Stratospheric Balloon Payloads for Cross-Band Repeaters, WSPR Propagation Analysis, and LoRa Mesh Networking

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***Abstract*—Our team's amateur radio background inspired us to project ideas focused on experimenting with amateur radio communications through reliable long-range emergency communication solutions, expanding our RF propagation knowledge, and advancing low-power aerial networking tech. We focused on this goal by proposing the development and deploying stratospheric balloons carrying three distinct communication systems: a cross-band repeater, a WSPR beacon, and a Meshtastic LoRa node.**

The cross-band repeater will extend amateur radio communication ranges by relaying signals from the stratosphere, enabling long-distance contacts with minimal ground equipment. The WSPR beacon will be transmitting high-frequency bands, allowing propagation analysis as the signal is received by stations worldwide, providing valuable data on ionospheric conditions and signal propagation at varying altitudes. The Meshtastic LoRa component will establish an aerial mesh network across multiple balloon platforms while simultaneously transmitting GPS telemetry data to ground stations.

***Keywords*— Weak Signal Propagation Reporter (WSPR), Low Range (LoRa), Radio Frequency (RF)**

I. HYPOTHESES

1. Deploying a cross-band repeater at stratospheric altitude will significantly increase its communication range compared to ground-level operation, due to extended line-of-sight and reduced terrestrial barriers.
2. WSPR beacon transmissions from high altitude will demonstrate measurable propagation pattern shifts such as increased reception range, variable SNR, and band-specific propagation anomalies due to altitude-dependent changes in atmospheric density and ionospheric reflection geometry.
3. A high altitude LoRa node will maintain connectivity with ground-based or airborne mesh nodes, validating the feasibility of long-range, delay-tolerant mesh networking using low-power ISM-band radios in near-space environments.
4. Environmental parameters specifically RF noise floor, magnetic field strength, and infrasound activity will correlate with observed anomalies in radio performance, indicating that such sensors can be used for real-time context-aware communication analysis

II. INTRODUCTION

At some point, everyone experiences conventional communication failures due to natural disasters, extreme weather events, and emergencies. Fortunately, amateur radio systems often become the only usable means of communication. Many real-life events like the Tōhoku earthquakes and tsunami in Japan (2011) show that even the most advanced communication networks we use daily remain vulnerable to widespread failure. Emergency communications systems that function on their own and do not require commercial infrastructure provide a safe fallback for coordinating disaster response, delivering life-saving information, and reconnecting isolated communities.

High-altitude balloons provide a cost-effective solution for establishing temporary communication networks, particularly in emergency situations. These balloons are relatively inexpensive to deploy and can achieve a communication range of approximately 400 miles when equipped with appropriate payloads, making them a practical choice for rapid response scenarios. Typically launched to altitudes of 60,000 to 100,000 feet, they can remain aloft for a couple of hours, offering a short but valuable window for communication coverage. By deploying balloons one after another, it's possible to create a large, overlapping emergency network, ensuring continuous connectivity across vast areas where traditional infrastructure may be unavailable or compromised. [2]

A notable example of high-altitude balloon technology is Google's Project Loon, which operated from 2011 to 2021. While Loon focused on long-duration flights (averaging 161 days), mesh network networking, and non-terrestrial based internet concepts, showed the potential of balloons as communication platforms. In contrast, our approach emphasizes affordability and rapid deployment.[2].

III. CROSS-BAND REPEATER

Cross-band repeating allows stations to communicate, which is likely not possible due to distance or terrain between. Our stratospheric payload will utilize the QSL PCB cross-band repeater design, which supplies signal relay while maintaining minimal weight and power requirements. The system uses an Atmel ATMEGA328 microcontroller to manage two Dorji DRA818 modules (VHF and UHF), helping create a functional cross-band repeater perfect for high-altitude deployment. Cross-band repeating operates by receiving signals on one band and retransmitting them on another. This method removes the expensive narrow filters needed for conventional single-band repeaters since the 2m (147 MHz) and 70cm (447 MHz) bands are approximately separated. 300 MHz, stopping receiver overload..

