National Airspace System (NAS) Scaling of C- Band Frequency Assignment Manager (FAM) and Channel Reuse Demonstration with Multiple UAS in Nearby Regions

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Executive Summary

This report presents the outcomes of the second phase of the National Frequency Assignment Manager (NFAM) project, a collaborative effort to address the challenges of spectrum management for Uncrewed Aircraft Systems (UAS) in the National Airspace System (NAS).

Building upon the success of the first phase, which demonstrated the basic capabilities of a Frequency Assignment Manager (FAM), this phase focused on enhancing the system to operate at a national scale. The primary objective was to develop and validate a C-Band frequency management application capable of meeting existing and anticipated RTCA specification requirements while informing the potential evolution of FAA TSO C-213a.

Key Achievements:

1. Enhanced NFAM Capabilities: We successfully integrated viewshed analysis and improved interference modeling into the NFAM, allowing for more accurate and efficient frequency assignments across diverse geographical areas.
2. Comprehensive Demonstrations: Through a series of three demonstrations, we validated the NFAM's performance in both controlled and real-world environments:
   - Demonstration 1 verified the NFAM's ability to make multiple frequency assignments across different regions.
   - Demonstration 2 validated the accuracy of the NFAM's RF propagation models and viewshed generation with real-world measurements closely matching expectations.
   - Demonstration 3 consisted of 88 live flight tests, achieving 100% continuity and availability of C2 links with minimal errors.
3. Large-Scale Simulations: We developed and executed sophisticated simulations to test the NFAM's performance across the continental United States, validating its scalability and effectiveness in high-density scenarios.
4. Spectrum Efficiency: The NFAM demonstrated its ability to manage the entire 5030-5091 MHz C-Band efficiently, including regional interference modeling, potentially allowing for higher density UAS operations.
5. National Airspace Density Models: As part of our simulation efforts, we generated multiple high-density models for the national airspace. These models, utilizing the full 5030-5091 MHz band, provided crucial insights into the NFAM's performance under various operational scenarios and helped identify potential capacity limits of the system.
6. Industry Applicability: The project showed that the NFAM could be adopted by the UAS industry in a way that encourages commercial build-out of C2 Communications Service Provider (C2CSP) infrastructure without limiting competition.

Implications and Future Directions:

The success of this project has significant implications for the future of UAS operations. By providing a robust solution for spectrum management, the NFAM addresses a critical challenge in expanding UAS integration into the NAS. The national airspace density models we developed offer valuable insights into potential UAS traffic patterns and spectrum utilization across diverse geographical areas, informing future planning and policy decisions.

Our work may contribute to the evolution of regulatory frameworks, potentially streamlining frequency allocation processes and reducing the need for individual Special Temporary Authorizations (STAs). The NFAM's demonstrated scalability also opens possibilities for nationwide implementation, which could significantly enhance the efficiency and safety of UAS operations at a national level.

Looking ahead, there are opportunities for further development, including:

- Integration with UTM systems for seamless airspace management
- Creation of regulatory frameworks based on NFAM capabilities
- Continued large-scale testing and validation in diverse environments
- Enhancement of NAS density models to improve capacity planning

In conclusion, the NFAM project represents a significant step forward in addressing the spectrum management challenges for UAS. It provides a scalable, efficient solution that could significantly contribute to the safe and effective integration of UAS into the NAS. The insights gained from our national airspace density modeling efforts offer a valuable tool for anticipating and managing future spectrum needs as the UAS industry continues to grow and evolve.

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1 Background

The integration of Uncrewed Aircraft Systems (UAS) into the National Airspace System (NAS) presents significant challenges, particularly in terms of spectrum management for Command and Control (C2) communications. This project, now in its second phase, addresses these challenges by developing and enhancing a National Frequency Assignment Manager (NFAM) for C-Band spectrum.

1.1 Document Overview

Section 1 Background: This section provides background on the project.

Section 2 Demonstration and Results: This section provides a summary of the demonstrations and simulation and their results.

Section 3 Key Findings: This section summarizes the demonstration and simulation learnings.

Section 4 Future Opportunities: This section provides the purpose, scope, document overview, reference documents, and acronyms found throughout this Plan.

Section 5 Conclusions: This section provides a project summary of achievements, future directions and final thoughts.

Section 6 Appendix A: This section enumerates reference documentation.

1.2 Current UAS Spectrum Usage and Associated Risks

Currently, UAS usage of licensed aeronautical spectrum is by exception, with the vast majority of UAS operations conducted using unlicensed ISM and cellular spectrum. This approach, while flexible, significantly increases operational risks compared to using licensed and protected frequencies.

Key challenges include:

- Interference: Unlicensed bands are susceptible to interference, potentially degrading control link performance or loss of link entirely.
- Reliability: Cellular networks regularly experience congestion or coverage gaps, particularly at higher altitudes.
- Security: Significant vulnerability to jamming or spoofing attacks.

These issues pose very real safety and reliability risks to UAS operations, undermining the operators ability to meet FAA requirements for C2 links, especially for BVLOS operations.

1.3 Recent Regulatory Actions

Several recent regulatory actions have paved the way for more structured use of C-Band spectrum for UAS operations:

- RTCA Publications: In December 2020, RTCA published an updated revision of the Minimum Operational Performance Specification (MOPS) (DO-362A). In February 2021, a revision of the Minimum Aviation System Performance Standards (MASPS) (DO-377A) was released. These documents provide further guidance on the role of a Frequency Management Organization (FMO) and the Frequency Management Application (FMA) process.

- FCC Actions: The Federal Communications Commission's (FCC) Wireless Telecommunications Bureau (WTB) issued a Public Notice to refresh the record on UAS in the 5 GHz band in August of 2021. This was in response to a petition filed by the Aerospace Industries Association (AIA) to adopt licensing and service rules for CNPC links in the 5030-5091 MHz band to support UAS operations.

- FAA Reauthorization Act of 2018: Under section 374 of this act, the FAA and FCC were directed to produce reports on the usage of various spectrum allocations, including C-Band for UAS Command and Control (C2). Both entities have provided responses supporting the use of the 5030-5091 MHz band.

- In January of 2023 the FCC proposed rules to enable wireless communications for UAS use in the 5030-5091 MHz band and sought comment. Over 100 comments were received from the UAS industry. The NPRM contained an extensive discussion on the use of Dynamic Frequency Management Services (DFMS).
- On August 29, 2024, the FCC released a Report and Order establishing the rules for UAS access to the 5030-5091 MHz band.

1.4 Need for Frequency Assignment Management Infrastructure

With the growing complexity of UAS operations in the NAS, there is a critical need for a reliable and scalable infrastructure to manage spectrum allocation. The NFAM is designed to address the operational challenges posed by the increasing density of UAS flights, particularly in BVLOS operations that require robust, interference-free and reliable C2 links.

NFAM's primary value lies in its ability to dynamically allocate the C-Band spectrum based on real-time geographical and operational parameters, ensuring that UAS operations remain safe and interference-free across diverse environments. This infrastructure leverages advanced interference modeling and viewshed analysis to maximize spectrum efficiency while preventing frequency conflicts.

Furthermore, NFAM plays a key role in securing the integrity of UAS communications, offering enhanced protection against jamming and interference, which are critical concerns in safety-critical UAS missions. NFAM's alignment with FAA TSO C-213a and RTCA standards further ensures that it is capable of supporting the evolving regulatory landscape and future UAS operational needs.

By serving as a backbone for national-level spectrum management, NFAM provides a scalable solution that integrates seamlessly with emerging airspace management systems such UTMs. This positions NFAM as a crucial component for the future of UAS operations in the NAS, enabling safe, efficient, and scalable growth.

1.5 First Phase Overview

The first phase of this project, completed in 2023 under the FAA's Broad Agency Announcement Call 3, focused on developing and demonstrating a C-Band Frequency Assignment Manager (FAM).

Key achievements of this phase included:

- Successful completion of 124 live flight demonstrations
- Development of a FAM integrated with the uAvionix SkyLine™ C2CSP management platform
- Demonstration of dynamic allocation of C-Band frequencies (5030-5091MHz) to multiple UAS platforms
- Achievement of 100% continuity and availability of C2 links assigned by the FAM
- Validation of the FAM's ability to manage spectrum efficiently and without interference

The first phase proved that the principles of a FAM could ensure efficient use of available spectrum safely and without frequency interference, even with multiple simultaneous flights.

1.6 Second Phase Scope and Enhancements

Building on the foundational success of the first phase, the second phase of the NFAM project expanded the system's capabilities, scaling it for NAS-wide deployment. This phase introduced several critical advancements aimed at improving both the functionality and scalability of the NFAM:

- **Enhanced Spectrum Management Capabilities**: The NFAM's core functionality was significantly upgraded with the integration of viewshed analysis and more sophisticated interference modeling. These enhancements allowed the system to allocate frequencies with greater precision, even in complex geographical areas with varying terrain and high-density UAS operations. This enabled the NFAM to handle multiple simultaneous nearby UAS flights with no interference, ensuring safe and efficient spectrum utilization.

- **Expansion to National Scale**: The scope of the NFAM was extended to manage frequencies across the entire NAS. This required not only improvements to the frequency allocation algorithms but also the ability to model and predict UAS behavior in diverse environments at a national scale. The system was designed to dynamically adapt to regional variations in UAS traffic and spectrum demand, while maintaining compliance with FAA regulations and RTCA standards.
- **Development of National Airspace Density Models**: A critical component of this phase was the creation of detailed national airspace density models. These models simulated high-density UAS operations across the continental United States, allowing us to test the NFAM's scalability under conditions that would be impractical or impossible to replicate in live demonstrations. The simulations were based on RTCA DO-362A Appendix H, but expanded to a national scale, incorporating a variety of operational scenarios impacted by terrain and Line of Sight calculations.
- **Large-Scale Simulations and Key Insights**: Through large-scale simulations, the NFAM was tested under multiple high-traffic scenarios to evaluate its ability to efficiently manage spectrum across different altitudes, terrains, and UAS operational types. The models provided critical insights into spectrum capacity limits and the system's overall performance under national-level operations. This stress-testing informed key decisions related to the NFAM's architecture and the future of UAS integration in the NAS.

The second phase demonstrated that the NFAM could not only scale to meet national demands but also efficiently manage the entire 5030-5091 MHz band with minimal interference, laying the groundwork for its potential nationwide implementation. The results from this phase are crucial for understanding the NFAM's ability to ensure the safe and effective integration of UAS into the NAS, and they set the stage for future regulatory and infrastructure planning.

1.7 Definition of Acronyms

Table 1 lists the acronyms found throughout this document.

Acronym	Definition
API	Application Programming Interface
ARS	Airborne Radio System
BAA	Broad Agency Announcement
C2	Command and Control
C2CSP	Command and Control Communications Service Provider
CNPC	Control and Non-Payload Communications
DFMS	Dynamic Frequency Management Service
FAA	Federal Aviation Administration
FAM	Frequency Assignment Manager
FCC	Federal Communication Commission
FMA	Frequency Management Application
FMO	Frequency Management Organization
GRS	Ground Radio System
HA	High Altitude
HAR	High Altitude Relay
LA	Low Altitude
LOS	Line of Sight
MA	Medium Altitude
MASPS	Minimum Aviation System Performance Standards
MOPS	Minimum Operational Performance Specification
NAS	National Airspace System
NFAM	National Frequency Assignment Manager

Acronym	Definition
RF	Radio Frequency
RLOS	Radio Line of Sight
RSSI	Received Signal Strength Indicator
RTCA	Radio Technical Commission for Aeronautics
TDD	Time Division Duplex
TSO	Technical Standing Order
UAS	Uncrewed Aircraft System
USGS	United States Geological Survey
UTM	Uncrewed Aircraft System Traffic Management
WTB	Wireless Telecommunications Bureau

Table 1 - Acronyms

2 Demonstrations and Results

The second phase of the NFAM project involved a series of structured demonstrations designed to validate the system's enhancements and scalability. These demonstrations progressively tested the NFAM's ability to manage frequency allocations in increasingly complex and realistic scenarios, providing critical validation before scaling to national deployment.

The demonstrations began with controlled bench tests of the NFAM's enhanced functionality and progressed to real-world validation through signal measurements and live flight tests. Each stage provided key insights into the system's performance, ensuring that NFAM could dynamically and reliably allocate spectrum in diverse geographic areas under varying operational conditions.

This section outlines the outcomes of these demonstrations, detailing how they validated NFAM's readiness for broader implementation across the National Airspace System (NAS).

2.1 Demonstration 1: NFAM Enhancement Demonstration

We began with a crucial bench test of the NFAM's enhanced capabilities. Our goal was to make at least twenty frequency assignments across four or more regions in close proximity, pushing the system with extended request parameters and complex viewshed generation and interference analysis tasks.

The results showcased the NFAM's ability to safely reassign frequencies across different geographic areas. We implemented innovative features like automatic generation of "merged" viewsheds and advanced intersection analysis capabilities.

Key Results:

- Completed 20 successful dynamic frequency allocations to C-Band CNPC radios
- Enhanced FAM to safely re-allocate in-use frequencies to other geographic areas
- Implemented automatic generation of "merged" viewsheds using USGS 3D Elevation Program data
- Utilized RLOS (Radio Line of Sight) propagation model for safety
- Incorporated DO-362A specification's Time Division Duplex (TDD) scheme
- Stored generated viewsheds and used PostGIS queries for intersection analysis

To illustrate the NFAM's capability in managing multiple flights across different regions, consider the following example:

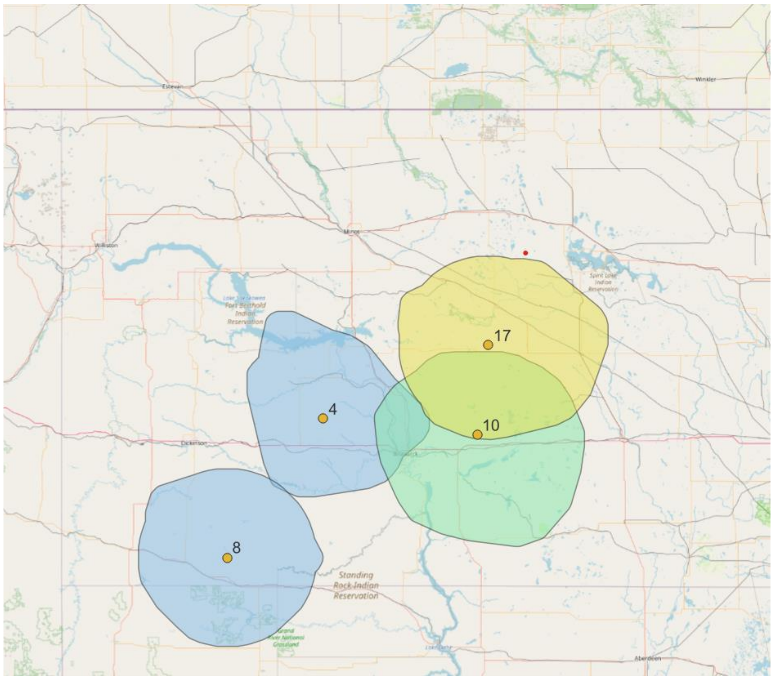

Figure 1 - NFAM Multiple Flight Management Example

Figure 1 demonstrates he NFAM's ability to manage four simultaneous flights in close proximity. Each color represents a different frequency, with the dot representing the GRS location and the shaded area representing the corresponding viewshed. In this example, GRS 4, 10 and 17 were allocated unique frequencies due to viewshed overlap. In general, NFAM attempts to minimize frequency allocations as depicted in the other outputs, but it operates on worst case LOS models to ensure non-interfering flights. The small overlap in the viewsheds from GRS 8 and GRS 4 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

This visual representation clearly shows how the NFAM successfully allocated frequencies to multiple UAS operations in close proximity while managing potential interference through careful viewshed analysis and frequency assignment.

This initial demonstration successfully validated the NFAM’s enhanced frequency assignment capabilities, laying the groundwork for more complex, real-world testing. These early results gave confidence that the system could scale effectively, leading to the next phase of validation with real-world signal propagation.

