (1–3 days) and efficient replacement protocols, ensures minimal disruption to constellation operations and sustained performance throughout the mission's lifespan. The resilient design guarantees reliable global coverage even under degraded conditions.