Conducting Extended BVLOS Operations in Challenging Terrain Leveraging Path and Link Diversity for Highly Reliable C2

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Executive Summary

uAvionix is pleased to submit this final report representing the results of a Link Diversity Demonstration project designed to enhance C2 performance in challenging terrain in support of Beyond Visual Line of Sight (BVLOS) operations through the integration of multiple communication links.

The project addressed a significant challenge in current BVLOS operations: the reliance on single active command and control (C2) links or manual switching between primary and backup links, especially in environments where no single link might be optimal due to changing terrain or remote areas. Our demonstrated solution integrated cellular network (LTE), C-Band radio, and satellite communications (SATCOM) into a unified C2 link system managed by a Link Executive Manager (LEM).

Initially planned for execution in Alaska with L-Band SATCOM, the project adapted to overcome operational, weather and technical challenges (including GPS interference). The demonstration was successfully relocated to Montana and transitioned to leveraging Starlink Low Earth Orbit (LEO) for SATCOM to replace the need for L-band SATCOM communications. Testing was conducted through a series of 15 flights, over Flathead Lake and its surrounding terrain, at altitudes ranging from takeoff and landing to 10000 ft. To overcome weather-related challenges, the final data collection was performed using a Cessna 182 equipped with UAS avionics and communication systems, allowing for comprehensive testing beyond the limitations of part 107 operations. The operational test flights represented a simulated long range inspection flight with a larger style UAS typically leveraged for this type of operations, to mimic long endurance flight as conducted in Alaska for the Trans-Alaska Pipeline

The integrated C2 link system demonstrated exceptional performance across all key metrics. Each radio type maintained individual availability rates above 90%, with C-Band at 90.19%, LTE 97.37%, and SATCOM 98.51%. The LEM's ability to select the best available link based on qualification and quality measurements resulted in a combined availability across all three radios of 99.98%.

The LEM successfully maintained continuous communications by dynamically selecting links based on real-time performance data. Analysis of specific flight segments revealed the LEM's ability to manage seamless transitions between links in response to changing conditions, though also highlighted opportunities for enhancement by incorporating latency measurements and link weighting into the selection algorithm.

This project has validated the concept of integrating multiple C2 links for enhanced BVLOS operations. The successful demonstration of automatic link management, coupled with the high-performance metrics achieved across all three link types, suggests that this approach could significantly improve the reliability and capability of C2 supporting BVLOS operations in challenging environments. Even without a single technology that covers 100% of the terrain, the diversity between links and automated fusion delivered a high integrity and high availability C2 environment

Future development opportunities include enhancing the LEM's link selection algorithm to incorporate latency measurements and link weighting and exploring emerging SATCOM technologies for even more robust C2 capabilities. The insights gained from this project contribute valuable data and experience to the advancement of safe and reliable BVLOS operations.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

The rapid advancement of Uncrewed Aircraft Systems (UAS) technology has opened up new possibilities for long-range, BVLOS operations. These operations have the potential to revolutionize various industries, from infrastructure inspection to delivery services. However, the success and safety of BVLOS missions critically depend on maintaining reliable C2 links between the ground control station and the uncrewed aircraft.

This report presents the findings of a project conducted under a Broad Agency Announcement (BAA) to demonstrate and evaluate the use of path and link diversity for highly reliable C2 in challenging terrain during extended BVLOS operations. The primary objective was to integrate multiple communication technologies - including cellular networks, C-Band radio, and SATCOM - into a unified C2 link system, managed by a LEM.

This report details the project from its initial conception to its final execution. It outlines the challenges faced, the solutions developed, and the valuable insights gained along the way.

1.1 Document Overview

This document is structured as follows:

Section 1 Introduction: This section introduces the project.

Section 2 Background: Presents the context and rationale for the project.

Section 3 Project Scope and Objectives: Defines project goals and success criteria.

Section 4 Challenges Encountered: Documents project obstacles and implemented solutions.

Section 5 System Overview and Integration: Details system architecture and components.

Section 6 Planning and Concept of Operations (CONOPS): Explains the operational approach.

Section 7 Demonstration Plan: Describes demonstration approach and data collection strategy.

Section 8 Results and Data Analysis: Presents demonstration results and performance analysis.

Section 9 Discussion of Findings: Reviews lessons learned and future directions.

Section 10 Conclusions and Recommendations: Summarizes findings and recommendations.

1.2 Definition of Acronyms

Table 1-1 lists the acronyms found throughout this document.

Acronym	Definition
ACUASI	Alaska Center for UAS Integration
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
AMSL	Above Mean Sea Level
APU	Auxiliary Power Unit
ARS	Airborne Radio System
BAA	Broad Agency Announcement
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
C2CSP	Command and Control Communication Service Provider

Acronym	Definition
COA	Certificate of Authority
CONOPS	Concept of Operations
CRC	Cyclic Redundancy Check
CS	Control Station
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GCS	Ground Control Station
GPS	Global Positioning System
GRS	Ground Radio Station
INS	Inertial Navigation System
KGPI	Glacier International Airport
LEM	Link Executive Manager
LEO	Low Earth Orbit
LTE	Long-Term Evolution
OCD	Operational Control Data
OUD	Operational User Data
PIC	Pilot in Command
POE	Power over Ethernet
RF	Radio Frequency
RLP	Radio Link Protocol
RPIC	Remote Pilot in Command
SATCOM	Satellite Communications
STA	Special Temporary Authority
TDD	Time Division Duplex
TET	Transaction Expiration Time
TFR	Temporary Flight Restrictions
TSO	Technical Standard Order
UA	Uncrewed Aircraft
UAS	Uncrewed Aircraft System
UTM	Uncrewed Traffic Management
VLOS	Visual Line of Sight
VTOL	Vertical Take-Off and Landing

Table 1-1 Acronyms

2 Background

Current BVLOS operations typically rely on single active C2 links, with an alternative standby link available in some cases. These alternative links, when present, may not provide diversity in spectrum choice, and often employ two airborne radios operating on the same spectrum. Remote Pilots in Command (RPIC) typically switch between primary and secondary links manually during take-off and landing operations when changes in link quality are expected; however, active and dynamic management of these links is lacking.

For extended range BVLOS operations in remote areas, the predominant solution is L-Band SATCOM, even though other links with potentially higher quality may be available for portions of the flight. The current operational environment often selects a link for a specific flight segment without considering link quality, link diversity, or path diversity, making it challenging to achieve consistent, high availability and predictable C2 performance

The Challenging Terrain Link Diversity BAA project was initiated to address these limitations by demonstration how integration multiple communication technologies with automated link management could significantly improve the reliability and capability of BVLOS operations in challenging environments.

3 Project Scope and Objectives

The Challenging Terrain Link Diversity BAA project was conceived with the following scope and objectives:

3.1 Primary Goal

To demonstrate the integration of cellular network, C-Band radio, and SATCOM into a unified C2 link, leveraging link diversity to minimize the risk of lost links during extended BVLOS operations in challenging terrain.

3.2 Key Objectives

We aimed to implement and demonstrate a LEM for seamless, automatic switching between different radio links. Through our demonstration flights, we planned to generate comprehensive data sets showcasing the performance of three distinct C2 connections (LTE, C-band, and SATCOM), as well as the effectiveness of the fused link. The project sought to conduct extended range BVLOS operations in remote areas, moving beyond the traditional reliance on L-Band SATCOM. We set out to achieve consistent link connections without errors or losses in at least 95% of total flights, demonstrating effective link and path diversity in a terrain-challenged environment. Additionally, we aimed to analyze system performance data elements and methods, validating the link manager's performance in accordance with RTCA DO-377A and DO-362A standards.

3.3 Project Scope

The project encompassed executing demonstration flights utilizing the integrated C2 link. These flights were designed to simulate long-range BVLOS UAS inspections of the Trans-Alaska Pipeline to test the system in real-world conditions. Our scope included evaluating and comparing the performance of individual communication links (LTE, C-band, and SATCOM) and the fused C2 link, developing and implementing a data analysis plan to assess the effectiveness of the link diversity approach, and providing insights and recommendations for future BVLOS operations in challenging environments.

3.4 Expected Outcomes

The project aimed to deliver a proven system for maintaining reliable C2 links in challenging terrain and extended BVLOS operations. We sought to generate empirical data demonstrating the benefits of link and path diversity in UAS operations, validate the performance of the LEM in real-world conditions, and provide compliance documentation with DO-362A and DO-377A standards. The project was designed to contribute significantly to the advancement of UAS operations, particularly in remote and challenging environments, by demonstrating the feasibility and benefits of a multi-link, dynamically managed C2 system.

4 Challenges Encountered

4.1 Challenges in Alaska

The initial plan for this project centered on conducting flight testing at the Alaska Center for UAS Integration (ACUASI). The primary objective was to carry out simulated inspections of the Trans Alaska Pipeline, which would provide a real-world scenario for testing the integrated C2 link system in challenging terrain with limited connectivity. We initially planned to use a relatively large UAS with long-range capabilities, but availability constraints led to the selection of the SuperVolo platform for integration testing.

4.1.1 SATCOM Integration and GPS Interference

Initially, the project specified the use of a SpaceLink Iridium (SATCOM) radio as the external link for the muLTElink system. However, during the integration of the SATCOM radio into the airborne platform, significant challenges were encountered on the airframe used:

- Previous integrations with Inmarsat and Iridium SATCOM modules were tested on larger platforms, with integration onto the smaller platform SuperVolo initiated as part of this project.
- Strong GPS interference was experienced on the smaller SuperVolo UAS platform in various GPS modules and test setups.
- The interference was due to the proximity of L-band SATCOM to GPS bands, also L-Band.
- The SATCOM provider recommended a physical separation of 10-12 feet between the GPS and SATCOM antennas, which was not feasible on the SuperVolo style platform. Referencing Figure 4-1, the large mass of the SATCOM antenna required it be installed at or very near to the center of mass for the airframe. Two of the GPS units were integrated into the air frame and could not be relocated (left and right GPS systems). Attempts were made to install the satcom system as far forward into the nose as possible while still allowing the aircraft to be balanced within the airframes operational limits, but this allowed for at most 1.5 ft of separation.
- The application of a GPS filter was not feasible due to the TSO status of the required GPS

Figure 4-1 - SuperVolo Antennas

These GPS interference issues posed a significant risk of hull loss and raised safety concerns, which outweighed the benefits of continued testing with L-band SATCOM.

4.1.2 Wildfires and Environmental Challenges

As the project progressed, Alaska experienced significant wildfire activity. Two fires were concentrated near the COA North of Fairbanks. This resulted in the grounding of general aviation and UAS flights through a Temporary Flight Restriction (TFR).

4.1.3 C-Band License Approval and Regulatory Hurdles

Delays in receipt of C-band licenses from the FCC for demonstrations in Alaska, which were secured in July, added a timeline conflict, added pressure to the already compressed project schedule. This necessitated the choice of an alternative test site that already had C-band license approvals to allow C-Band operations.

4.2 Revisions to the Original Plan

Following the challenges encountered in Alaska, revisions were made to the original plan to ensure the project's objectives could still be met. The period of performance for the contract was extended to ensure a valuable result could be delivered. These changes included:

4.2.1 Shift from L-Band SATCOM to Starlink

The project pivoted from using L-Band SATCOM on the SuperVolo to implementing a Starlink terminal on the Watts Prism quadcopter. This adaptation proved advantageous for several reasons:

- Starlink operates on a different spectrum, utilizing the Ku-Band with a frequency range between 12-18 GHz, avoiding the interference issues encountered with L-Band.
- Initial testing indicated that the Starlink link exhibited high-bandwidth and low-latency characteristics.
- The shift aligned with the project's main deliverable under the BAA, which was to demonstrate the link manager's capability on multiple links, including SATCOM, rather than specifically demonstrating L-band technology.

4.2.2 Relocation to Montana

The decision to relocate testing to Montana offered several benefits:

- uAvionix already possessed active C-band licenses for the area near its manufacturing and test facility in Montana.
- The new location provided access to a lake area with existing C-band deployment.
- The terrain in Montana presented known challenges for C-band and LTE, allowing for robust testing of the link diversity system.

4.2.3 Revised Flight Operations

The new plan for flight operations in Montana included:

- Conducting flights under part 107 regulations.
- Utilizing the lake area and existing C-band deployment for testing.
- Planning 20 short-duration flights (15 minutes each) to be stitched together, simulating the initially proposed pipeline inspection route.
- Demonstrating the ability of a fused link to enable long-range BVLOS UAS operations through the combination of these flights.

This revised approach maintained the core objective of demonstrating link manager functionality across multiple links, including SATCOM, while adapting to the challenges encountered in the original plan. The use of Starlink and the relocation to Montana allowed the project to proceed with testing the link diversity system in a challenging environment, aligning with the BAA's primary goals.

4.3 Final Amendment to Data Collection Method

Weather conditions, particularly winds on Flathead Lake, prevented the completion of the test as originally planned. The limited testing we were able to conduct revealed technical challenges with landing the Watts quadcopter on the deck of the boat as it traversed Flathead Lake. Considering these obstacles, a final amendment to the data collection method was implemented.

4.3.1 Transition to Cessna 182 for Data Collection

With FAA approval, it was decided that a viable alternative was to proceed with the testing by installing a UAS autopilot (George G3), GPS, INS, and the C2 radios in a Cessna 182, which carries an experimental R&D certificate for equipment testing. This configuration allowed for safe evaluation of link performance without the VLOS and 400' altitude limitations of part 107.

4.3.2 Flight and Ground Control Setup

Flights would be conducted by a crew of two: one crewed part 61 PIC and one flight test engineer. A Ground Control Station (GCS) was set up at the office near Glacier International Airport (KGPI). The GCS would perform the same functions as if actively flying a UAS mission. The George autopilot was configured with a RTL timeout of 15 seconds, our primary TET parameter.

4.3.3 Equipment Integration

The entire UAS avionics suite was installed in the baggage compartment of the Cessna 182. LTE and C-Band antennas were installed on existing RF mounts on the belly of the aircraft, mirroring a configuration that would be feasible on a UAS platform. The Starlink SATCOM terminal was located in the rear window, positioned to simulate potential mounting on a larger UAS. This antenna arrangement was carefully designed to closely replicate the spatial relationships and orientations that would be present in a UAS configuration, ensuring that the data collected would be representative of actual UAS operations.

An APU was used for powering payloads and test avionics, ensuring no connection to the aircraft's systems, further simulating the independent power supply of a UAS. The total weight of the added equipment was less than 10lbs, having a negligible impact on weight and balance, which is crucial for maintaining flight characteristics similar to those of the intended UAS platforms.

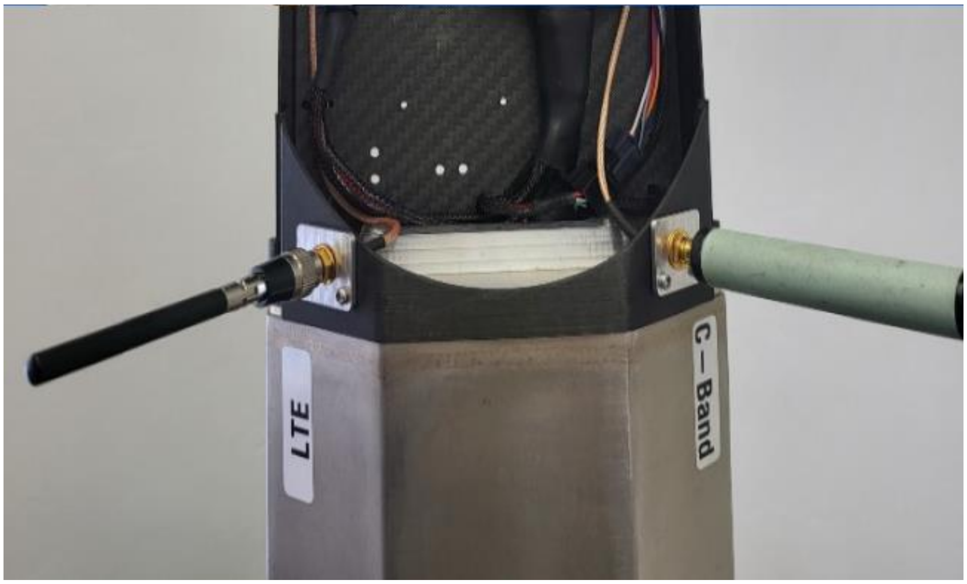

Figure 4-2 - Antenna Installations on SuperVolo

Figure 4-3 – Antenna Installations on Watts Quadcopter

Figure 4-4 - Antenna Installations on Cessna 182

These images demonstrate the progression of antenna installations from the originally planned SuperVolo platform, through the Watts Quadcopter, to the final Cessna 182 configuration. As can be seen, the antenna placements on the Cessna 182 closely mirror those of the UAS platforms, ensuring that the signal propagation characteristics and potential interference patterns would be similar to those experienced in an actual UAS operation.

4.3.4 Data Collection Process

SkyLine, the Command-and-Control Communications Service Platform (C2CSP), logged messages between the GCS and the UAS avionics. Aircraft and GCS heartbeats and commands sent by the operator were captured as if the aircraft was actively flying a UAS mission.

4.3.5 Supplementary UAS Data Collection

In addition to the crewed operation, limited data collection with a UAS was conducted in the same general area, utilizing the Pine Needle installed C-Band GRS infrastructure.

This final adaptation allowed for the collection of valuable data while overcoming the challenges posed by weather conditions and technical difficulties with the original UAS-based plan.

4.4 Impact on Project Timeline and Scope

The challenges encountered and subsequent revisions to the project plan had several impacts on the project timeline and scope:

- Extended Timeline: The period of performance for the contract was extended to accommodate the necessary changes and ensure the delivery of valuable results.
- Shift in Testing Location: Moving from Alaska to Montana required adjustments in logistics, regulatory compliance, and test planning.
- Change in UAS Platform: The transition from SuperVolo to Watts Prism Quadcopter necessitated new integration efforts and testing protocols.
- Adaptation of SATCOM Technology: Switching from L-Band to Starlink required modifications to both hardware integration and data analysis plans.
- Revised Flight Operations: The new plan for multiple short-duration flights, while still meeting the objective of demonstrating long-range BVLOS capabilities, required a different approach to data collection and analysis.

- Final Adaptation to Crewed Aircraft: The use of a Cessna 182 for data collection introduced new considerations, but the data collection methodology and its interpretation remain applicable to UAS operations whether the link was C2 or ride along.

Despite these changes, the core objectives of the project remained intact, focusing on demonstrating the effectiveness of the link manager across multiple communication links in challenging environments.

4.5 Summary of Adaptations and Solutions

In response to the challenges encountered, the project team implemented several key adaptations:

1. Technology Shift: Pivoted from L-Band SATCOM to Starlink, leveraging its different spectrum and promising performance characteristics.
2. Platform Change: Transitioned from SuperVolo to Watts Prism Quadcopter, offering greater flexibility for integrating new communication systems. Subsequently, adapted to using a Cessna 182 for data collection, maintaining applicability to UAS operations while overcoming environmental and technical challenges.
3. Location Relocation: Moved testing operations from Alaska to Montana, utilizing existing C-band licenses and suitable terrain for diverse link testing.
4. Test Plan Modification: Developed a new approach using multiple short-duration flights to simulate long-range operations, demonstrating the fused link's capabilities.
5. Timeline Extension: Worked with stakeholders to extend the project timeline, allowing for thorough implementation and testing of the revised plan.

These adaptations allowed the project to overcome initial setbacks and proceed with testing the link diversity system in a challenging environment, aligning with the BAA's primary goals of demonstrating multi-link management and SATCOM integration for enhanced C2 reliability in BVLOS operations.

5 System Overview and Integration

5.1 System Architecture Overview

To provide a clear visual representation of the integrated C2 link system, Figure 5-1 illustrates the overall system architecture. The integrated system combines cellular network, C-Band radio, and SATCOM technologies to form a unified C2 link. This architecture is designed to leverage both link and path diversity, significantly reducing the likelihood of link losses during extended BVLOS operations in challenging terrain.

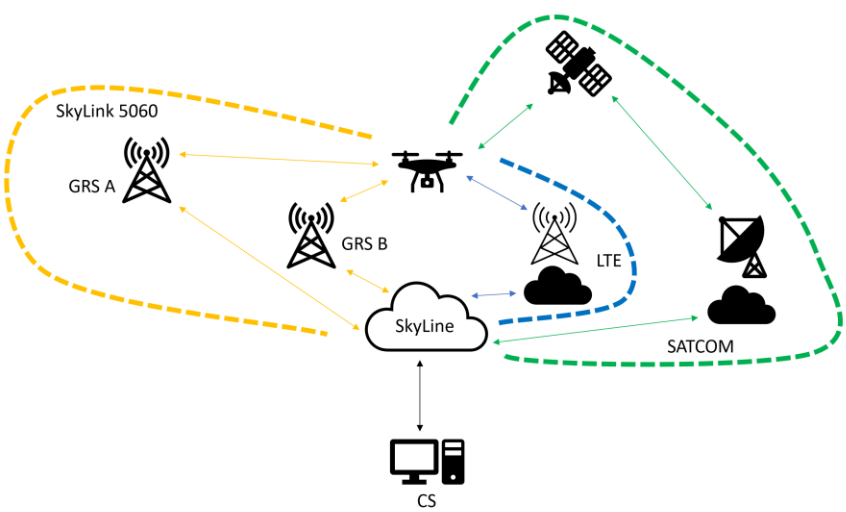

Figure 5-1 System Architecture Diagram

5.2 Components and Technologies

5.2.1 SkyLine C2CSP Operational Platform

SkyLine is a C2CSP operational platform that manages multiple GRS and ARS resources. It provides flight assurance through centralized management of the C2 infrastructure. Guided by DO-377A, the platform functions like an Uncrewed Traffic Management (UTM) platform in that it allows for the flight planning, initiation, monitoring, and termination of a UAS flight. The feature set is primarily focused on management of the C2 components, including managing and monitoring link quality, make-before-break roaming operations, backhaul data management, and network health and real-time status. SkyLine is available with a front-end web-based application or as an API interface for integration into a larger UTM system or similar application.

5.2.2 muLTElink + SATCOM

muLTElink is a multiple link airborne radio system that combines a DO-377A LEM with integrated LTE and C-Band C2 radios plus support for an external radio. Initially, this external link was specified as the SpaceLink Iridium (SATCOM) radio. However, as the program progressed and faced challenges with L-band integration, this was replaced with the Starlink system.

The Starlink terminal was chosen for its operation on a different spectrum, which avoided the interference issues encountered with L-band. Initial testing indicated that the Starlink link exhibited high-bandwidth and low-latency characteristics, making it a suitable alternative for demonstrating SATCOM integration in the multi-link system.

The muLTElink system, including the Starlink terminal, connects to the George G3 autopilot via a transparent RS-232 serial interface. This setup allows for seamless integration of the SATCOM link with the other communication technologies, enabling the LEM to effectively manage and switch between all available links as needed.

5.2.3 SkyStation-5060

The SkyStation-5060 family of products include a PoE tower-mounted GRS and an LTE-enabled portable GRS. All SkyStation-5060 products integrate seamlessly with SkyLine and integrate a DO-362A compliant ground radio system and GPS receiver.

5.2.4 Uncrewed Aircraft Platform

Initially, the project planned to use the SuperVolo, a durable, long-range Vertical Take-Off and Landing (VTOL) UAS with a hybrid gas/electric powerplant. The SuperVolo was modified to accommodate the Iridium-based SATCOM system.

Figure 5-2 - SuperVolo with Iridium antenna mounted

The integration of the SATCOM system required careful placement of components within the SuperVolo's airframe.

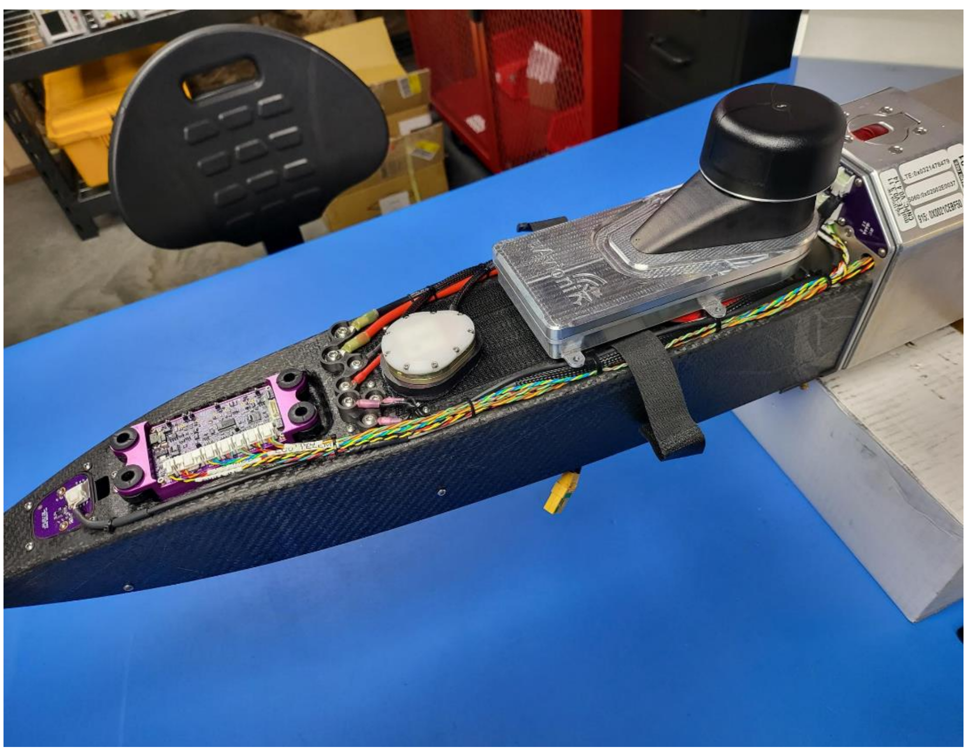

Figure 5-3 - SuperVolo interior showing autopilot, GPS, and Iridium-based SpaceLink

The LEM was a crucial component in the SuperVolo's communication system.

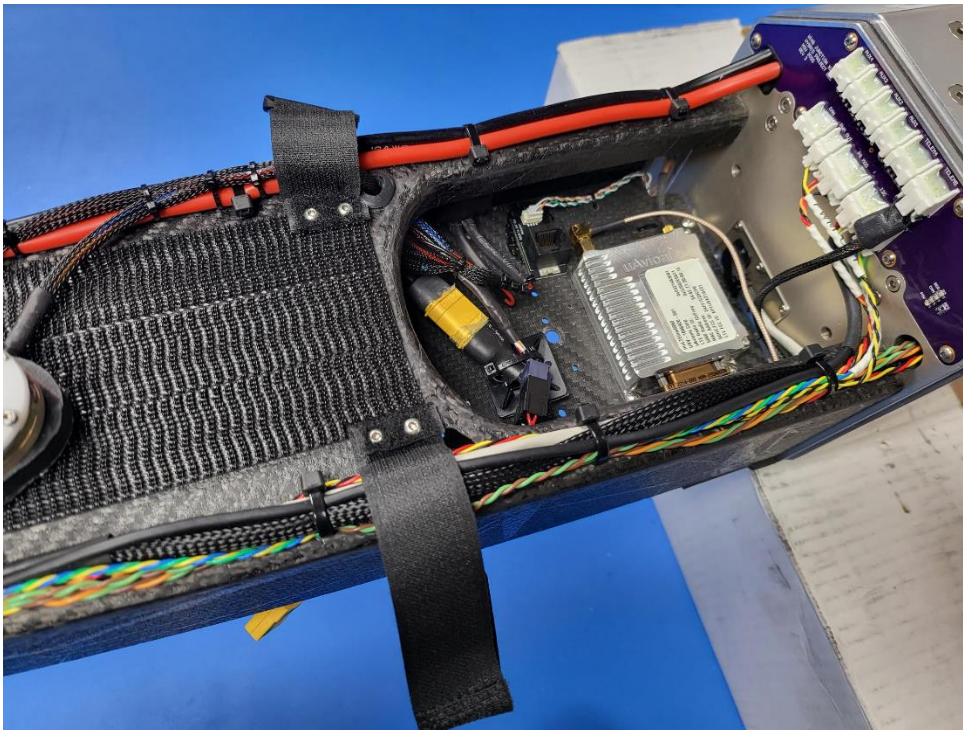

Figure 5-4 - LEM mounted in SuperVolo

As the project evolved, the SuperVolo was replaced with the Watts Prism Quadcopter, a highly versatile UA commercial platform designed to address package delivery and geospatial payloads for surveying projects. It features a configurable payload capacity ranging from 2.4 lb to 10.8 lb, depending on battery and endurance requirements. Its adaptable design made it an ideal test vehicle for integrating the Starlink antenna and other communication systems. Like the SuperVolo, it maintains VTOL abilities, crucial for the intended operations.

To accommodate the Starlink terminal, several modifications were made to the Watts Prism Quadcopter.

Figure 5-5 - Watts Prism Quadcopter with Starlink Mini Terminal mounted

To accommodate the Starlink terminal, several modifications were made to the Watts Prism Quadcopter. The Watts Prism Quadcopter was modified to accommodate the Starlink terminal. This involved custom mounting solutions to securely attach the Starlink antenna while maintaining optimal positioning for signal reception. Power system modifications were also made to support the additional power requirements of the Starlink terminal. The muLTElink system, including LTE and C-Band radios, was integrated into the Watts Prism Quadcopter's avionics bay. Careful consideration was given to the placement of additional components to maintain the aircraft's center of gravity and flight characteristics.

These adaptations allowed the Watts Prism Quadcopter to serve as a suitable platform for testing the multi-link C2 system, including the Starlink SATCOM capabilities, in a configuration representative of potential real-world BVLOS operations.

5.2.5 Cessna 182 Test Platform

As an alternative method to safely collect data and evaluate link performance, a Cessna 182 was utilized. This crewed aircraft, which carries an experimental R&D certificate for equipment testing, was adapted to simulate UAS operations. The Cessna 182 allowed for testing without the VLOS and 400' altitude limitations of part 107 operations.

Key aspects of the Cessna 182 test platform include:

- Installation of a UAS George autopilot, GPS, INS, and C2 radios in the aircraft's baggage compartment
- LTE and C-Band antennas installed on existing RF mounts on the belly of the aircraft
- Starlink SATCOM terminal located in the rear window
- Use of an APU for powering payloads and test avionics, ensuring no connection to the aircraft's systems
- Total weight of added equipment less than 10 lbs, ensuring negligible impact on weight and balance

Figure 5-6 - Starlink Terminal, autopilot, GPS and LEM installed in Cessna 182

Figure 4-4 illustrates the position of the C-Band and LTE antennas on the belly of the Cessna 182. This setup allowed for the simulation of UAS missions, with a crew consisting of one part 61 PIC and one flight test engineer. The Ground Control Station was set up at the office near Glacier International Airport (KGPI), performing the same functions as if actively flying a UAS mission. Mission profiles were intended to replicate UAS operations. UAS often carry remote sensing payloads which often have limitations on their ability to perform pitch and roll compensation. With this type of operation in mind the following limitations were communicated to the flight crew.

- Aircraft roll was requested to kept below 20 degrees
- Climbs and descents limited to 500 ft/min

- Ground speeds were to remain below 100mph/87kts
- Flight plans from the UAS GCS were loaded into the crewed team's electronic flight bag

The start of each simulated mission consisted of:

- Creation of a mission in the SkyLine C2CSP
- Connection of the GCS software to the aircraft
- Parameter exchange from flight controller (autopilot) to GCS
- Reading and writing mission waypoints from the GCS to the flight controller
- Placing the aircraft in an Auto flight mode
- Arming the aircraft

Occasional mode changes and waypoint commands were sent to the aircraft by the simulated RPIC. For example, changing the flight mode from Auto to Manual and verifying the command was sent and acknowledged. The GCS indicates the mode was sent by highlighting the mode in red. When the aircraft reports/acknowledges the mode has been received the mode indicator turns white. The RPIC reported no anomalies or unexpected delays with respect to the aircraft acknowledgment of commands during the simulated operations.