2.2 Demonstration 2: NFAM Viewshed Validation

Building on the success of our first demonstration, we moved to validate the NFAM's performance against real-world measurements. We focused on a viewshed generated during the first demonstration, aiming to collect Received Signal Strength Indicator (RSSI) measurements from at least twenty locations within this viewshed.

This phase was crucial in ensuring our RF propagation models accurately reflected the performance of the SkyLink 5060 equipment in real-world conditions. The results gave us confidence in the accuracy of our models and set the stage for our most ambitious demonstration.

Key Results:

- Collected RSSI samples from ARS at 100 ft AGL
- Validated NFAM-generated RF viewshed against real-world observations
- Verified signal presence within viewshed boundaries and absence beyond

To illustrate the process and results of our viewshed validation efforts, consider the following image:

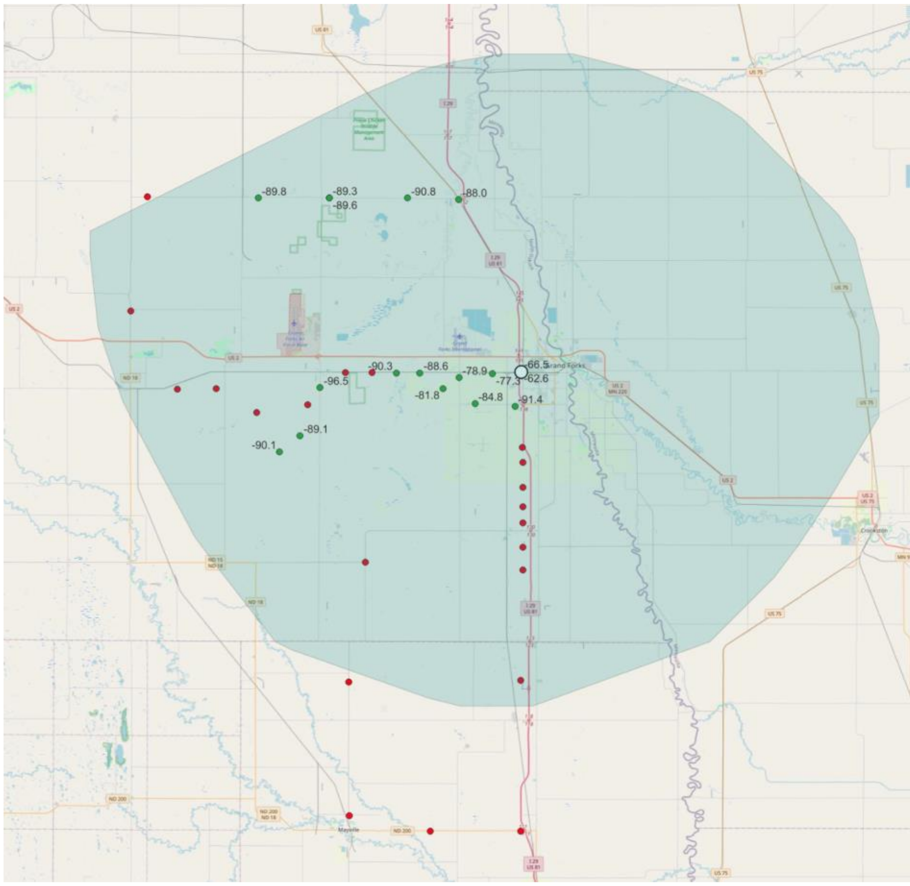

Figure 2 - NFAM Viewshed Validation Results

Figure 2 represents the NFAM-generated viewshed and the real-world data collection points used for validation.

Key elements in this image:

1. White dot: Represents the Ground Radio System (GRS) location at the center of the viewshed.
2. Green dots: Indicate locations where a connection was successfully established between the Airborne Radio System (ARS) and the GRS. Each green dot is labeled with the average collected RSSI at that point.
3. Red dots: Represent locations where no connection could be established between the ARS and GRS.
4. Shaded area: Depicts the NFAM-generated viewshed prediction.

It's important to note that the collection points were taken opportunistically, resulting in real-world heights that varied from those used in the viewshed generation. This discrepancy provides valuable insights into the robustness of our models under diverse conditions.

A notable example of terrain impact can be observed in the southern portion of the image. The series of red dots along a frontage road west of and parallel to a raised highway illustrates how physical obstacles can block the line-of-sight back to the GRS location. In this case, the GRS was positioned on the east side of the highway in Grand Forks, and the raised highway effectively blocked the signal to these collection points.

This visual representation clearly demonstrates the accuracy of the NFAM-generated viewshed in predicting signal coverage, while also highlighting the importance of considering real-world terrain and obstacles in refining our models.

The successful validation of the NFAM's RF propagation models against real-world measurements confirmed the accuracy of its viewshed analysis and interference management. With these results, the system was ready to be tested in a live operational environment to further demonstrate its real-time performance.

2.3 Demonstration 3: Live Flight Demonstration

The culmination of our testing came with a series of live flight demonstrations. We conducted flights across four distinct locations in North Dakota, allowing us to test the NFAM's capabilities in managing spectrum across diverse areas. The results demonstrated the system's ability to handle concurrent flights on different frequencies without interference.

Key Results:

- Completed 88 test flights (80 of 15-minute minimum duration)
- Conducted flights at four locations: Grand Forks, Niagara, Mayville, and Carrington, ND
- Achieved 100% continuity and availability of C2 links assigned by NFAM
- Minimal CRC errors (0.04% to 0.36%) and missed packets (1.66% to 6.99%)
- Demonstrated non-interference of concurrent flights on different frequencies
- Successfully managed protected spectrum across multiple geographically distinct regions

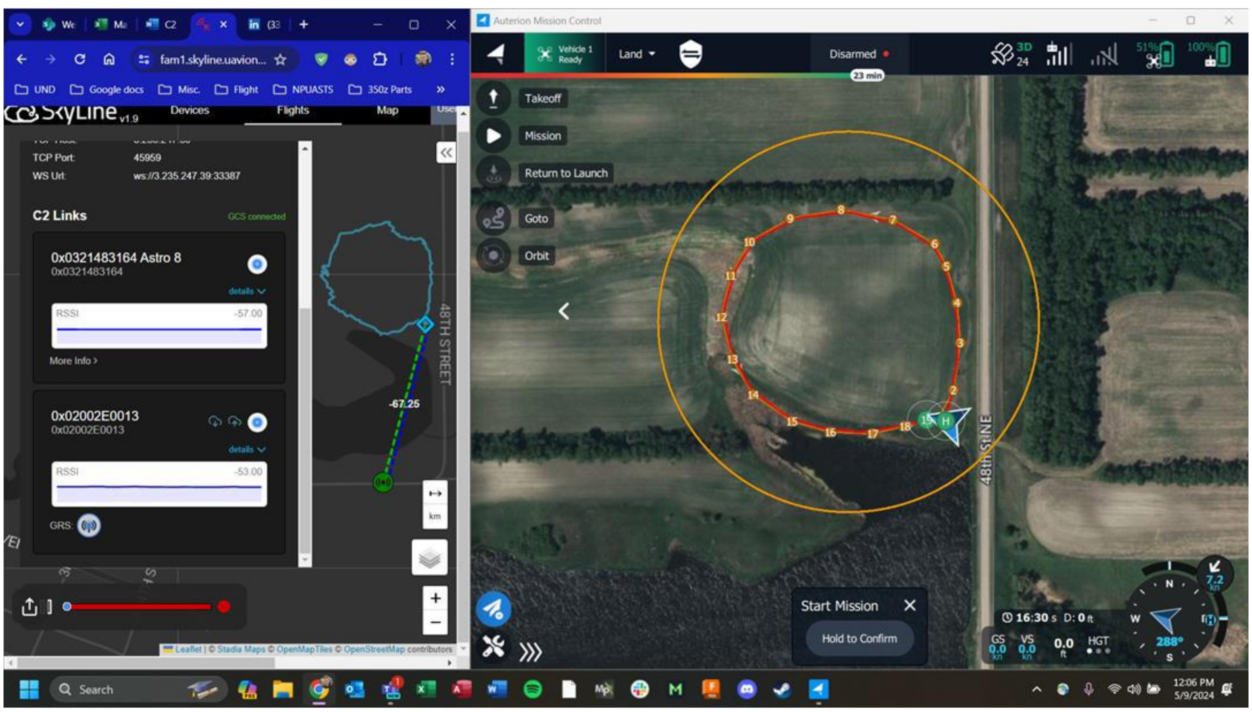

Figure 3 - Skyline and Auterion PIC Interface for Niagara, ND Test Flights

Figure 4 - FreeFly Astro RTH for Landing Following Test Flight

The live flight tests demonstrated the NFAM's ability to manage concurrent UAS operations across multiple regions with 100% availability of C2 links. This real-world validation paved the way for larger-scale simulations and modeling to evaluate the system's national scalability.

2.4 National Scale Modeling

While our demonstrations provided crucial validation of the NFAM's capabilities in real-world scenarios, they also highlighted the need for testing at a much larger scale. The success of these demonstrations laid the groundwork for the subsequent simulation phase, which included the generation of national airspace density models. The previous results directly informed the parameters and scenarios used in creating NAS high density models.

The simulations incorporated various UAS operational scenarios, accounting for differences in geographical areas, altitudes, terrain, and UAS traffic density. These high-density models stressed the NFAM's ability to dynamically allocate spectrum efficiently while maintaining adherence to RTCA DO-362A specifications.

Key aspects of the simulations included:

- **Scalability Testing**: We simulated nationwide UAS traffic to evaluate the NFAM's capacity to handle spectrum assignments across the entire continental US, managing frequency allocations into the tens of thousands of simultaneous simulated UAS operations.
- **Terrain and Environmental Factors**: The simulations incorporated terrain data and line-of-sight calculations to test the system's ability to allocate spectrum in regions with varying topographical challenges, including mountainous and densely built environments.

- **Traffic Density**: Multiple high-density scenarios were generated to push the limits of the NFAM's performance, ensuring that the system could handle peak operational loads without frequency conflicts or degradation of service.
- **Automation and Efficiency**: The NFAM's ability to autonomously and efficiently reuse spectrum without interference was tested across different UAS operational types and altitudes, ensuring its versatility in real-world conditions.

These simulations confirmed that the NFAM can scale effectively to manage spectrum nationally, even in high-traffic and geographically complex environments. The insights gained here laid the groundwork for the system's future national deployment, providing a strong foundation for continued regulatory development and operational planning.

The development and analysis of these national airspace density models form a critical component of our project, bridging the gap between localized testing and potential nationwide implementation. The insights gained from these models as discussed below provide a comprehensive view of the NFAM's potential to manage UAS spectrum allocation at a truly national scale.

3 Key Findings

The NFAM project yielded significant insights into the system's performance, effectiveness, and scalability. Through both live demonstrations and national-scale simulations, we validated the NFAM's ability to manage spectrum dynamically and efficiently across diverse operational environments. The following key findings highlight the most critical outcomes from these efforts, offering a clear view of the NFAM's readiness for nationwide implementation and its potential impact on UAS operations within the NAS. Based on these findings, in section 4 we highlight opportunities and recommendations as next steps.

3.1 Demonstration Learnings

The three live demonstrations provided a robust validation of the NFAM's capabilities in real-world operational environments. Each demonstration progressively increased in complexity, allowing us to validate core functions, model accuracy, and real-time performance under various operational conditions.

- **Enhanced Spectrum Allocation Accuracy**: The NFAM successfully managed dynamic frequency allocation across multiple UAS in close proximity, without interference or loss of service. This validated the system's ability to optimize frequency assignments through advanced viewshed analysis and interference modeling.
- **Real-Time Operational Reliability**: Across 88 live flights in four distinct locations, the NFAM achieved 100% continuity and availability of Command and Control (C2) links, with minimal errors and packet loss. The system consistently maintained interference-free communications between UAS, demonstrating its operational reliability in both controlled and real-world environments.
- **Validation of RF Propagation Models**: Real-world measurements collected during the viewshed validation phase closely matched the NFAM's predicted coverage areas. This confirmed the accuracy of the system's RF propagation models and its ability to forecast interference-free zones in complex terrains.
- **Scalability in Regional Operations**: The demonstrations showed the NFAM's ability to scale effectively within localized high-traffic areas. The system efficiently reused spectrum across geographically distinct regions, paving the way for larger-scale tests at the national level.

3.2 Simulation Learnings

The national-scale simulations were designed to test the NFAM's ability to manage spectrum across the entirety of the NAS, simulating operational conditions that are impractical to recreate in live tests. These simulations provided critical insights into the NFAM's performance under high-density traffic and complex geographical scenarios.

- **National Scalability**: The simulations confirmed that the NFAM can manage spectrum allocation effectively across the entire continental United States, handling diverse traffic densities and geographical conditions. The system demonstrated robust performance under high-traffic loads, ensuring efficient spectrum reuse without significant interference or degradation in service.

- **Performance in Complex Terrains**: The incorporation of terrain data and line-of-sight calculations revealed the NFAM's resilience in managing spectrum in regions with challenging topography, such as mountainous areas and dense urban environments. This highlighted the system's adaptability to various operational environments, ensuring consistent service regardless of terrain complexity.
- **Spectrum Efficiency**: The simulations demonstrated that the NFAM could allocate and reuse spectrum dynamically across different UAS operational types and altitudes, optimizing spectrum efficiency even in high-demand areas. This efficiency ensures that the system can support higher-density UAS operations in the future.
- **Identification of Potential Bottlenecks**: While the system performed well under most conditions, the simulations helped identify potential bottlenecks in certain high-density scenarios, particularly in areas with extreme geographical constraints. These findings will guide further optimization of the NFAM to ensure resilience under all operational conditions.
- **Informing Regulatory and Infrastructure Planning**: The insights gained from these simulations are crucial for future regulatory and infrastructure planning. They provide a foundation for addressing spectrum allocation at a national level and support the continued development of policies and technologies necessary for large-scale UAS integration into the NAS.

4 Recommendations and Future Opportunities

The successful development and testing of the NFAM has revealed numerous opportunities for the future of UAS operations and spectrum management. As we look ahead, we recommend several promising avenues for further development and implementation.

4.1 Industry Adoption

One of the most exciting prospects is the potential for widespread adoption of the NFAM across the UAS industry. Our demonstrations have shown that the NFAM can efficiently manage C-Band spectrum for multiple operators without interference, a capability that will become increasingly crucial as UAS operations continue to expand.

Key Opportunities:

- Integration with existing UTM systems for seamless operations
- Adoption by various UAS operators, from small businesses to large enterprises
- Expedited approvals to use the protected spectrum, leading to more efficient and safe operations
- Utilization of national airspace modeling to inform strategic planning for UAS operations and infrastructure development

4.2 C2CSP Infrastructure Development

The NFAM has the potential to encourage the commercial build-out of C2CSP infrastructure. By providing a fair and efficient method of spectrum allocation, the NFAM could stimulate investment in C-Band communications infrastructure.

Key Opportunities:

- Encouragement of a competitive C2CSP market without regional lockups
- Potential for reduced operational costs for UAS operators
- C-Band infrastructure investment becomes more accessible with a clear ROI

4.3 Regulatory Advancement

Our work with the NFAM could play a significant role in shaping future regulations and standards for UAS spectrum management. The data and insights gained from our demonstrations and simulations provide valuable input for regulatory bodies.

Key Opportunities:

- Informing the evolution of FAA TSO C-213a
- Contributing to the development of international standards for UAS spectrum management, supporting a coordination mechanism on the borders between countries
- Potential for significantly streamlining the frequency allocation process, reducing the need for individual STAs
- Development of a multi-FAM standard that would support a national market of FAM providers for operators to choose from

4.4 Enhanced Capabilities and Features

While the current version of the NFAM has proven highly capable, there's always room for improvement and expansion of features. Future refinement of the NFAM's algorithms based on insights gained from national airspace density modeling, could improve its performance in various operational scenarios.