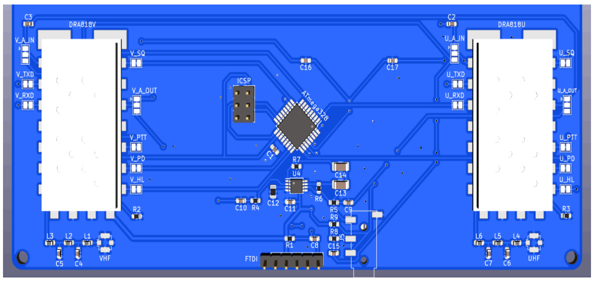

Fig. 1. Example PCB QSL Card that can be used as a cross band repeater [6].

IV. WSPR BEACON

Our stratospheric payload will have a custom WSPR (Weak Signal Propagation Reporter) transmitter inspired by the U4B (Ultimate4 for Balloons) design, to collect propagation data across the 10m (28 MHz) HF band, while also being lightweight for stratospheric operation. WSPR is a protocol, implemented in a computer program, used for weak-signal radio communication between amateur radio operators. It lets reporting reception stations receive extraordinarily low signal-to-noise ratios (as low as -28 dB in a 2.5 kHz bandwidth), ideal for studying propagation.. The beacon transmits compressed messages containing our callsign, Maidenhead grid location from GPS coordinates, and transmitter power (10 dBm). These packets are encoded using WSPR's convolutional code (constraint K=32, rate r=½), creating a narrow 6 Hz F1D emission. Key components include a 32-bit ARM microcontroller, Si5351 direct digital synthesizer, and a GPS module. The beacon sequentially operates on the 10m band, transmitting for 110.6 seconds every 10 minutes with precise GPS timing. The implementation provides global reception via the terrestrial WSPR reporters, where we will be able to see all stations that received our transmissions, as well as the signal strength at that location. The collected data will reveal how stratospheric altitude affects HF propagation across various ionospheric conditions. We then plan to run data analysis on everything we collected, and will help better our understanding of radio propagation.

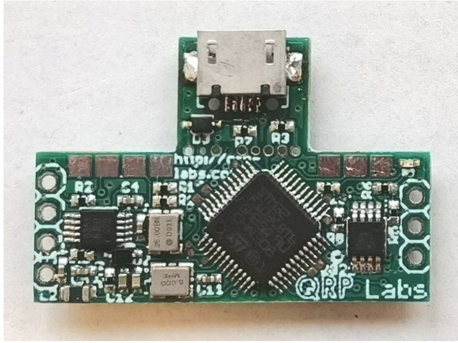

Fig. 2. U4B [6]

V. MESHTASTIC LORA NODE

Here's your original text modified to specify the GPS as the RAK12500 WisBlock GNSS Location Module, while retaining the previous updates (u-blox ZOE-M8Q in flight mode, RAK1906 WisBlock Environmental Sensor Module, and three AAA Energizer Ultimate Lithium batteries). The changes ensure clarity that the RAK12500 is the module being used, integrating seamlessly with the existing description.

Our stratospheric payload will incorporate a Meshtastic LoRa mesh networking node, utilizing a RAK Wireless Meshtastic baseboard equipped with an nRF52 microcontroller and paired with a RAK12500 WisBlock GNSS Location Module operating in flight mode. This configuration establishes a robust aerial node within a decentralized LoRa mesh network, enabling seamless message relaying between multiple high-altitude balloons and simultaneous transmission of GPS telemetry data to ground stations. The nRF52 microcontroller ensures efficient operation with its ultra-low power consumption and integrated Bluetooth connectivity, while the RAK12500 WisBlock GNSS Location Module, featuring the u-blox ZOE-M8Q chip, provides precise positioning with a sensitivity of -160 dBm, capable of functioning effectively at the high altitudes required for stratospheric missions. Additionally, the payload includes a RAK1906 WisBlock Environmental Sensor Module, enhancing data collection with measurements of temperature, humidity, pressure, and air quality.

The Meshtastic LoRa mesh networking system excels in its ability to create a self-healing, decentralized communication network. Each node, including our aerial payload, can dynamically route messages through the network by relaying data to other nodes within range, extending communication coverage far beyond the line-of-sight limitations of a single node. This mesh topology ensures reliable data transfer even if individual nodes fail or move out of direct range, making it ideal for coordinating multiple balloons across vast stratospheric distances. The system supports both point-to-point and broadcast messaging, allowing for flexible communication strategies, such as relaying critical telemetry or coordinating balloon positions.