5.3 Data Link Architecture

5.3.1 muLTElink-5060 LEM (Airborne)

The muLTElink-5060 integrates an airborne LEM, as described in Appendix K of DO-377A, section K.6.2.2. It transmits and receives simultaneously on all available links, offering tri-band link diversity. Each link also transmits link statistics down to the ground. The muLTElink's telemetry port was connected to the uAvionix George G3 autopilot system and configured with a TET of 15 seconds.

5.3.2 SkyLine LEM (Ground-based)

The SkyLine C2CSP operational platform implements a LEM on the ground side, which individually monitors all available links for availability and continuity based on information received from the ARS. CNPC data is received by the muLTElink LEM from the ARS on all three links, and the link that is currently available and has the highest recent continuity is chosen to receive incoming data from. A similar operation is performed by the SkyLine LEM to choose the best uplink data path and enable transmission from the GRS to the ARS. Additionally, the SkyLine LEM implements path diversity through selection of the best GRS for each link when there are multiple, automatically roaming between individual ground stations as suitable.

5.3.3 Link Integration and Management

SkyLine performs the link management, enabling seamless switching between cellular, C-Band, and SATCOM links. It conducts real-time link quality assessment and optimization. The system ensures compliance with DO-377A standards for C2 link reliability.

6 Planning and Concept of Operations (CONOPS)

6.1 Project Planning Overview

The initial planning for this project centered on conducting flight testing in Alaska, specifically at ACUASI. This location was chosen to demonstrate the system's capabilities in an environment with notably challenged C2 connectivity due to limited cellular coverage and the prohibitive cost of tower installations. The primary objective was to carry out simulated inspections of the Trans Alaska Pipeline, which would provide a real-world scenario for testing the integrated C2 link system.

6.2 Flight Planning and C2 Coverage Strategy

6.2.1 Viewshed Analysis

Viewshed analysis was employed as a key tool in the planning process. This analysis leveraged field elevation data, known site information, and terrain models to determine optimal locations for C-Band Ground Radio Stations (GRS). The goal was to provide sufficient coverage of the chosen flight path while also incorporating deliberate gaps in coverage.

6.2.2 C-Band GRS Deployment

Two C-band radios were planned for use during the flights, with a third available to enhance coverage or create different coverage scenarios if needed. This setup was designed to force seamless and automatic switching between radios and GRS using the LEM, thereby testing the system's ability to ensure uninterrupted communication.

6.2.3 Anticipated GRS Installation Sites

For the demonstration, the following GRS installation sites were anticipated to be used:

- Poker Flat Launch Site
- Pump Station C-band
- Turning Point

6.2.4 C-Band Coverage Analysis

As part of the planning process, detailed analyses of C-band coverage for the proposed flight route were conducted. These analyses considered scenarios both with and without the inclusion of Pump Station 7, providing valuable insights into the expected communication coverage and potential challenges.

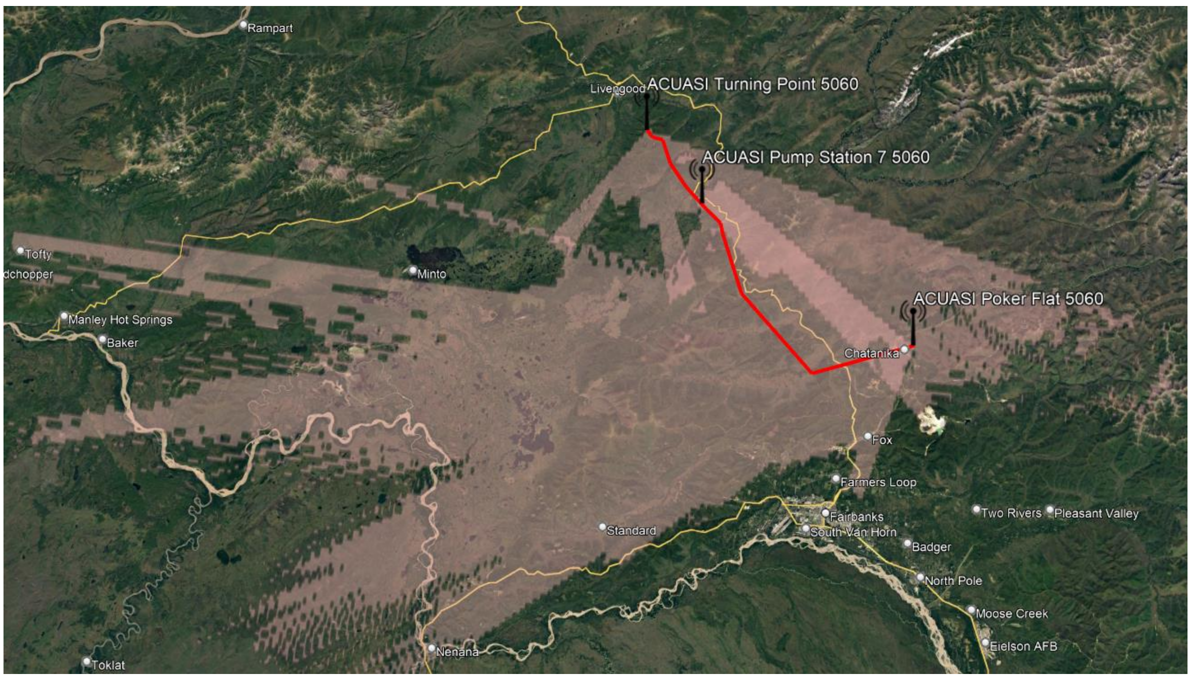

Figure 6-1 - C-band coverage and flight route

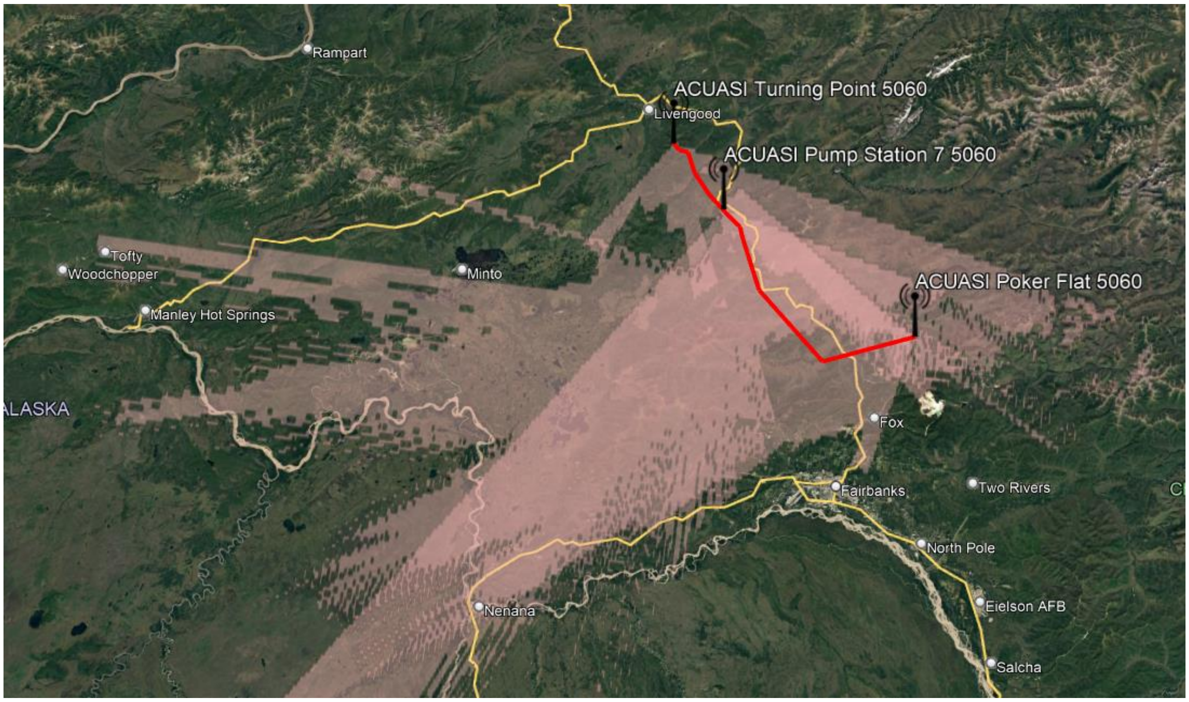

Figure 6-2 - Pump Station Coverage Added

These coverage analyses were crucial in determining optimal GRS placements and in planning for link transitions during flight operations. They also helped in identifying potential challenge areas where the LEM would need to manage seamless transitions between available links.

6.3 Link Diversity and Management

The flight plan was specifically designed to test the LEM's capability to manage multiple links and perform seamless transitions. By incorporating areas of varying coverage quality, the plan aimed to demonstrate the system's ability to maintain reliable communication in challenging terrain and connectivity environments.

6.4 Operational Objectives

The primary operational objective was to simulate pipeline inspection tasks while simultaneously evaluating the performance of the integrated C2 link system. This approach would allow for the assessment of the system's reliability and effectiveness in a scenario closely mimicking potential real-world applications of BVLOS UAS operations.

6.5 Pivot to Montana

Due to various challenges encountered with the initial Alaska-based plan, the project pivoted to conducting flight tests in Montana. This change necessitated a comprehensive re-analysis of the testing environment and strategy.

6.5.1 New Testing Environment

Flight testing was planned to be conducted under part 107 regulations over Flathead Lake in northwest Montana. This location was chosen for its unique characteristics. Terrain and distance variations create natural areas to demonstrate effective link management. The environment also offers opportunities for the vehicle to move in and out of C-band, LTE, and SATCOM availability.

6.5.2 Revised C-Band Coverage Strategy

In contrast to the multi-GRS setup planned for Alaska, the Montana tests were designed around a single C-Band radio. This adjustment was necessitated by the limitations of our Special Temporary Authority (STA), which only permitted the operation of a single GRS. Despite this constraint, we were able to design a test plan that would still effectively demonstrate the capabilities of our integrated C2 link system.

The single C-Band GRS was located at Pine Needle, situated at the top of a hill overlooking the northeast end of Flathead Lake, approximately 190' above the operations area. This strategic placement allowed us to maximize the coverage area while working within the constraints of our STA.

While the use of a single GRS presented some limitations compared to our original multi-GRS plan, it also provided an opportunity to test our system's performance in a scenario more typical of initial BVLOS deployments, where operators might begin with limited ground infrastructure. This setup allowed us to evaluate how effectively our LEM could manage transitions between C-Band, LTE, and SATCOM links as the aircraft moved in and out of the single GRS's coverage area.

6.5.3 Viewshed Analysis for Montana

Similar to the Alaska planning, viewshed analysis was conducted for the Montana location. The analysis leveraged field elevation data and known sites, and incorporated terrain models from available tools. The aim was to provide sufficient coverage while also incorporating deliberate gaps.

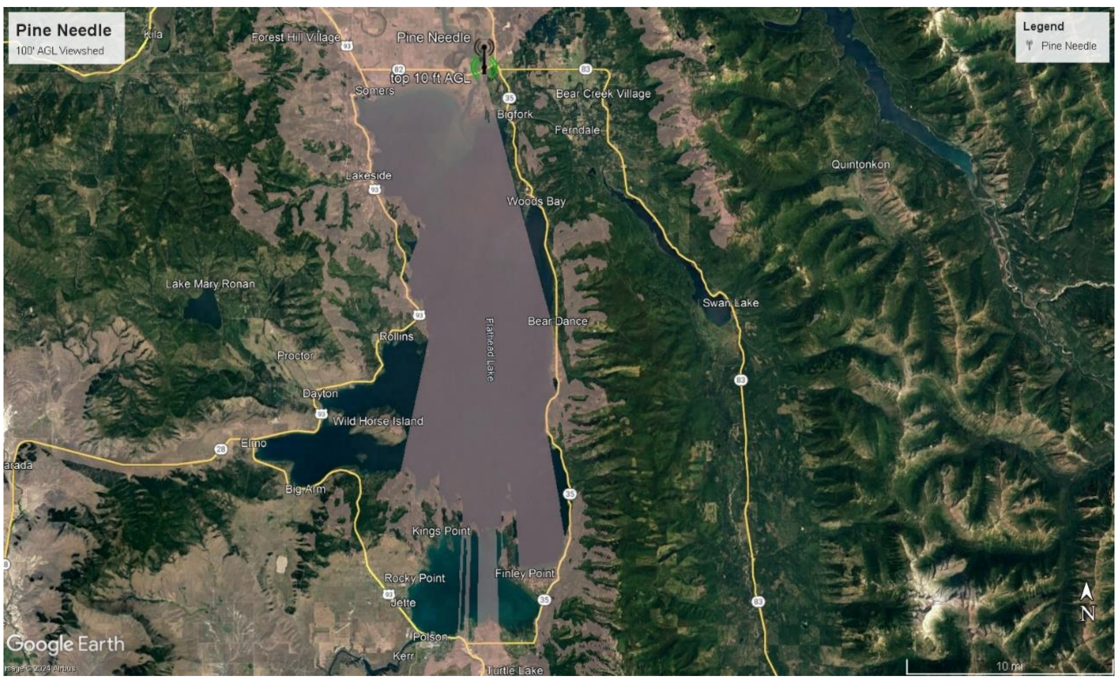

Figure 6-3 - Pine Needle C-Band Coverage (100' AGL)

Figure 6-4 - Pine Needle C-Band Coverage (400' AGL)

These images illustrate the expected C-band coverage for the Flathead Lake testing area at different altitudes, highlighting areas of strong signal, potential gap areas, and the range of the single GRS at Pine Needle site.

6.5.4 Link Management Objectives

The revised plan maintained the original objective of forcing seamless and automatic switching between different communication links. This included transitions between C-band, LTE, and SATCOM as the vehicle moves through areas of varying coverage. The plan continued to focus on demonstrating the effectiveness of the LEM in ensuring uninterrupted communication.

6.6 Adaption to Data Collection

Persistent challenges with weather conditions and technical difficulties in executing the UAS flights over Flathead Lake necessitated a final adaptation to our data collection method. This adaptation involved transitioning from UAS platforms to a Cessna 182 for data collection. This final adaptation allowed for the collection of valuable data while overcoming the limitations faced with the UAS platforms.

The Cessna 182, carrying an experimental R&D certificate for equipment testing, provided a viable alternative that allowed for safe evaluation of link performance without the VLOS and 400' altitude limitations of part 107 operations. This adaptation enabled us to collect data across a broader range of altitudes and distances, providing insights that would be applicable to future BVLOS UAS operations.

To understand the coverage area at different altitudes, viewshed analyses were conducted for the Pine Needle C-Band GRS. Interestingly, the viewsheds generated at our test altitudes of 4500' AMSL, 6500' AMSL, and 10000' AMSL were not noticeably different than those generated at 100' AGL (Figure 6-3) and 400' AGL (Figure 6-4). This suggests that terrain features, rather than altitude, were the primary factor affecting C-Band coverage in our test area.

The detailed CONOPS for the manned Cessna 182 flights, including the flight operations, equipment setup, ground control station configuration, data collection methodology, flight patterns, and link transition testing, are described in Section 4.3.

This adapted CONOPS allowed the project to meet its primary objectives of demonstrating and evaluating multi-link C2 performance, despite the challenges encountered with UAS operations. The use of a Cessna 182 enabled the team to collect data that closely simulated UAS operations while overcoming the environmental and technical obstacles faced during the project.

7 Demonstration Plan

7.1 Overview of Demonstration Evolution

The demonstration plan for this project underwent significant evolution in response to various challenges encountered during its execution. Initially, the contract was to be executed with the University of Alaska Fairbanks UAS Test Site, with UAS flight operations to be conducted under 14 CFR Part 107 and/or using the AK UAS Test Site's 49 USC 44803(c) Waiver. However, as the project progressed, circumstances necessitated a change in both location and executing organization.

The plan progressed through three distinct phases, each designed to showcase the capabilities of the integrated C2 link system:

1. Initial Alaska-based Demonstration
2. Revised Montana-based UAS Demonstration
3. Final Cessna 182-based Demonstration

Throughout these phases, despite the changes in location and methodology, the core objective remained consistent: to demonstrate the performance and reliability of the integrated C2 link system in challenging environments.

7.2 Initial Alaska-based Demonstration Plan

The initial demonstration plan centered on leveraging the unique terrain and infrastructure of Alaska to test the integrated C2 link system. This plan aimed to demonstrate the system's performance during simulated inspections of the Trans-Alaska Pipeline, showcasing its ability to maintain reliable communication in areas with limited connectivity and challenging terrain.

The plan called for 20 demonstration flights, each lasting at least 20 minutes. These flights were designed to utilize multiple GRS sites for C-Band coverage along the pipeline route. The flight paths were carefully planned to incorporate deliberate coverage gaps, allowing for comprehensive testing of the LEM capability to manage transitions between C-Band, LTE, and SATCOM links.

This initial plan was ambitious in its scope, aiming to validate the system's ability to maintain continuous C2 links during extended BVLOS operations across varied terrain and connectivity conditions. The involvement of the University of Alaska Fairbanks UAS Test Site was intended to provide valuable expertise and resources for conducting these complex operations in the challenging Alaskan environment.

7.3 Revised Montana-based UAS Demonstration Plan

As detailed in Section 4.1, various challenges necessitated a shift in the demonstration location from Alaska to Montana. Despite this change, the core objective of demonstrating link management across multiple links in a challenging environment was maintained. The revised plan, now to be executed by uAvionix, focused on showcasing the integrated C2 link system's performance in a new environment with its own unique challenges.

The Montana-based demonstration plan centered around a series of flights over Flathead Lake. The plan called for 20 short-duration flights, each lasting 15 minutes. These flights were designed to move in and out of C-band, LTE, and SATCOM coverage areas, providing ample opportunities to test the LEM's performance in managing link transitions.

While the terrain and operational environment differed from the original Alaskan setting, Flathead Lake and its surroundings offered their own set of challenges for maintaining reliable C2 links. This new setting allowed for a demonstration of the system's adaptability to different types of challenging environments, further validating its potential for diverse BVLOS operations.

7.4 Final Cessna 182-based Demonstration Plan

As explained in Section 4.3, persistent challenges with UAS flights led to a final adaptation of the demonstration plan. This revised approach involved using a Cessna 182 aircraft to simulate UAS operations, allowing for a comprehensive demonstration of the integrated C2 link system's performance across a broader range of altitudes and distances.

The Cessna 182-based demonstration plan involved multiple flights near Glacier International Airport (KGPI), with flight profiles designed to simulate UAS missions. The aircraft was equipped with the same C2 equipment intended for UAS use, including the muLTElink system, LTE and C-Band antennas, and a Starlink SATCOM terminal. This setup allowed for the collection of data that closely simulated UAS operations while operating beyond the limitations of part 107 regulations.

The proposed flight routes at three different altitudes (4500' AMSL, 6500' AMSL, and 10000' AMSL) are illustrated in Figure 7-1. The flight path at 4500' AMSL is in white, at 6500' AMSL in red and at 10000'AMSL in blue.

Figure 7-1 - Proposed flight routes for Cessna 182 demonstrations at 4500' AMSL, 6500' AMSL, and 10000' AMSL

Each flight was crewed by two personnel: one part 61 Pilot in Command (PIC) and one flight test engineer. A GCS was established near KGPI, performing the same functions as if actively flying a UAS mission. This arrangement allowed for a realistic simulation of UAS operations while ensuring the safety and control afforded by a crewed aircraft.

The flights were designed to test link transitions at various altitudes and distances from the GRS, providing a comprehensive dataset on the performance of the integrated C2 link system in varied flight conditions. This approach allowed for the validation of the system's capability to maintain reliable communication in a simulated BVLOS environment, even when operating at altitudes and distances not typically achievable with UAS under current regulations.

7.5 Data Collection and Analysis Plan

Throughout all demonstration phases, a consistent and comprehensive data collection and analysis approach was maintained. This approach was designed to gather detailed information on the performance of the integrated C2 link system across all flight conditions and link transitions.

The SkyLine platform was utilized for continuous recording of Operational User Data (OUD) and Operational Control Data (OCD). This data provided insights into the actual communication occurring between the ground and the aircraft, as well as detailed information about the state and performance of each communication link.

Key performance metrics as defined in RTCA DO-377A were collected, including Availability, Continuity, Integrity, and Latency. These metrics were crucial for assessing the overall performance of the C2 link system. Additionally, individual link performance data for C-Band, LTE, and SATCOM was recorded, allowing for comparative analysis of each communication technology.

The analysis plan focused on evaluating the performance of the LEM, particularly during link transitions. By correlating link performance with flight paths, terrain, and environmental factors, the plan aimed to provide a comprehensive understanding of the integrated C2 link system's capabilities in maintaining reliable communication during simulated BVLOS operations in challenging environments.

This data collection and analysis plan remained a constant throughout the project's evolution, ensuring that despite changes in location and methodology, the core objectives of the demonstration could be thoroughly evaluated and validated.

8 Results and Data Analysis

8.1 Overview of Flight Data Collection

This section presents the results and analysis of data collected during 15 test flights conducted as part of the Link Diversity Demonstration project. Detailed data for each individual flight can be found in Section 11, which provides comprehensive flight-by-flight breakdowns including tracks, link performance metrics, and message transmission data. These flights, carried out using a Cessna 182 equipped with UAS avionics and communication systems, were designed to simulate UAS operations and test the performance of our integrated C2 link system across various altitudes and terrains.

It's important to note that the data collection and analysis presented in this report is primarily from the perspective of the ground side. The data in the graphs is collected by the SkyLine LEM, as described in Section 5.3.2. The SkyLine LEM receives data on all three links (C-Band, LTE, and SATCOM) simultaneously and then selects which link to listen to, effectively choosing the primary downlink. A similar but reverse operation happens in the airborne LEM (Section 5.3.1), which selects the primary uplink. Because these are reciprocal but independent actions, we only need to look at one path to assess the performance of the link. This approach allows for a comprehensive evaluation of link performance from the ground control station's perspective, which is valuable for assessing the system's capability in real-world BVLOS operations.

8.1.1 Data Collection Methodology

For each flight, we collected comprehensive data including:

1. Flight identification and basic details (name, ID, date, time, duration, altitude)
2. Flight track information from three sources: George autopilot telemetry logs, ADS-B data and SkyLine C2CSP operational platform
3. Link performance metrics for individual links (C-Band, LTE, SATCOM) and the unified link
4. Message transmission data, including counts of messages received and lost

8.1.2 Performance Metrics

To evaluate the performance of our C2 link system, we utilized the key performance indicators as defined in RTCA DO-377A. These metrics were calculated for both individual links (C-Band, LTE, SATCOM) and for the unified link:

- **Availability**: The probability that an individual transaction can be initiated when needed for a C2 Link System that supports a specific UAS design for a reference operation.

- **Continuity**: The probability that an individual transaction will be completed before the RLP Transaction Expiration Time (TET), assuming the C2 Link System is available at the initiation of that single Transaction that supports a specific UAS design for a reference operation.
- **Integrity**: The probability that the C2 Link System does not cause an undetected error in an individual transaction that supports a specific UAS design for a reference operation.
- **Latency**: The time for 95% of the User Data to pass, one way, through the C2 Link System.

8.1.3 Data Analysis Approach

Our analysis focused on several key areas:

1. Evaluation of individual link performance (C-Band, LTE, SATCOM)
2. Assessment of the unified C2 link system performance
3. Verification of link transitions and LEM effectiveness
4. Calculation and interpretation of DO-377A performance metrics

This dataset enables us to evaluate the performance of individual communication links, assess the effectiveness of the LEM in managing transitions between links, and analyze the overall reliability and robustness of the integrated C2 link system.

In the following subsections, we will present detailed analyses of each flight, followed by aggregate data analysis, examination of environmental and operational factors affecting link performance, assessment of key performance indicators, and a summary of our findings.

8.2 Summary and Analysis of Demonstration Data

Our demonstration consisted of 15 flights, all conducted on October 8, 2024, over Flathead Lake and its surrounding terrain in Montana. These flights provided a comprehensive dataset across varied altitudes and geographic features, allowing us to thoroughly evaluate our integrated C2 link system's performance in a challenging environment. Detailed data for each individual flight, including flight tracks and link performance metrics, can be found in Section 11.

In analyzing the performance across these demonstration flights, it's important to note the specific identifiers for each radio type in the accompanying graphs:

- LTE Radio (0x0320873670): Represented by orange in the graphs
- C-Band Radio (0x010039001E): Represented by blue in the graphs
- SATCOM Radio (0x040021002B): Represented by green in the graphs

This color-coding allows us to clearly distinguish the performance characteristics of each link type throughout our analysis. The location of the C-Band GRS is identified by a red dot. The flights were conducted at multiple altitudes from ground up to10000 ft, providing insights into how altitude affects the performance of each link type.

The following subsections provide a detailed examination of key performance indicators and data transmission metrics for each radio type, as well as the overall integrated system performance. Our analysis considers how the system performed across different altitudes, varied terrain, and throughout the duration of the test flights.

8.2.1 Overview of Flight Tracks

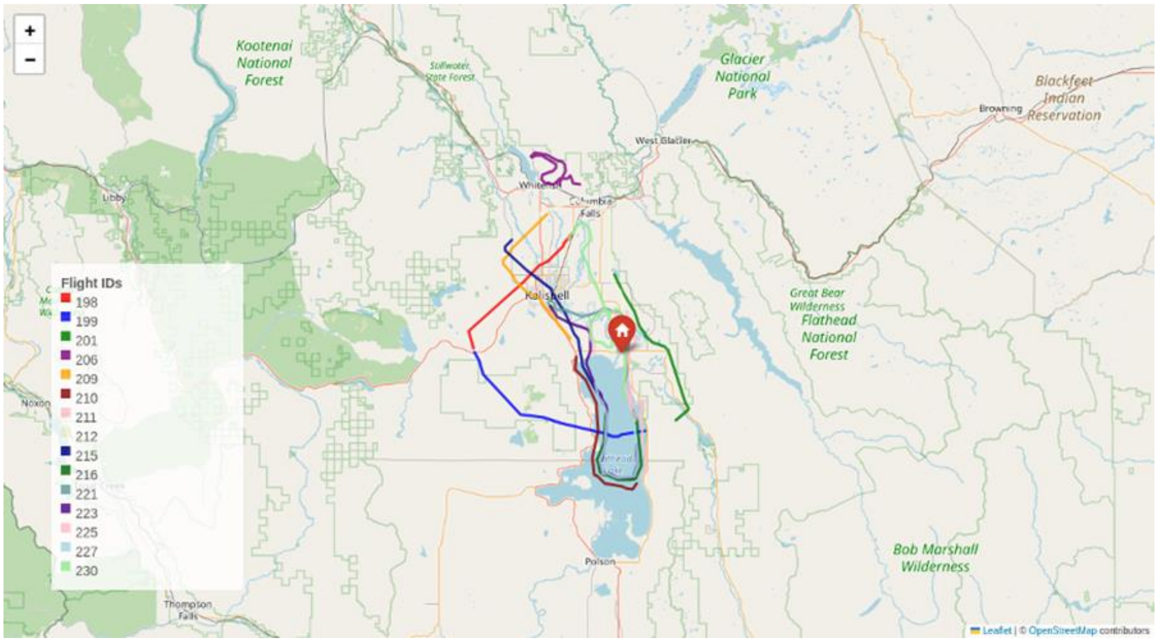

Figure 8-1 – Overview of Flight Tracks as recorded by SkyLine C2CSP operational platform

The track map in Figure 8-1 provides a comprehensive overview of all flight paths conducted during our demonstration flights. To better match the original statement of work, which called for shorter duration flights, new missions were started in Mission Planner for flights in 15-minute ride along segments during the broader Cessna flight. Individual flight tracks and detailed performance data can be found in Sections 11.1-11.15, organized chronologically by flight.

The red pin indicates the location of the C-Band GRS at Pine Needle. This visual representation offers valuable insights into the scope and diversity of our testing conditions:

1. **Geographical Coverage**: The flights covered a substantial area, primarily concentrated over Flathead Lake and its surrounding terrain. This diverse landscape allowed us to test our C2 link system in varied environmental conditions, from open water to more challenging mountainous terrain.
2. **Flight Patterns**: The map reveals a series of overlapping circular and linear flight patterns. These patterns were intentionally designed to: a) Simulate various real-world UAS mission profiles b) Test the C2 link system at different distances and orientations relative to our ground stations c) Ensure thorough coverage of the testing area to identify any location-specific performance variations
3. **Altitude Variations**: Our flight tracks included operations at multiple altitudes as seen in Figure 8-2 below. This vertical diversity allowed us to evaluate the impact of altitude on C2 link performance across our different radio types.
4. **Consistency and Repeatability**: The overlapping nature of many flight paths indicates repeated testing under similar conditions, enhancing the reliability of our data and allowing for the identification of consistent performance patterns.

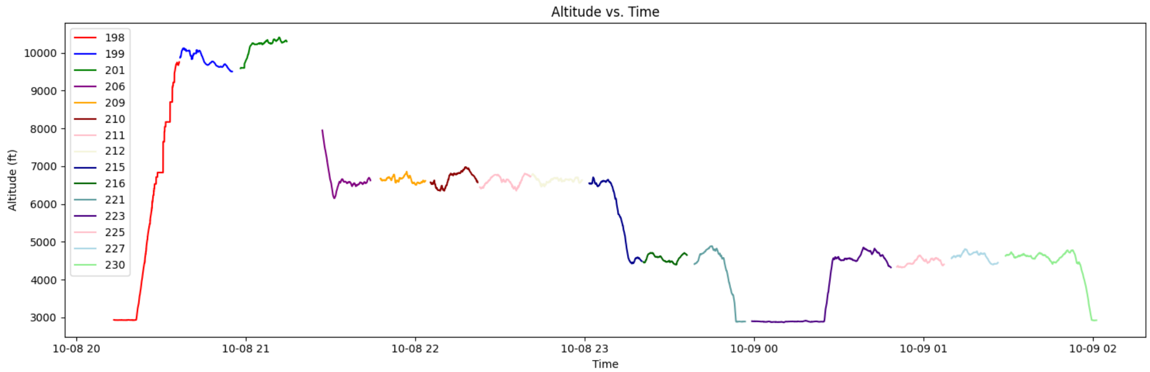

Figure 8-2 - Chart of altitudes for each flight track

Track	Duration (min)	Start Altitude (ft)	End Altitude (ft)	Distance Traveled (mi)	Start GRS Slant (mi)	End GRS Slant (mi)
198	23.1	2933	9754	21.6	16.7	19.5
199	18.5	9871	9504	27.4	19.3	10.9
201	16.5	9590	10300	23.2	11.6	10.5
206	17.1	7948	6621	21.2	22.8	23.5
209	15.9	6671	6612	22.3	20.6	7.0
210	16.7	6572	6571	23.0	6.0	17.6
211	18.0	6444	6731	25.0	16.7	5.5
212	17.8	6765	6628	24.2	6.2	20.8
215	18.6	6548	4486	26.7	20.7	7.3
216	15.4	4464	4648	22.6	8.0	7.8
221	18.0	4409	2889	21.6	3.9	11.0
223	49.2	2898	4320	34.8	11.0	12.3
225	16.7	4336	4401	23.6	9.2	3.5
227	16.4	4561	4445	23.6	5.2	9.9
230	32.2	4627	2923	42.8	6.1	16.7

This comprehensive set of flight tracks provided an ideal testing ground for our integrated C2 link system, allowing us to evaluate its performance across a wide range of operational scenarios and environmental conditions.