Key Considerations:

- Improve viewshed generation to incorporate specific antenna parameters such as the emission pattern, gain, and orientation
- Additional optimization and verification of viewsheds to support even denser allocations
- Continuous refinement of the simulation models as UAS operations evolve, ensuring the NFAM remains effective as the industry grows
- Development of strategies to address regional variations in UAS density and spectrum demand identified through the models

4.5 Research and Development Opportunities

The development of the NFAM has also opened new avenues for research in spectrum management, UAS communications, and related fields.

Potential Research Areas:

- Advanced interference modeling in complex urban environments
- Further development and refinement of more realistic national airspace models that include key areas of operations to improve their predictive capabilities
- Integration of automated and ongoing detailed RSSI performance data into the NFAM to enable a continuous improvement model

5 Conclusions

As we conclude this report on the NFAM, we find ourselves at an exciting juncture in the evolution of UAS spectrum management. From the initial proposal through demonstrations and simulations, including the development of national airspace density models, has yielded valuable insights and promising results.

5.1 Summary of Key Achievements

The development and testing of the NFAM represents a significant step forward in addressing the challenges of spectrum management for UAS operations. Through our series of demonstrations and simulations, we have achieved several critical milestones:

Key Achievements:

- Successfully developed and enhanced a Frequency Assignment Manager capable of operating at a national scale
- Demonstrated dynamic allocation of C-Band frequencies across multiple geographic regions without interference
- Achieved 100% continuity and availability in live flight tests, with minimal errors and packet loss
- Validated the accuracy of RF propagation models and viewshed generation

- Simulated NFAM performance across the entire continental United States, stress-testing its capabilities in high-density scenarios
- Developed national airspace density models to simulate NFAM performance across the continental United States, providing crucial insights into system capabilities and potential limitations in various operational scenarios

5.2 Implications for UAS Integration into the National Airspace System

The success of the NFAM, coupled with our national airspace density modeling efforts, has far-reaching implications for the integration of UAS into the National Airspace System. By providing a robust, scalable solution for spectrum management and a tool for predicting future spectrum needs, the NFAM addresses key challenges in expanding UAS operations.

Potential Impacts:

- Enhanced safety through reliable, interference-free C2 communications
- Increased efficiency in spectrum utilization, potentially allowing for higher density of UAS operations
- Facilitation of beyond visual line of sight (BVLOS) operations by ensuring reliable long-range communications
- Support for the growth of the UAS industry by providing a standardized approach to spectrum management
- Improved strategic planning for UAS integration, based on insights from national airspace density models

5.3 Addressing Current Challenges

Our work with the NFAM and the associated national airspace density models directly addresses several of the challenges currently facing the UAS industry:

- Spectrum Scarcity: By optimizing the use of available C-Band spectrum, the NFAM helps mitigate the issue of limited spectrum resources.
- Interference Management: The NFAM's sophisticated interference modeling and channel assignment algorithms minimize the risk of harmful interference between UAS operations.
- Scalability: Our simulations demonstrate the NFAM's potential to manage spectrum assignments at a national scale, a crucial capability as UAS operations continue to expand.
- Future Planning: The national airspace density models provide a valuable tool for anticipating future spectrum needs and potential congestion points in the national airspace, allowing for proactive management and infrastructure development.

5.4 Future Directions

While the NFAM has shown great promise, our work, particularly with the national airspace density models, has also highlighted areas for future development and research:

- Integration with UTM Systems: Further work is needed to seamlessly integrate the NFAM with existing and emerging Uncrewed Traffic Management (UTM) systems.
- Regulatory Framework: Collaboration with regulatory bodies will be crucial in developing appropriate standards and regulations for the implementation of NFAM-like systems with multiple providers.
- Continued Testing: While our simulations provided valuable insights, continued real-world testing at increasing scales will be important for validating the NFAM's performance under diverse conditions.
- Refinement of National Airspace Density Models: Continued development and validation of these models will be crucial for accurately predicting future UAS traffic patterns and spectrum needs.
- Dynamic Spectrum Management: Exploring ways to incorporate detailed signal strength data into the NFAM to enable a more responsive and efficient spectrum allocation.

5.5 Final Thoughts

The development and successful demonstration of the NFAM, along with our efforts in national airspace density modeling, represent significant milestones in UAS spectrum management. We've shown that it's possible to efficiently manage C-Band spectrum at a national scale and provided tools to anticipate future needs and challenges.

As we look to the future, we're excited about the potential impact of this technology and the insights gained from our modeling efforts. The NFAM not only addresses current challenges in spectrum management but also lays a foundation for the continued growth and integration of UAS into our national airspace.

We believe that the insights gained from this project will play a crucial role in shaping the future of UAS communications and spectrum management. As we move forward, we remain committed to refining and expanding the capabilities of the NFAM and our modeling techniques, working towards a future where UAS can operate safely and efficiently as an integral part of our national aviation system.

6 Appendix A: Reference Documentation

Please refer to

Table 2 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
UAV-1007035-001 Rev A	uAvionix Freefly Astro UAS Operation Manual
UAV-1004752-001 Rev M	uAvionix Service Layer API ICD
UAV-1004775-001 Rev M	uAvionix Link Event WebSocket ICD
UAV-1007074-001 v2.0	uAvionix Frequency Allocation Manager API Reference
12/19/2023 v1.0	NAS FAM ConOps 697DCK-23-C-00291 UAVION-ND
12/19/2023 v1.0	NAS FAM Data Analysis Plan 697DCK-23-C-00291 UAVION-ND
1/22/2024 v2.0	NAS FAM SMRD 697DCK-23-C-00291 UAVION-ND
1/31/2024	NAS FAM 697DCK-23-C-00291 UAVION-ND Flight Test Plan
5/1/2024 Rev 1.1	NAS FAM 697DCK-23-C-00291 UAVION-ND Demo 1 and 2 Test Plan
5/21/2024 v1.0	NFAM Upgrades Interim Project Outbrief 697DCK-23-C-00291 UAVION-ND
6/29/2024 Rev C	NFAM Demo 1 and 2 Test Report 697DCK-23-C-00291 UAVION-ND [*]
6/29/2024 Rev C	NFAM Demo 3 Test Report 697DCK-23-C-00291 UAVION-ND [*]
8/30/2024 Rev C	NFAM Simulation Report 697DCK-23-C-00291 UAVION-ND [*]

Table 2 - Reference Documents

[*] Attached

NFAM Simulation Report

for

National Airspace System (NAS) Scaling of C-Band Frequency Assignment Manager (FAM) and Channel Reuse Demonstration with Multiple UAS in Nearby Regions

Rev C August 2024

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Revision History

Date	Revision	Author	Reason for Change
8/15/2024	A	Jeremie Miller	Initial release
8/27/2024	B	Jaymie Oehler	Updates based on FAA feedback
09/4/2024	C	Cyriel Kronenburg	Marking Updates

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1 Introduction

This NFAM Simulation Report documents results from the validated NFAM and associated simulation tool. This was used to create multiple high-density models for the national airspace utilizing the full 5030-5091 frequency band in support of uAvionix C-Band National Frequency Assignment Manager (NFAM) as awarded by the FAA's Solicitation 692M15-19-R-00020-03 Broad Agency Announcement (BAA) Call 4.

1.1 Purpose

The purpose of this report is to document the results of a simulation tool, paired with the NFAM, to create multiple high-density models for the national airspace. The NFAM is an available option to manage the entire 5030- 5091MHz band (C-Band), inclusive of interference modeling regionally.

1.2 Scope

This report presents the results of five simulation models, based on DO-362A Appendix H "Spectral Capacity Analysis".

1.3 Document Overview

Section 1 Introduction: This section provides the purpose, scope, document overview, reference documents, and acronyms found throughout this Plan.

Section 2 Simulation Objectives: This section outlines the goals of the simulation effort.

Section 3 Simulation Environment: This section provides information on the simulation environment and configurations.

Section 4 Simulation Results: This section provides the results of the simulations.

1.4 Reference Documents

Table 1-1 identifies the documents referenced and/or applicable to this test plan.

Table 1-1 - Reference Documents

Document # / Date	Description
UAV-1007074-001 v2.0	uAvionix Frequency Allocation Manager API Reference

1.5 Definition of Acronyms

Table 1-2 lists the acronyms found throughout this document.

Table 1-2 - Acronyms

Acronym	Definition
ARS	Airborne Radio System
C2CSP	Command and Control Communications Service Provider
CNCP	Command and Non-Payload Control
FMO	Frequency Management Organization
GCS	Ground Control System
GRS	Ground Radio System
HA	High altitude
HAR	High altitude relay

Acronym	Definition
LA	Low altitude
MA	Medium altitude
NFAM	National Frequency Assignment Manager
RF	Radio Frequency
RLOS	Radio Line of Sight
RSSI	Received Signal Strength Indicator
UAS	Uncrewed Aircraft System

2 Simulation Objectives

This simulation effort's main objective is to demonstrate and validate the scalability and effectiveness of the National Frequency Assignment Manager (NFAM) for C-Band frequency management across the National Airspace System (NAS). This aligns with the broader goals of the FAA's Broad Agency Announcement (BAA) to advance UAS integration into the NAS by addressing spectrum management challenges.

Specific objectives of the simulation include:

1. Validate the NFAM's capability to manage the entire 5030-5091 MHz (C-Band) spectrum efficiently, as specified in the SOW.
2. Demonstrate the NFAM's ability to perform regional interference analysis and channel reuse, maximizing spectrum utilization.
3. Create and analyze multiple high-density models for the national airspace to determine the maximum number of frequency assignments possible under various scenarios.
4. Evaluate the NFAM's performance in handling different UAS types (HAR, HA, MA, LA) and their respective operational altitudes, as outlined in DO-362A Appendix H.
5. Assess the NFAM's adherence to adjacent channel separation logic, as described in DO-362A Appendix R.
6. Determine the scalability limits of the NFAM by simulating assignments until they reach predefined thresholds (e.g., 100th consecutive denial, 100th total denial).
7. Compare simulation results with the spectral capacity analysis provided in DO-362A Appendix H to validate the NFAM's performance against industry standards.
8. Provide data-driven insights to inform potential evolution of FAA TSO C-213a and support the development of a robust C-Band frequency management infrastructure for UAS operations.

These objectives collectively aim to demonstrate that the NFAM can effectively manage C-Band frequency assignments on a national scale, supporting the safe and efficient integration of UAS into the National Airspace System while maximizing spectrum utilization.

3 Simulation Environment

3.1 Software Configuration

All tests were performed with prototype NFAM software.

3.1.1 C-Band NFAM

The C-Band National Frequency Assignment Manager (NFAM) is a custom-developed software module central to this project. It is designed to manage frequency assignments across the entire 5030-5091 MHz spectrum for UAS operations in the National Airspace System. The NFAM incorporates advanced algorithms for frequency allocation, interference modeling, and channel reuse, allowing for efficient spectrum utilization while maintaining operational safety. Key features include:

1. Full spectrum management (5030-5091 MHz) in 200 kHz bands

2. Regional interference analysis and modeling
3. Support for multiple UAS types and operational altitudes
4. Implementation of adjacent channel separation logic
5. API-based architecture for scalability and integration
6. Compliance with RTCA DO-362A specifications

This module has been validated through previous demonstrations (1, 2, and 3) and serves as the core component for the simulations described in this report. The NFAM's performance in these simulations is crucial for assessing its capability to handle national-scale frequency management for UAS operations.

3.1.2 Simulation infrastructure

The simulation infrastructure developed for this project provides a comprehensive environment for testing and validating the National Frequency Assignment Manager (NFAM). This section details the key components and methodologies employed in our simulation setup.

3.1.2.1 Core Architecture

At the heart of our simulation infrastructure lies the Node.js-based Frequency Assignment Manager (FAM) API. This API, previously validated in earlier demonstrations, maintains consistent logic across all simulation runs. For this project, we implemented performance optimizations to accelerate simulation completion, allowing for more extensive testing scenarios.

The simulation framework itself is built using Python, chosen for its robust ecosystem of scientific and geospatial libraries. Key components include:

- PostGIS for spatial data handling
- GDAL for geospatial data processing
- pyproj for cartographic projections
- shapely for manipulation and analysis of planar geometric objects

This combination of tools enables us to accurately model and analyze complex spatial relationships inherent in national airspace frequency management.

3.1.2.2 Simulation Parameters and Methodology

Our simulations closely adhere to RTCA DO-362A with a focus on Appendix H. We implement four Command and Non-Payload Control (CNPC) Link types as defined in Table H-1 of this document:

CNPC Link Type	GRS Antenna Gain (dBi)	SV Radius (NM)	SV Height (feet)
High altitude relay (HAR)	22.5	159.0	120,000
High altitude (HA)	22.5	7.0	47,000
Medium altitude (MA)	13.0	49.0	34,000
Low altitude (LA)	13.0	18.5	3,500

Table 3-1 – DO-362A Appendix H Table H-1 CNPC Link Types

The entire 5030-5091 MHz spectrum is utilized in our simulations, divided into 200 kHz bands to also match Appendix H. Adjacent channel separation logic, crucial for preventing interference, is implemented according to the guidelines in Appendices H and R.

To ensure realistic and unbiased results, we chose the 'pure rand' Node.js module for enhanced random number generation. All simulation points are randomly selected within the continental United States, providing a comprehensive test of the NFAM's capabilities across diverse geographical areas.

3.1.2.3 Geospatial and Terrain Considerations

Accurate representation of terrain is crucial for realistic RF propagation modeling. Our simulation incorporates Mapzen terrain tiles, with U.S. terrain data sourced from the USGS 3D Elevation Program (3DEP). This high-quality elevation data allows us to account for geographical variations that can significantly impact frequency assignments and potential interference.

3.1.2.4 Hardware and Performance

Given the computational intensity of national-scale frequency assignment simulations, we utilize robust hardware to ensure efficient processing. Our simulations run on an Amazon EC2 cc6.4xlarge instance, featuring 32 GB of RAM and 16 cores. This configuration allows us to handle the complex calculations and large datasets involved in our comprehensive testing scenarios.

3.1.2.5 Data Analysis and Visualization

The simulation generates extensive datasets that require careful analysis. We utilize DBeaver for database management and result analysis, allowing us to efficiently process and visualize the outcomes of our simulations. This tool enables us to extract meaningful insights from the vast amount of data generated during each simulation run.

3.1.2.6 Simulation Design and Termination Criteria

Each simulation’s parameters were chosen to either provide a comparable reference to the previous work in DO-362A Appendix H, or to help illuminate certain high-density scenarios that are impacted by the terrain and LOS calculations.

Depending on the specific configuration, simulations run until reaching either the 100th consecutive frequency assignment denial or the 100th total denial. The 100th total denial matches the logic described in Appendix H, but at a national scale that threshold is reached quickly due to High Altitude Relays and ends up creating a lower density / utilization models. We decided that the best compliment to that existing work was to explore alternative high density and utilization models by having simulation runs continue until the 100th consecutive denial (meaning no plans were accepted in the last 100 generation attempts). The insights gained from this approach when compared to Appendix H therefore provide two different sets of results which act as a sort of bounds of the overall capacity of the spectrum, a lower (Appendix H) and upper (Section 3.2) range.

Through this comprehensive simulation infrastructure, we can rigorously test the NFAM's ability to manage frequency assignments across the national airspace, providing valuable insights into its performance, scalability, and adherence to industry standards.

3.2 Simulation Configurations and Results

Many dozens of test simulations were performed during the development of the simulation tool as described earlier. These provided a foundation for understanding what parameters were available for different configurations.

The following simulation configurations were the result of this earlier discovery work and selected to provide both narrow and broad results.

Each result includes one or more screenshots showing a sampling of the viewsheds for a single channel or a set of seven adjacent channels.

3.2.1 Simulation Configuration 1 (SC-1)

3.2.1.1 SC-1 Definition

This first configuration is designed to provide a rudimentary baseline understanding, scoped to just a single GRS and one fixed waypoint directly above the GRS at Low Altitude, with only one channel available.