Operating frequencies for the LoRa module depend on regional regulations; however, in North America, LoRa operates in the 915 MHz ISM band, spanning between 902–928 MHz. These sub-GHz bands enable long-range communication, with potential ranges exceeding 10 kilometers in line-of-sight conditions at ground level. In the stratospheric environment, where line-of-sight is unobstructed, ranges could extend significantly further, potentially tens to hundreds of kilometers, depending on antenna design, power output, and atmospheric conditions. Because of this, having a Meshtastic node at such an advantageous position could allow for very long communication distances, even with low power and low-gain antennae. The LoRa modulation uses spread-spectrum technology (somewhat similar to Bluetooth), offering adjustable data rates and spreading factors (SF7–SF12), balancing range and bandwidth to optimize performance for our high-altitude application.

Power requirements for the system are minimal, aligning with the nRF52's low-power design. The nRF52 microcontroller consumes approximately 4.2 mA in active mode and as little as 1.5 µA in deep sleep, while the LoRa radio draws around 20 mA during transmission (at 13 dBm output) and 0.2 µA in standby. The RAK12500 WisBlock GNSS Location Module requires about 25 mA during acquisition and 20 mA in tracking mode, with a cold start time of 34 seconds and a hot start of 1 second. The RAK1906 WisBlock Environmental Sensor Module operates with low power consumption, typically a few mA when active. For our stratospheric payload, three AAA Energizer Ultimate Lithium batteries, connected in series to the battery connector, provide power, leveraging the nRF52's power-saving modes and the Meshtastic firmware's configurable sleep cycles to improve mission duration under the power constraints we are working with.

The nRF52's interfaces and the Meshtastic platform's open-source nature facilitate integration with other systems. The RAK Wireless baseboard supports I2C, SPI, and GPIO pins, allowing the RAK12500 WisBlock GNSS Location Module to connect via UART for reliable position data input and the RAK1906 WisBlock Environmental Sensor Module to interface seamlessly via the WisBlock modular ecosystem. This enhances the payload's scientific capabilities with environmental data collection. Bluetooth connectivity enables real-time configuration or data retrieval by ground crews before launch, while the LoRa mesh network integrates seamlessly with ground-based Meshtastic nodes, forming a hybrid air-to-ground communication system. The firmware supports MQTT bridging, potentially allowing telemetry data to be relayed to internet-connected nodes for global dissemination, provided a ground station with internet access is within the mesh. This combination of hardware and software ensures our stratospheric payload can operate as a fully integrated node in a broader communication and data collection network.

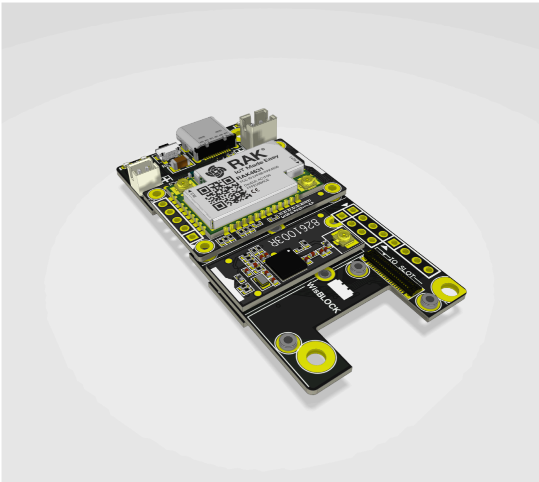

Fig. 3. Meshtastic LoRA Node

VI. DATA COLLECTION METHODOLOGY

Our stratospheric balloon project will collect multiple useful datasets to enhance understanding of high-altitude radio propagation and environmental conditions. The following includes our methodology that outlines our approach to data collection, analysis, and expected insights.

A. Data Collection Systems

1. *WSPR propagation Data*

   Our analysis will utilize reception reports from the global WSPRnet monitoring network [5]. Key metrics collected include signal-to-noise ratio, reception distance, and frequency band performance. Timestamp and location correlation will enable propagation path analysis, with automatic logging through the WSPRnet database facilitating comprehensive post-flight analysis.