8.2.2 Key Performance Indicators Analysis

8.2.2.1 Availability

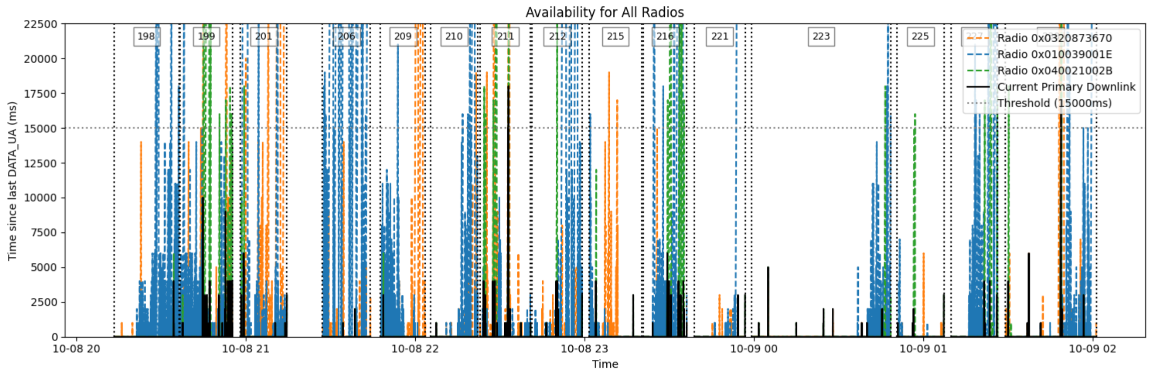

Figure 8-3 - Availability for All Radios

Figure 8-3 illustrates the availability of each radio type throughout our demonstrations. Availability in this context refers to the probability that an individual transaction can be initiated when needed, which was determined by the availability of any data reception within our configured TET of 15 seconds (the dotted horizontal line). Lower availability is better in the graph, lines that went above the TET would be considered unavailable. Our analysis of this data reveals several key insights.

The C-Band radio (blue) shows the lowest availability at approximately 90.19%. This limited performance was the direct result of our test flight's intended goal to maximize the reliance on the LTE and SATCOM links. This was accomplished by only utilizing a single C-Band GRS located in an area that would have ideal coverage over only a limited area of the test flight volume.

LTE availability (orange) is somewhat improved over C-Band at 97.37%. This high availability demonstrates the robustness of cellular networks for UAS communications, even in more remote areas like the Flathead Lake region. As can be seen in the graph though, LTE experienced frequent short outages likely due to the architecture of tower cell-based antennas being optimized for ground performance.

The SATCOM (Starlink) link (green) showed the best availability at 98.51%, likely due to the stability of the test flights and the continuous clear view of the sky.

Finally, the combined LEM-based availability (black) shows an exceptional overall availability of 99.98%. This is accomplished as a result of choosing the individual link as the primary based on if it is currently available. As seen in the graph there were only two instances where no links were available and there was a brief period of combined availability beyond our TET of 15 seconds.

The high availability when combined across all three radio types underscores the effectiveness of our multi-link approach. Even if one link experiences a brief unavailability, the other two links can maintain communication, enhancing overall system reliability. The availability percentages for all radio types exceed the typical requirements for safety-critical aviation communications, which often demand 99.9% availability. This performance suggests that our integrated C2 link system is well-suited for BVLOS operations, where maintaining consistent communication is crucial.

8.2.2.2 Continuity

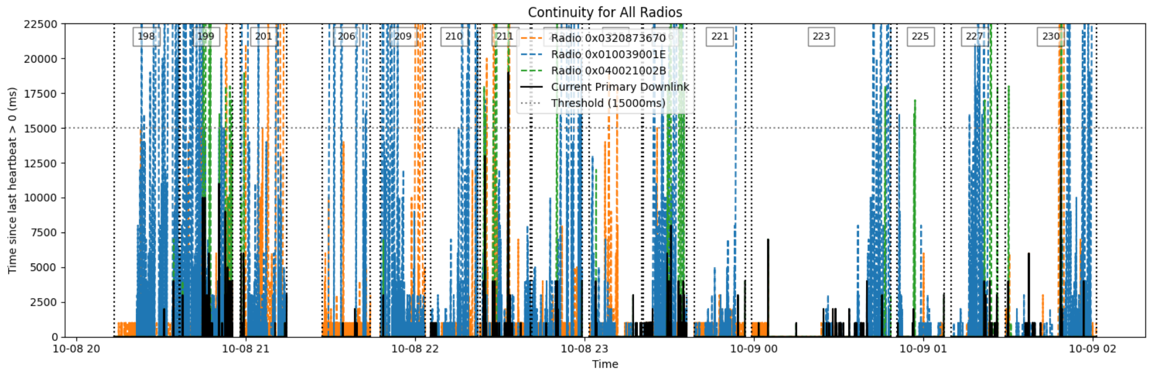

Figure 8-4 - Continuity for All Radios

Figure 8-4 illustrates the continuity performance of each radio type throughout our demonstrations. Continuity, in this context, refers to the probability that an individual transaction will be completed before the RLP TET, assuming the C2 Link System is available at the initiation of that single transaction. For our measurements we based this on the time since the last completed heartbeat transaction, which occurs once every second, and our TET set to 15 seconds.

The graph shows that all three radio types (C-Band, LTE, and SATCOM) demonstrate a continuity similar to the availability, which is logical given that an unavailable link also has no continuity. This performance indicates that once a transaction is initiated, it is highly likely to be completed successfully across all link types.

The C-Band radio (blue) exhibits the lowest continuity at approximately 84.54%. LTE (orange) has a continuity of about 96.75%. The SATCOM (Starlink) link (green) shows a continuity at around 98.18.

The combined LEM-based continuity (black) came in at 99.97%, again showing the value of using multiple links. This high continuity rate when using the best of three radio types further validate the robustness of our multi-link approach, ensuring that ongoing communications are rarely interrupted regardless of the active link.

8.2.2.3 Integrity

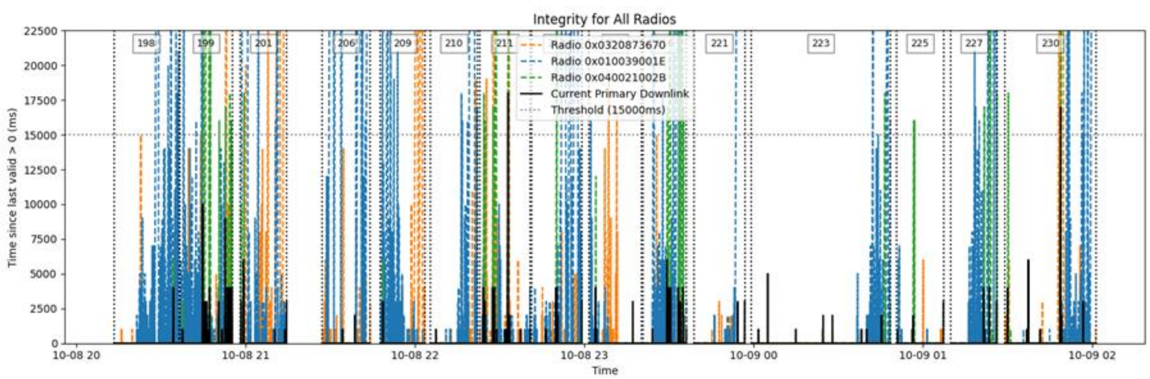

Figure 8-5 - Integrity for All Radios

Figure 8-5 presents the integrity measurements for each radio type. Integrity in the context of DO-377B refers to the probability that the C2 Link System does not cause an undetected error in an individual transaction. Since our flight operations were performed using Mission Planner with the MAVLink protocol which relies on 16-bit CRCs, one interpretation of Integrity would be that CRC's probability of an error, or 0.0015%. We chose instead to interpret Integrity as the measure of the time since the last validated error-free data was received, which is more interesting and relevant to individual link performance analysis.

The graph demonstrates that Integrity consistently performs worse concurrently to Availability and Continuity issues, as would be expected since those are times where a link is failing. During a total of over 4.3 total hours of flight test time, C-Band had almost 40 minutes total time with no valid messages, LTE with just over 8 minutes, and SATCOM with only 4 and a half minutes.

When combined, there were only 3 seconds that occurred which did not have valid data within our TET. This high Integrity across all radio types underscores the reliability and accuracy of our integrated C2 link system, which is crucial for ensuring the safety and effectiveness of BVLOS operations.

8.2.2.4 Latency

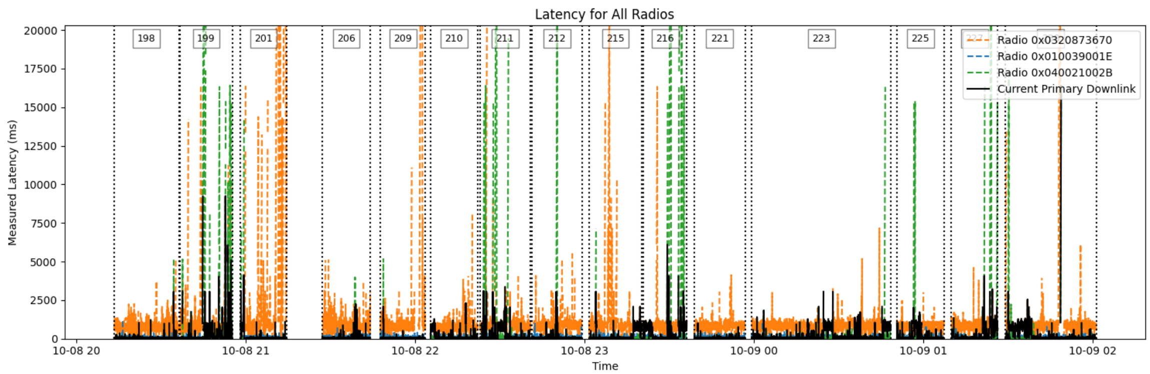

Figure 8-6 - Latency for All Radios

Figure 8-6 illustrates the latency performance of each radio type. Latency here represents the time taken for 95% of the User Data to pass, one way, through the C2 Link System from the aircraft to the ground systems.

The graph reveals distinct latency characteristics for each radio type:

1. The C-Band link (blue) demonstrates the lowest latency at an average of 25ms due to the DO-362A 50ms TDD scheme ensuring a guaranteed delivery time window for all data when the radio link is up. This low latency is a significant advantage for applications requiring a rapid response.
2. The LTE link (orange) shows notable latency spikes of over our TET of 15 seconds. It also has a higher average latency of approximately 1s even when the connection is stable just due to the inherent architecture of 4G LTE.
3. The SATCOM (Starlink) link (green) also exhibits numerous latency spikes but when the connection is stable it has an average latency of <100ms. This performance is particularly impressive for satellite communications. To put this in perspective, other L-band SATCOM links we tested in previous experiments demonstrated latencies over 1s on average and often 5 to 10 seconds. The Starlink system's latency, being more than 10 times lower, represents a significant advancement in SATCOM technology for UAS applications.

When combined the overall latency was within our TET 99.98% of the time. The variation in latency across link types highlights the importance of our multi-link approach. In Section 9.3 we discuss potential LEM enhancements to allow the system to prioritize lower-latency links when available while maintaining connectivity through higher-latency links when necessary.

The consistently low latencies across all radio types, particularly for C-Band and SATCOM, suggest that our integrated C2 link system can support a wide range of UAS applications, including those requiring near-real-time responsiveness. Furthermore, the impressive performance of the Starlink SATCOM link opens new possibilities for reliable, low-latency BVLOS operations in areas where terrestrial communications may be limited or unavailable.

8.2.3 Data Transmission Performance

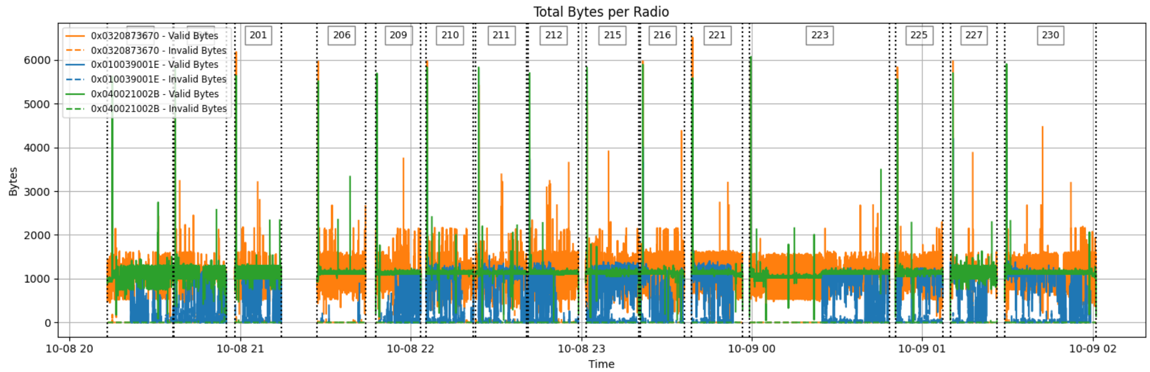

Figure 8-7 - Total Bytes per Radio

Figure 8-7 illustrates the total volume of data transmitted by each radio type during our demonstration flights, distinguishing between valid and invalid bytes. This data provides crucial insights into the efficiency and reliability of each link type within our integrated C2 system.

Key observations from this graph include:

1. **Overall Data Volume**: The LTE (orange) data transmissions showed a lot of variability (due to the aggressive scheduling of cell network data links).SATCOM (green) had the most consistency, with C-Band radio (blue) having the most inconsistency due to the use of a single GRS with limited coverage.
2. **Data Validity**: While not as visible in this combined graph (but more useful in the individual flight segments later in the report), the vast majority of transmitted bytes were valid indicating high data integrity and efficient use of bandwidth. This corroborates the high integrity rates observed in our earlier analysis.

The distribution of data across the three radio types reflects our multi-link strategy. LTE provides widespread coverage, C-Band serves as a consistent low-latency link when within range of ground stations and SATCOM enables extended connectivity, especially in areas beyond terrestrial network coverage.

This data transmission analysis demonstrates the effectiveness of our integrated C2 link system in leveraging the strengths of each radio type. The high proportion of valid bytes across all links indicates that the system efficiently manages data flow, likely contributing to the high availability, continuity, and integrity observed in our earlier analyses.

8.2.4 LEM Performance

A key component of our integrated C2 link system is the LEM, which is responsible for managing transitions between different communication links to ensure continuous and optimal connectivity. The performance of the LEM is critical to the overall effectiveness of our multi-link approach.

Throughout our demonstration flights, the LEM demonstrated several key capabilities:

1. **Seamless Link Transitions**: The LEM successfully managed transitions between C-Band, LTE, and SATCOM links without any noticeable interruptions in communication. This seamless switching is evident in the high availability and continuity rates across all flight scenarios.
2. **Rapid Response to Changing Conditions**: The LEM showed the ability to quickly respond to changing signal conditions, such as when the aircraft moved in and out of C-Band coverage areas or experienced variations in LTE signal strength.
3. **Optimal Link Selection**: By analyzing the performance data, we can infer that the LEM consistently made link selections based on qualification (receiving data) and quality (primarily signal strength).

4. **Maintenance of Communication Integrity**: The high integrity rates across all link types suggest that the LEM successfully maintained data integrity during link transitions, preventing data loss or corruption.

To illustrate these capabilities, we present two case studies from our flight data where we observed particularly interesting link transition behavior. To illustrate these capabilities, we present two case studies from our flight data where we observed particularly interesting link transition behavior. The first case study examines Flight 227 (Section 11.14), which demonstrates dynamic link transitions during extended flight operations. The second analyzes Flight 211 (Section 11.7), showcasing multi-link utilization in proximity to the GRS.

In these analyses, it's important to note that the background color of the graphs indicates the primary downlink radio being used at that time (blue for C-Band, green for SATCOM, and orange for LTE).

8.2.4.1 Case Study: Dynamic Link Transitions During Extended Flight

During Flight 227 (Section 11.14), between 01:21 and 01:25, we observed a series of transitions between SATCOM and LTE links that effectively demonstrate our system's ability to adapt to changing link conditions.

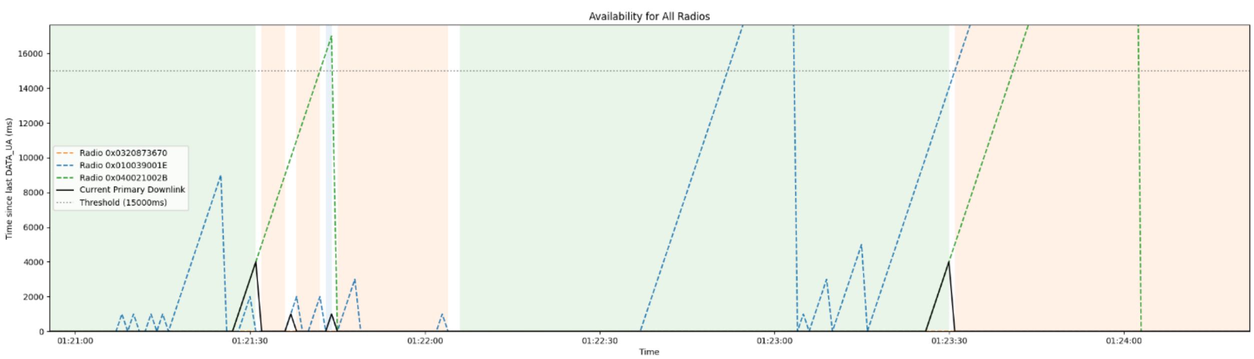

Figure 8-8 - Flight 227 Availability

During this period, the LEM executed multiple transitions between SATCOM (shown in green) and LTE (shown in orange) based on link performance degradation. These transitions show the system actively managing communication paths to maintain connectivity, switching from SATCOM to LTE, back to SATCOM, and again to LTE. At each link transition, we observe the deterioration of the availability (and other key performance indicators) of the link the LEM is switching away from. While C-Band (shown in blue) generally had poor availability during this segment, there was one brief transition to C-Band at 01:21:45 when both LTE and SATCOM became temporarily unavailable. It's noteworthy that despite these multiple transitions between links, the fused link maintained availability well below our TET of 15 seconds (shown by the dotted horizontal line), demonstrating the effectiveness of the LEM's link selection strategy. However, as discussed in Section 9.3, there are opportunities to enhance the LEM algorithm further by incorporating additional metrics into the link selection decision process.

8.2.4.2 Case Study: Multi-Link Utilization in Proximity to Ground Station

A particularly interesting example of the system's link management capabilities can be observed in Flight 211 (Section 11.7) between 22:26 and 22:33. During this brief but notable period, the system utilized all three available links while operating in close proximity to the C-Band GRS (indicated by the green tower in Figure 8-9).

Figure 8-9 - Flight 211 Flight Path and C-Band GRS

This segment is especially significant because it demonstrates the system's ability to manage all three links simultaneously and make selection decisions based on link qualification and quality measurements in a scenario where all links were available.

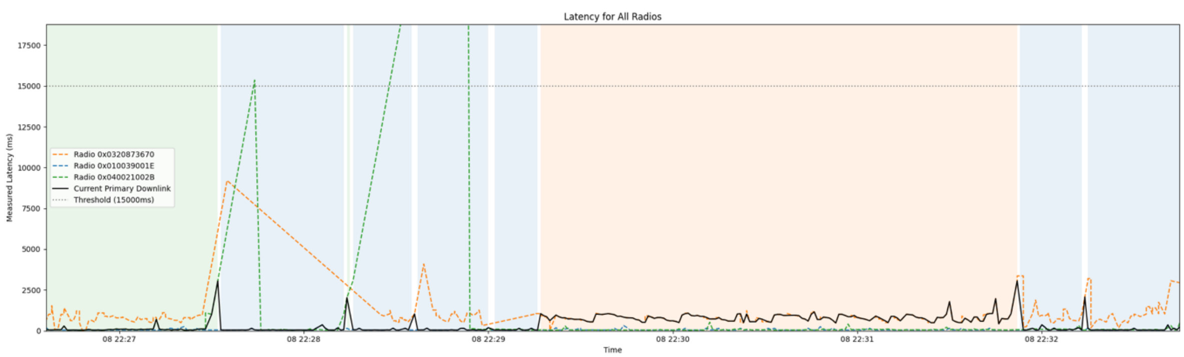

Figure 8-10 – Flight 211 Latency

This segment is especially significant because it demonstrates the system's ability to manage all three links simultaneously and make selection decisions based on link qualification and quality measurements in a scenario where all links were available. As shown in Figure 8-9, the flight path moves from south to north, with the primary link starting as SATCOM at the beginning of the flight segment. At the first link transition to C-Band, we observe an increase in latency on both the SATCOM and LTE links prior to the switch. At the second link switch, to LTE, we see the primary latency increase to track with the LTE latency measure. Notably, during this period, SATCOM appeared to maintain lower latency, suggesting it might have been a better choice for primary link. This observation directly influenced our recommendations for enhancing the LEM algorithm to consider link latency in its decision-making process, as discussed in Section 9.3. The final selection, back to the C-Band link, reduces the primary link latency back to the lower C-Band latency.

Overall, the LEM's performance was crucial in achieving the high reliability and consistency observed in our integrated C2 link system. Its ability to manage multiple diverse links effectively demonstrates the viability of our approach for maintaining robust communications in challenging and varied BVLOS operational environments. However, this flight segment also highlighted opportunities for further optimization of the link selection process.

8.3 Overall Integrated C2 Link System Performance Summary

The comprehensive analysis of our demonstration flights reveals that the integrated C2 link system, combining C-Band, LTE, and SATCOM (Starlink) technologies, performed exceptionally well across a variety of operational scenarios. Key findings include:

1. **High Reliability**: The three radio types maintained individual availability rates above 90%, with C-Band at 90.19%, LTE at 97.37%, and SATCOM at 98.51%. The use of multiple links managed by the LEM achieved a remarkable combined availability of 99.98%, demonstrating the effectiveness of our multi-link approach.
2. **Robust Continuity**: The performance analysis showed C-Band continuity at 84.54%, LTE at 96.75%, and SATCOM at 98.18%. The combined LEM-based continuity reached 99.97%, highlighting how the multi-link system effectively maintains communications even when individual links experience interruptions.
3. **Exceptional Integrity**: During the total of over 4.3 hours of flight test time, C-Band had almost 40 minutes total time with no valid messages, LTE with just over 8 minutes, and SATCOM with only 4.5 minutes. When combined through the LEM, there were only 3 seconds that occurred which did not have valid data within our TET.
4. **Low Latency Performance**: The multi-link approach provided consistent low-latency options, with C-Band demonstrating the lowest average latency at approximately 25ms, SATCOM (Starlink) impressively averaging under 100ms when stable, and LTE showing higher but manageable latency averaging around 1s. These latency characteristics allowed the system to maintain responsive control across various operational scenarios.
5. **Efficient Data Transmission**: The system demonstrated effective data handling across all links, with the LTE data transmissions showing high variability, SATCOM demonstrating the most consistency, and C-Band showing variability due to the single GRS with limited coverage. The vast majority of transmitted bytes were valid, indicating high data integrity and efficient use of bandwidth.
6. **Effective Link Management**: The LEM successfully managed transitions between links based on qualification (receiving data) and quality (signal strength), ensuring optimal connectivity throughout the flights. The LEM's performance was crucial in achieving the high combined availability and continuity rates observed across all test scenarios.

The integrated C2 link system's performance consistently exceeded typical requirements for safety-critical aviation communications. The multi-link approach proved highly effective, providing redundancy and allowing for seamless transitions between different communication technologies. This adaptability ensures reliable connectivity across varying distances, altitudes, and geographical locations.

The system's robust performance, particularly the impressive capabilities of the Starlink SATCOM link, opens up new possibilities for reliable, low-latency BVLOS operations in areas where terrestrial communications may be limited or unavailable.

In conclusion, the demonstration results strongly support the viability of this integrated C2 link system for enhancing the safety, reliability, and operational capabilities of BVLOS UAS operations across a wide range of scenarios and environments.

9 Discussion of Findings

9.1 Implications for BVLOS Operations

Our integrated C2 link system directly addresses the challenges outlined in the project background:

1. **Multi-Link Integration**: We successfully demonstrated the integration of cellular network (LTE), C-Band radio, and SATCOM into a unified C2 link. This approach significantly mitigates the risks associated with relying on a single active C2 link, as is common in many current BVLOS operations.
2. **Spectrum Diversity**: By incorporating LTE, C-Band, and SATCOM (Starlink), our system provides true spectrum diversity. This diversity proves crucial in maintaining reliable communications across varying geographical and operational conditions.
3. **Dynamic Link Management**: The LEM demonstrated effective, automatic switching between radios, eliminating the need for manual RPIC intervention. This represents a significant advancement over current practices where pilots manually switch between primary and secondary links.
4. **Alternative to L-Band SATCOM**: While we shifted from L-Band to Starlink SATCOM due to GPS interference issues, the principle of providing alternatives to traditional L-Band SATCOM for extended range operations was upheld. The Starlink link's performance, particularly its low latency, suggests it could be a viable or even superior alternative in many scenarios.
5. **Consistent Performance in Challenging Environments**: Although we relocated from Alaska to Montana, our system still demonstrated high availability and predictable C2 performance in challenging terrain. This success suggests potential applicability in various remote and difficult environments.

Limitations and areas for further development include testing in more diverse environments. While Montana provided challenging terrain, future tests in a wider variety of environmental conditions would be beneficial for further validating the system's performance and adaptability

9.2 Comparison with Initial Expectations

Our project outcomes largely aligned with or exceeded initial expectations:

1. **Link Integration and Diversity**: We successfully integrated cellular, C-Band, and SATCOM links, achieving the primary goal of leveraging link diversity to minimize lost link risks.
2. **Automatic Switching**: The LEM performed exceptionally well in managing seamless, automatic transitions between links, meeting a key project objective.
3. **Performance Metrics**: Our system demonstrated high availability, continuity, and integrity across all links, adhering to the standards outlined in DO-362A and DO-377A.
4. **Data Generation**: We successfully generated comprehensive data sets showing the performance of individual links (LTE, C-Band, Starlink SATCOM) and the effectiveness of the fused C2 link.

Unexpected findings and adaptations include the move from L-Band to Starlink SATCOM, which, while unplanned, resulted in better-than-expected performance, particularly in terms of latency. Additionally, despite relocating from Alaska to Montana, we were able to test in environments that still presented significant challenges for achieving RF path and link diversity.

9.3 Lessons Learned and Future Directions

Key takeaways from this project include:

1. **Value of Multi-Link Redundancy**: The project reinforced the importance of link diversity in ensuring reliable BVLOS communications.
2. **SATCOM Potential**: The impressive performance of the Starlink link highlighted the evolving potential of satellite communications in UAS operations.
3. **Importance of Intelligent Link Management**: The LEM's effectiveness demonstrated the crucial role of smart switching algorithms in optimizing multi-link systems. However, our analysis also revealed opportunities for enhancing the LEM's decision-making process.

4. **Adaptability to Varied Environments**: The system's consistent performance across different altitudes and terrains underscored the importance of adaptability in C2 link systems.
5. **LEM Algorithm Improvement Opportunity**: Our current LEM algorithm bases link selection on qualification (receiving data) and quality (primarily signal strength). We have signal strength data for C-Band and LTE links, but not for SATCOM. This leads to a bias where SATCOM is often preferred, as it's never considered poor quality. Our analysis suggests that incorporating latency as an additional metric could enhance link selection decisions. Furthermore, implementing a weighting system could allow for preferential selection of terrestrial networks (C-Band and LTE) over SATCOM when multiple links meet quality thresholds, potentially reducing operational costs and network congestion.

Based on these lessons, we've identified two key areas for future development and research:

1. **Enhanced LEM Algorithm**: Developing an improved link selection algorithm that incorporates latency and link preference alongside availability and signal strength. This would involve utilization of the continuous latency measurements we already collect for all link types and creation of a weighted scoring system balancing signal strength and latency. Prioritization of links could be solely based on Skyline’s static understanding of the link characteristics or could accept operator input to prefer one link over another based on the operator’s knowledge of the performance and operational cost of the underlying links.
2. **Further SATCOM Exploration**: Given the promising performance of Starlink, investigating other emerging SATCOM technologies that could potentially enhance BVLOS C2 capabilities, particularly in remote areas.

These focal points for future work will build upon the insights gained from this project, further refining our integrated C2 link system to provide even more robust and efficient communication solutions for a wide range of UAS applications.

10 Conclusions and Recommendations

10.1 Conclusions

The Link Diversity Demonstration project has successfully showcased the potential of an integrated, multi-link C2 system for enhancing BVLOS UAS operations. Our demonstration proved the feasibility and effectiveness of integrating cellular network (LTE), C-Band radio, and SATCOM into a unified C2 link. This integrated approach significantly enhances communication reliability and robustness for BVLOS operations.

The LEM demonstrated its capability to manage seamless, automatic transitions between different communication links. This dynamic management represents a significant improvement over manual link switching, potentially reducing operator workload and enhancing safety. The integrated C2 link system consistently achieved high availability (>99% for all links), continuity, and integrity across various operational scenarios. These performance levels meet or exceed typical requirements for safety-critical aviation communications.

The unexpected shift to Starlink SATCOM revealed promising capabilities, particularly in terms of low latency (approximately 60ms). This performance suggests that newer SATCOM technologies could play a more significant role in BVLOS operations than previously anticipated. Despite relocating from Alaska to Montana, the system demonstrated robust performance in challenging terrain, indicating its potential applicability across diverse operating environments.

Importantly, the system's performance adhered to the requirements outlined in DO-362A and DO-377A, validating its potential for integration into standardized UAS operations.

10.2 Recommendations

Based on the outcomes of this project, we propose several key recommendations for future work. First, we recommend conducting expanded environmental testing in a wider variety of conditions, including areas with limited cellular coverage, varied terrain, and diverse weather conditions. This will help validate the system's performance across a broader range of potential operating scenarios.

To fully assess the system's performance over longer periods and greater distances, we suggest planning and executing long-duration BVLOS flights. This will be particularly relevant for applications such as long-range infrastructure inspections or delivery operations.

During the data and performance analysis we had to interpret the definitions in DO-377B for Availability, Continuity, Integrity, and Latency, as they don't readily apply to a protocol like MAVLink where there is only a singular global timeout for a mission abort. These issues are well known with the RTCA SC-228 WG-2 members where discussions are actively progressing on a supplementary document that will provide additional context for applying those definitions to traditional communication technologies. DO-362A performance was excellent, no recommendations, the specification is extremely well designed.

Lastly, given the promising performance of Starlink, we recommend further exploration of other emerging SATCOM technologies. This investigation could potentially enhance BVLOS C2 capabilities, particularly in remote areas where terrestrial communication infrastructure is limited.

By addressing these recommendations, we can further refine and validate this technology, paving the way for its widespread adoption in the rapidly evolving UAS industry.

11 Appendix A: Demonstration Data

This section presents detailed data from the 15 individual flights conducted as part of our Link Diversity Demonstration project. The data presented here directly supports the analysis and conclusions discussed in Section 8, providing a comprehensive record of our system's performance across different operational scenarios. All flights were performed on October 8, 2024, over Flathead Lake and its surrounding terrain in Montana. These flights, carried out at various altitudes, provided a comprehensive data set for evaluating our integrated C2 link system's performance across different environmental conditions.

In the graphs that follow, each radio type is represented by a specific color:

- LTE Radio (0x0320873670): Represented by orange in the graphs
- C-Band Radio (0x010039001E): Represented by blue in the graphs
- SATCOM Radio (0x040021002B): Represented by green in the graphs

This color-coding allows for easy visual distinction between the performance characteristics of each link type throughout our analysis. The background color of the graphs indicates the primary downlink radio being used at that time. The location of the C-Band GRS is identified by a red dot, when within the map area.