Channels	Waypoints	Altitudes	Termination
1	1	LA: 100%	100 Consecutive

Table 3-2 - SC-1 Configuration

3.2.1.2 SC-1 Results

This simulation is a theoretical maximum concurrent density model for a single channel at a single low altitude. It does not consider any channel adjacency protection logic, so it is not a useful measure when considering a larger band. Table 3-3 summarizes the results of the simulation. Figure 3-1 depicts the combined viewsheds for frequency allocation of the single channel.

Runtime	Total Assignments	Average Per Channel
1 Hour	3430	N/A

Table 3-3 - SC-1 Simulation Results

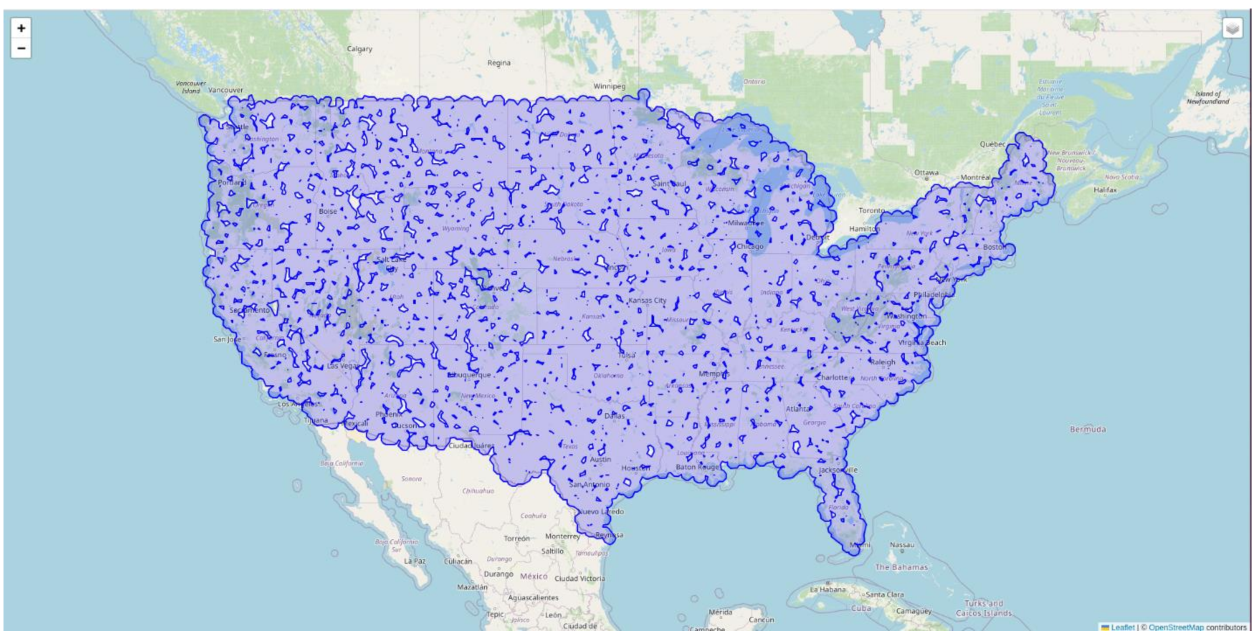

Figure 3-1 - SC-1 Single Channel Frequency Allocation

3.2.2 Simulation Configuration 2 (SC-2)

3.2.2.1 SC-2 Definition

The second configuration builds on SC-1. This was a low-altitude simulation with all 250 channels in the spectrum available for allocation. While these parameters aren't representative of the real world (see 4.4), they do provide a data point demonstrating a maximum theoretical density, or an upper bound of the total channels available simultaneously.

Channels	Waypoints	Altitudes	Termination
250	1	LA: 100%	10 Consecutive

Table 3-4 - SC-2 Configuration

3.2.2.2 SC-2 Results

Results for this simulation are presented in Table 3-5. Figure 3-2 illustrates the combined viewsheds for frequency allocation of a single channel while Figure 3-3 shows the combined viewsheds for multiple channels.

Runtime	Total Assignments	Average Per Channel
170 Hours	206114	825

Table 3-5 - SC-2 Simulation Results

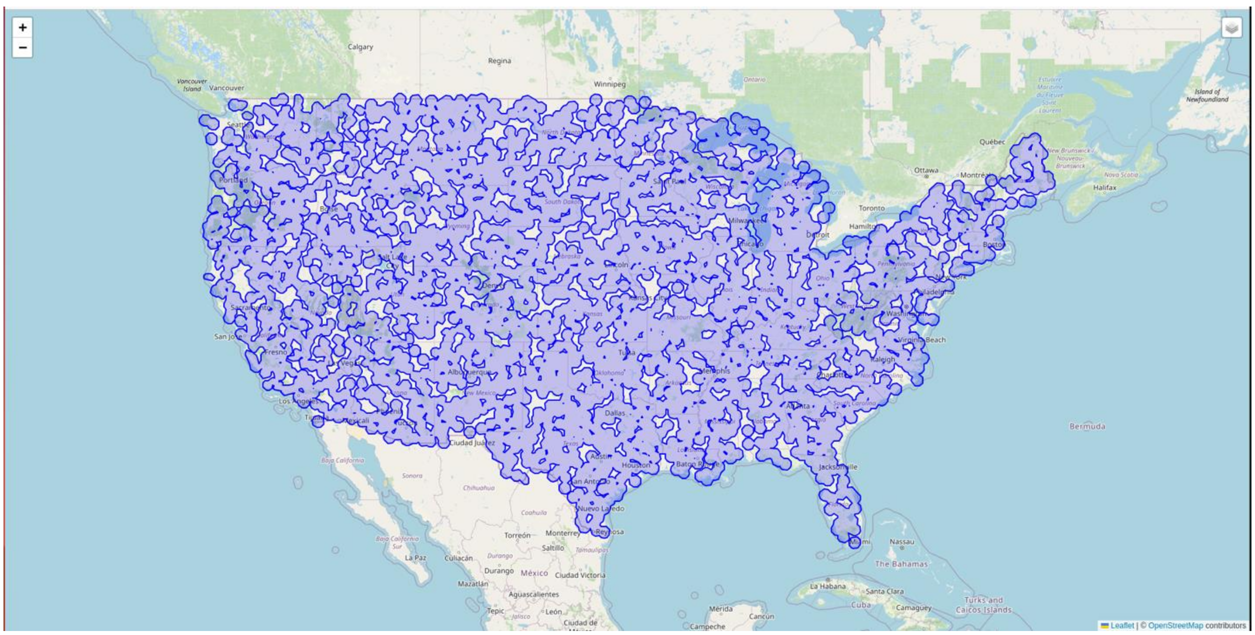

Figure 3-2 - SC-2 Single Channel Frequency Allocation

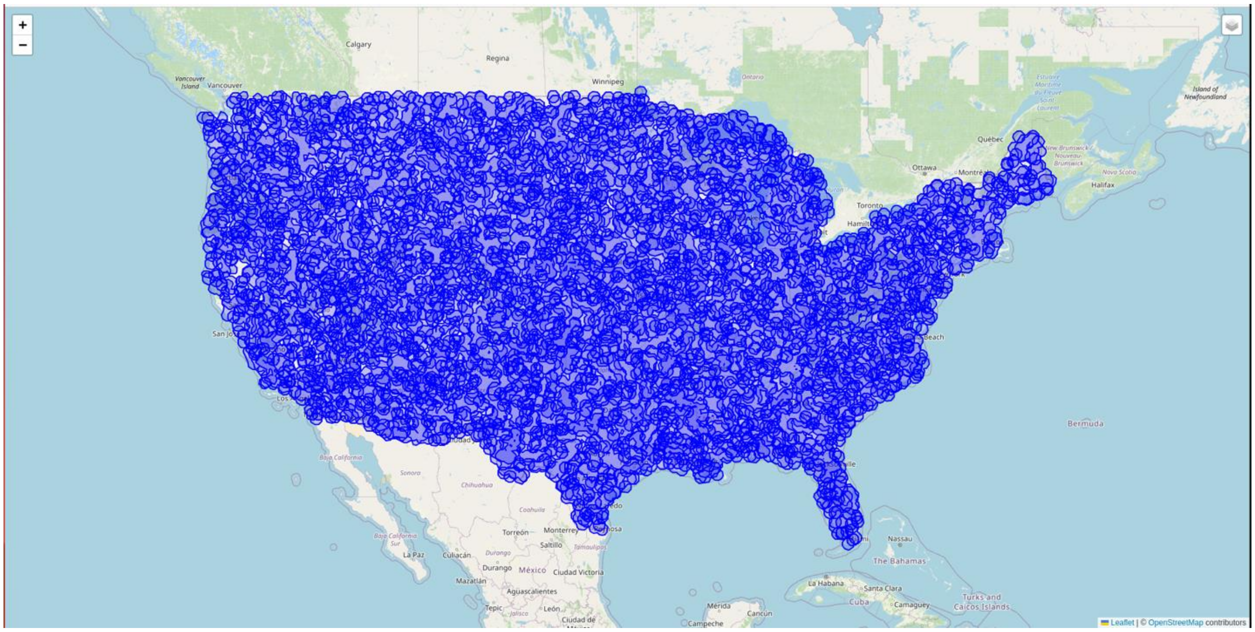

Figure 3-3 - SC-2 Multiple Channel Frequency Allocation

3.2.3 Simulation Configuration 3 (SC-3)

3.2.3.1 SC-3 Definition

The third configuration was designed to as closely as possible mimic the parameters described in DO-362A Appendix H Table H-3 in the last row, a mix of altitudes.

To best approximate the table H-3 we chose to automatically generate four waypoints located at the extents of the GRS viewshed in order to maximize the combined viewshed and represent a worst case similar to Appendix H (where the UAS could be transmitting anywhere in range of the GRS). To simplify the calculations we did not add additional waypoints simulating travel between them. As a result of these four individual waypoints you will see a clover-like visual pattern on the viewshed.

This was also the only configuration to terminate after the first 100 cumulative denials.

Channels	Waypoints	Altitudes	Termination
250	4	5% HAR, 30% HA, 55% MA, 10% LA	100 Cumulative

Table 3-6 - SC-3 Configuration

3.2.3.2 SC-3 Results

Results for this simulation are presented in Table 3-7. Figure 3-4 illustrates the combined viewsheds for frequency allocation of a single channel while Figure 3-5 shows the combined viewsheds for multiple channels.

Runtime	Total Assignments	Average Per Channel
1 Hour	6307	25

Table 3-7 - SC-3 Simulation Results

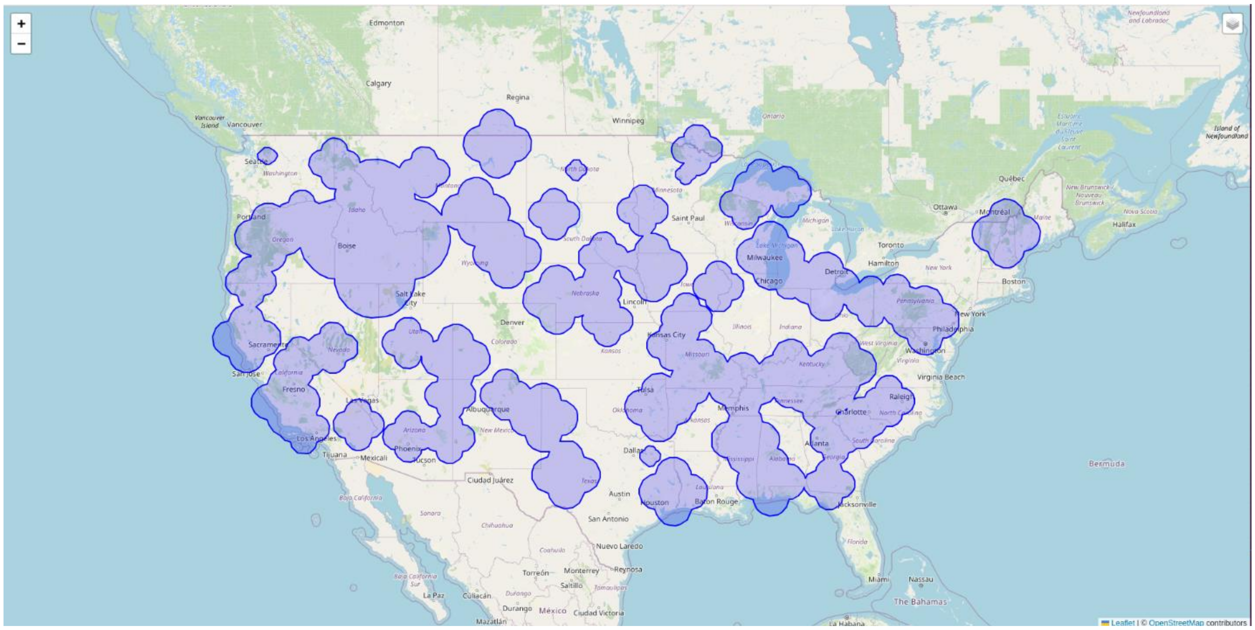

Figure 3-4 - SC-3 Single Channel Frequency Allocation

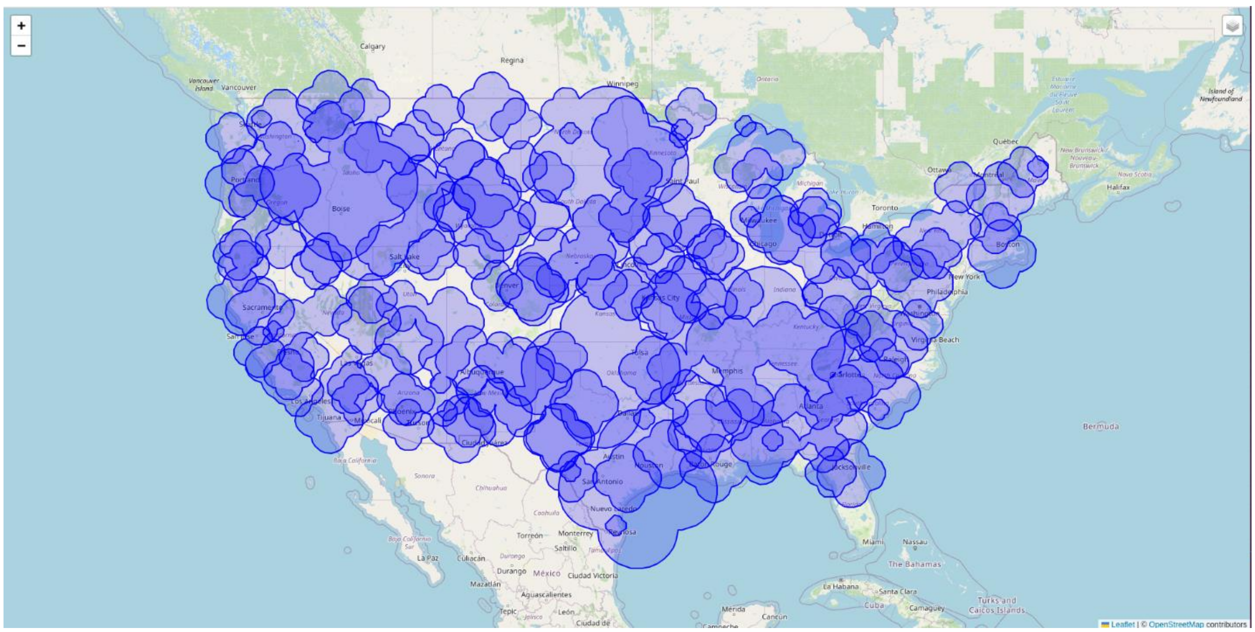

Figure 3-5 - SC-3 Multiple Channel Frequency Allocation

3.2.4 Simulation Configuration 4 (SC-4)

3.2.4.1 SC-4 Definition

This configuration is identical to SC-3, with the only change being allowing it to continue running until the 100th consecutive denial, versus cumulative denial.