2. *Magnetometer Readings*

A three-axis magnetometer sampling at 1Hz will measure local magnetic field variations throughout the flight. Proper RF filtering will prevent interference from onboard transmitters. The system will correlate data with transmission events to verify filtering effectiveness and establish baseline measurements before and after transmission cycles.

3. *Acoustic and Atmospheric Sensing*

The payload includes a low-frequency microphone for detecting infrasound (0.1-20 Hz range) and pressure sensor measurements synchronized with acoustic data. This configuration enables the detection of atmospheric gravity waves and distant meteorological phenomena. Sampling rates will be optimized for extended recording duration throughout the flight.

B. *Data Analysis Approach*

1. *RF Noise Floor Analysis*

Post-flight will include plotting noise floor measurements against altitude to establish correlation patterns. Frequency-specific analysis will identify bands with optimal signal clarity. Additional analysis includes geospatial mapping of noise patterns across the flight path and comparative analysis with ground-based measurements.

2. *Propagation Performance Metrics*

We will conduct statistical analysis of WSPR reception reports, examining distance, signal-to-noise ratio, and temporal factors. This enables modeling of signal propagation patterns at different altitudes, comparison of day/night propagation characteristics, and evaluation of multi-band performance differences.

3. *Environmental Correlation*

Our methodology includes cross-referencing radio performance with magnetometer and acoustic data. This process identifies patterns between atmospheric conditions and signal propagation, enables time-series analysis to detect anomalies and significant events, and supports development of predictive models for optimal transmission windows.

C. *Expected Insights*

1. *Altitude-Dependent RF Performance*

The results will quantify the relationship between altitude and noise floor across frequency bands. This allows for the determination of optimal altitude ranges for different types of radio communication and the identification of altitude thresholds where propagation characteristics significantly change.

2. *Stratospheric Mesh Network Capabilities*

Data will establish range limits and reliability metrics for LoRa communication in stratospheric conditions. Findings will provide performance benchmarks for future emergency communication systems and real-world validation of theoretical mesh networking models at extreme altitudes.

3. *Environmental Effects on Radio Propagation*

Analysis will reveal a correlation between altitude and ionospheric propagation on the HF band.

4. *Emergency Communications Applications*

Results will yield practical recommendations for rapid-deployment stratospheric communication systems, optimal configuration guidelines for multi-balloon communication networks, and performance expectations for different types of emergency communication scenarios.

All data collected will be made available to the amateur radio community and researchers, contributing to the broader understanding of stratospheric radio propagation characteristics and advancing the field of emergency communication technology.

VII. SAFETY PROTOCOLS

Our stratospheric balloon project addresses several important protocols to ensure successful deployment and operation.

A. *Regulatory Compliance*

Zenith will be operating within the amateur radio service, requiring appropriate licensing and frequency coordination. We are licensed amateur radio operators and members who are actively studying for their licenses to ensure legal operation of all communications systems. All transmissions will be supervised by appropriately licensed team members in compliance with FCC Part 97 regulations. The cross-band repeater will utilize the 2-meter (144-148 MHz) and 70-centimeter (420-450 MHz) amateur bands, adhering to bandwidth and power limitations specified in FCC regulations. The WSPR beacon will operate on the

10-meter (28.0-28.3 MHz) amateur band, using the standardized WSPR protocol frequency. The Meshtastic LoRa implementation will utilize frequencies within the 902-928 MHz ISM band in North America, which permits unlicensed operation below specified power levels. For balloon operations, we will comply with FAA regulations (14 CFR Part 101) governing unmanned free balloons, including weight restrictions, payload package construction requirements, and notice of launch. Our system design includes proper radar reflectors for tracking and visibility to aircraft as required by regulations.

B. *Technical Integration*

Each of our communication systems presents unique technical challenges that we have addressed through careful design considerations and are following the engineering design process.

1. *Cross-Band Interference Prevention*

   To mitigate potential interference between our radio systems with other balloons, we have implemented specific filtering on all transmitters and planned strategic antenna placement on each balloon. Our design involves sequential transmission timing to minimize simultaneous operations, reducing the potential for intermodulation and desensitization between other systems.

2. *Power Management*

   Each system requires reliable power to maintain operations throughout the flight. We will be designing efficient power systems incorporating Energizer Ultimate Lithium AA batteries paired with small solar panels for critical components. Power regulation circuits will ensure stable voltage to sensitive RF components despite the temperature fluctuations expected at high altitudes.