For each flight, we present the following information:

1. Flight Details: Including date, time, duration, and altitude
2. Flight Track: As recorded by the SkyLine C2CSP operational platform
3. Link Performance: Graphs showing Availability, Continuity, Integrity, and Latency for each radio type
4. Message Transmission Data: Illustrating the total bytes transmitted by each radio type

It's important to note that all data presented here is from the perspective of the ground side, collected by the SkyLine LEM as described in Section 5.3.2. The LEM attempts to receive data on all three links simultaneously and then selects the primary downlink based on its link selection algorithm.

The following subsections provide a flight-by-flight breakdown of our demonstration data, offering insights into the performance of our integrated C2 link system across various operational scenarios.

11.1 Flight 198: ACUASI 8500-10000 03

11.1.1 Flight Details

Detail	Value
Date	10/8/2024
Time	14:13:23 to14:36:30
Duration	23 min 7 secs
Altitude	9800 - 10000ft

11.1.2 Flight Track

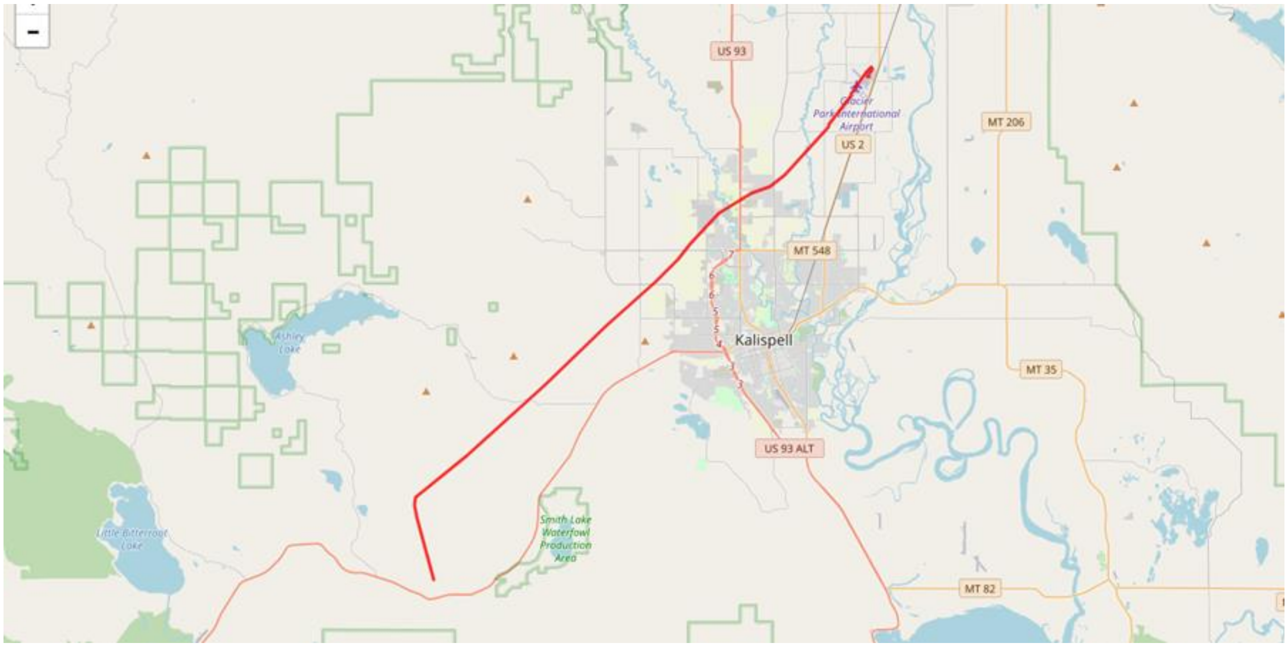

Figure 11-1 - Flight Track for Flight 198 as recorded by SkyLine C2CSP operational platform

11.1.3 Link Performance

11.1.3.1 Availability

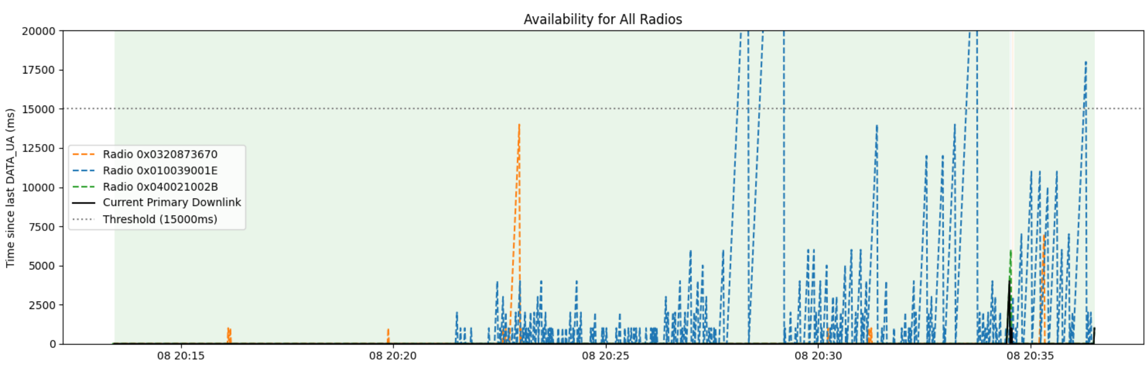

Figure 11-2 - Availability for Flight 198

11.1.3.2 Continuity

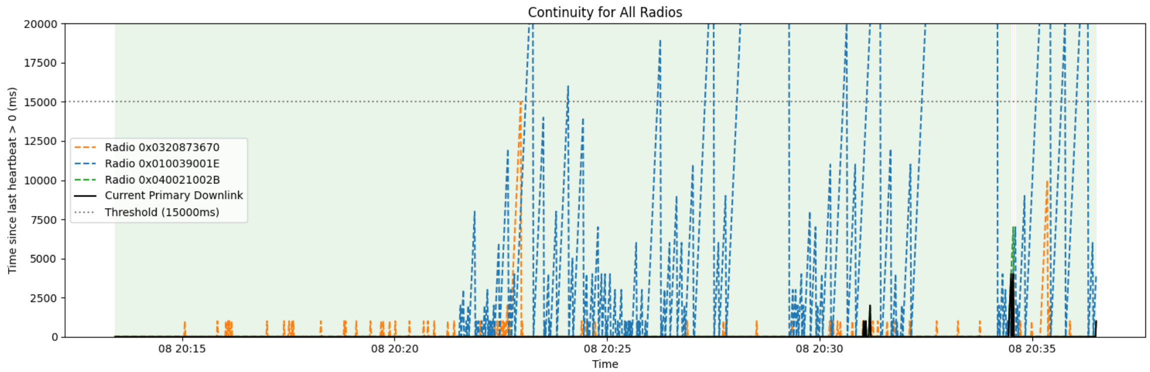

Figure 11-3 - Continuity for Flight 198

11.1.3.3 Integrity

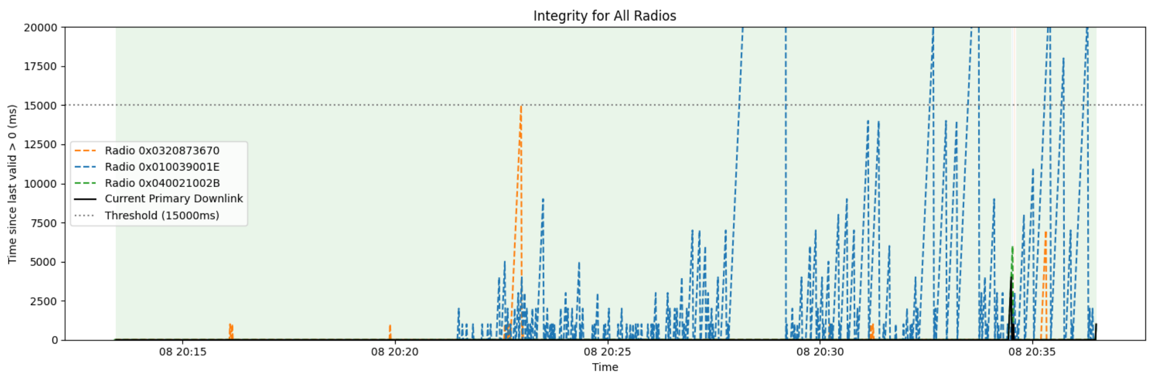

Figure 11-4 - Integrity for Flight 198

11.1.3.4 Latency

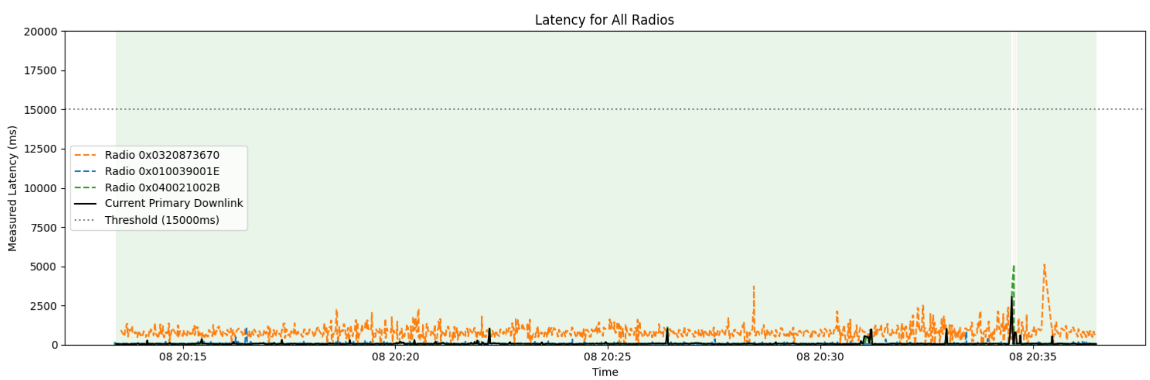

Figure 11-5 - Latency for Flight 198

11.1.4 Message Transmission Data

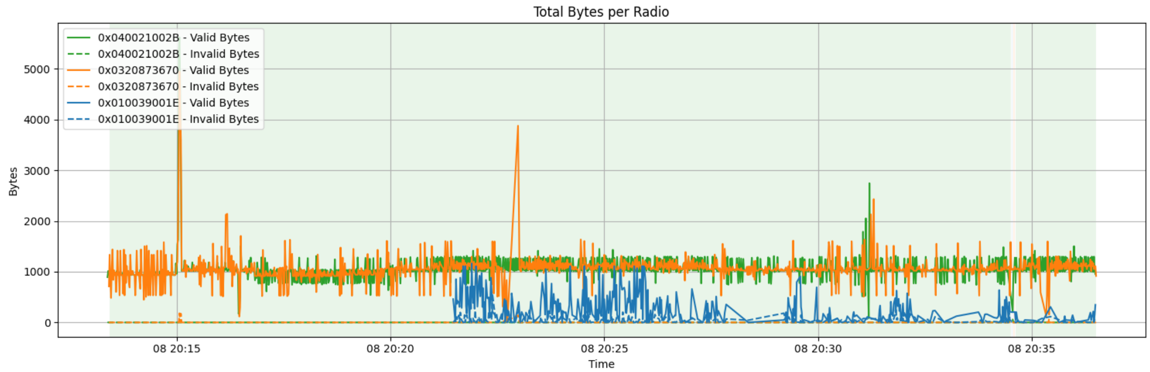

Figure 11-6 - Total Bytes for Flight 198

11.2 Flight 199: ACUAS 8500-10000 04

11.2.1 Flight Details

Detail	Value
Date	10/8/2024
Time	14:36:48 to 14:55:19
Duration	18 min 31 secs
Altitude	9800 - 10000 ft

11.2.2 Flight Track

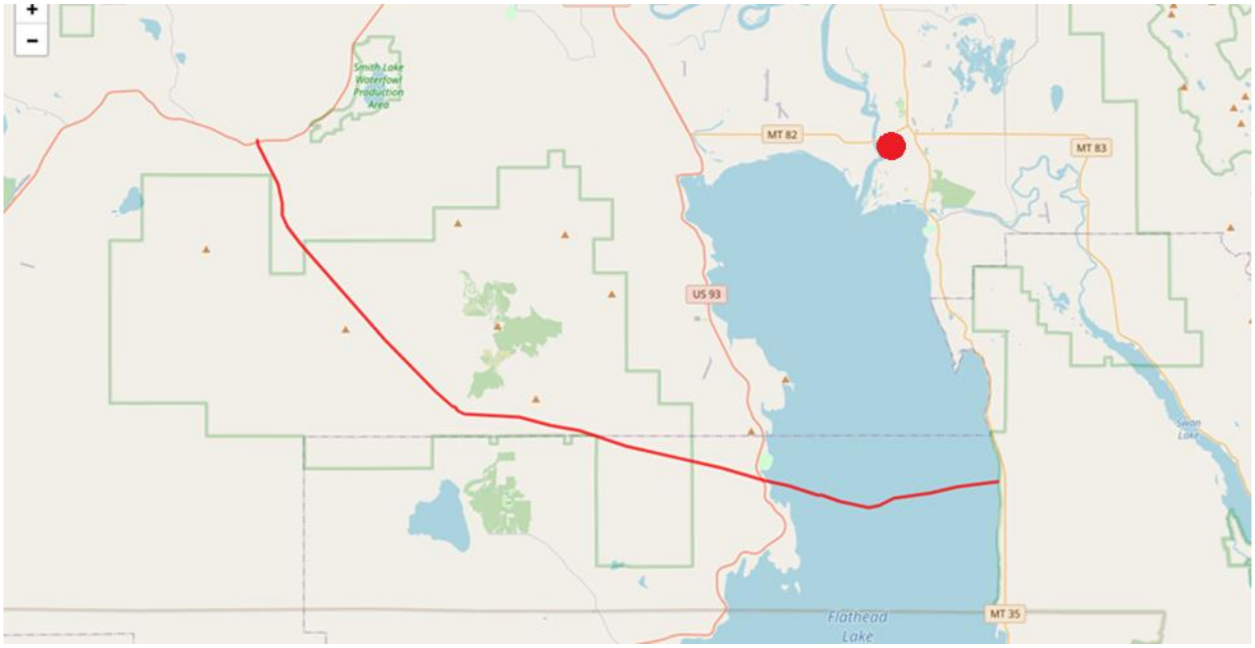

Figure 11-7 - Flight Track for Flight 199 as recorded by SkyLine C2CSP operational platform

11.2.3 Link Performance

11.2.3.1 Availability

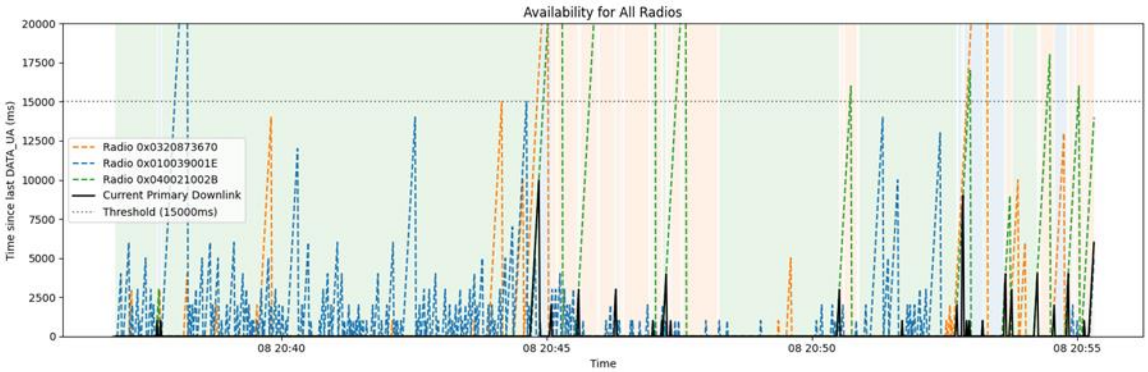

Figure 11-8 - Availability for Flight 199

11.2.3.2 Continuity

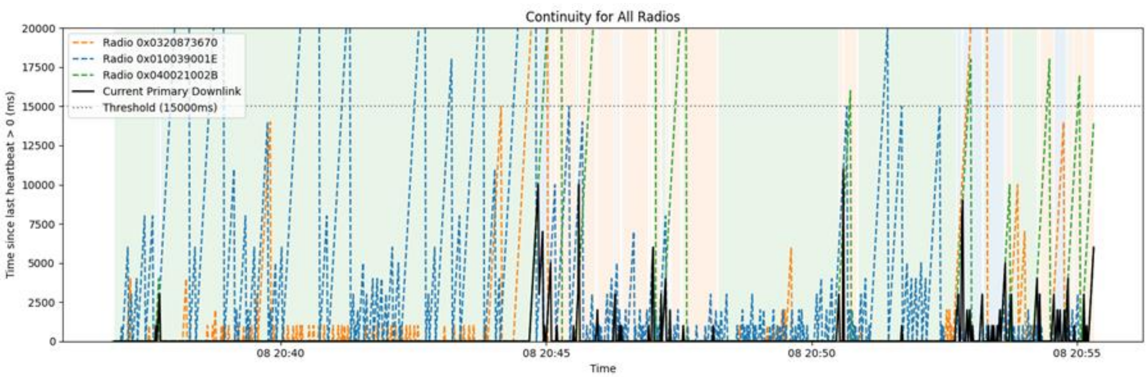

Figure 11-9 - Continuity for Flight 199

11.2.3.3 Integrity

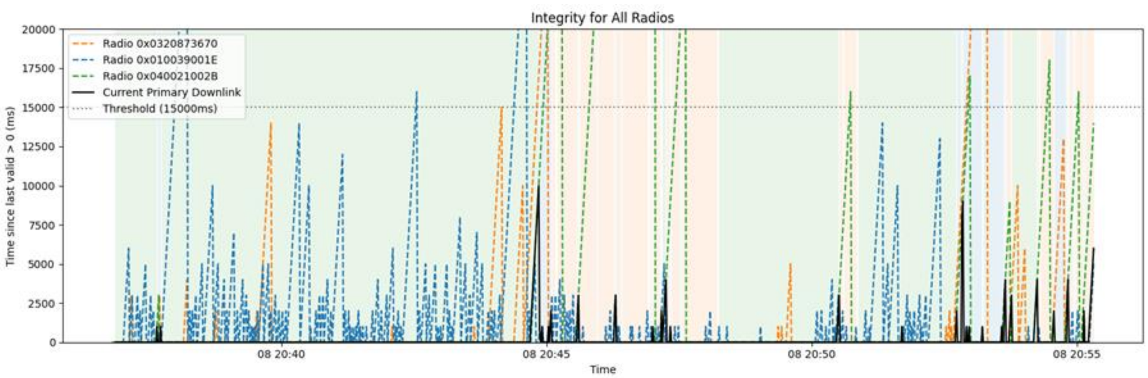

Figure 11-10 - Integrity for Flight 199

11.2.3.4 Latency

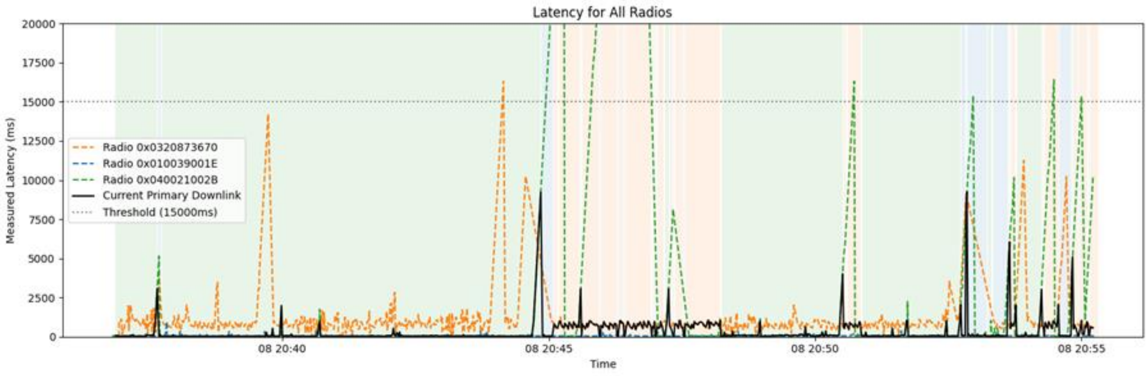

Figure 11-11 - Latency for Flight 199

11.2.4 Message Transmission Data

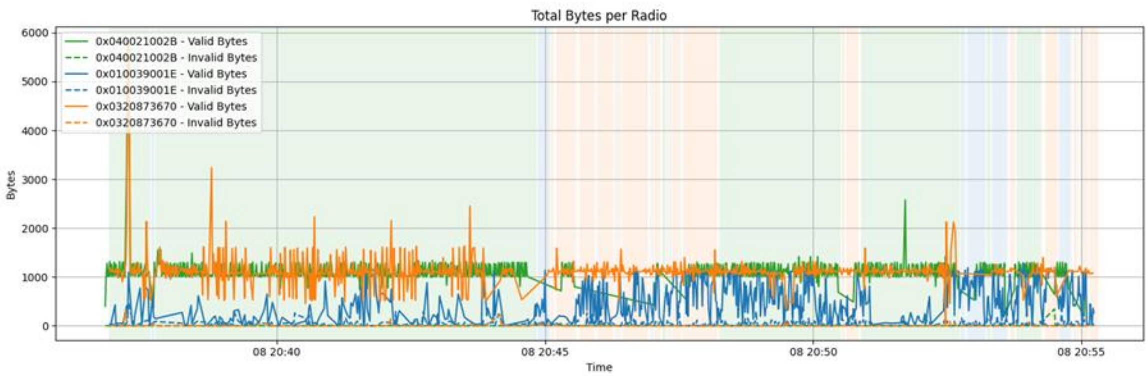

Figure 11-12 - Total Bytes for Flight 199

11.3 Flight 201: ACUASI 8500-10000 06

11.3.1 Flight Details

Detail	Value
Date	10/8/2024
Time	14:58:06 to 15:14:35
Duration	16 min 29 secs
Altitude	9800 - 10000 ft

11.3.2 Flight Track

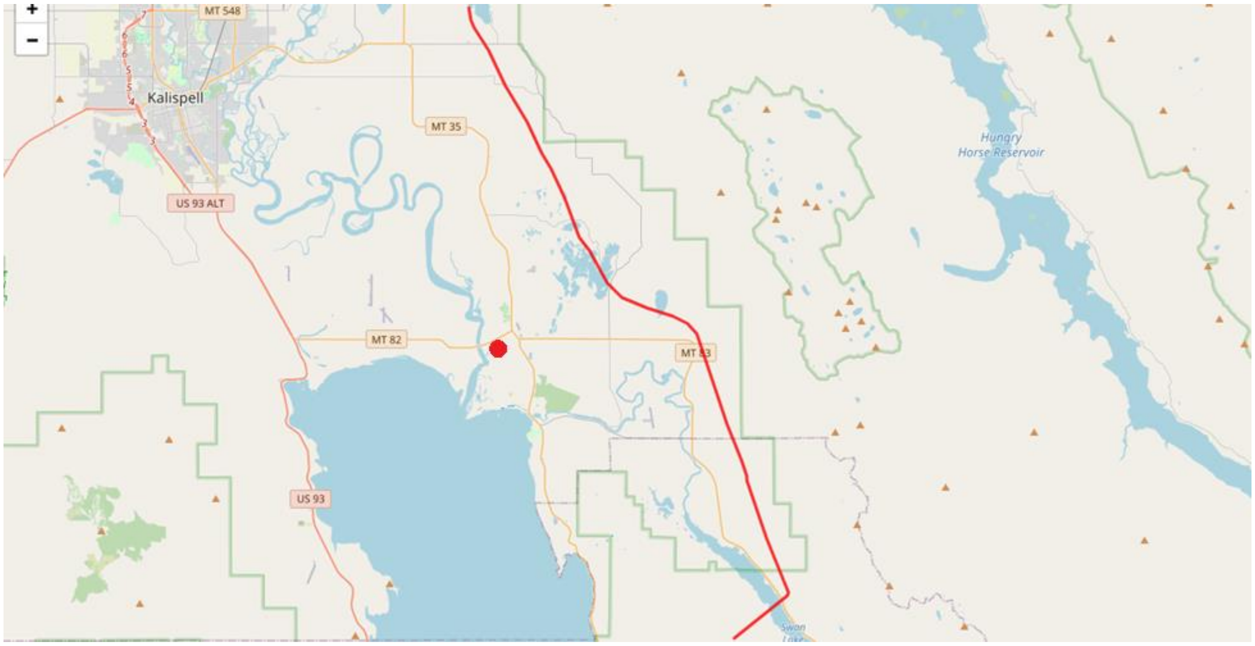

Figure 11-13 - Flight Track for Flight 201 as recorded by SkyLine C2CSP operational platform

11.3.3 Link Performance

11.3.3.1 Availability

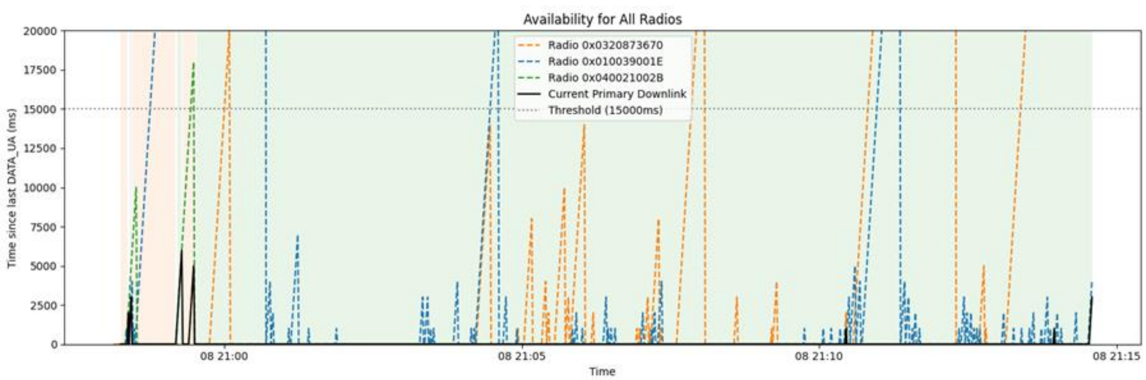

Figure 11-14 - Availability for Flight 201

11.3.3.2 Continuity

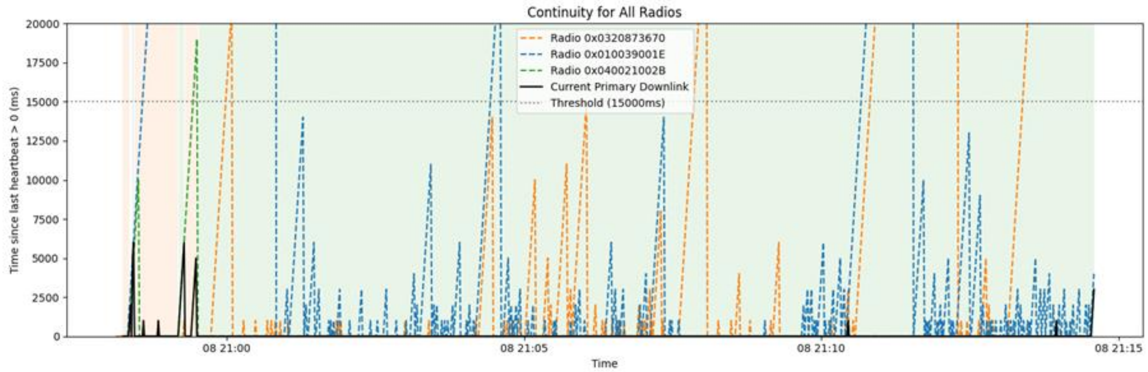

Figure 11-15 - Continuity for Flight 201

11.3.3.3 Integrity

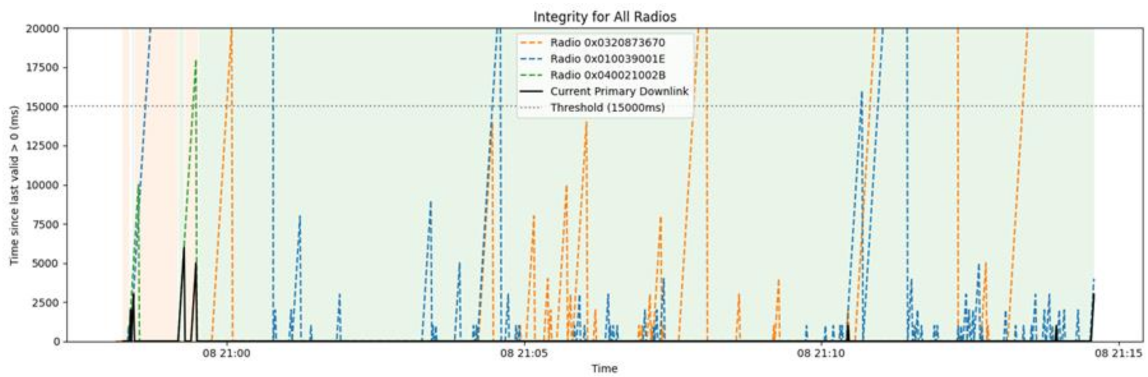

Figure 11-16 - Integrity for Flight 201

11.3.3.4 Latency

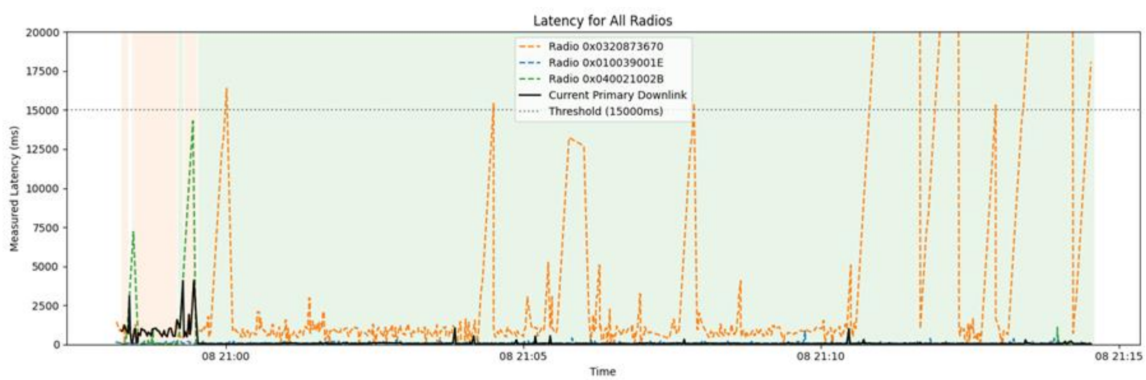

Figure 11-17 - Latency for Flight 201

11.3.4 Message Transmission Data

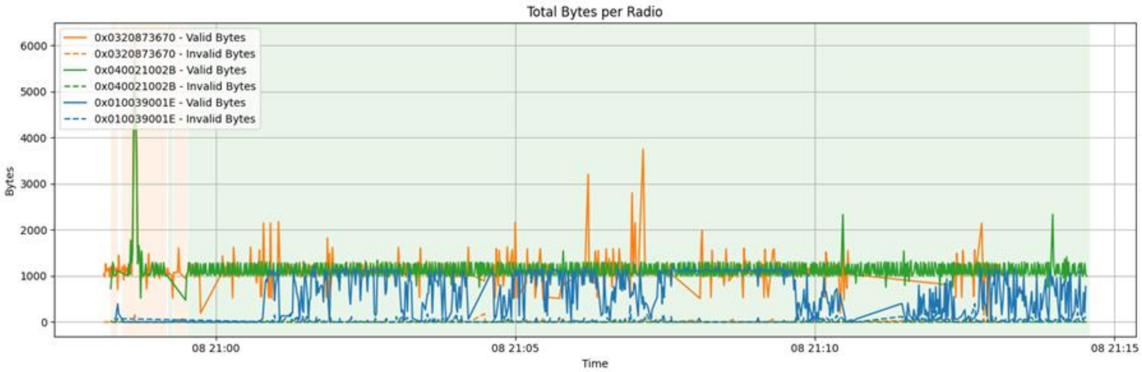

Figure 11-18 - Total Bytes for Flight 201

11.4 Flight 206: ACUASI 8500-10000 10

11.4.1 Flight Details

Detail	Value
Date	10/8/2024
Time	15:27:08 to 15:44:12
Duration	17 min 4 secs
Altitude	9800 - 10000 ft