Channels	Waypoints	Altitudes	Termination

250	4	5% HAR, 30% HA, 55% MA, 10% LA	100 Consecutive

Table 3-8 - SC-4 Configuration

3.2.4.2 SC-4 Results

Results for this simulation are presented in Table 3-9. By allowing the simulation to run to the 100th consecutive failed allocation, the number of allocations increases from 6307 to 18639, or nearly a 200% increase.

Runtime	Total Assignments	Average Per Channel
1 Hour	18639	75

Table 3-9 - SC-4 Simulation Results

Figure 3-6 illustrates the combined viewsheds for frequency allocation of a single channel while Figure 3-7 shows the combined viewsheds for multiple channels.

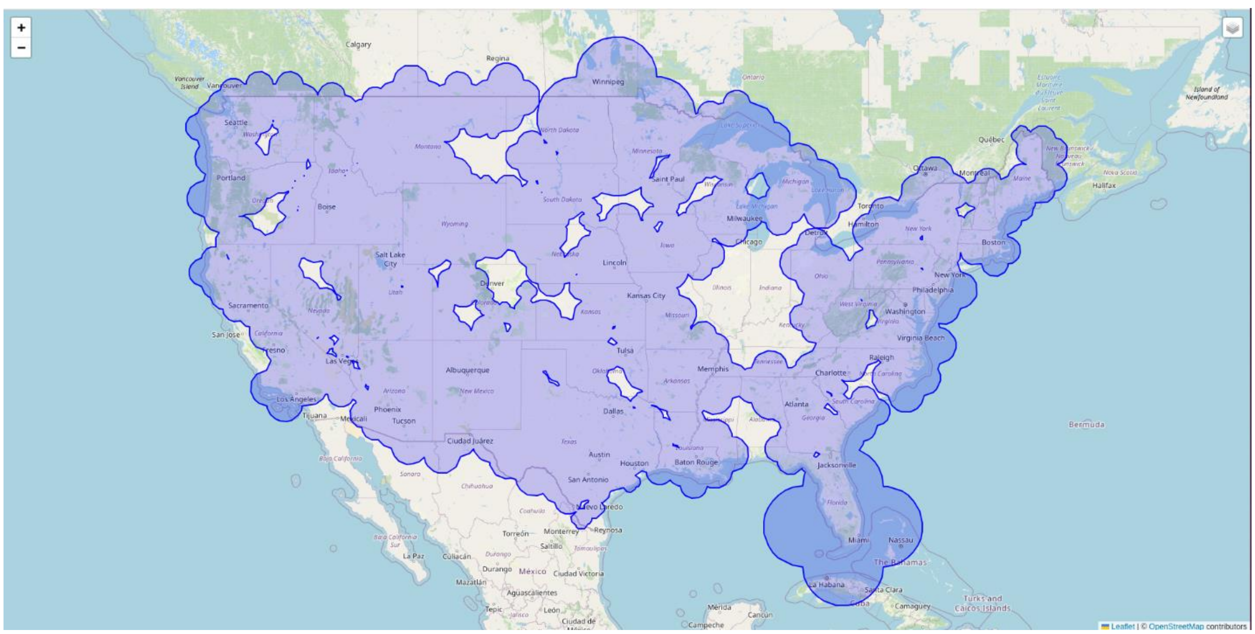

Figure 3-6 - SC-4 Single Channel Frequency Allocation

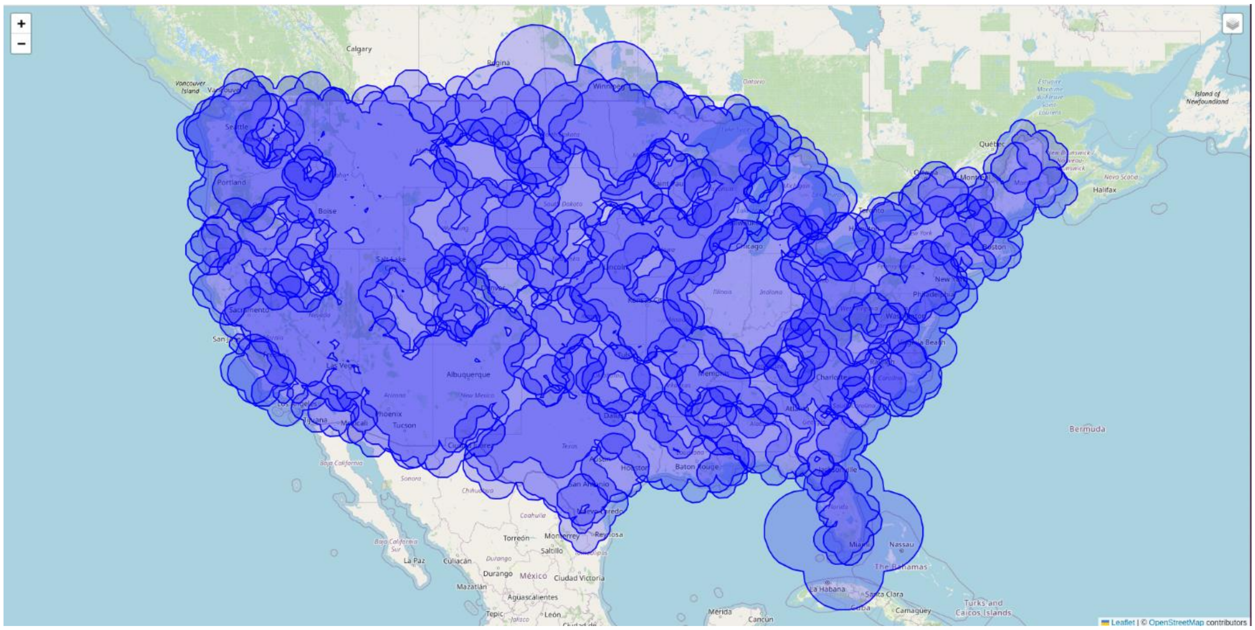

Figure 3-7 - SC-4 Multiple Channel Frequency Allocation

3.2.5 **Simulation Configuration 5 (SC-5)**

3.2.5.1 SC-5 Definition

The final configuration is identical to SC-4 with one altered parameter. This configuration has only one way point. This is also like SC-2, but with the mix of altitudes. We believe this is the closest approximation of a mixed altitude *maximum density* national simulation. While this doesn't represent any realistic scenario (see section 4.4), it is useful as an upper bound of the available spectrum with usage a variety of altitudes.

Channels	Waypoints	Altitudes	Termination
250	1	5% HAR, 30% HA, 55% MA, 10% LA	100 Consecutive

Table 3-10 - SC-5 Configuration

3.2.5.2 SC-5 Results

Results for this simulation are presented in Table 3-11Table 3-7. This configuration allows for an average of 193 assignments per channel.

Runtime	Total Assignments	Average Per Channel
40 Hours	48249	193

Table 3-11 - SC-5 Simulation Results

Figure 3-8 illustrates the combined viewsheds for frequency allocation of the first channel, which had the highest utilization. Figure 3-9 shows the combined viewsheds for multiple channels.

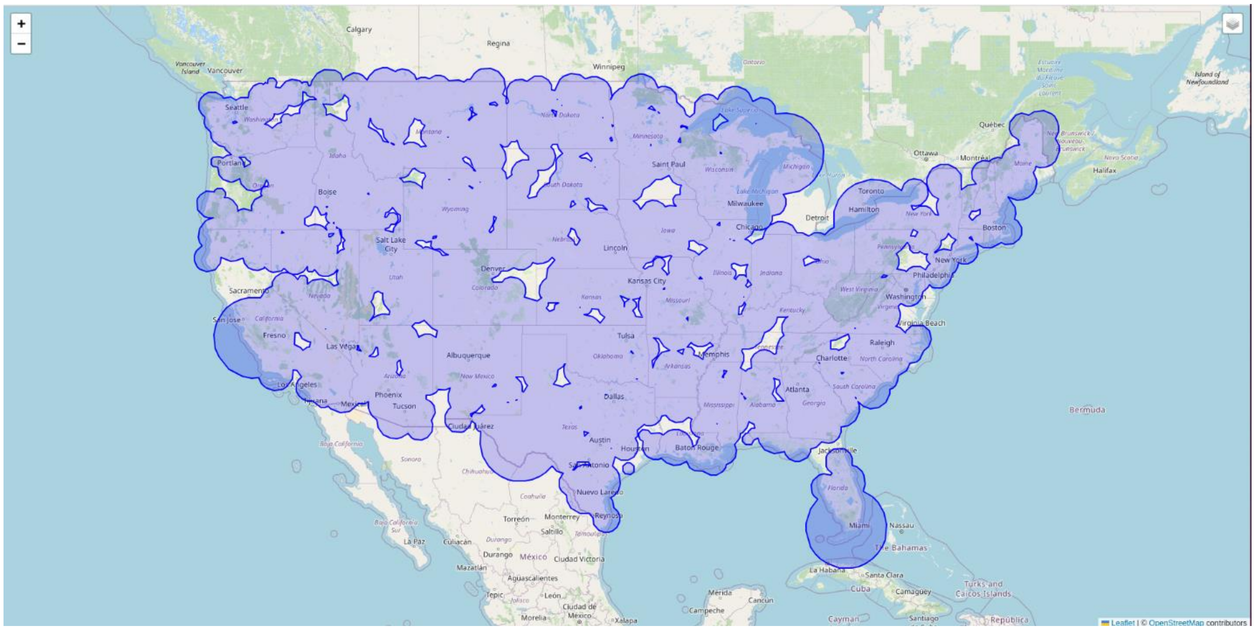

Figure 3-8 - SC-5 Single Channel Frequency Allocation

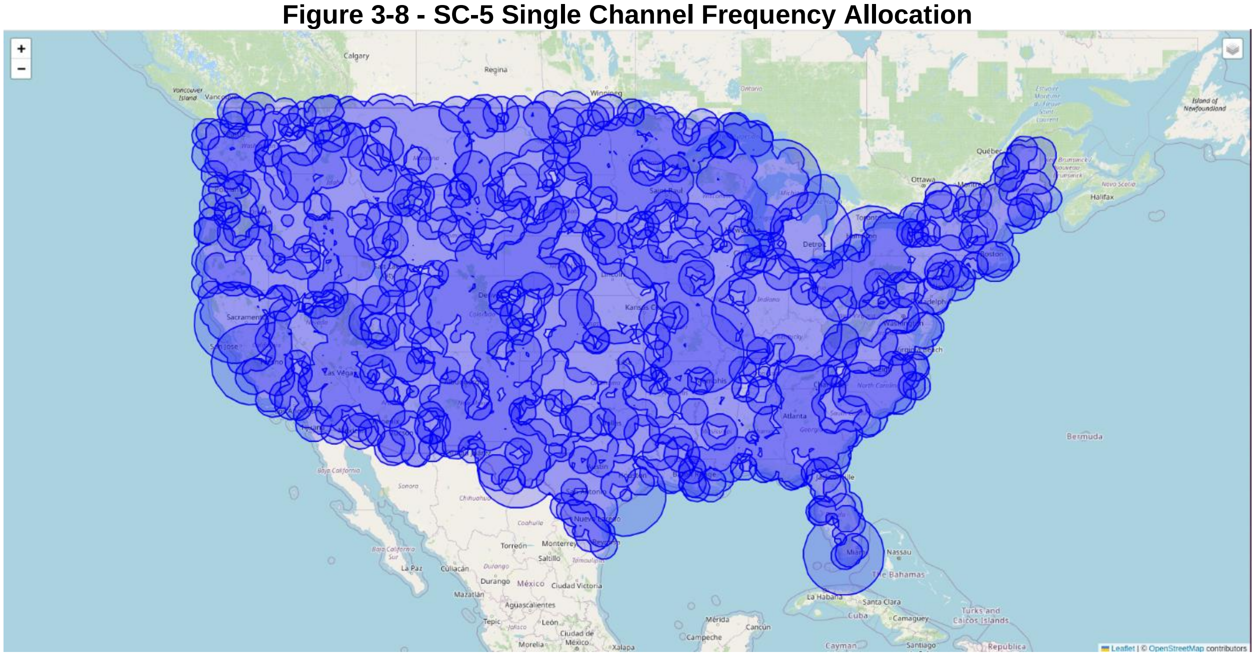

Figure 3-9 - SC-5 Multiple Channel Frequency Allocation

4 Key Learnings

The simulation exercises conducted as part of this report yielded several critical insights that have significant implications for the future development and deployment of the National Frequency Assignment Manager (NFAM). These key learnings are summarized below, along with their potential impact on operational planning and frequency management strategies for Uncrewed Aircraft Systems (UAS) within the National Airspace System (NAS).

4.1 Terrain and Earth's Curvature Impact on Low-Altitude Flights

One of the primary observations from the simulations was the notable influence of terrain and the Earth's curvature on the viewsheds of low-altitude flights. At lower altitudes, the line-of-sight (LOS) for radio frequency (RF) signals is often obstructed by natural features such as mountains, hills, and valleys, and by the Earth's curvature. This obstruction significantly reduces the effective communication range and, consequently, increases the frequency assignment availability for UAS operating at these altitudes.

Impact: The NFAM must account for these geographical factors in its frequency assignment algorithms to ensure robust communication channels are maintained for UAS operating at lower altitudes.

4.2 Signal Propagation Limits for High-Altitude Flights

For UAS operating at higher altitudes, the simulations revealed that the maximum signal propagation range quickly becomes the sole limiting factor for viewshed determination. Unlike low-altitude flights, where terrain plays a significant role, high-altitude flights are primarily constrained by the inherent propagation characteristics of the RF signals. Our viewshed generation utilized a uniform omnidirectional antenna in order to be conservative as a starting point. Actual high-altitude platforms use very directional beam-formed antennas which would greatly reduce the viewshed and impact, allowing a higher density and reuse.

Impact: The NFAM's algorithms need to incorporate the transmit powers, gains and loss, beam shape, mounting orientation, and receiver sensitivity in order to determine the maximum range for higher altitude viewsheds.

4.3 Importance of Adjacent Channel Management

Another critical learning was the significant impact of adjacent channel usage on channel availability in each region. Proper management of adjacent channels including adequate separation is essential to maximize spectrum utilization.

Impact: NFAM must incorporate stringent adjacent channel separation logic into its operational framework to ensure optimal channel availability.

4.4 Limitations of Theoretical Models

While the simulation data provided valuable insights, it is important to note that the models used do not fully reflect the complexities of real-world operations. For instance, in an operational scenario, UAS operators cannot simply relocate to another position if a frequency assignment denial occurs. Real-world constraints, such as realistic flight paths and areas of operation, must be considered when considering how these simulation results might represent practical scenarios.

Impact: Future simulation efforts should strive to incorporate more realistic operational constraints, including complex flight paths, variable density of operations, and much more diverse altitudes.

4.5 Optimization of RLOS Calculations

The simulations highlighted the computational intensity of Radio Line of Sight (RLOS) calculations, particularly when applied at a national scale. Given that RLOS calculations are more resource-intensive than simple viewshed analyses, an efficient optimization strategy is to first identify intersecting viewsheds and then apply RLOS calculations only within the relevant matrix of positions.

Impact: Implementing this optimization within the NFAM will significantly enhance its computational efficiency, enabling faster processing times and more scalable operations. This approach allows for the practical deployment of the NFAM across larger geographical areas without compromising on accuracy or performance.

NFAM Enhancement (Demo 1) and Viewshed Verification (Demo 2) Test Report

for

National Airspace System (NAS) Scaling of C-Band Frequency Assignment Manager (FAM) and Channel Reuse Demonstration with Multiple UAS in Nearby Regions

Rev C August 2024

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Revision History

Date	Revision	Author	Reason for Change
5/30/2024	A	Jaymie Oehler	Initial release
6/29/2024	B	Jaymie Oehler	With updates based on FAA feedback
09/4/2024	C	Cyriel Kronenburg	Marking Updates

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1 Introduction

This NFAM Demonstration 1 and 2 Test Report defines the results from demonstration of the upgrades made to the NFAM in support of testing of uAvionix C-Band National Frequency Assignment Manager (NFAM) as awarded by the FAA's Solicitation 692M15-19-R-00020-03 Broad Agency Announcement (BAA) Call 4. This application is an available option to manage the entire 5030- 5091MHz band (C-Band), inclusive of interference modeling regionally.