3. *Environmental Hardening*

   Stratospheric conditions present extreme temperature variations and reduced atmospheric pressure. Our circuit designs will include components rated for extended temperature ranges, with enclosures including insulation to maintain operational temperatures. All connections will be secured against vibration and thermal cycling to prevent failures during flight.

4. *Weight Optimization*

   Weight optimizations represent a critical factor in extending flight duration and achieving target altitudes. Our approach includes

   1. Using lightweight PCB designs for all radio systems
   2. Employing efficient wire antenna designs that balance performance with weight
   3. Selecting battery and solar components based on energy density
   4. Utilizing lightweight enclosures that provide adequate protection
   5. Optimizing balloon envelope size based on calculated payload weight

Through systematic component selection and design optimization, we'll maintain each payload under 200 grams.

VIII. CONSTRUCTION PLAN

A. *Components and Materials*

System	Operation Frequency	Power Requirements	Key Components	Weight Estimate
Cross-Band Repeater	2m (144-148 MHz) & 70cm (420-450MHz)	400-700 mA TX	ATMEGA328, DRA818 modules	150g
WSPR beacon	10m (28.0-28.3 MHz)	27 mW TX	ARM MCU, si5351, GPS	100g
Meshtastic LoRa node	915 MHz (902-928 MHz)	20 mA TX, 25 mA GPS	nRF52, u-blox ZOE-M8Q GPS	125g

Item	Qty	Unit Price	Total (U	Category
ATMEGA328 Microcontrollers	2	4	8	Core
RAK19007 WisBlock Base Board	2	9.99	19.98	Core
RAK4631 nRF52840 Core Module	2	17.99	35.98	Core
RAK12500 WisBlock GNSS Location Module	2	19	38	Core
RAK1906 WisBlock Environmental Sensor Module	2	15.2	30.4	Sensors
Si5351 Clock Generator	1	7	7	Core
ARM MCU (e.g. STM32 or Teensy)	1	15	15	Core
AAA Energizer Ultimate Lithium Batteries	3	2.5	7.5	Power
Solar Panels	2	8	16	Power
PCB Fabrication + Assembly	1	30	30	Core
Antennas (VHF/UHF/HF/LoRa)	4	5	20	Core
Sensors (magnetometer, mic, etc)	1	25	25	Sensors
SD Card + Breakout + RTC	1	15	15	Data Logging
Low-pass Filters / Shielding	1	15	15	RF Filtering
Payload Enclosure (foam, 3D print)	1	20	20	Mechanical
Balloon Attachment Hardware	1	10	10	Mechanical
Misc. (wires, headers, insulation)	1	25	25	Misc

B. *Assembly Procedures*

1. *Circuit Assembly and Testing*

   For the cross-band repeater, we program the ATMEGA328 with repeater firmware and test transmit/receive functions individually. The WSPR beacon requires loading firmware onto the ARM microcontroller and calibrating the Si5351 frequency. The Meshtastic node preparation involves flashing the latest Meshtastic firmware and configuring networking parameters.

2. *Power System Integration*
This process includes designing power regulation circuits for each system, testing power consumption under various operational scenarios, verifying solar charging capabilities, and implementing power saving modes where appropriate.

3. *Environmental Protection*
We apply conformal coating to circuit boards for moisture protection, construct thermal insulation using lightweight materials, seal enclosures against moisture, and test component operation in cold conditions to simulate the stratospheric environment.

4. *Antenna Construction and Testing*
This phase involves building and tuning antennas for each frequency band, testing radiation patterns and efficiency, ensuring lightweight but durable construction, and verifying proper impedance matching.

C. *Testing Methodology*

1. *Functional Testing*
We verify cross-band repeater operation with handheld radios, confirm WSPR transmission and reception using local receivers, test Meshtastic mesh network functionality between nodes, and validate sensor data collection and storage.

2. *Environmental Testing*
This includes temperature and vibration testing to ensure mechanical stability, testing low-pressure environment when possible, and verifying battery performance under temperature extremes.

3. *Integration Testing*
Test how the different systems work together, checking for interference between systems.

4. *Pre-Launch Verification*
Final checkings immediately before launch, checking all payloads are reporting telemetry correctly and that our ground station is receiving them.

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