11.4.2 Flight Track

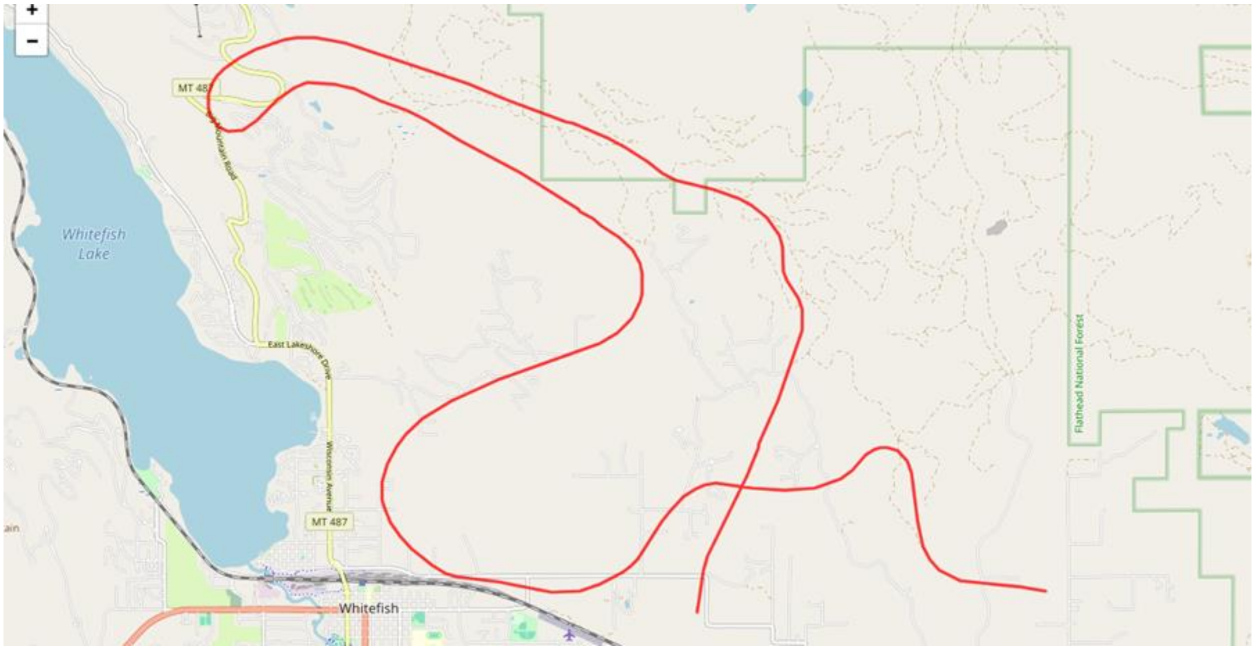

Figure 11-19 - Flight Track for Flight 206 as recorded by SkyLine C2CSP operational platform

11.4.3 Link Performance

11.4.3.1 Availability

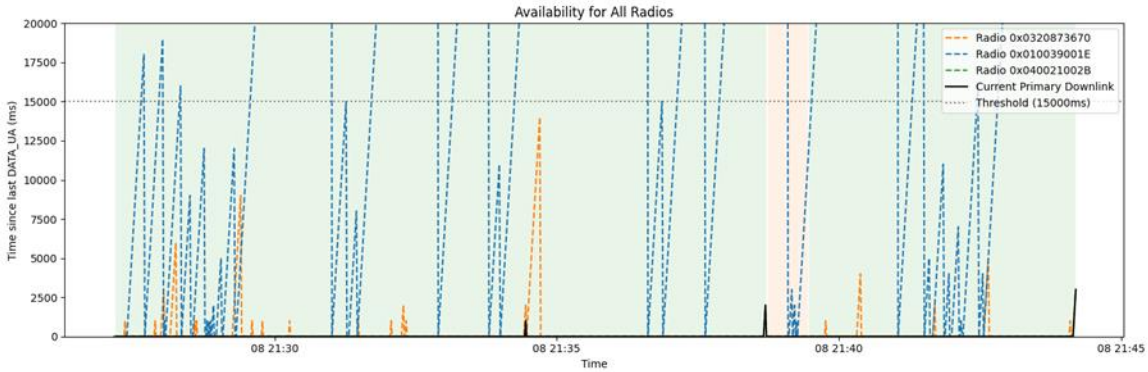

Figure 11-20 - Availability for Flight 206

11.4.3.2 Continuity

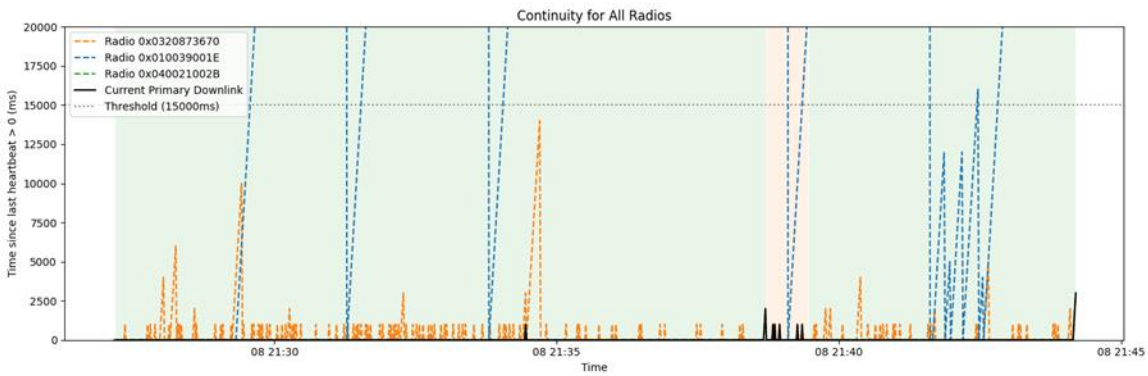

Figure 11-21 - Continuity for Flight 206

11.4.3.3 Integrity

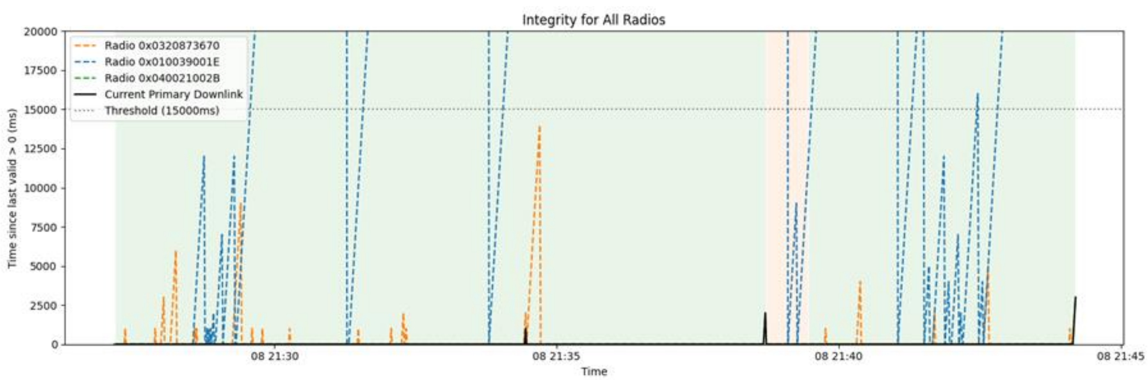

Figure 11-22 - Integrity for Flight 206

11.4.3.4 Latency

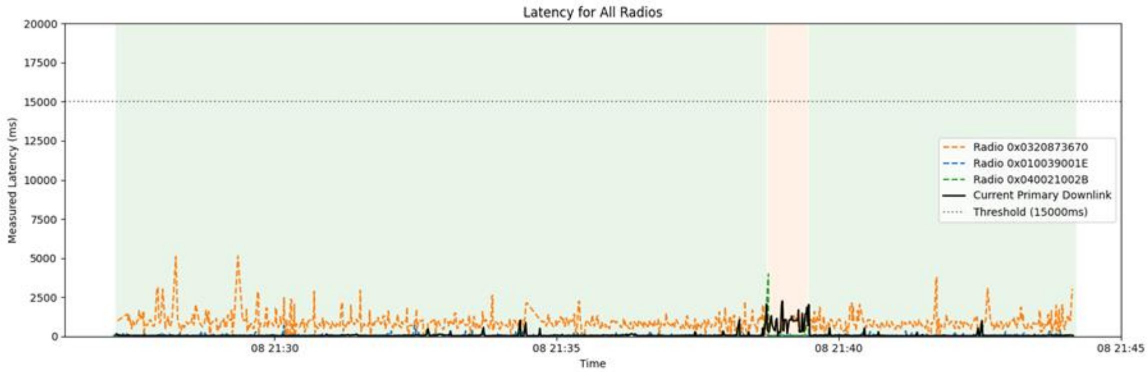

Figure 11-23 - Latency for Flight 206

11.4.4 Message Transmission Data

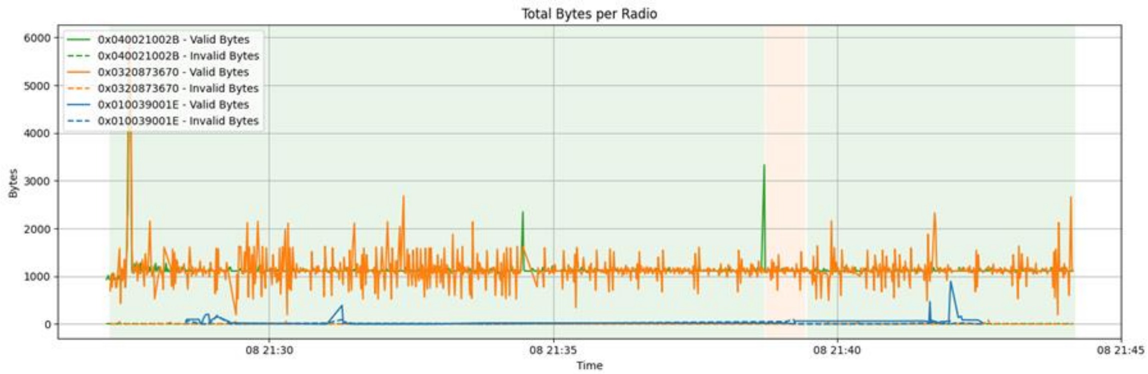

Figure 11-24 - Total Bytes for Flight 206

11.5 Flight 209: ACUASI 6500 03

11.5.1 Flight Details

Detail	Value
Date	10/8/2024
Time	15:47:45 to 16:03:37
Duration	15 min 52 secs
Altitude	6500 ft

11.5.2 Flight Track

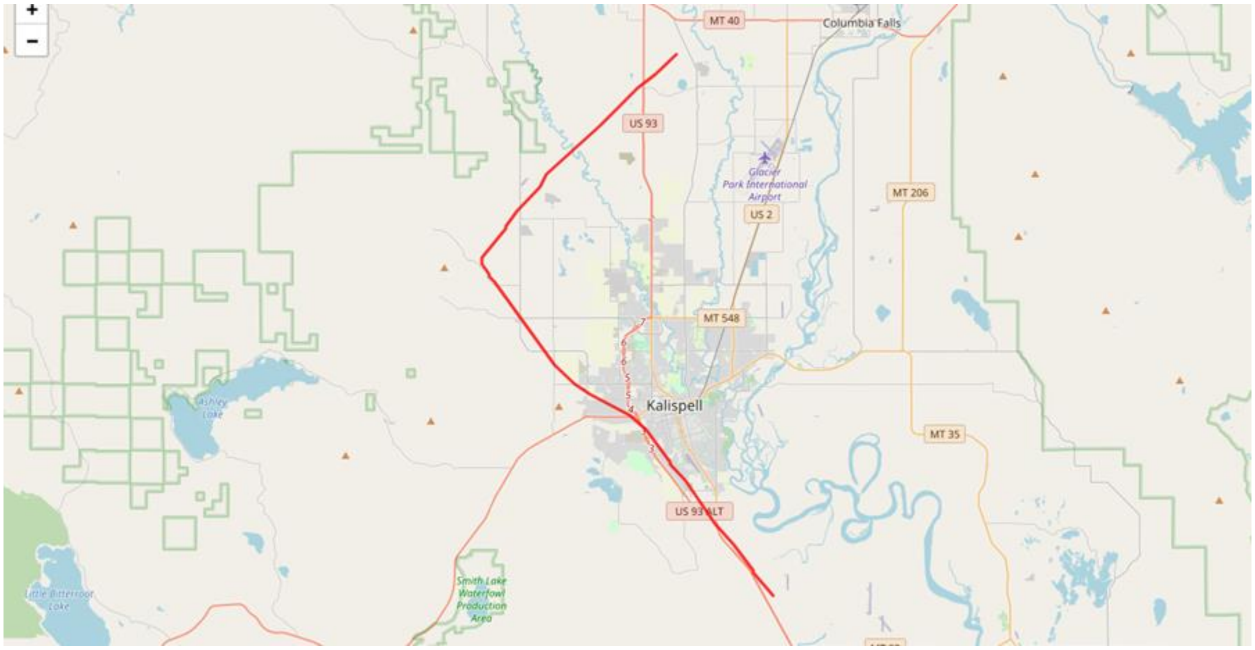

Figure 11-25 - Flight Track for Flight 209 as recorded by SkyLine C2CSP operational platform

11.5.3 Link Performance

11.5.3.1 Availability

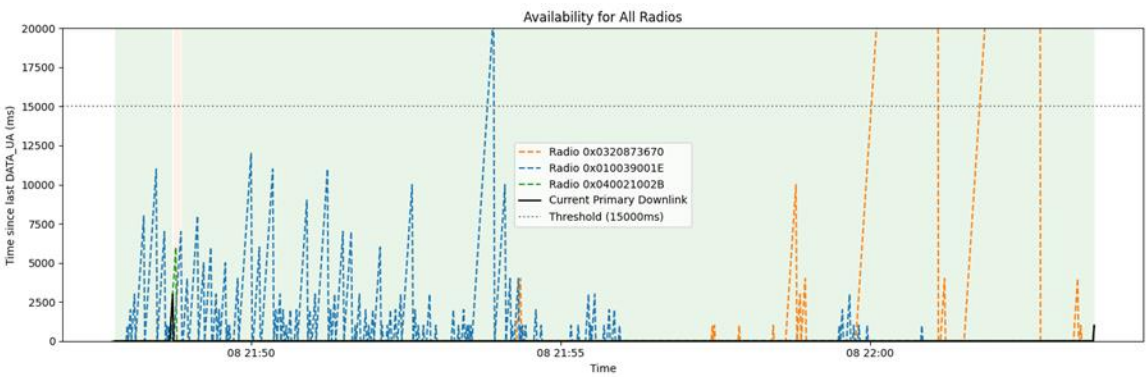

Figure 11-26 - Availability for Flight 209

11.5.3.2 Continuity

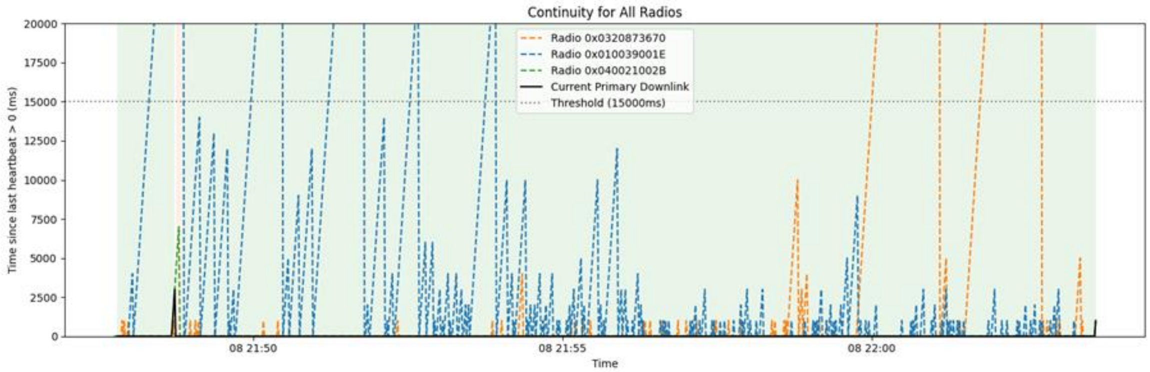

Figure 11-27 - Continuity for Flight 209

11.5.3.3 Integrity

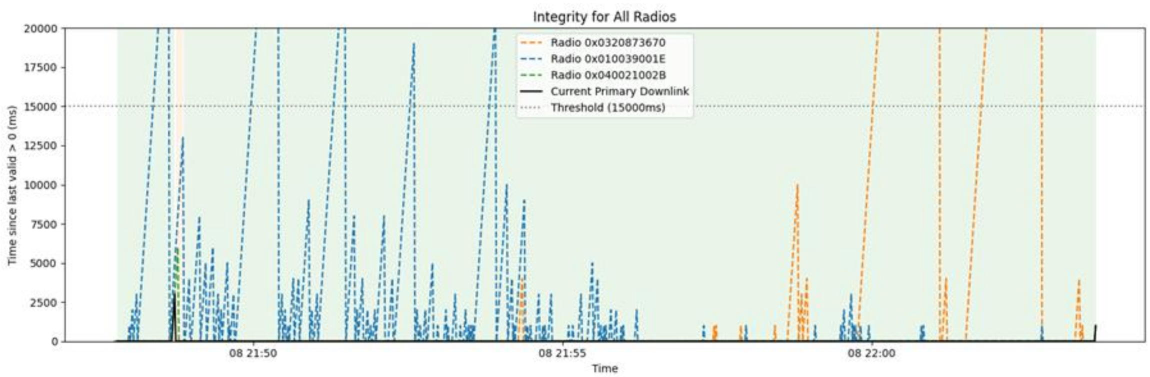

Figure 11-28 - Integrity for Flight 209

11.5.3.4 Latency

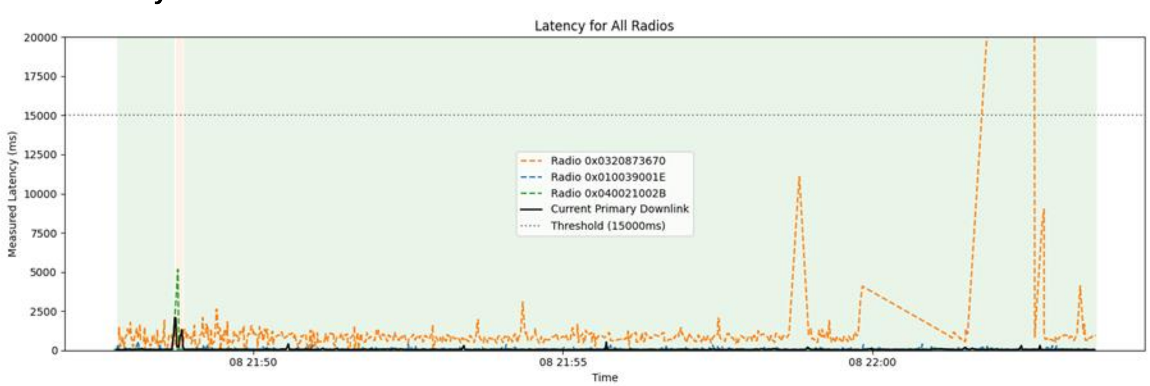

Figure 11-29 - Latency for Flight 209

11.5.4 Message Transmission Data

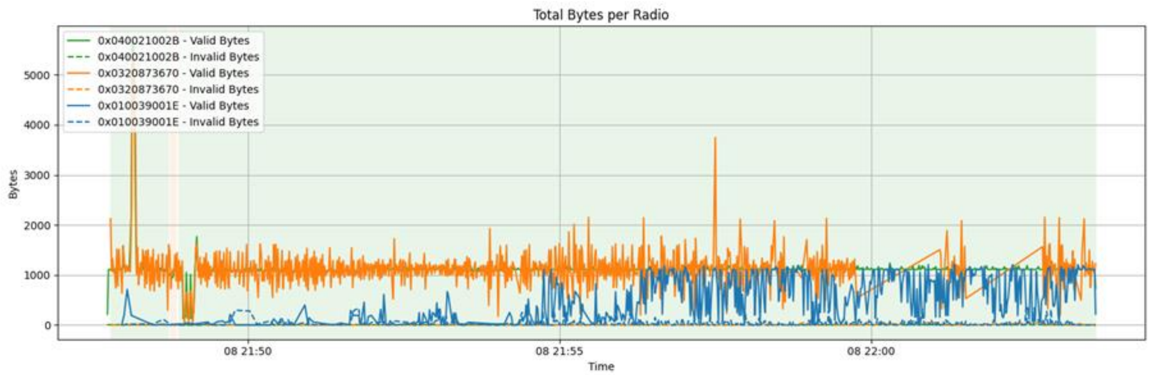

Figure 11-30 - Total Bytes for Flight 209

11.6 Flight 210: ACUASI 6500 04

11.6.1 Flight Details

Detail	Value
Date	10/8/2024
Time	16:05:27 to 16:22:08
Duration	16 min 41 secs
Altitude	6500 ft

11.6.2 Flight Track

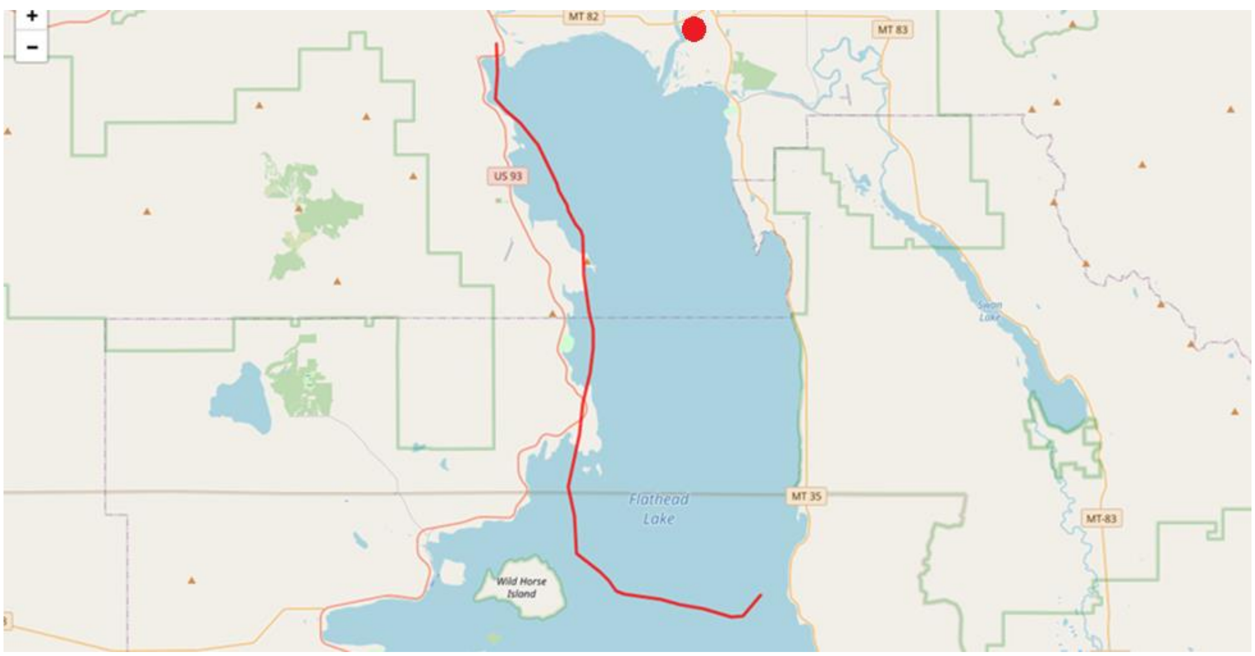

Figure 11-31 - Flight Track for Flight 210 as recorded by SkyLine C2CSP operational platform

11.6.3 Link Performance

11.6.3.1 Availability

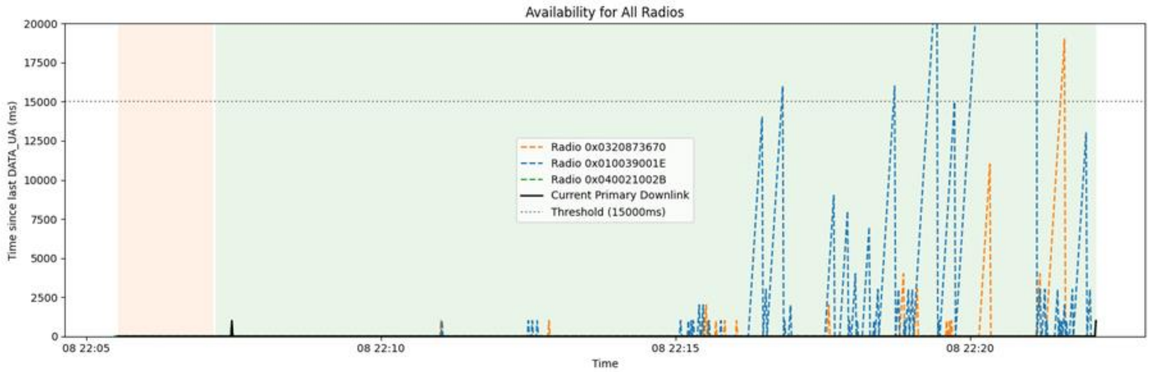

Figure 11-32 - Availability for Flight 210

11.6.3.2 Continuity

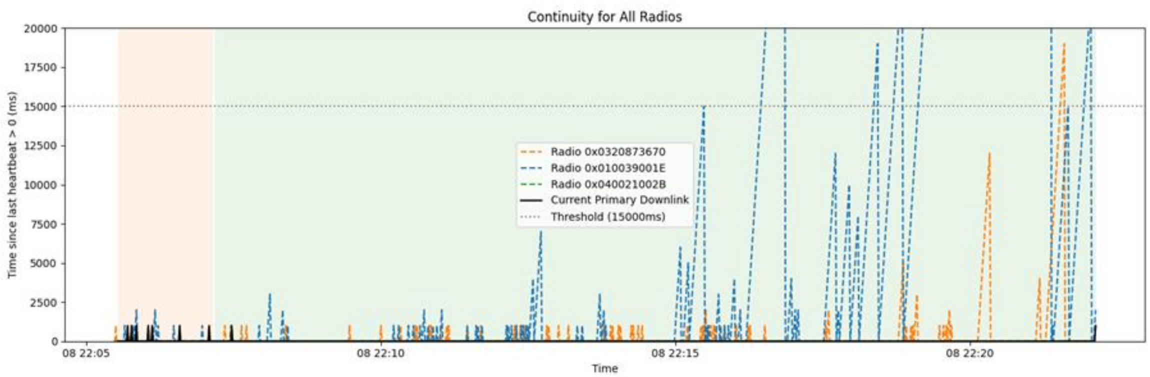

Figure 11-33 - Continuity for Flight 210

11.6.3.3 Integrity

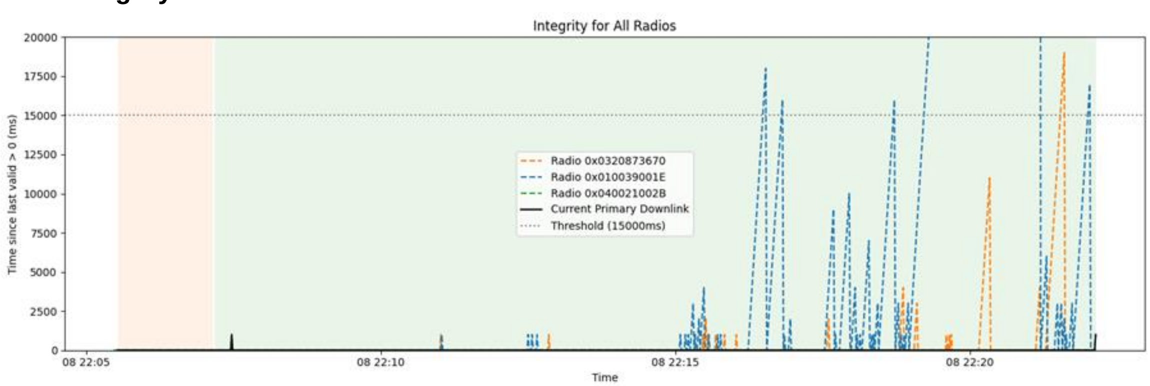

Figure 11-34 - Integrity for Flight 210

11.6.3.4 Latency

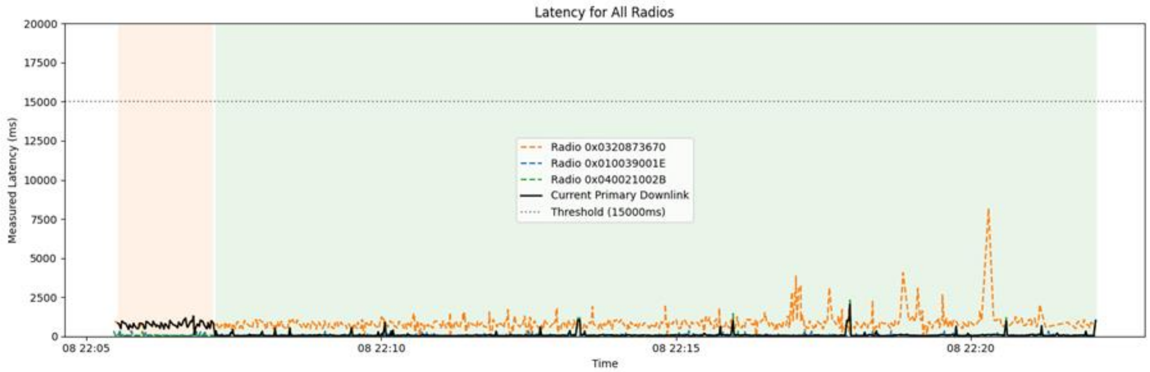

Figure 11-35 - Latency for Flight 210

11.6.4 Message Transmission Data

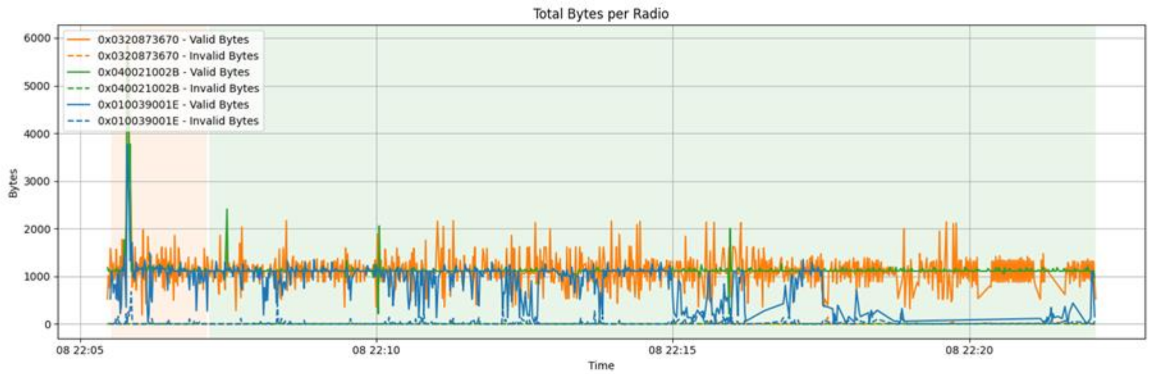

Figure 11-36 - Total Bytes for Flight 210

11.7 Flight 211: ACUASI 6500 05

11.7.1 Flight Details

Detail	Value
Date	10/8/2024
Time	16:22:55 to 16:40:53
Duration	17 min 58 secs
Altitude	6500 ft