1.1 Purpose

The purpose of the test report is to describe the results of deconflicted frequency assignment to an Airborne Radio System (ARS)/Ground Radio System (GRS) pair by a NFAM based on radio frequency a (RF) viewshed generation engine using extended assignment request parameters and to validate the viewshed generation by gathering Received Signal Strength Indicators (RSSI) at various locations within the generated viewsheds.

1.2 Scope

This test report outlines verification of frequency assignment to the Airborne Radio System (ARS) and Ground Radio System (GRS) to enable nationwide C-Band frequency management. This includes safely assigning frequencies to multiple regions (at least four) in close proximity, the extended assignment requests, storage and verification of generated viewsheds, and regional interference analysis to guarantee that simultaneous frequency assignments pose minimal risk of interference.

1.3 Document Overview

Section 1	Introduction: This section provides the purpose, scope, document overview, reference documents, and acronyms found throughout this Plan.
Section 2	Test Objectives: This section outlines the goals of the testing effort.
Section 3	Test Environment: This section provides information on the hardware and software configurations, test equipment and configurations.
Section 4	Test Data: This section provides data used for testing.
Section 5	Test Event Summary: This section describes time, date, locations and equipment used during testing.
Section 6	Test Results: This section defines the conditions under which testing will be considered complete.

1.4 Reference Documents

Table 1-1 identifies the documents referenced and/or applicable to this test plan.

Table 1-1 Reference Documents

Document # / Date	Description
UAV-1006980-001 Rev B	uAvionix muLTElink5060 Datasheet
UAV-1006979-001 Rev A	uAvionix SkyStation5060LTE 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
UAV-1007035-001 Rev A	uAvionix Freefly Astro UAS Operation Manual
UAV-1004752-001 Rev M	uAvionix Service Layer API ICD
UAV-1004775-001 Rev M	uAvionix Link Event WebSocket ICD
UAV-1007074-001 v2.0	uAvionix Frequency Allocation Manager API Reference

1.5 Definition of Acronyms

Table 1-2 lists the acronyms found throughout this document.

Table 1-2 Acronyms

Acronym	Definition
ARS	Airborne Radio System
C2CSP	Command and Control Communications Service Provider
CNCP	Command and Non-Payload Control
FMO	Frequency Management Organization
GCS	Ground Control System
GRS	Ground Radio System
NFAM	National Frequency Assignment Manager
RF	Radio Frequency
RLOS	Radio Line Of Sight
RSSI	Received Signal Strength Indicator
UAS	Uncrewed Aircraft System

2 Test Objectives

This test plan defined two distinct phases: TP-1 and TP-2.

2.1 NFAM Enhancement Demonstration (TP-1)

This demonstration phase aimed to validate the enhancements implemented in the NFAM system. This activity was a bench test during which the NFAM was tasked with successfully making a minimum of twenty (20) frequency assignments across at least four (4) regions in close proximity. The NFAM utilized extended request parameters for these assignments.

To ensure the effectiveness of the enhancements, generated viewsheds for the requests and associated regional interference analyses was conducted. The goal was to guarantee that the simultaneous frequency assignments carry minimal risk of interference.

2.2 NFAM Viewshed Validation (TP-2)

In the second phase, a viewshed generated during the NFAM Enhancement Demonstration was validated against real-world measurements to ensure the accuracy of RF propagation models in reflecting the performance of the SkyLink 5060 equipment.

Validation involved gathering RSSI measurements in the field at a minimum of twenty (20) locations within the generated viewshed and comparing them to the values estimated by the NFAM viewshed. The collected results were utilized verify that no updates were needed to the viewshed modeling parameters.

3 Test Environment

3.1 Hardware and Software Configuration

All tests were performed with prototype NFAM software.

3.1.1 C-Band NFAM

The C-Band National Frequency Assignment Manager (NFAM) is a module developed specifically for this project and the subject of this test report. The NFAM is initialized by registering specific regionally licensed protected spectrum frequencies. These frequencies and licenses were coordinated with the FAA and FCC STA and are enumerated in Table 4-1.

3.1.2 SkyLine™

SkyLine™ is a C2CSP operational platform that manages multiple ground radio system (GRS) and airborne radio system (ARS) resources. It provides flight assurance through centralized management of the Command and Control (C2) infrastructure. Guided by DO-377A, the platform functions similar to 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, frequency assignments, RF viewshed analysis, 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.

The licensed frequencies are managed by the NFAM via the uAvionix SkyLine™ platform on behalf the operator. The NFAM integrates with SkyLine™ via a standard REST-based API. This allows a specific frequency band to be allocated to a UAS operator for the duration of a flight while the remaining protected spectrum in the licenses can be assigned to additional operators as requested in the same regional area.

3.1.3 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™. When a frequency has been assigned by the FAM, SkyLine™ will configure this frequency in the GRS involved in the flight.

3.1.4 muLTElink-5060

muLTElink is a multiple link airborne radio system that combines a DO-377A Link Executive Manager (LEM) with integrated LTE and C-Band command and control (C2) radios. muLTElink connects to an autopilot via a transparent RS-232 serial interface. When a frequency has been assigned by the FAM, SkyLine™ will configure this frequency in the ARS involved in the flight.

3.2 Test Equipment

3.2.1 Equipment

The following equipment was used for test execution.

Manufacturer	Model #	Description
CubePilot	Cube Orange+	Pixhawk autopilot

Table 3-1 Test Equipment

3.2.2 Test Configurations

The following test configurations were used in this test report.

3.2.2.1 Test Configuration 1 (TC-1)

Test Configuration 1 is defined in Figure 3-1. The computer is a Windows 10 laptop (or comparable device). The user interacts with the NFAM API to request a frequency assignment.

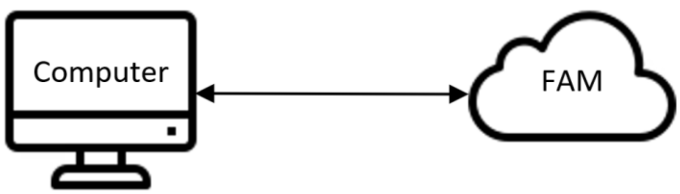


Figure 3-1 FAM Test Configuration 1

3.2.2.2 Test Configuration 2 (TC-2)

Test Configuration 2 is defined in Figure 3-1. The GCS can be run on a Windows 10 laptop (or comparable device). The GCS interacts with SkyLine™ via a web browser. Mission Planner GCS runs on the same computer. SkyLine™ C2CSP handles all interactions with the NFAM for frequency allocation and relays the frequency assignment to the GRS and ARS radios. The GRS can be a SkyStation-5060 POE or SkyStation-5060 LTE. The ARS will be a muLTElink-5060. A Pixhawk autopilot is used to terminate the GCS/ARS connection.

Initially, it was our intention to mount the ARS on a pole to collect the RSSI samples, but it was discovered during test execution that this did not allow the ARS to reliably make a connection due to LOS obstructions. We modified the test configuration to popup the ARS to a height of 100 ft AGL for sample collection.

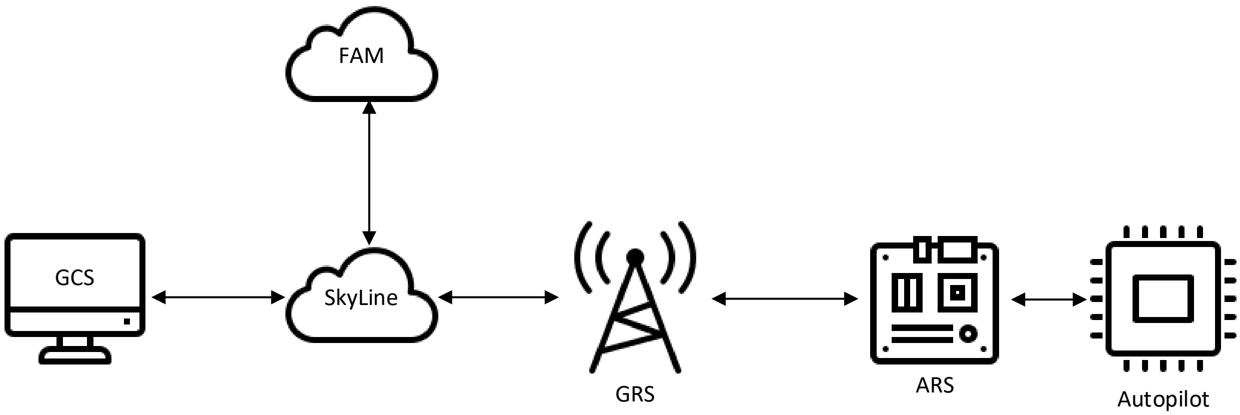


Figure 3-2 FAM Test Configuration 2

4 Test Data

The frequencies in Table 4-1 have been request from the FCC with an Experimental Special Temporary Authorization and will be available to the FAM for assignment to flights based on the geographic area where the flight will be operated.

Table 4-1 FCC STA Requested Frequencies

Freq (MHz)	Location	Lat / Long	AGL Alt (ft)	Radius (Air) (NM)	Radius (Ground) (NM)
5035	Kloten, ND	N 47° 43' 25.43" W 98° 03' 40.99"	1000	50	50
5045	Kloten, ND	N 47° 43' 25.43" W 98° 03' 40.99"	1000	50	50
5065	Kloten, ND	N 47° 43' 25.43" W 98° 03' 40.99"	1000	50	50
5075	Kloten, ND	N 47° 43' 25.43" W 98° 03' 40.99"	1000	50	50
5085	Kloten, ND	N 47° 43' 25.43" W 98° 03' 40.99"	1000	50	50

5 Test Event Summary

Test plan execution was split over several test events. The subsections below detail tests, test equipment, test plan version used, test locations and UUTs used during the specific tests. Each of these “test events” are captured in the following subsections and referenced in the Section 6 test results.

5.1 Test Event 1

Location: uAvionix, Virtual
Test Engineer: Thomas Muldowney, uAvionix.
Test Plan Version: 1.0
Test Notes: None.

5.2 Test Event 2

Location: Grand Forks, ND
Test Engineer: Alex Logan, uAvionix.
Test Plan Version: 1.1
Test Notes: None.

Table 5-1 Test Event 2 - UUT Software/Hardware Details

Part Description	Part Number	FW Rev	UUT
muLTElink-5060 muLTElink Internal CNPC LTE Device	UAV-1006920-001	v0.3.11 v0.4.14 v0.13.161	UUT01
SkyStation-5060 POE	UAV-1006090-001	v0.4.12	UUT02

6 Test Results

6.1 NFAM Enhancement Demonstration

Demonstration 1 completed twenty (20) successful dynamic frequency allocations to C-Band CNPC radios and demonstrated the enhancements to the FAM. The previous FAM was designed to allocate unique non-conflicting frequencies from a specific licensed range for a single geographic area. The upgrade work was to take that system and enable it to safely re-allocate in-use frequencies to other geographic areas. To accomplish this FAM would need to ensure that there wouldn't be any interference between the two users of the same frequency even if they're in adjacent regions, supporting allocations that maximize the availability of the limited spectrum.

The FAM was augmented to automatically generate a "merged" viewshed for the given flight parameters that include the one or more GRS positions (lat/long/altitude (height AGL)) and the one or more waypoints for the aircraft (lat/long/max-altitude). These viewsheds are calculated using data from the USGS 3D Elevation Program so that they consider any terrain that would impact performance and builds on the open source GDAL tools to perform the terrain calculations. The propagation model used is RLOS (Radio Line Of Sight) so that it is always assuming the strongest safety case of non-interference. There is an upper limit on the RLOS range calculation for the ARS radio at 100mW below 1000 feet AGL, but not for the 10W transmissions as the curvature of the Earth becomes the dominant factor at that power level.

The DO-362A specification defines a strict Time Division Duplex (TDD) scheme to ensure compatible and efficient use of the limited C-Band spectrum. It splits the transmission time into two different segments, one for all ground transmissions (GRS), and one for all airborne ones (ARS). This ensures that no aircraft is attempting to receive a transmission when another nearby aircraft would be transmitting and thereby disrupting that reception, exactly at a time when reception becomes critical (potential avoidance maneuvers). This pattern also simplifies the analysis required as the interference can only be in one direction during each transmission segment, from any ARS to any GRS, or from any GRS to any ARS, which reduce to a matrix of linear RLOS validations with all GRS locations to all ARS waypoints whenever a viewshed overlaps. This TDD scheme is also partly why there are only two power levels defined, to ensure that a low flying ARS doesn’t transmit at a high-power level that would interfere with a nearby GRS’s reception of a distant ARS on an adjacent channel.

These generated viewsheds are stored for each planned flight activity and used when a new plan is submitted, whose viewshed is then compared to any stored ones to look for intersections using PostGIS (PostgreSQL GIS extension) queries. All overlapping/intersecting viewsheds then have their specific waypoints and GRS positions loaded and a direct line-of-sight is calculated between each unique ARS-GRS pair of them with the new plan's positions. The total number of potential interfering plans is totaled and then compared to the available spectrum licensed for the region. If the total exceeds the channel capacity of the spectrum, the new plan is denied.

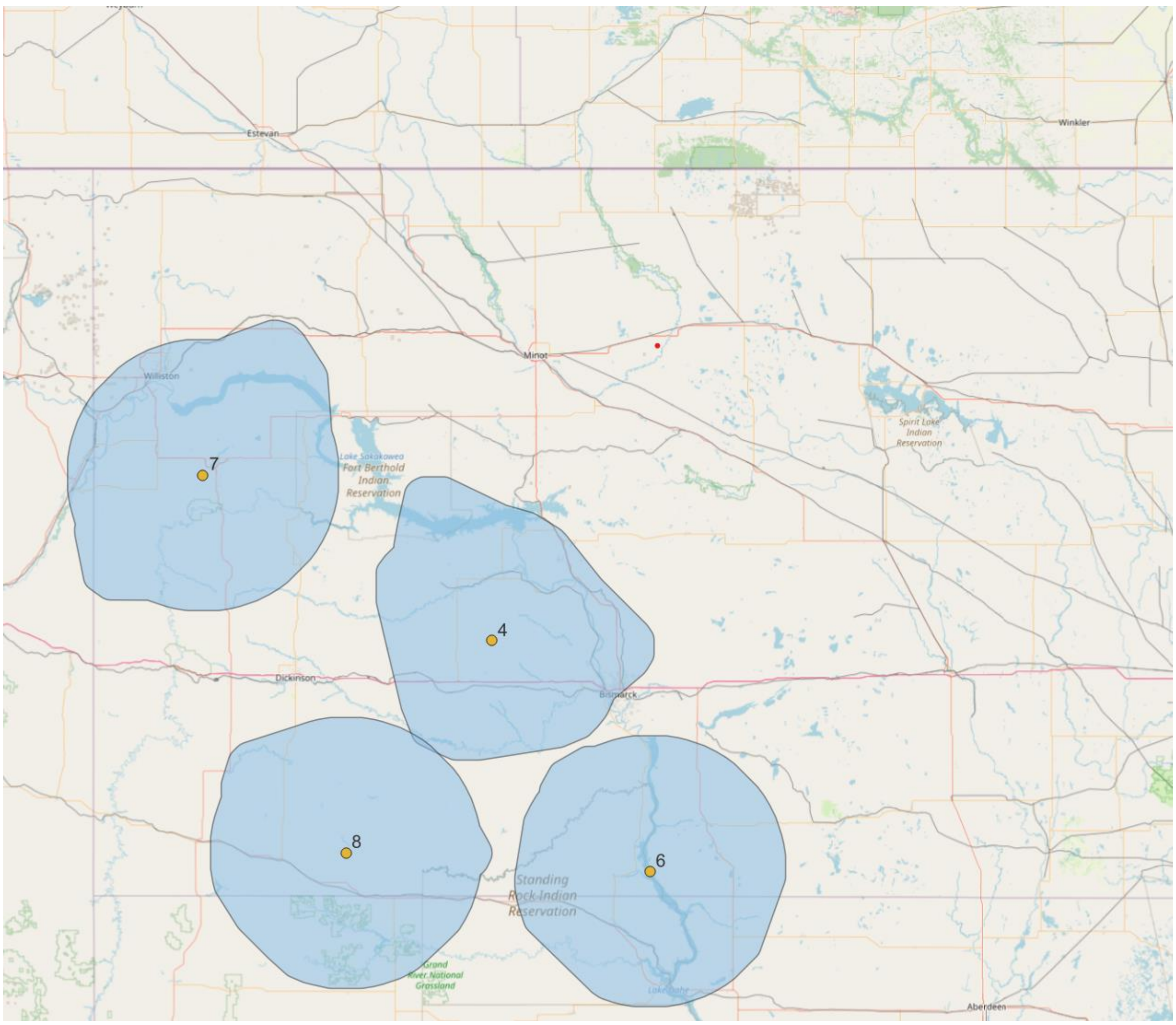
6.1.1 TC-NFAM-DEMO1-001

Tester Name(s)	Thomas Muldowney
Test Event	1
Dates	03/28/2024 to 03/29/2024
Test Facility	uAvionix virtual
Test Equipment	TC-1
UUT	none
Pass/Fail	see table below
Tester Remarks	See detailed results in Sections 6.1.1.1 through 6.1.1.20. Each section shows the GRS location, the plan frequency assignment and resultant viewshed. The simulation incorporates random ARS waypoints which are not captured in the test output.