11.7.2 Flight Track

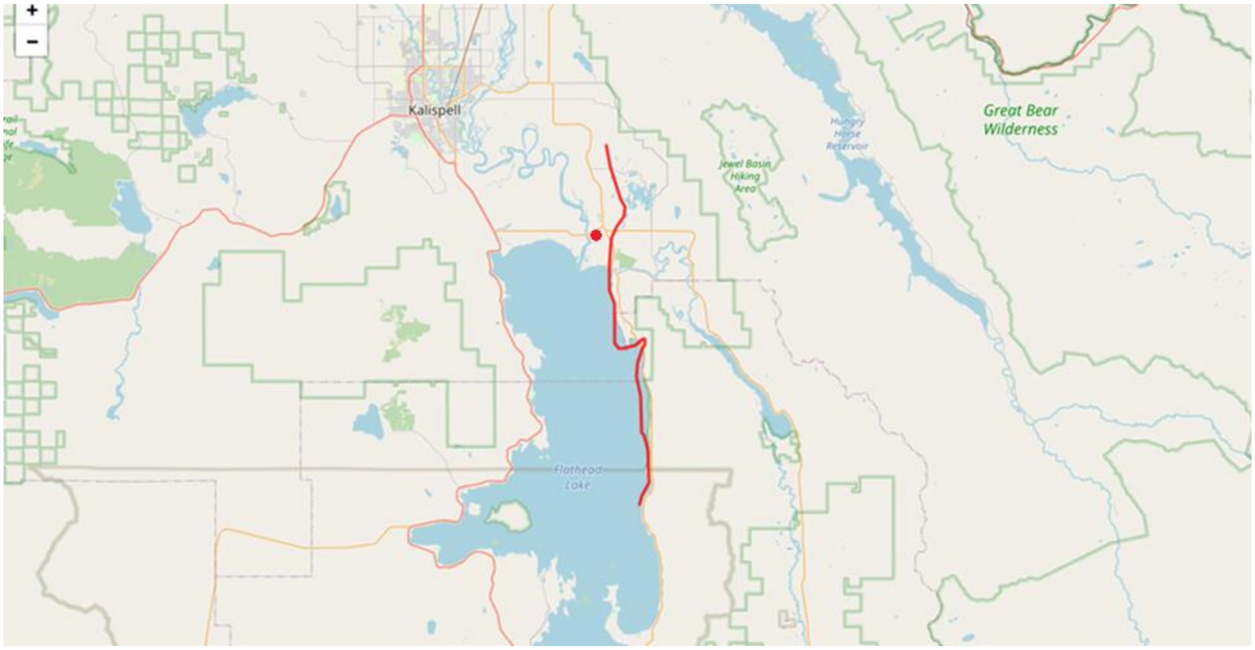

Figure 11-37 - Flight Track for Flight 211 as recorded by SkyLine C2CSP operational platform

11.7.3 Link Performance

11.7.3.1 Availability

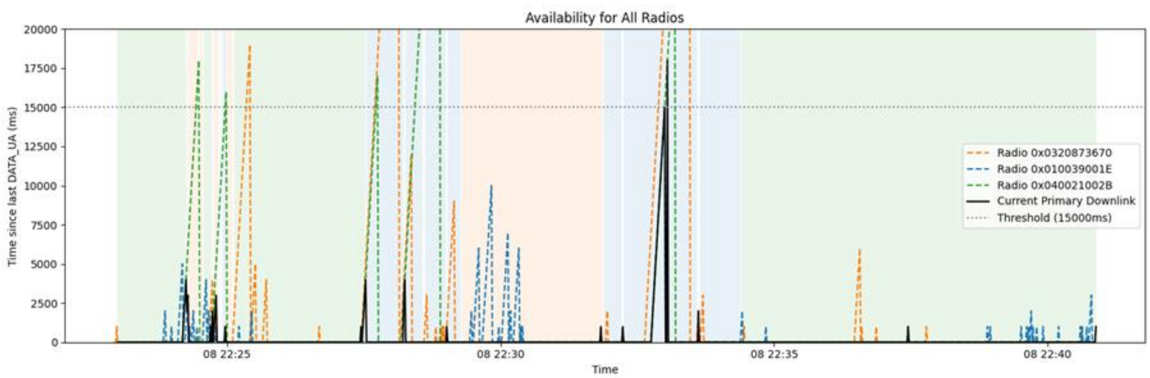

Figure 11-38 - Availability for Flight 211

11.7.3.2 Continuity

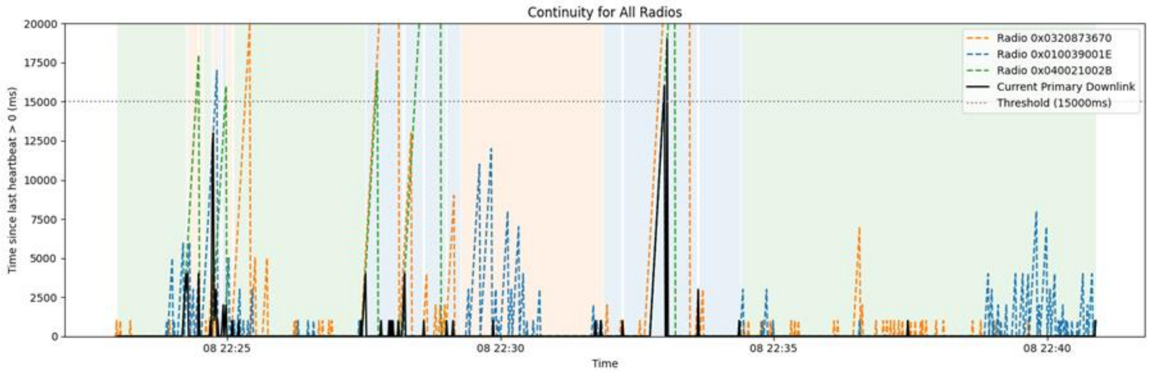

Figure 11-39 - Continuity for Flight 211

11.7.3.3 Integrity

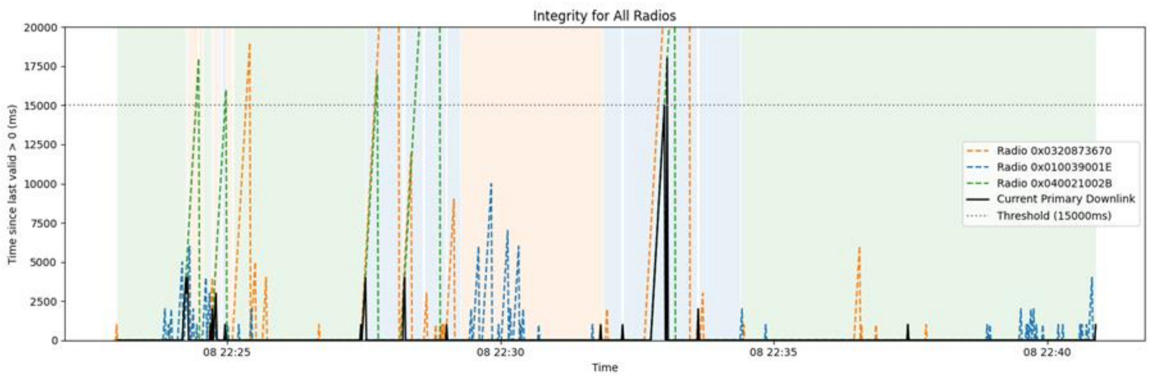

Figure 11-40 - Integrity for Flight 211

11.7.3.4 Latency

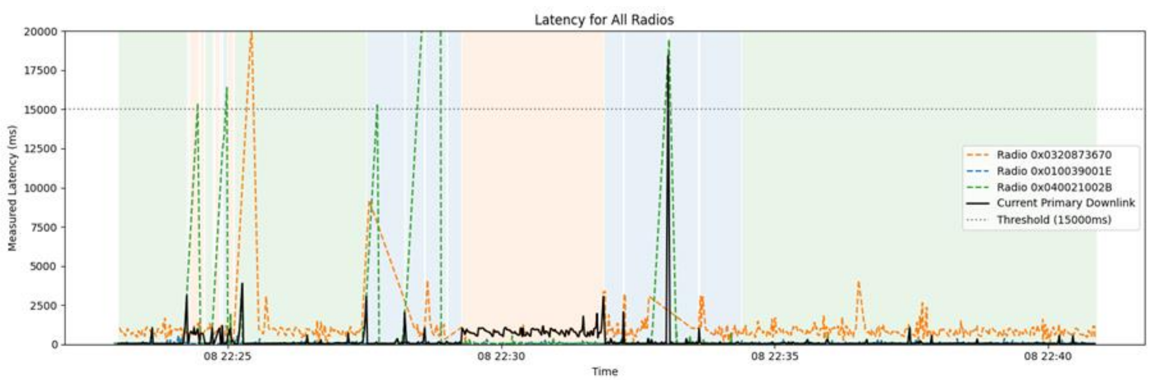

Figure 11-41 - Latency for Flight 211

11.7.4 Message Transmission Data

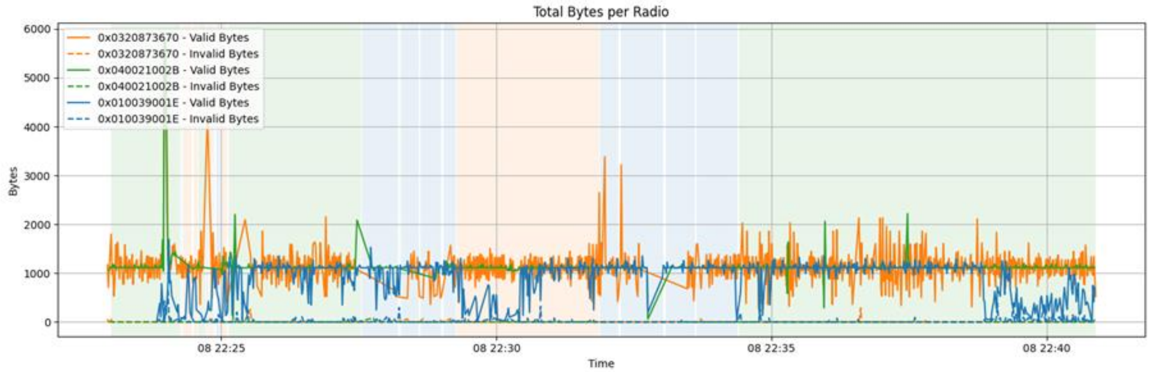

Figure 11-42 - Total Bytes for Flight 211

11.8 Flight 212: ACUASI 6500 06

11.8.1 Flight Details

Detail	Value
Date	10/8/2024
Time	16:41:22 to 16:59:07
Duration	17 min 45 secs
Altitude	6500 ft

11.8.2 Flight Track

Figure 11-43 - Flight Track for Flight 212 as recorded by SkyLine C2CSP operational platform

11.8.3 Link Performance

11.8.3.1 Availability

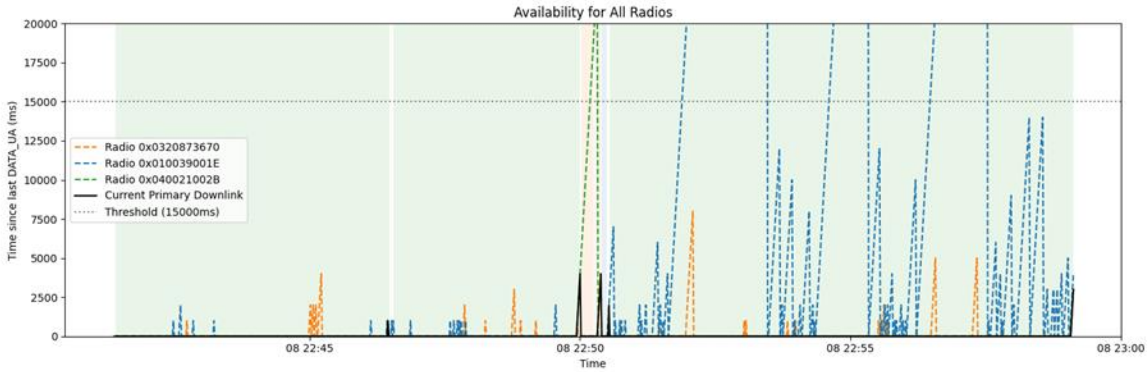

Figure 11-44 - Availability for Flight 212

11.8.3.2 Continuity

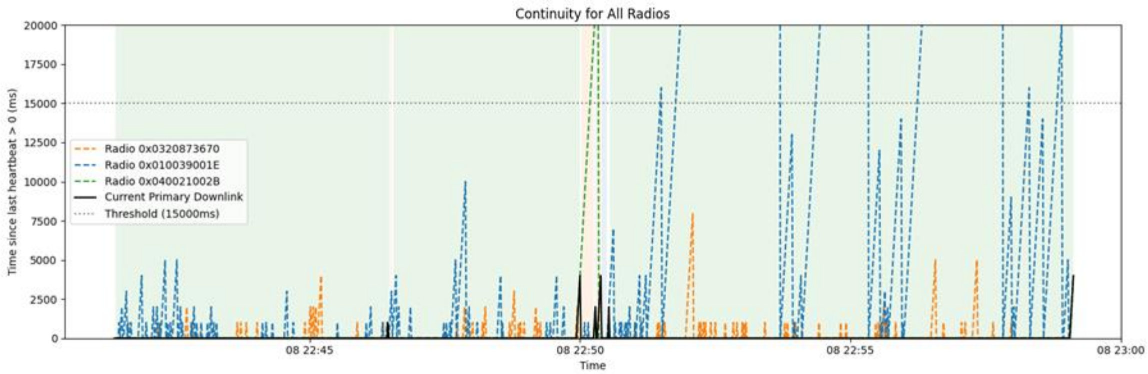

Figure 11-45 - Continuity for Flight 212

11.8.3.3 Integrity

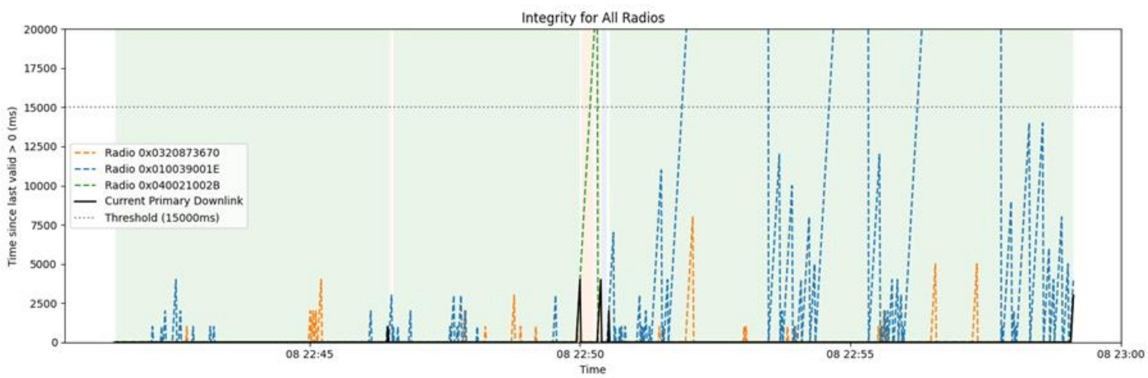

Figure 11-46 - Integrity for Flight 212

11.8.3.4 Latency

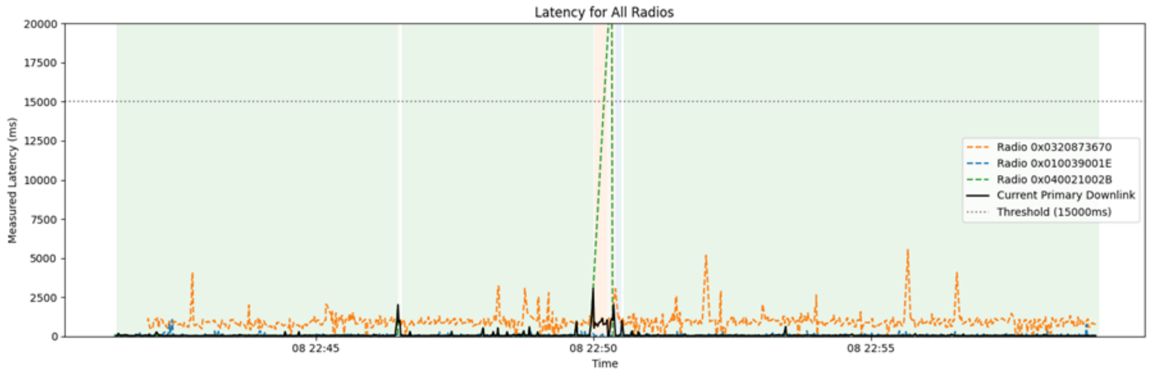

Figure 11-47 - Latency for Flight 212

11.8.4 Message Transmission Data

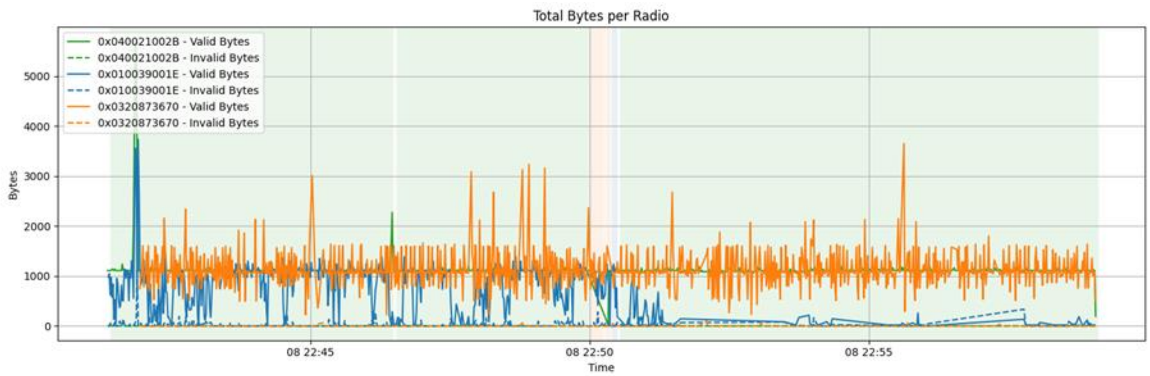

Figure 11-48 - Total Bytes for Flight 212

11.9 Flight 215: ACUASI 4500 03

11.9.1 Flight Details

Detail	Value
Date	10/8/2024
Time	17:01:38 to 17:20:14
Duration	18 min 36 sec
Altitude	4500 ft

11.9.2 Flight Track

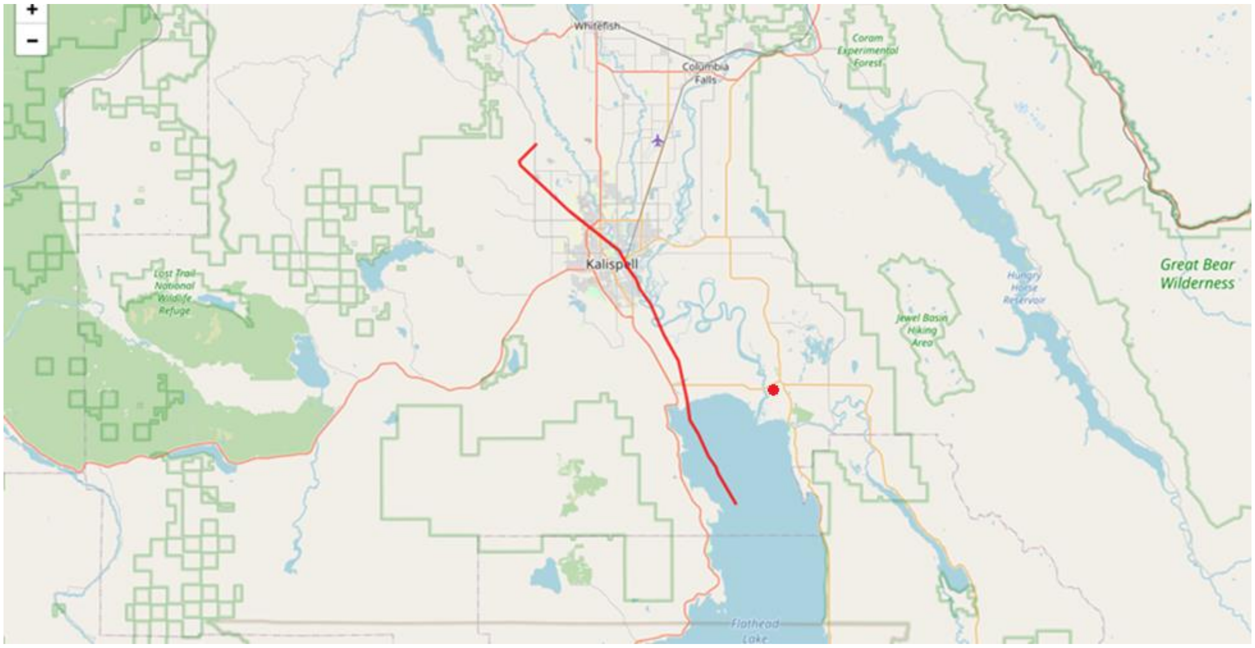

Figure 11-49 - Flight Track for Flight 215 as recorded by SkyLine C2CSP operational platform

11.9.3 Link Performance

11.9.3.1 Availability

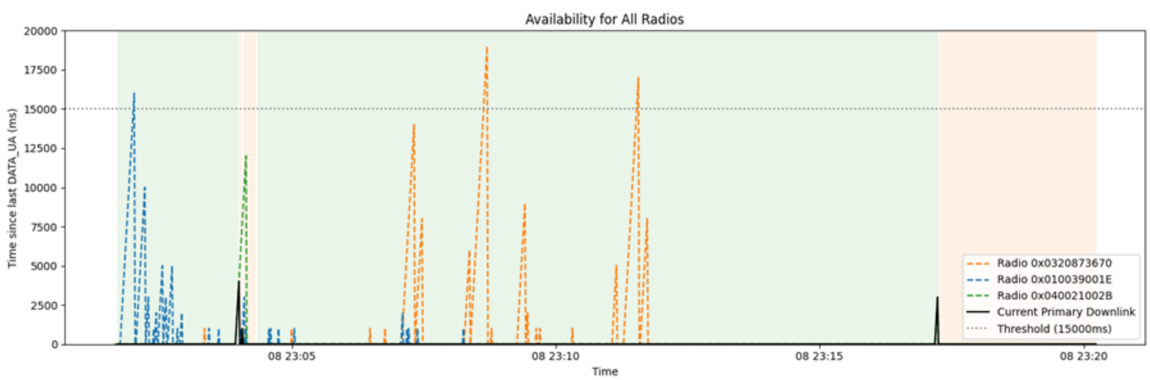

Figure 11-50 - Availability for Flight 215

11.9.3.2 Continuity

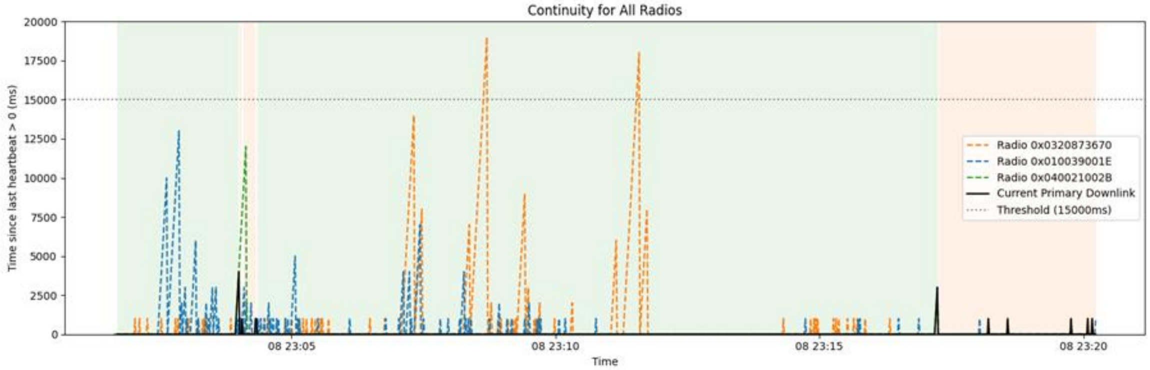

Figure 11-51 - Continuity for Flight 215

11.9.3.3 Integrity

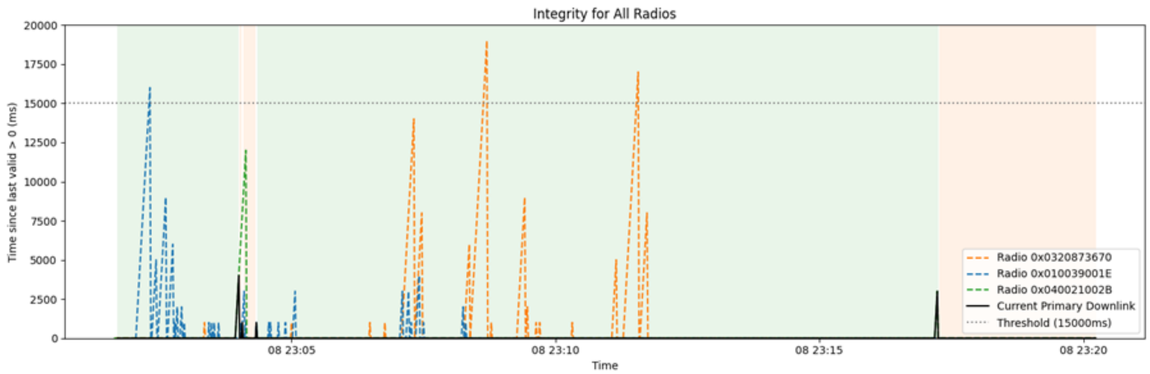

Figure 11-52 - Integrity for Flight 215

11.9.3.4 Latency

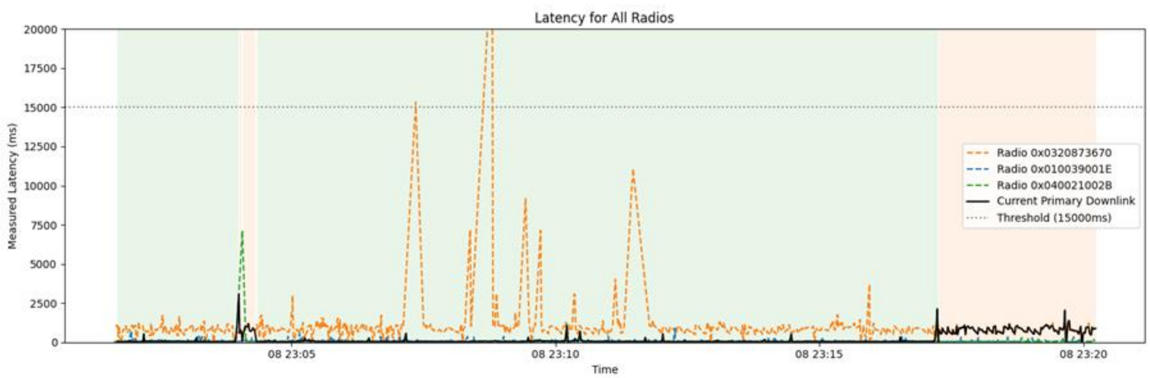

Figure 11-53 - Latency for Flight 215

11.9.4 Message Transmission Data

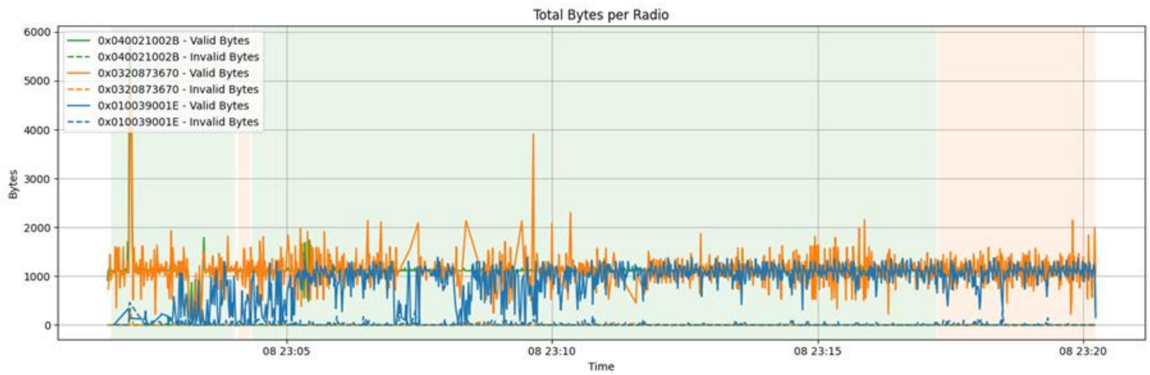

Figure 11-54 - Total Bytes for Flight 215

11.10 Flight 216: ACUASI 1500 04

11.10.1 Flight Details

Detail	Value
Date	10/8/2024
Time	17:20:50 to 17:36:13
Duration	15 min 23 sec
Altitude	4500 ft

11.10.2 Flight Track

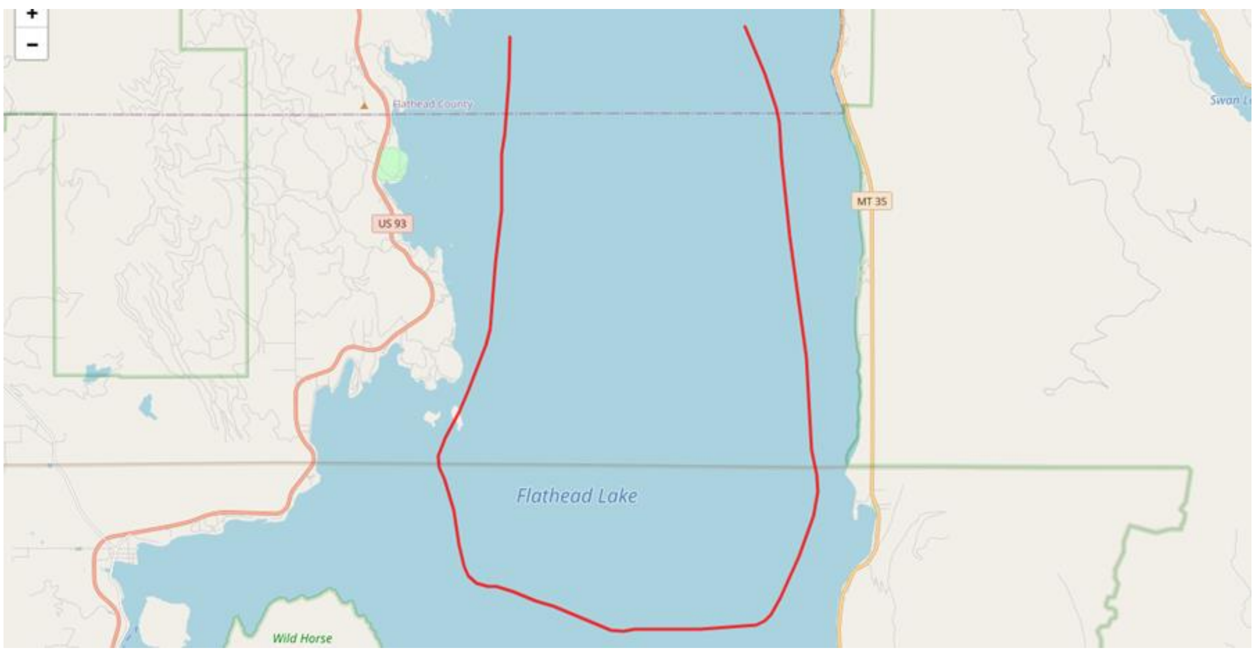

Figure 11-55 - Flight Track for Flight 216 as recorded by SkyLine C2CSP operational platform