Allocation	Result
1	**PASS**
2	**PASS**
3	**PASS**
4	**PASS**
5	**PASS**
6	**PASS**
7	**PASS**
8	**PASS**
9	**PASS**
10	**PASS**
11	**PASS**
12	**PASS**
13	**PASS**
14	**PASS**
15	**PASS**
16	**PASS**
17	**PASS**
18	**PASS**
19	**PASS**
20	**PASS**

6.1.1.1 Allocation 1

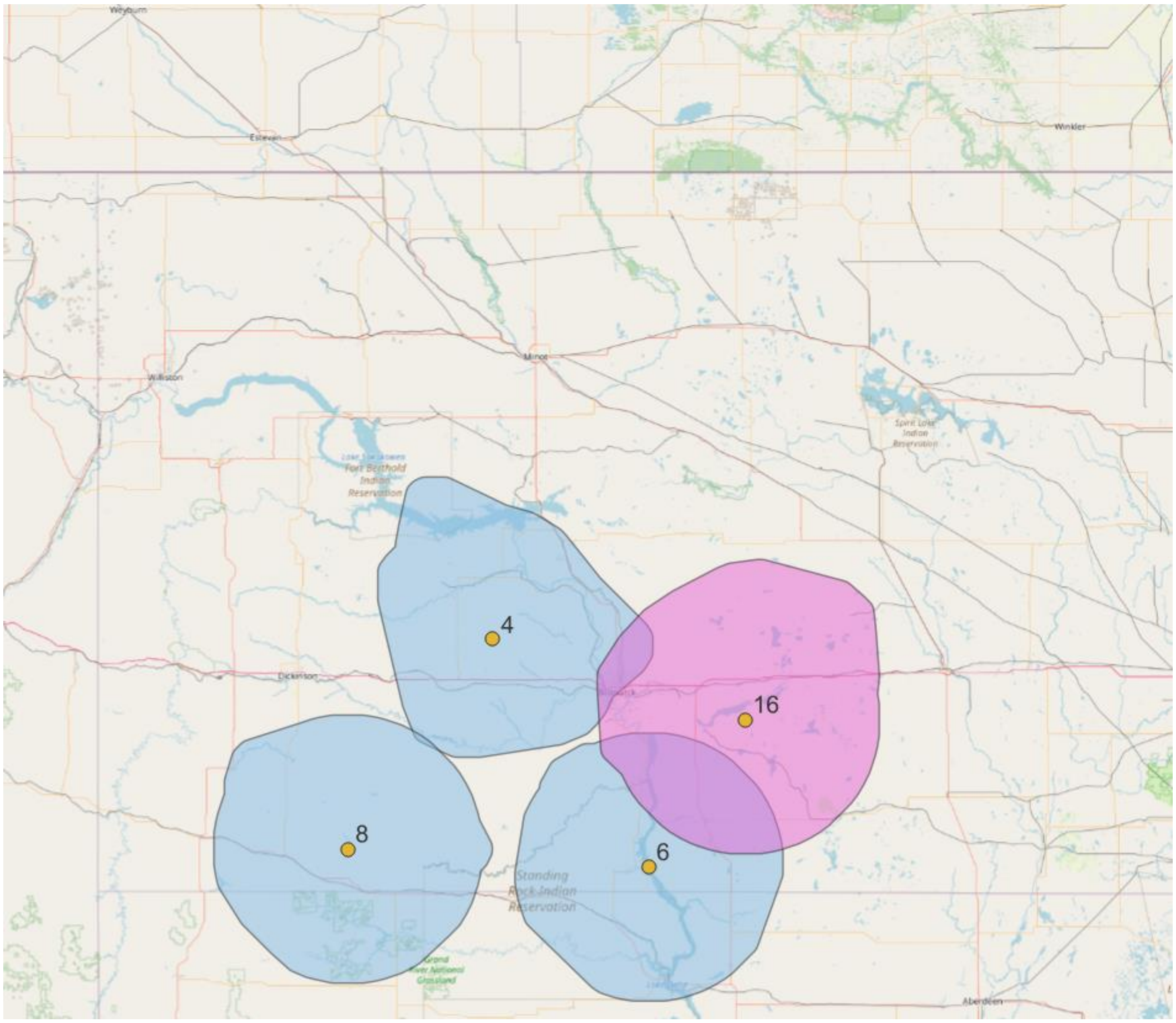
GRS ID	Longitude	Latitude	Frequency
4	-101.5639	47.037	5.040625 GHz
6	-102.4729	46.1292	5.040625 GHz
7	-102.5494	47.1754	5.040625 GHz
8	-100.1028	46.9325	5.040625 GHz



All GRS were allocated to the same frequency. The small overlap in the viewsheds from GRS 8 and GRS 4 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

6.1.1.2 Allocation 2

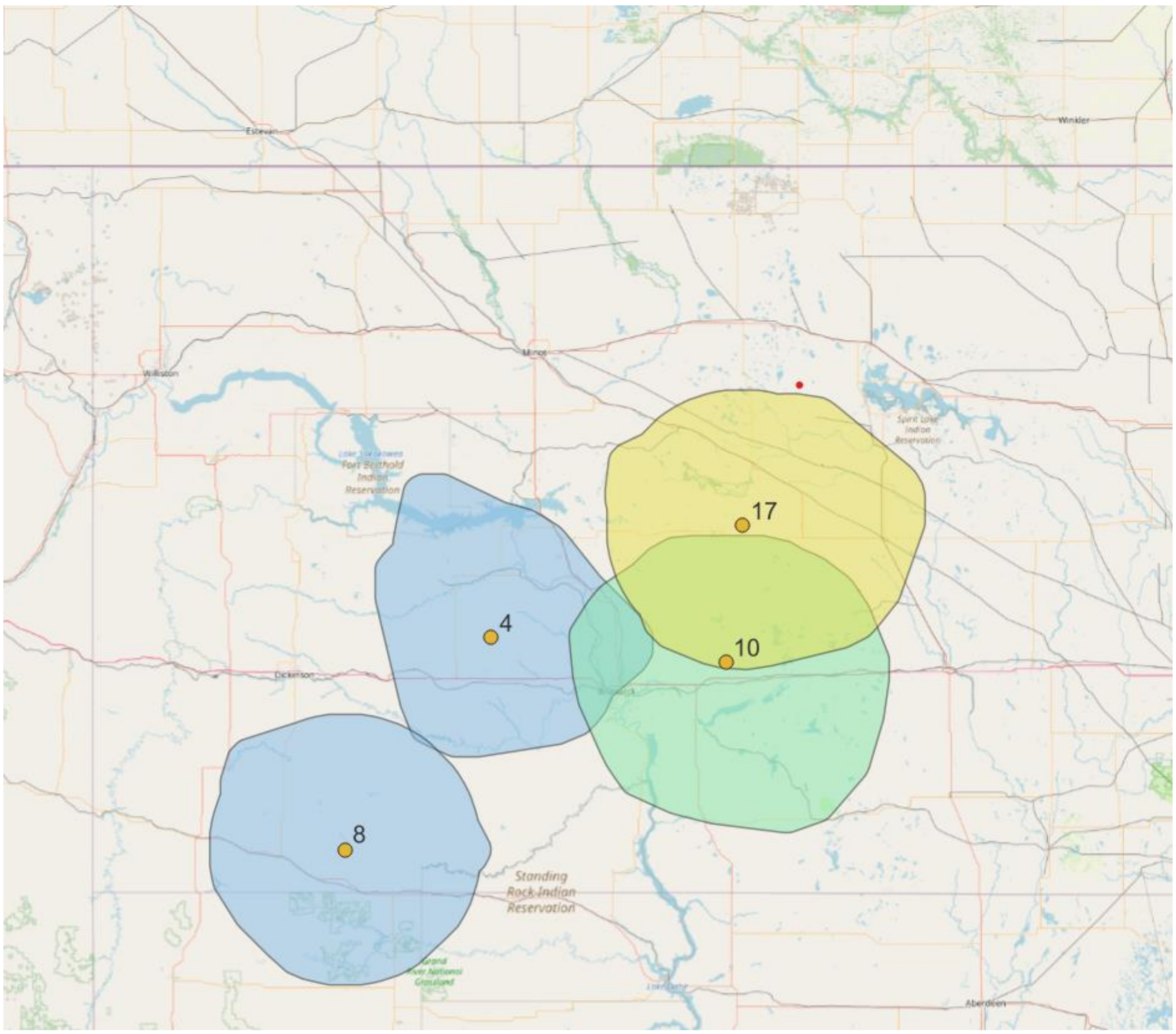
GRS ID	Longitude	Latitude	Frequency
4	-101.5639	47.037	5.040625 GHz
6	-102.4729	46.1292	5.040625 GHz
8	-100.1028	46.9325	5.040625 GHz
16	-99.9759	46.6902	5.041375 Ghz



GRS 16 was allocated a separate frequency due to the overlap with the viewsheds from GRS 4 and 6.

6.1.1.3 Allocation 3

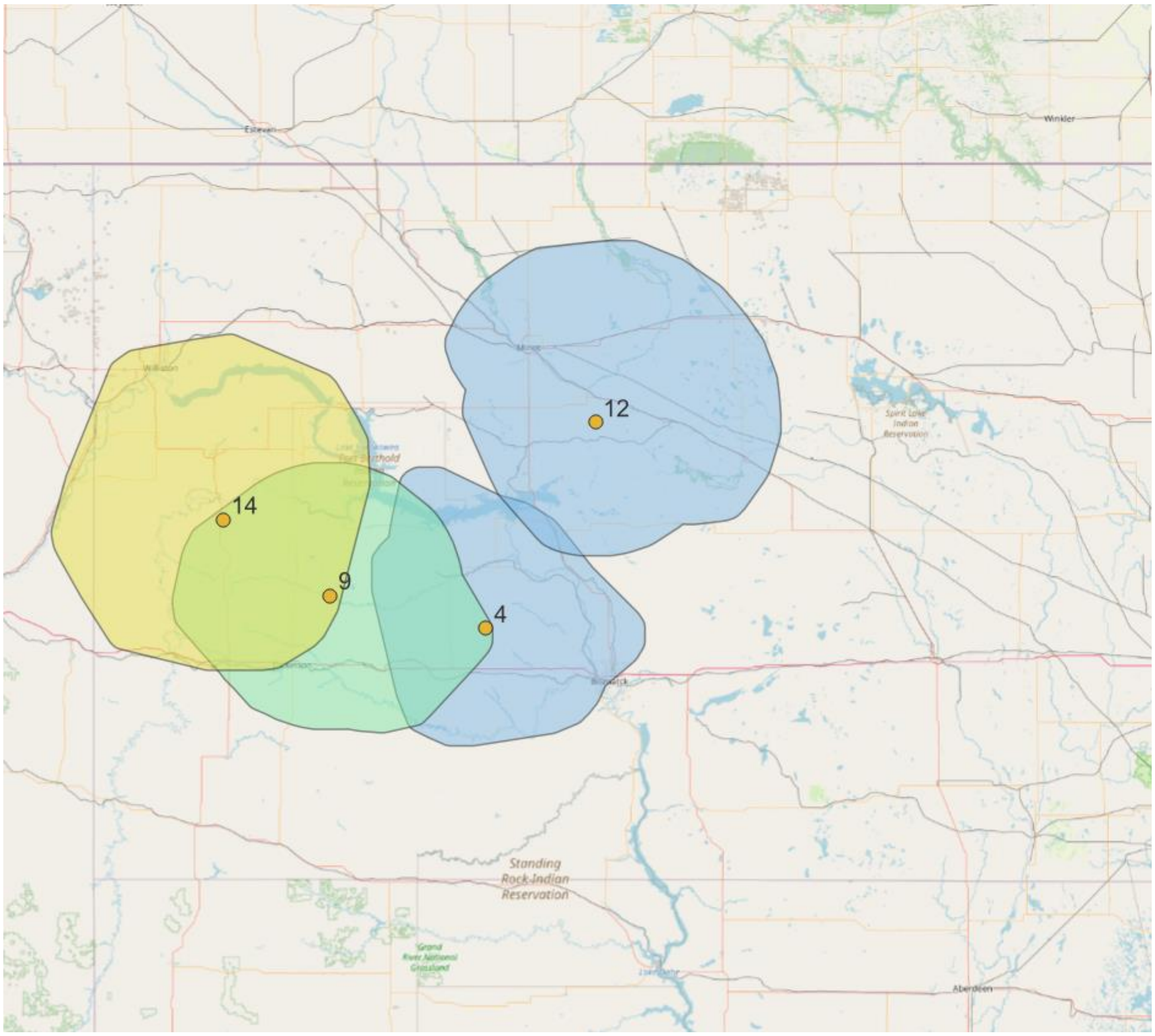
GRS ID	Longitude	Latitude	Frequency
4	-101.5639	47.037	5.040625 GHz
8	-100.1028	46.9325	5.040625 GHz
10	-100.8686	47.9158	5.040875 GHz
17	-102.5627	46.2713	5.041125 GHz



GRS 4, 10 and 17 were allocated unique frequencies due to viewshed overlap. In general, NFAM attempts to minimize frequency allocations as depicted in the other outputs, but it operates on worst case LOS models to ensure non-interfering flights. The small overlap in the viewsheds from GRS 8 and GRS 4 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