11.10.3 Link Performance

11.10.3.1 Availability

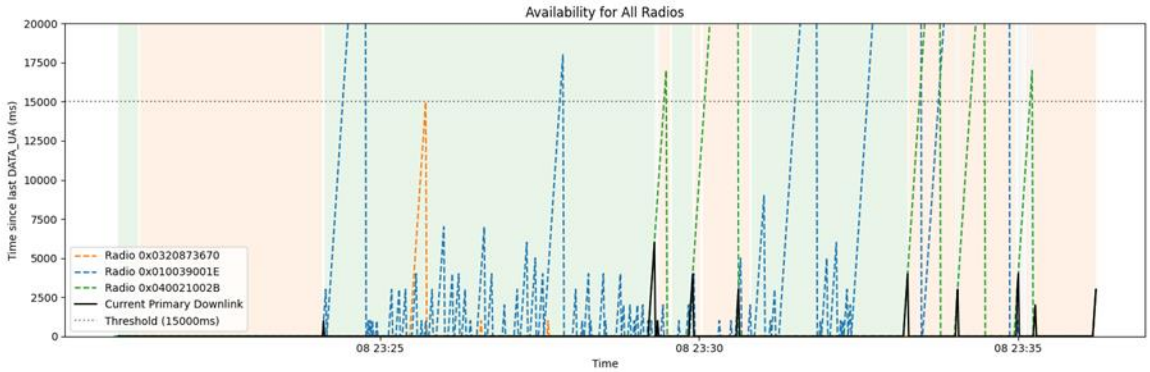

Figure 11-56 - Availability for Flight 216

11.10.3.2 Continuity

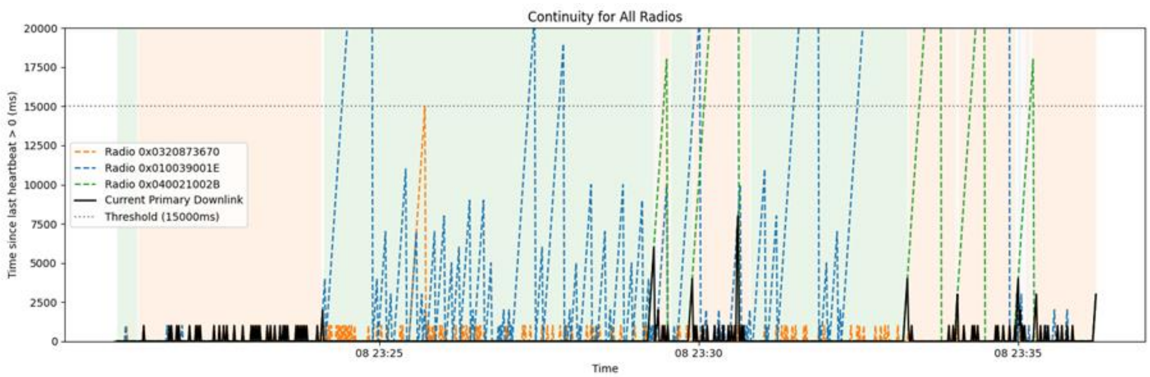

Figure 11-57 - Continuity for Flight 216

11.10.3.3 Integrity

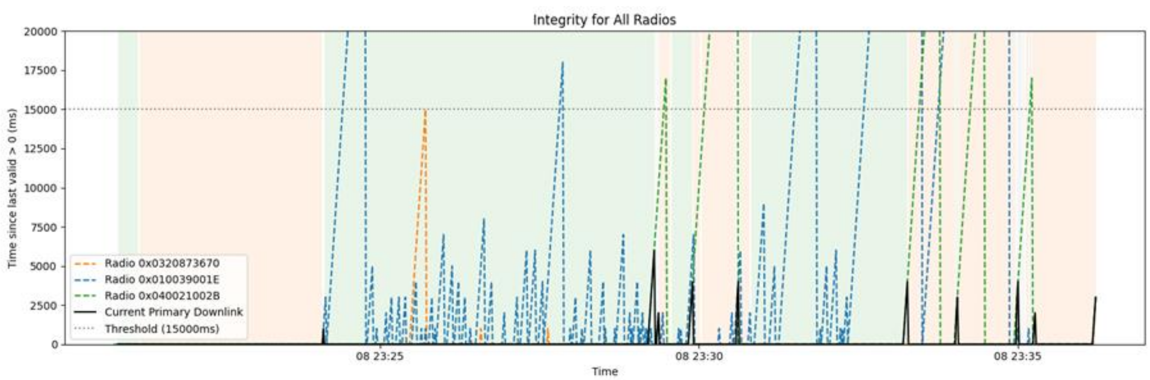

Figure 11-58 - Integrity for Flight 216

11.10.3.4 Latency

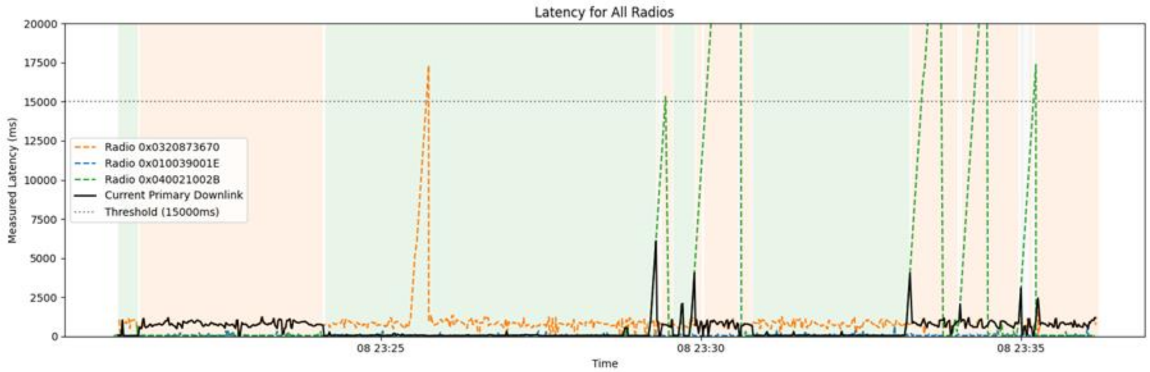

Figure 11-59 - Latency for Flight 216

11.10.4 Message Transmission Data

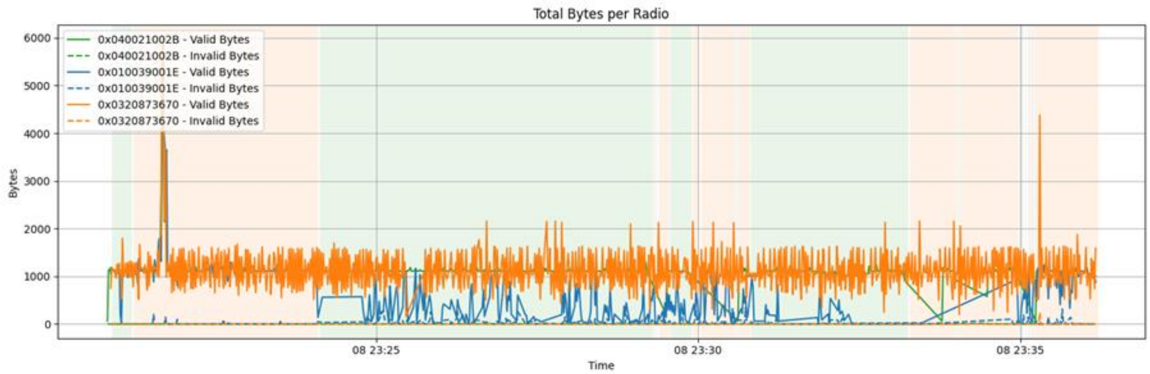

Figure 11-60 - Total Bytes for Flight 216

11.11 Flight 221: ACUASI 1500 08

11.11.1 Flight Details

Detail	Value
Date	10/8/2024
Time	17:38:51 to 17:56:51
Duration	18 min 0 sec
Altitude	4500 ft

11.11.2 Flight Track

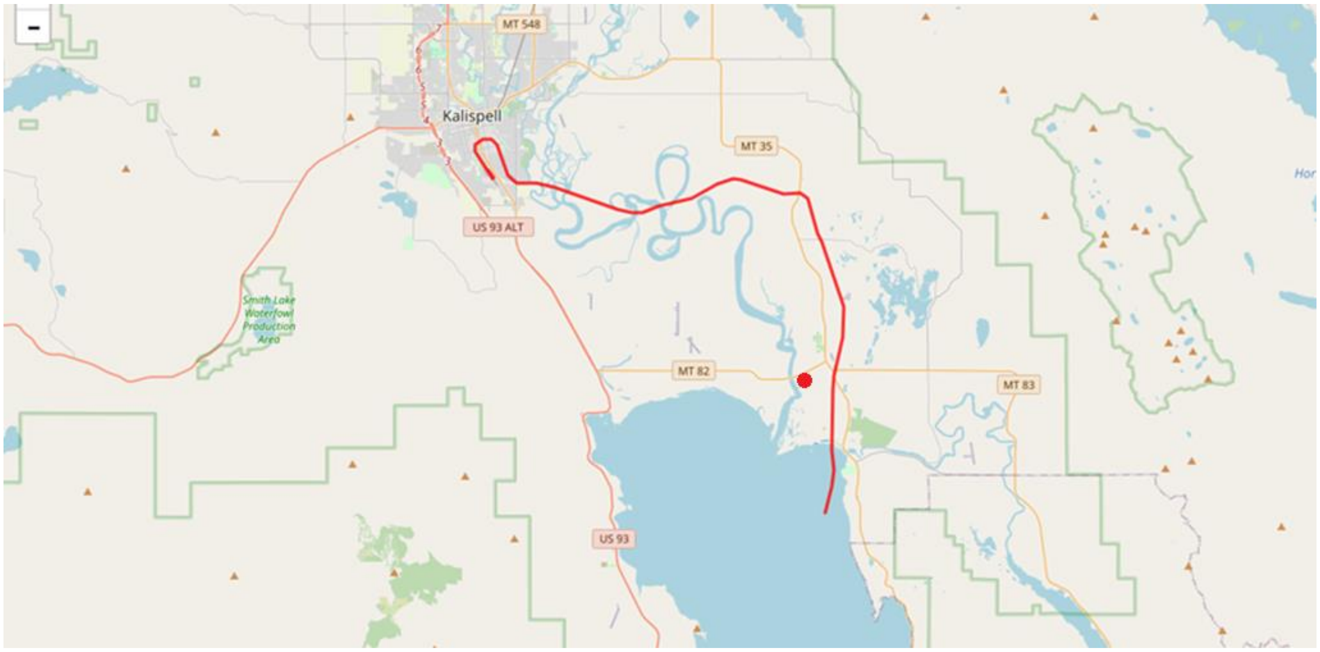

Figure 11-61 - Flight Track for Flight 221 as recorded by SkyLine C2CSP operational platform

11.11.3 Link Performance

11.11.3.1 Availability

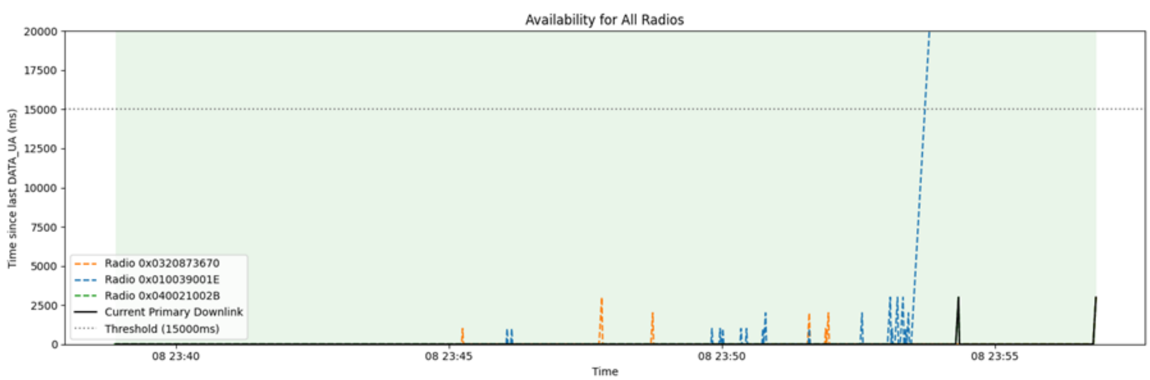

Figure 11-62 - Availability for Flight 221

11.11.3.2 Continuity

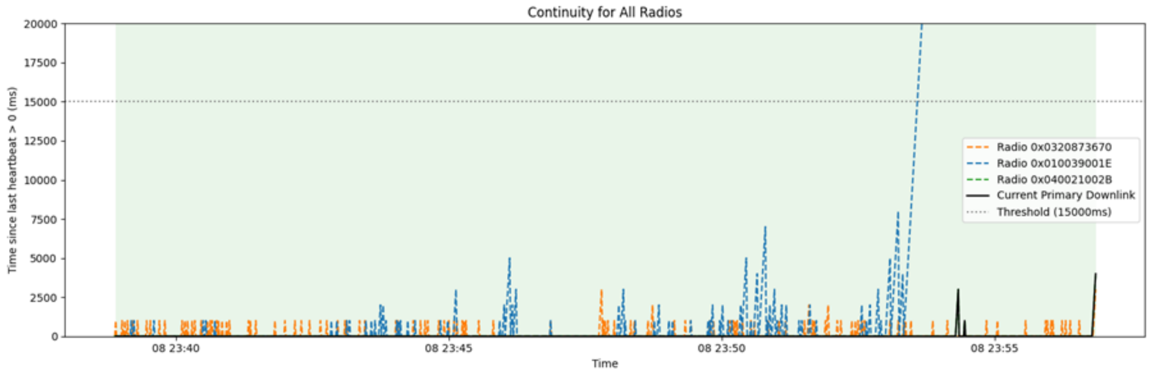

Figure 11-63 - Continuity for Flight 221

11.11.3.3 Integrity

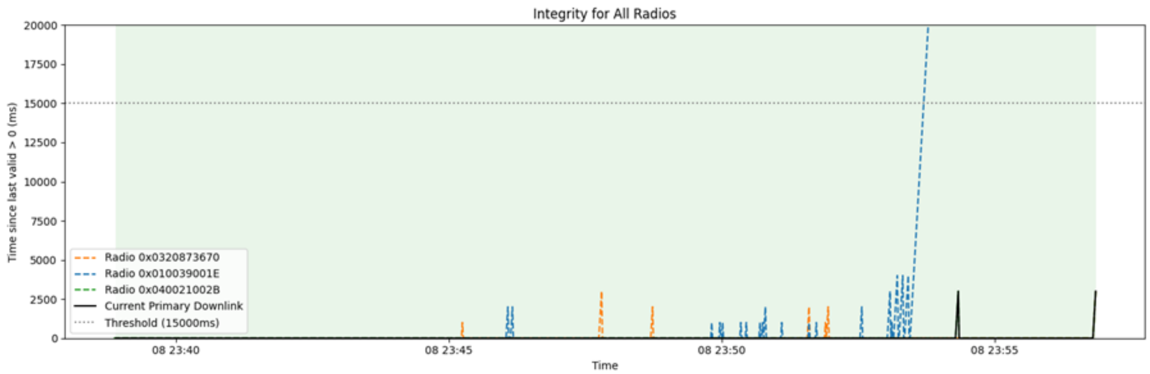

Figure 11-64 - Integrity for Flight 221

11.11.3.4 Latency

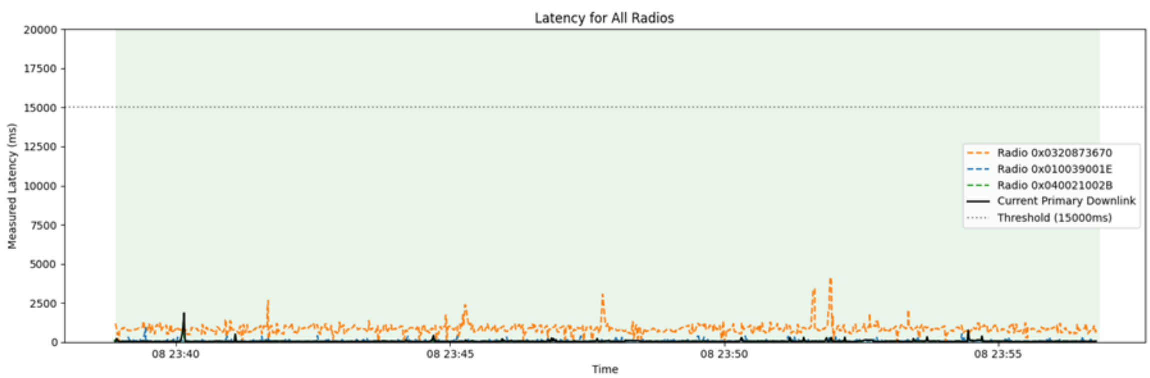

Figure 11-65 - Latency for Flight 221

11.11.4 Message Transmission Data

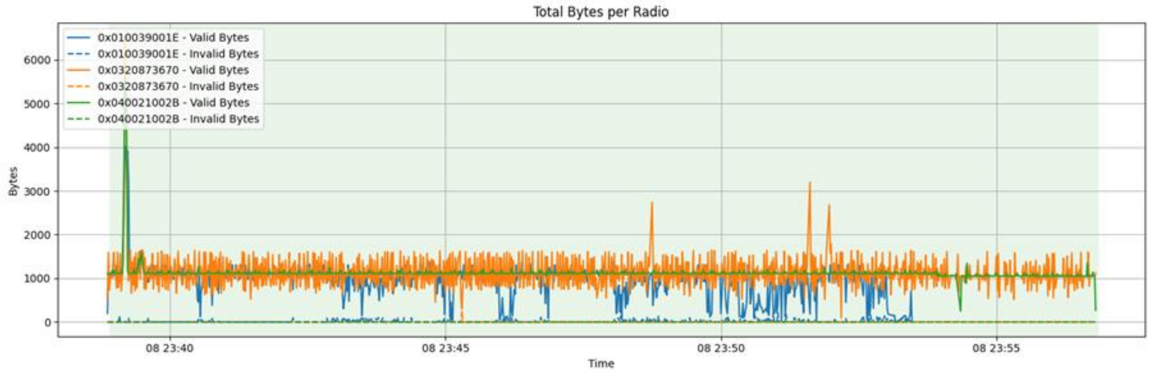

Figure 11-66 - Total Bytes for Flight 221

11.12 Flight 223: ACUASI 1500 10

11.12.1 Flight Details

Detail	Value
Date	10/8/2024
Time	17:59:14 to 18:48:27
Duration	49 min 13 sec
Altitude	4500 ft

11.12.2 Flight Track

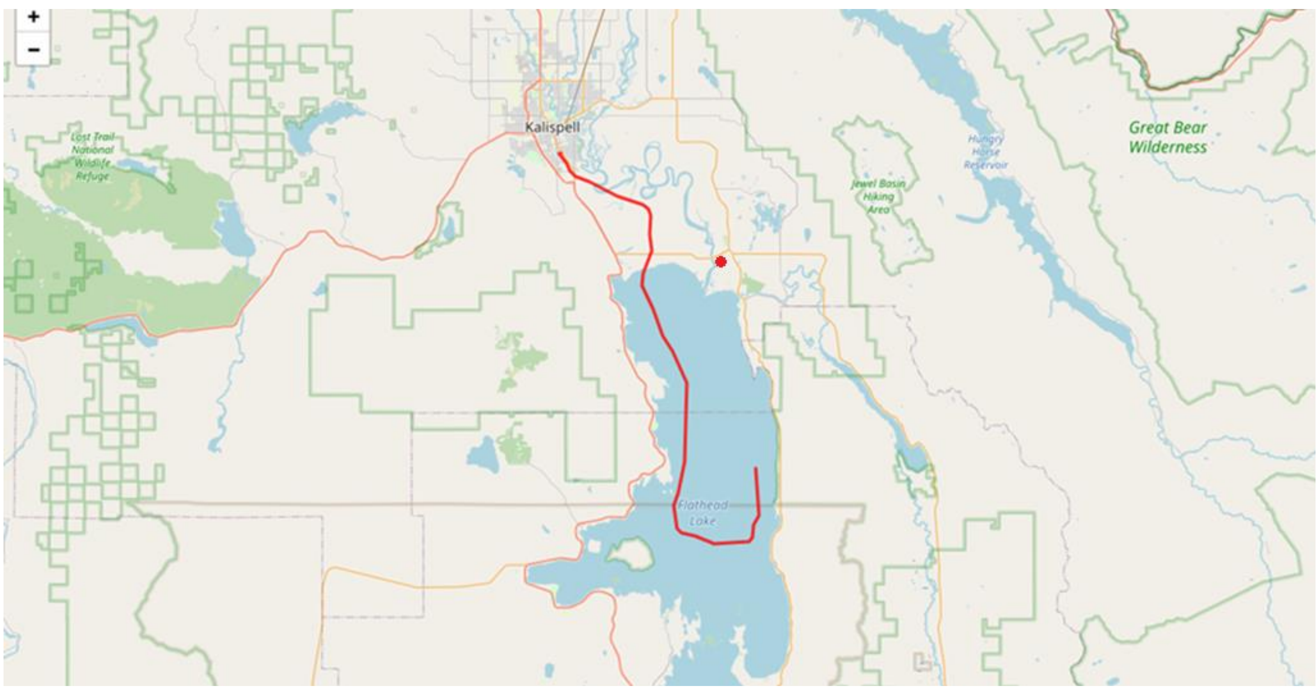

Figure 11-67 - Flight Track for Flight 223 as recorded by SkyLine C2CSP operational platform

11.12.3 Link Performance

11.12.3.1 Availability

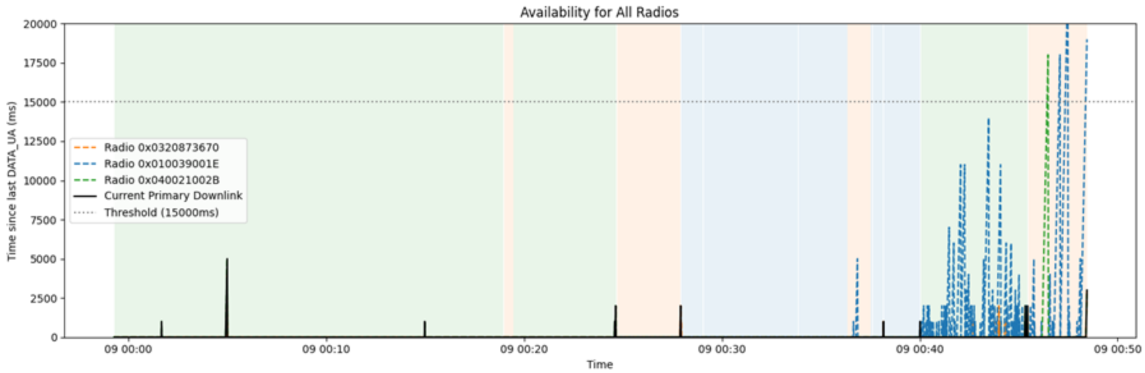

Figure 11-68 - Availability for Flight 223

11.12.3.2 Continuity

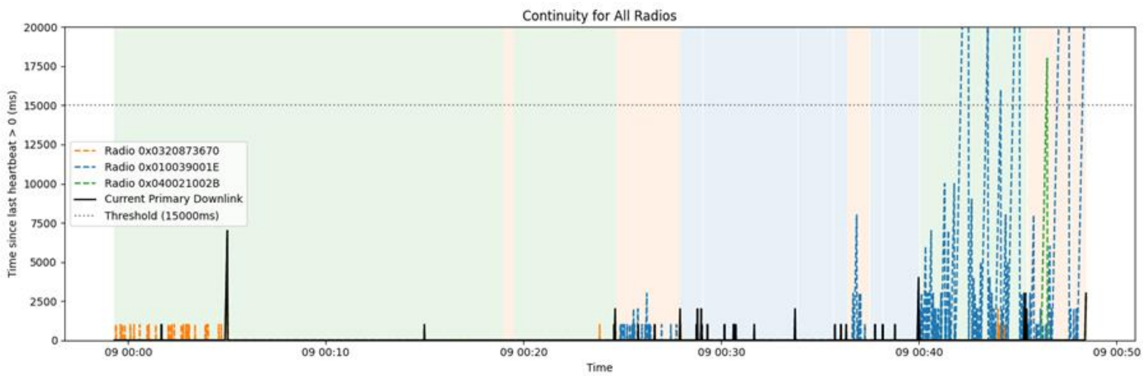

Figure 11-69 - Continuity for Flight 223

11.12.3.3 Integrity

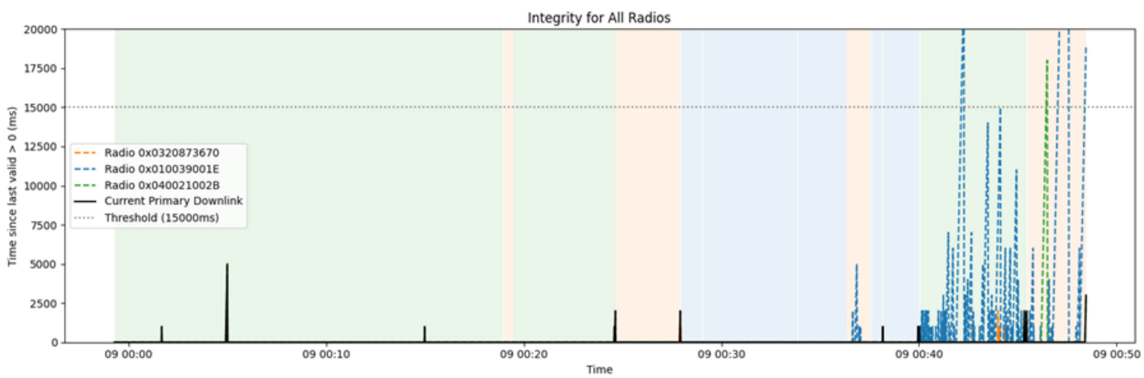

Figure 11-70 - Integrity for Flight 223

11.12.3.4 Latency

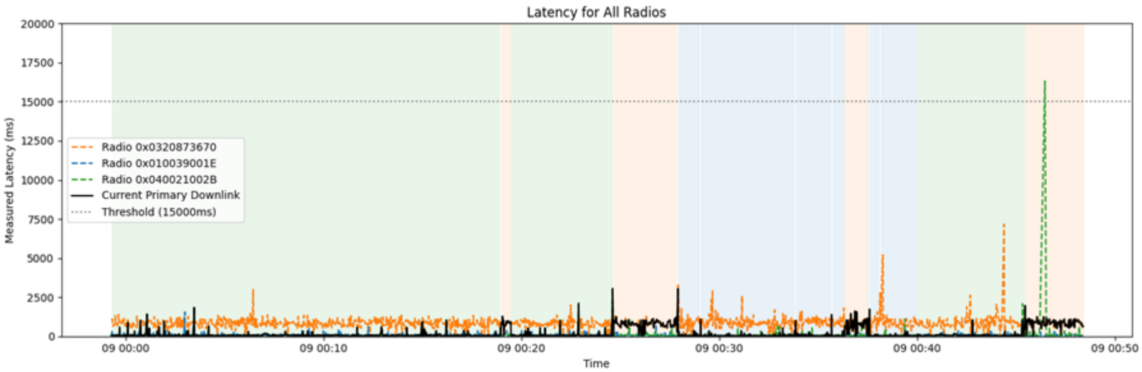

Figure 11-71 - Latency for Flight 223

11.12.4 Message Transmission Data

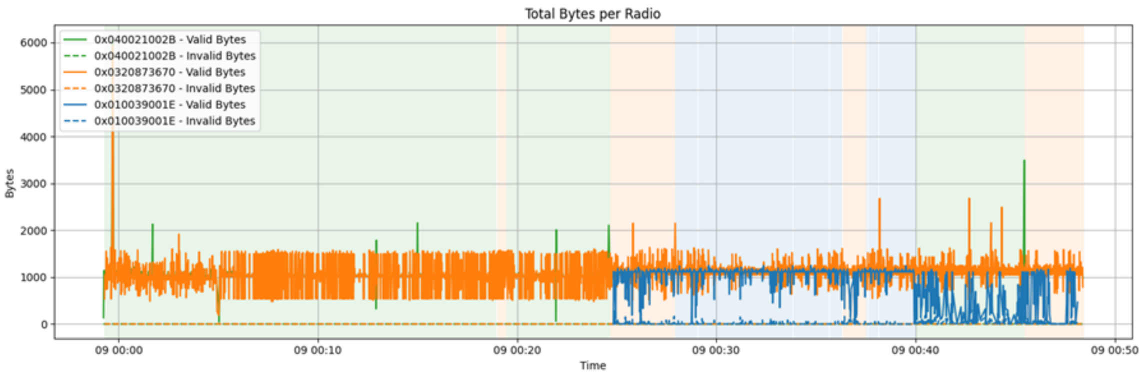

Figure 11-72 - Total Bytes for Flight 223

11.13 Flight 225: ACUASI 1500 12

11.13.1 Flight Details

Detail	Value
Date	10/8/2024
Time	18:50:33 to 19:07:15
Duration	16 min 42 sec
Altitude	4500 ft

11.13.2 Flight Track

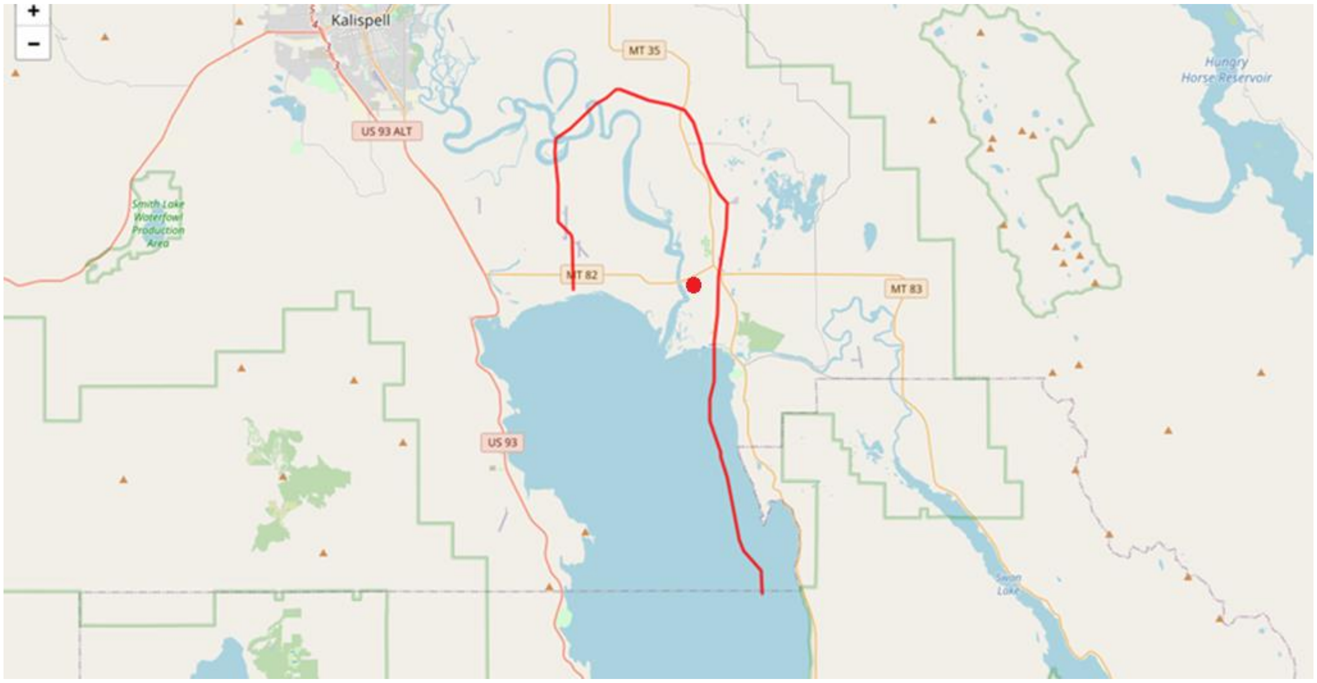

Figure 11-73 - Flight Track for Flight 225 as recorded by SkyLine C2CSP operational platform

11.13.3 Link Performance

11.13.3.1 Availability

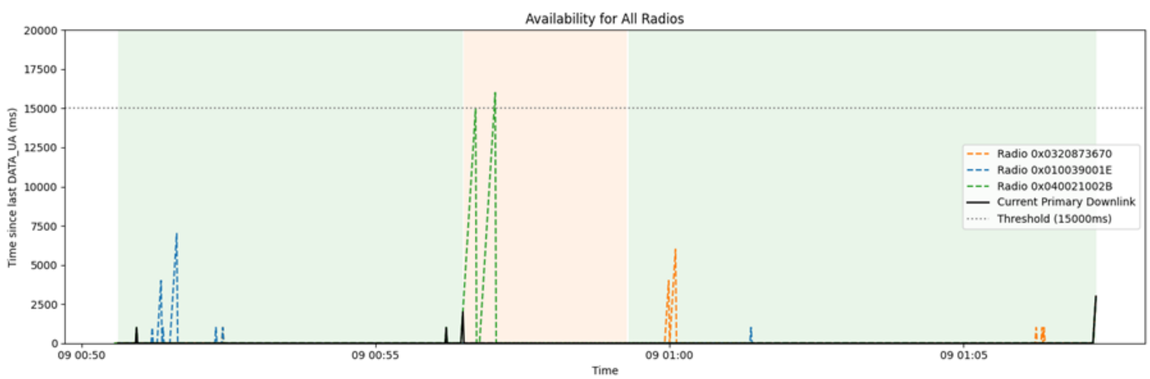

Figure 11-74 - Availability for Flight 225

11.13.3.2 Continuity

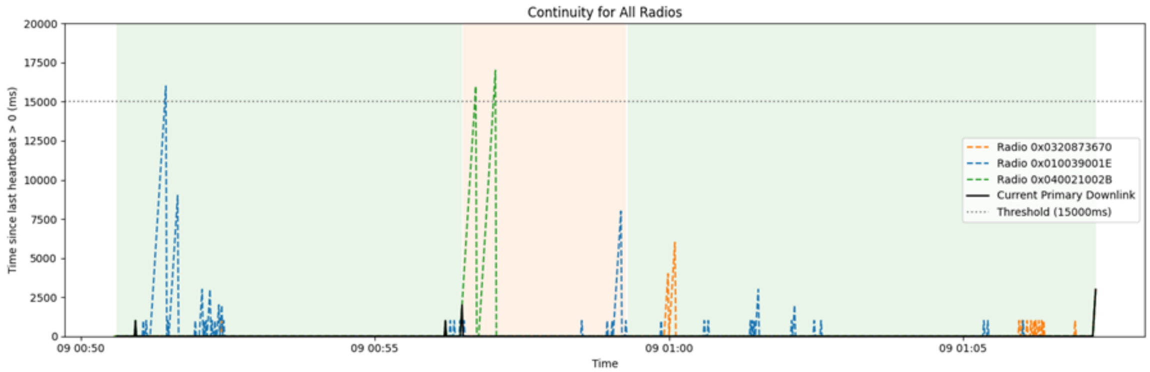

Figure 11-75 - Continuity for Flight 225

11.13.3.3 Integrity

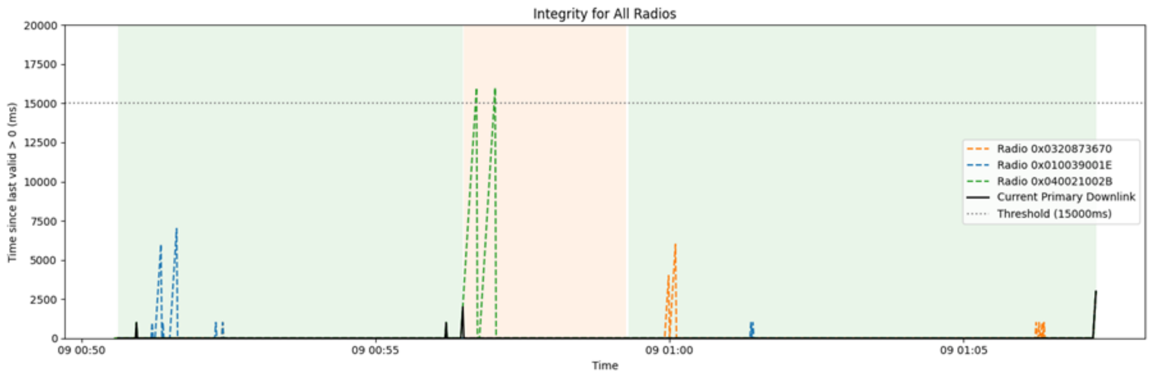

Figure 11-76 - Integrity for Flight 225

11.13.3.4 Latency

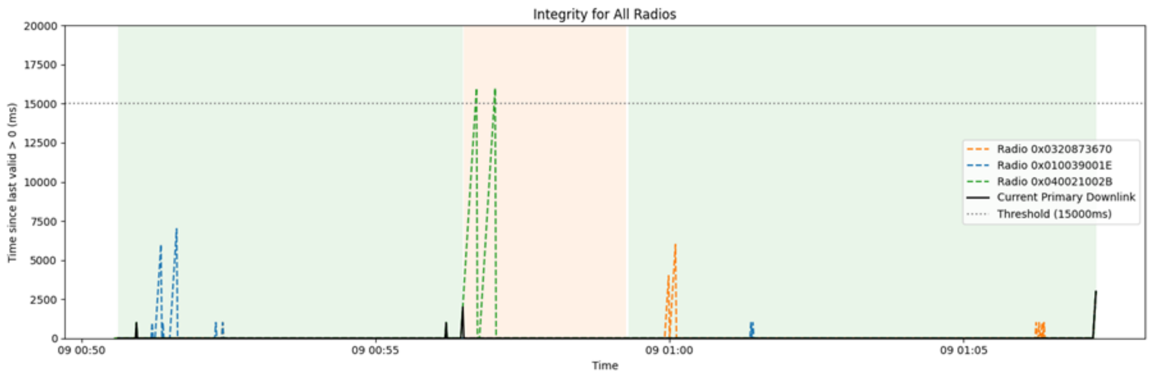

Figure 11-77 - Latency for Flight 225

11.13.4 Message Transmission Data

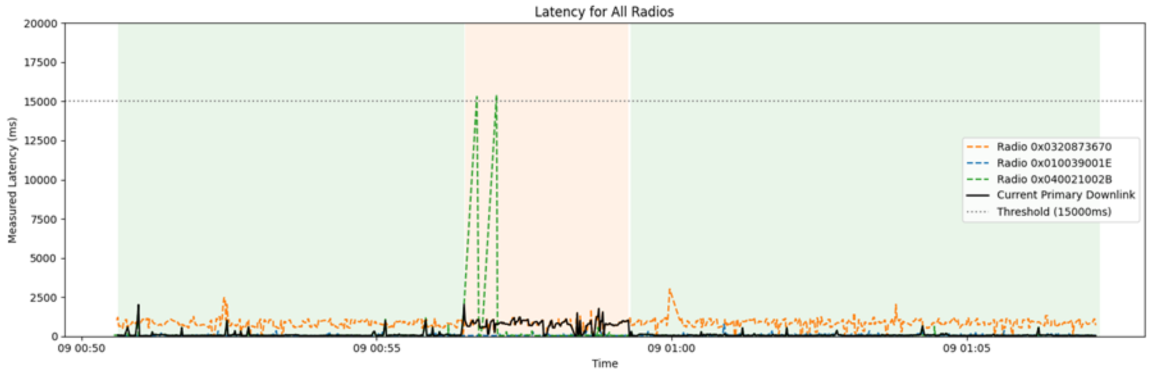

Figure 11-78 - Total Bytes for Flight 225

11.14 Flight 227: ACUASI 1500 13

11.14.1 Flight Details

Detail	Value
Date	10/8/2024
Time	19:09:53 to 19:26:20
Duration	16 min 27 sec
Altitude	4500 ft

11.14.2 Flight Track

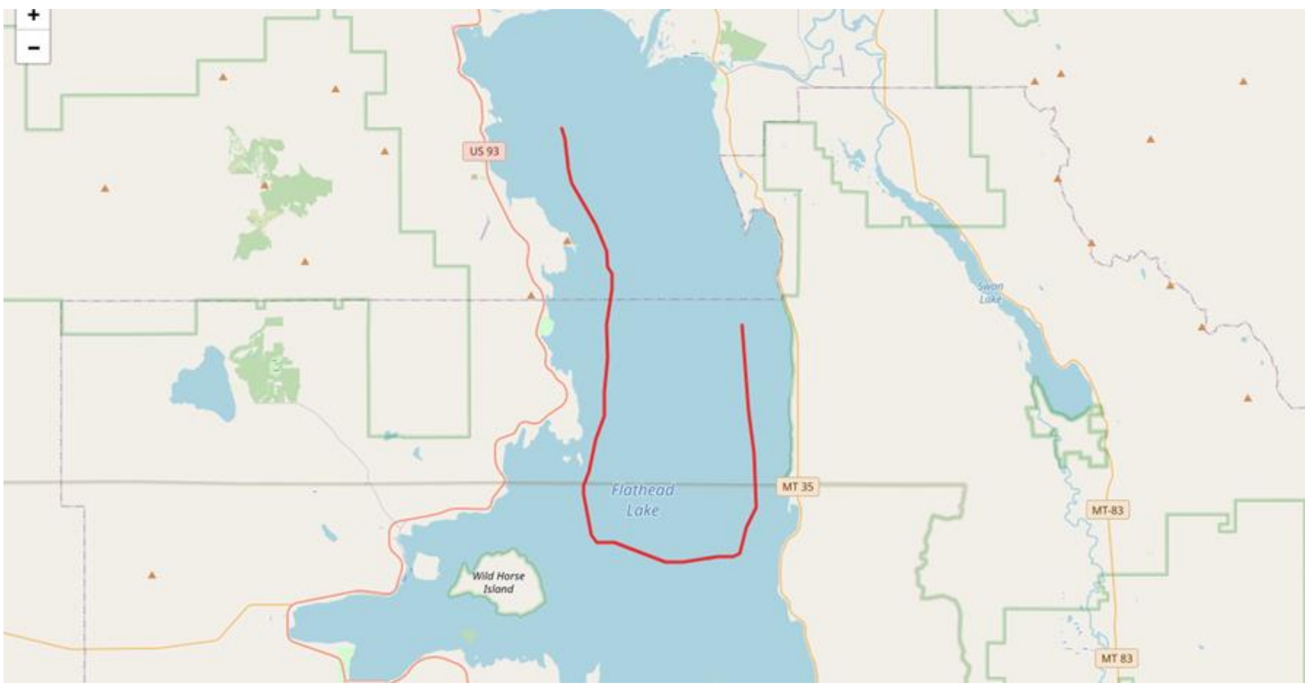

Figure 11-79 - Flight Track for Flight 227 as recorded by SkyLine C2CSP operational platform

11.14.3 Link Performance

11.14.3.1 Availability

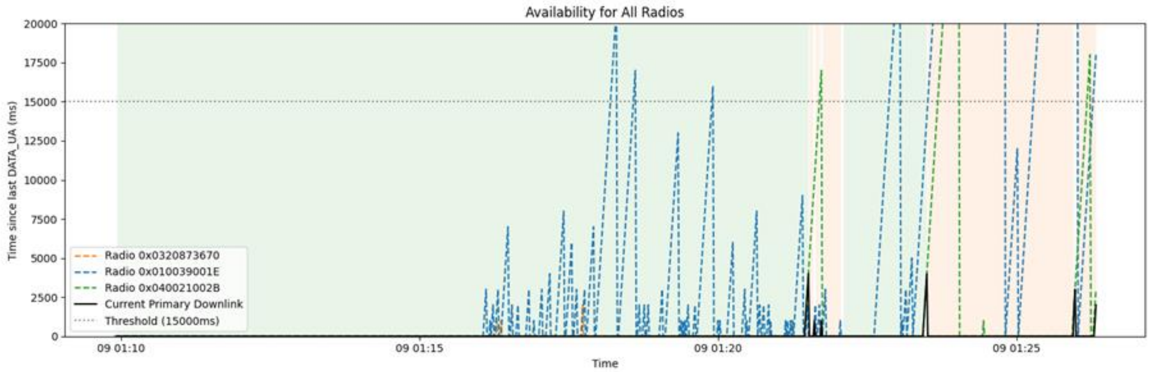

Figure 11-80 - Availability for Flight 227

11.14.3.2 Continuity

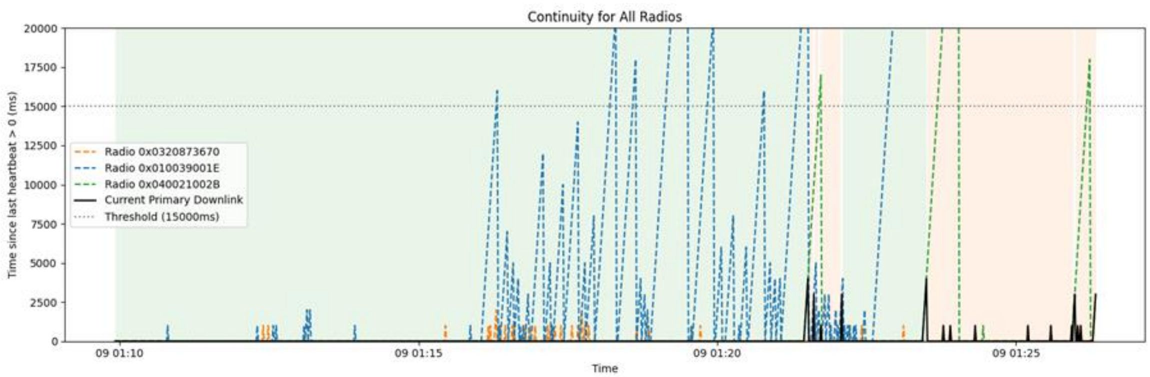

Figure 11-81 - Continuity for Flight 227

11.14.3.3 Integrity

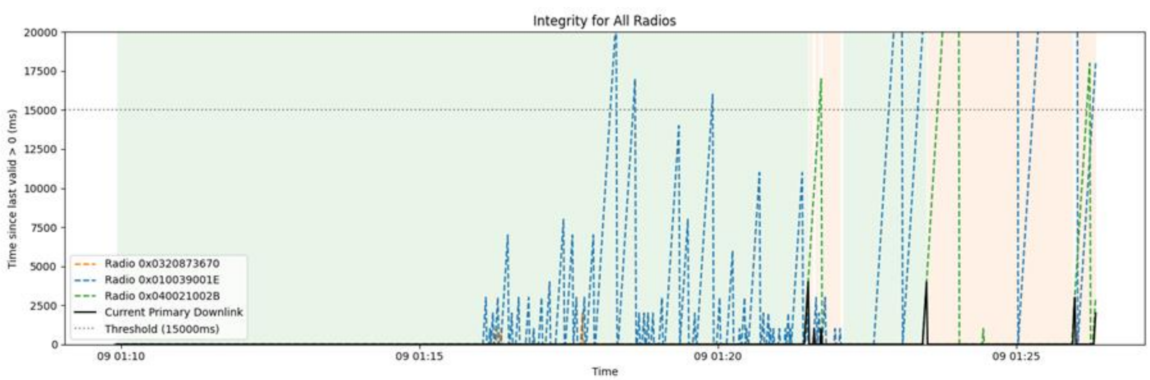

Figure 11-82 - Integrity for Flight 227

11.14.3.4 Latency

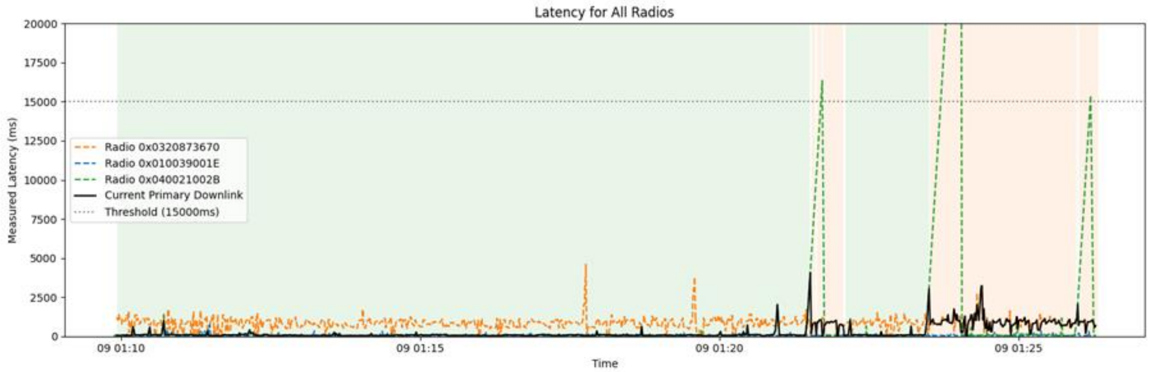

Figure 11-83 - Latency for Flight 227

11.14.4 Message Transmission Data

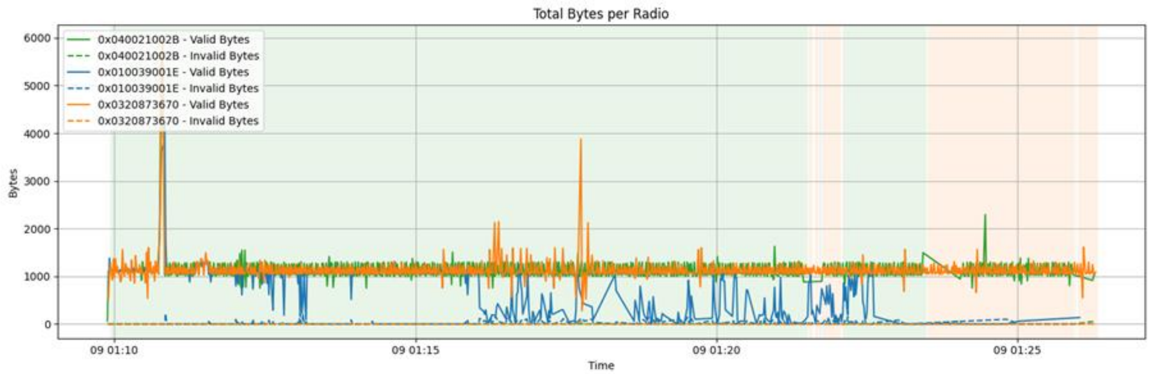

Figure 11-84 - Total Bytes for Flight 227

11.15 Flight 230: ACUASI 1500 16

11.15.1 Flight Details

Detail	Value
Date	10/8/2024
Time	19:29:00 to 20:01:10
Duration	32 min 10 sec
Altitude	4500 ft

11.15.2 Flight Track

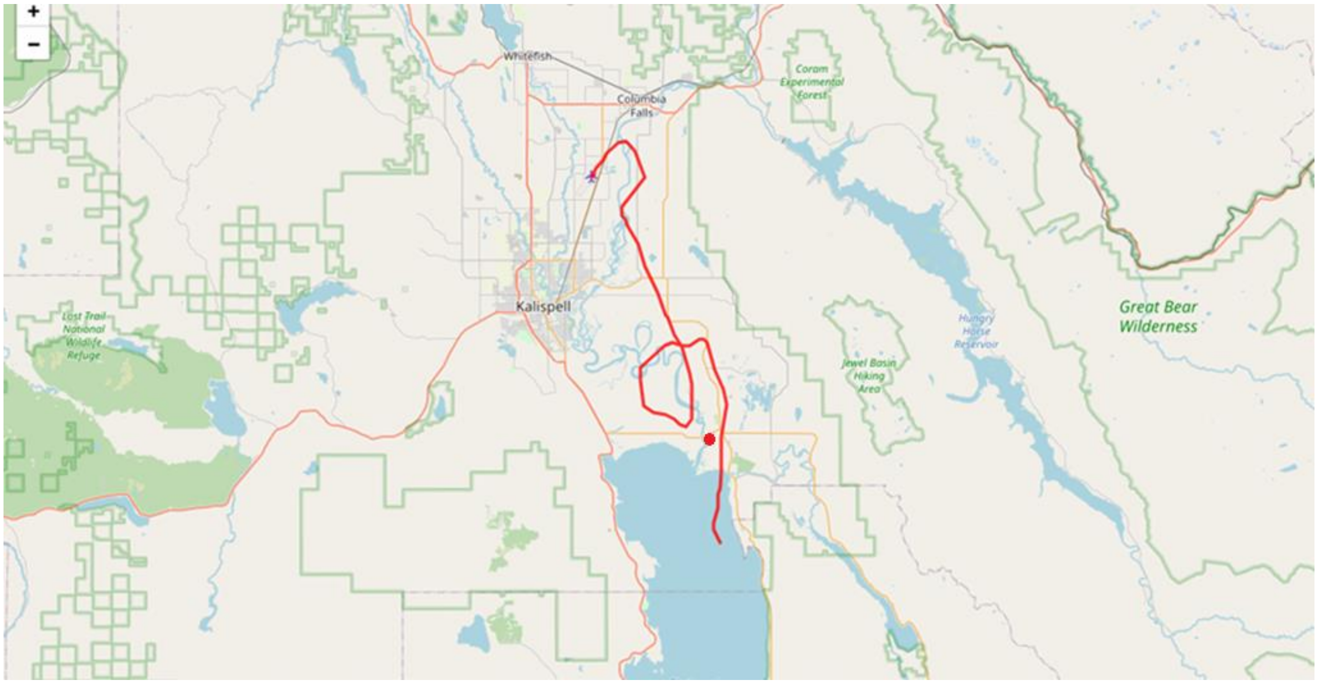

Figure 11-85 - Flight Track for Flight 230 as recorded by SkyLine C2CSP operational platform

11.15.3 Link Performance

11.15.3.1 Availability

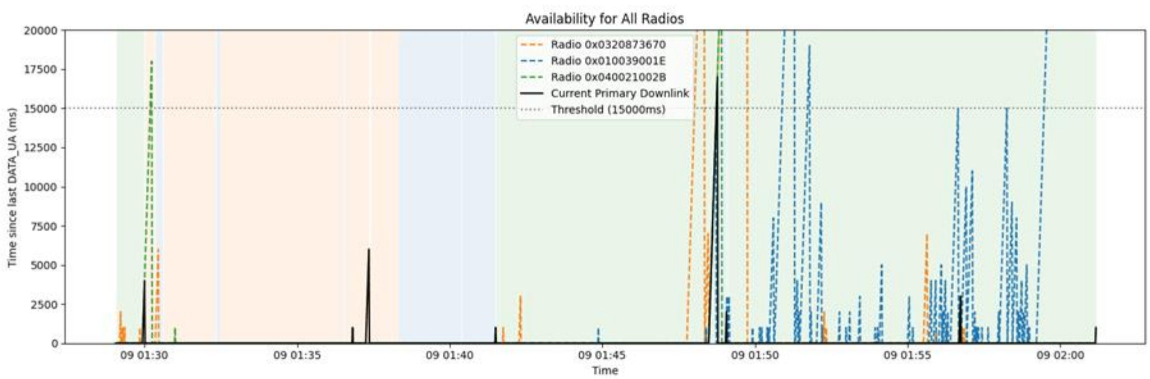

Figure 11-86 - Availability for Flight 230

11.15.3.2 Continuity

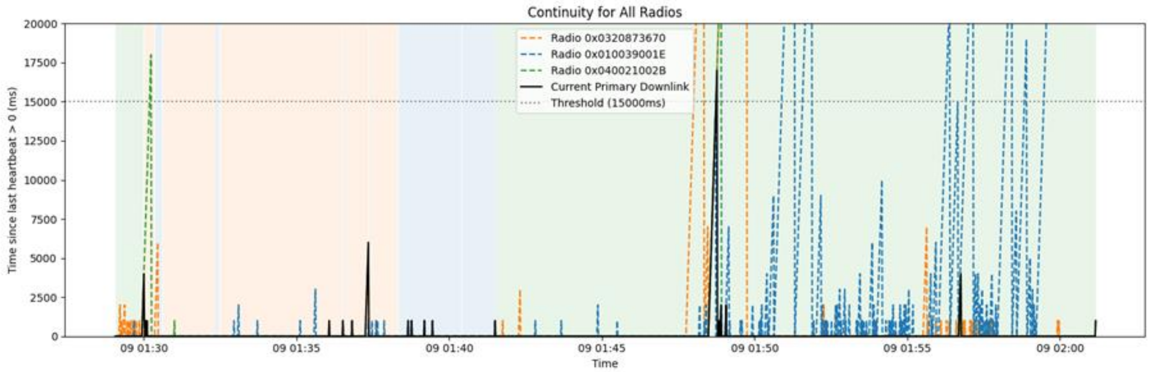

Figure 11-87 - Continuity for Flight 230

11.15.3.3 Integrity

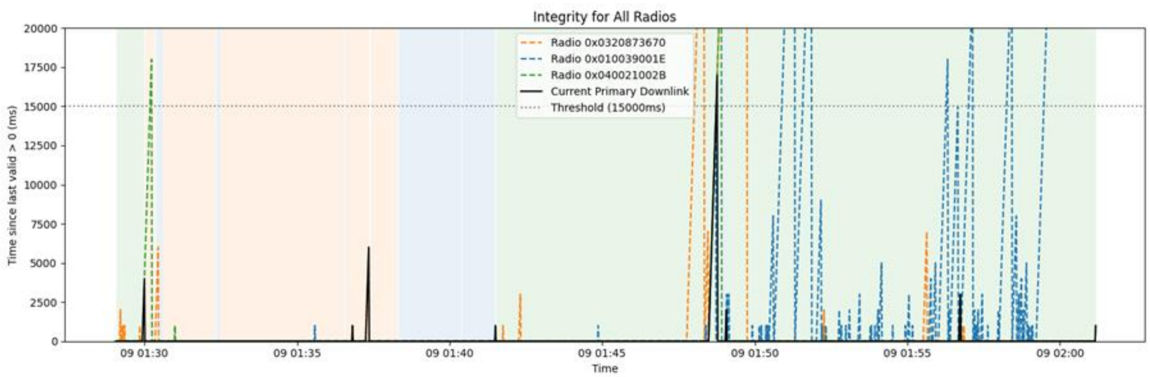

Figure 11-88 - Integrity for Flight 230

11.15.3.4 Latency

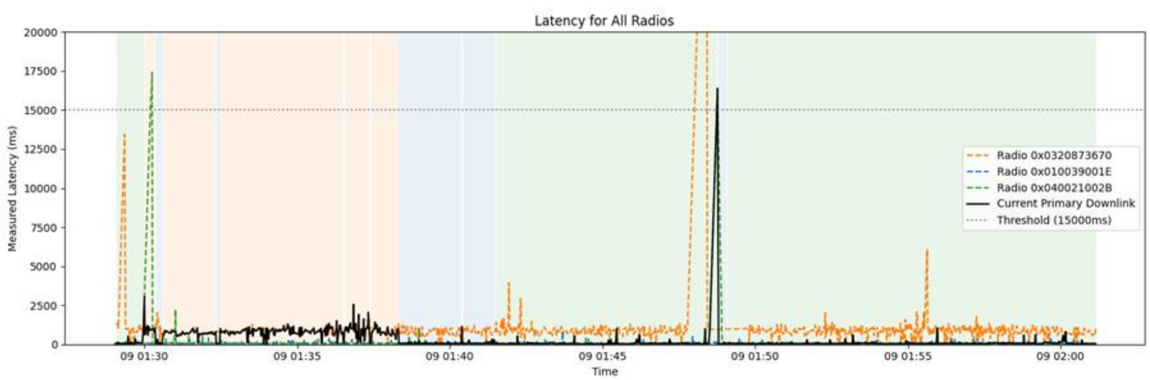

Figure 11-89 - Latency for Flight 230

11.15.4 Message Transmission Data

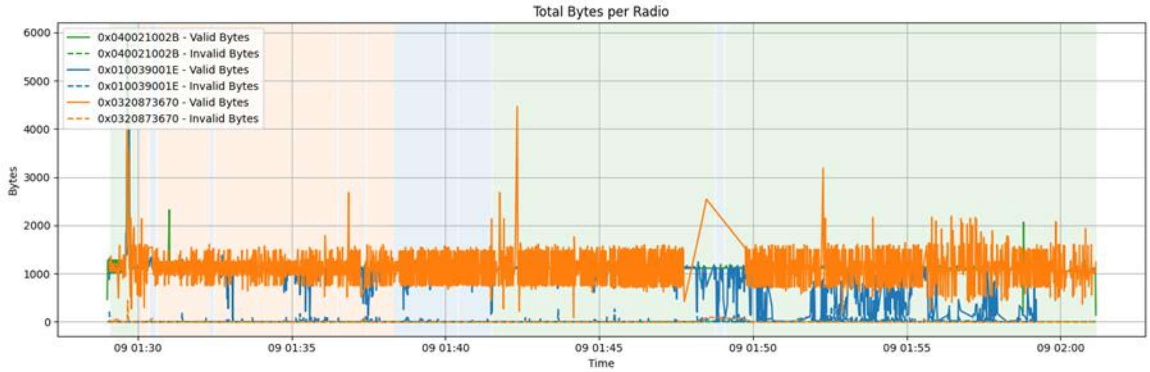

Figure 11-90 - Total Bytes for Flight 230

12 Appendix B: Reference Documentation

Please refer to Table 12-1 below for supporting documentation for this final report.

Document # / Date	Description
UAV-1006980-001 Rev B	uAvionix muLTElink5060 Datasheet
UAV-1006993-001 Rev B	uAvionix SkyStation5060POE Datasheet
UAV-1005905-001 Rev F	uAvionix SkyLine User and Installation Manual
UAV-1006972-001 Rev A	uAvionix SkyLine Airborne Radio System User and Installation Manual
UAV-1006973-001 Rev A	uAvionix SkyLine Ground Radio System User and Installation Manual
v2.0	Ground C-Band Viewshed and Plan 697DCK-23-C-00289 UAVION-AK
v2.0	Aircraft Integration Plan
v1.0	Link Diversity Data Analysis Plan 697DCK-23-C-00289
v2.0	Demonstration Test Plan 697DCK-23-C-00289 UAVIONIX
v1.0	Safety Plan 697DCK-23-C-00289 UAVION-AK
v2.0	CNPC Systems Integration Plan 697DCK-23-C-00289 UAVION-AK
UAV-1004752-001 Rev M	uAvionix Service Layer API ICD
UAV-1004775-001 Rev M	uAvionix Link Event WebSocket ICD
RTCA DO-362A	Command and Control (C2) Data Link Minimum Operating Performance Standards (MOPS) (Terrestrial)
RTCA DO-377A	Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Uncrewed Aircraft Systems in U.S. Airspace

Table 12-1 - Reference Documents