6.1.1.4 Allocation 4

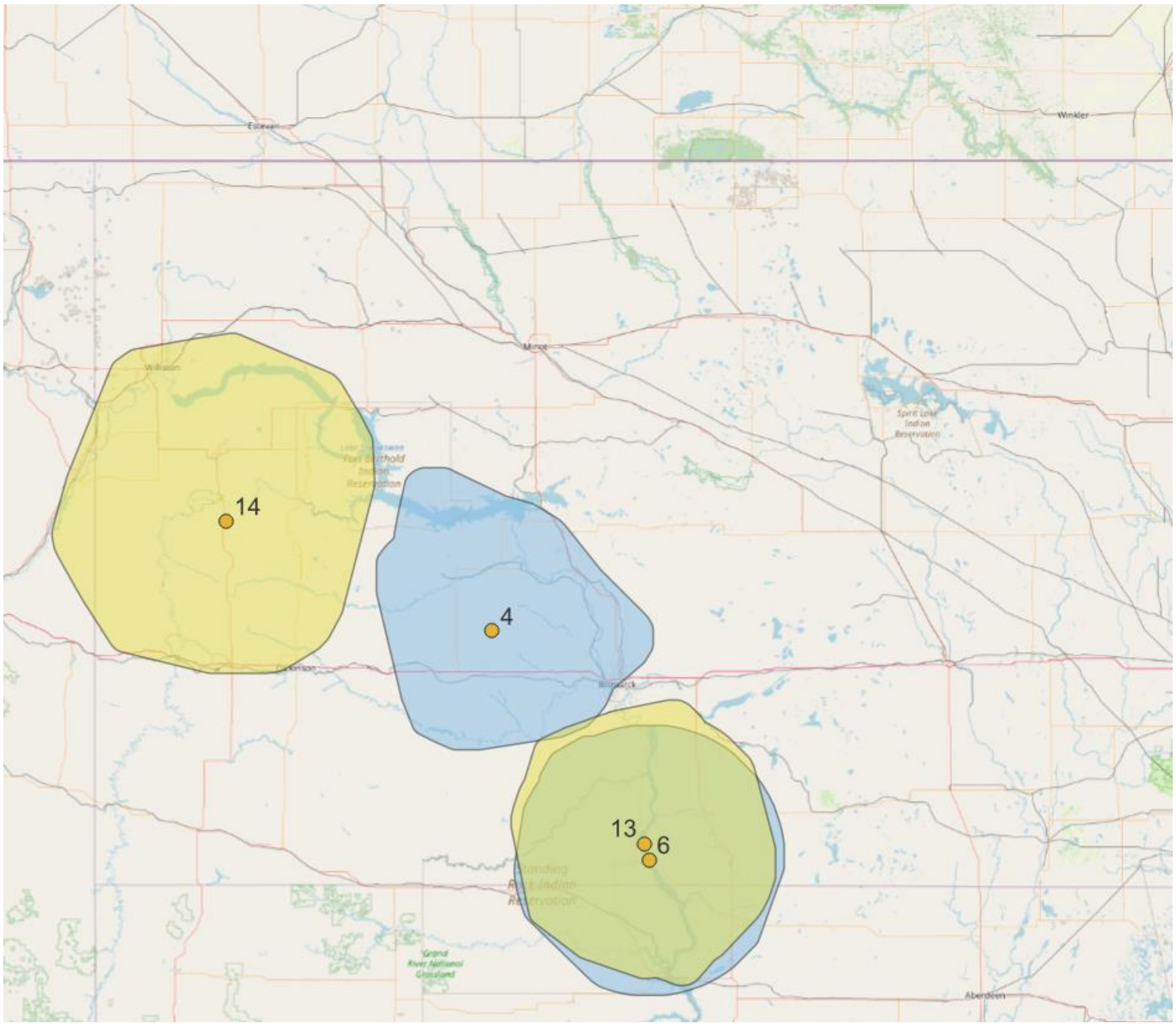
GRS ID	Longitude	Latitude	Frequency
4	-101.5639	47.037	5.040625 GHz
9	-102.3916	46.3872	5.040875 GHz
12	-103.227	47.5027	5.040625 GHz
14	-99.9759	46.6902	5.041125 GHz



GRS 4, 9 and 14 were allocated unique frequencies due to viewshed overlap. The small overlap in the viewsheds from GRS 4 and GRS 12 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

6.1.1.5 Allocation 5

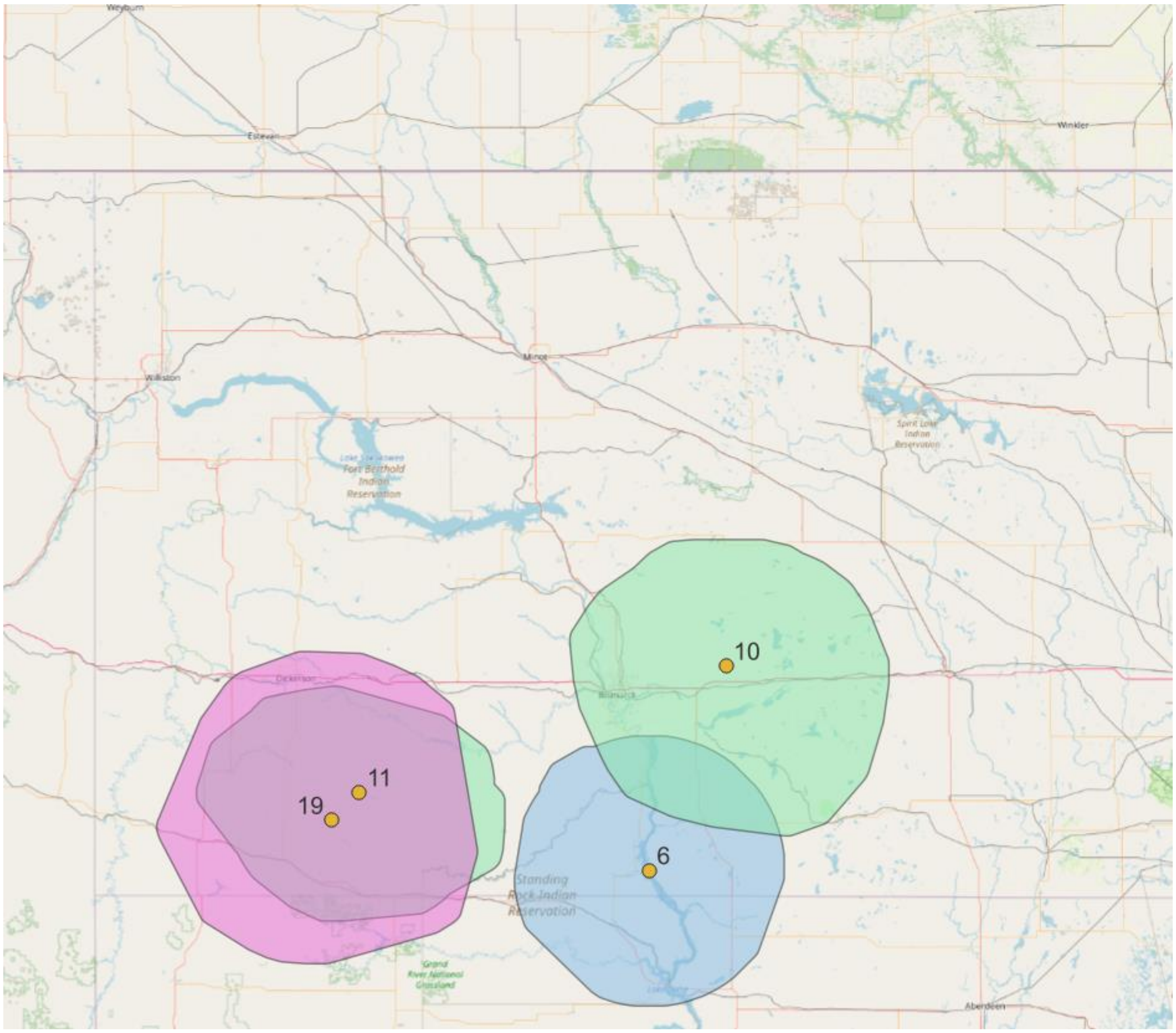
GRS ID	Longitude	Latitude	Frequency
4	-101.5639	47.037	5.040625 GHz
6	-102.4729	46.1292	5.040625 GHz
13	-101.7416	48.1508	5.041125 GHz
14	-99.9759	46.6902	5.041125 GHz



GRS 6 and 13 were allocated unique frequencies due to viewshed overlap. The small overlap in the viewsheds from GRS 4 and GRS 12 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

6.1.1.6 Allocation 6

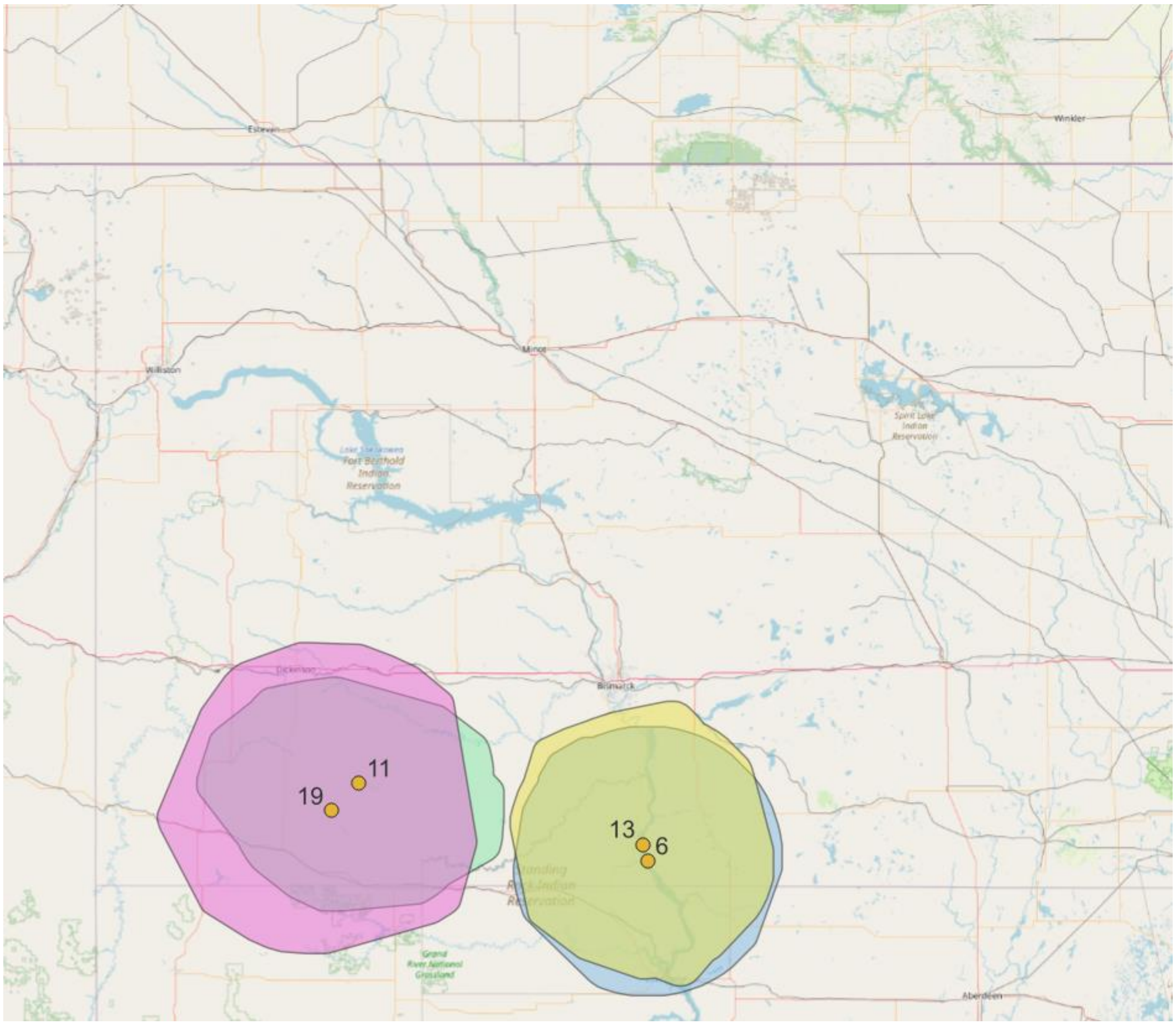
GRS ID	Longitude	Latitude	Frequency
6	-102.4729	46.1292	5.040625 GHz
10	-100.1028	46.9325	5.040875 GHz
11	-102.3916	46.3872	5.040875 GHz
19	-102.5627	46.2713	5.041375 Ghz



GRS 11 and 19 and GRS 10 and 6 were allocated unique frequencies due to viewshed overlap.

6.1.1.7 Allocation 7

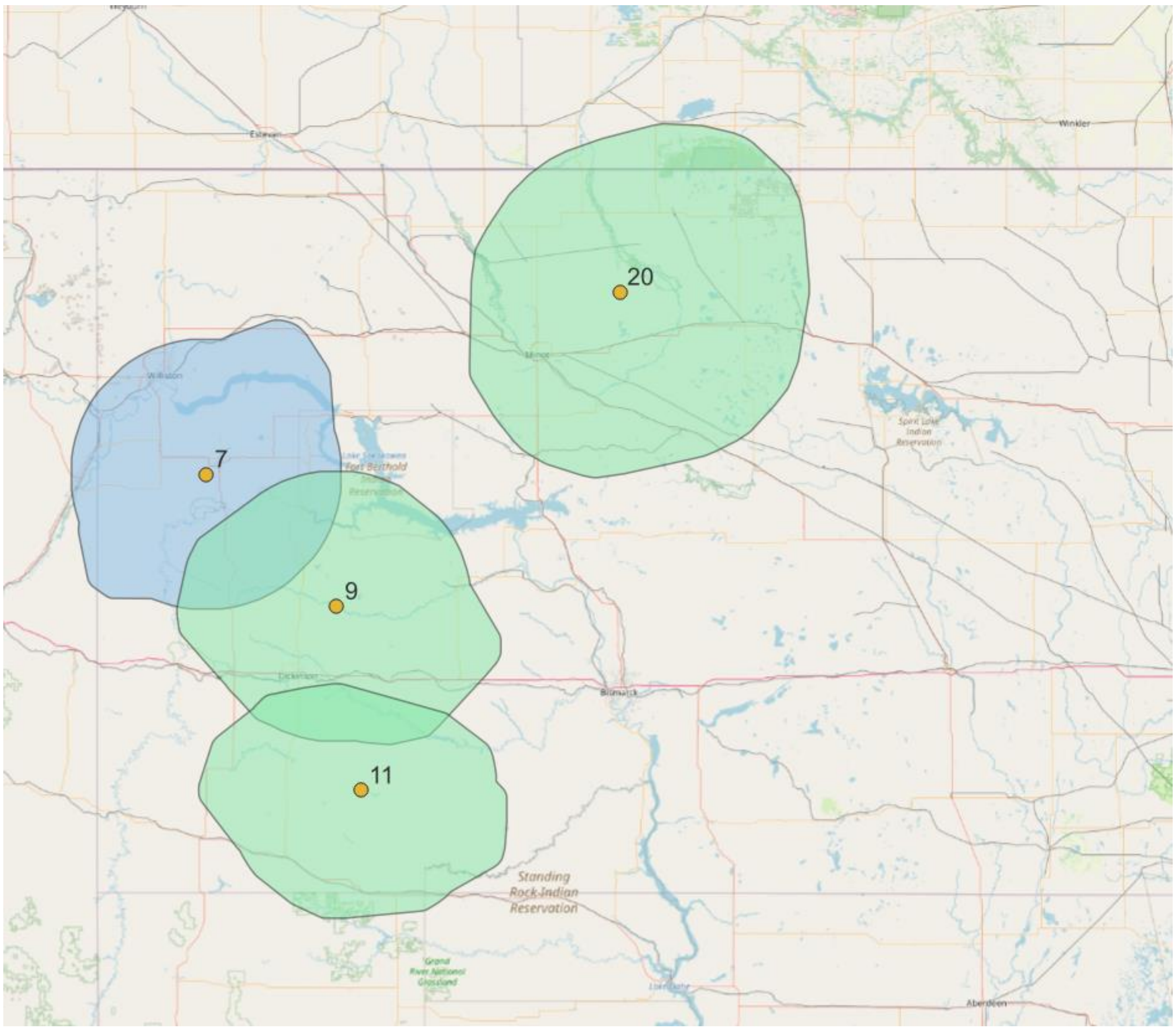
GRS ID	Longitude	Latitude	Frequency
6	-102.4729	46.1292	5.040625 GHz
11	-102.3916	46.3872	5.040875 GHz
13	-100.6133	46.1232	5.041125 GHz
19	-102.5627	46.2713	5.041375 Ghz



GRS 11 and 19 and GRS 13 and 6 were allocated unique frequencies due to viewshed overlap.

6.1.1.8 Allocation 8

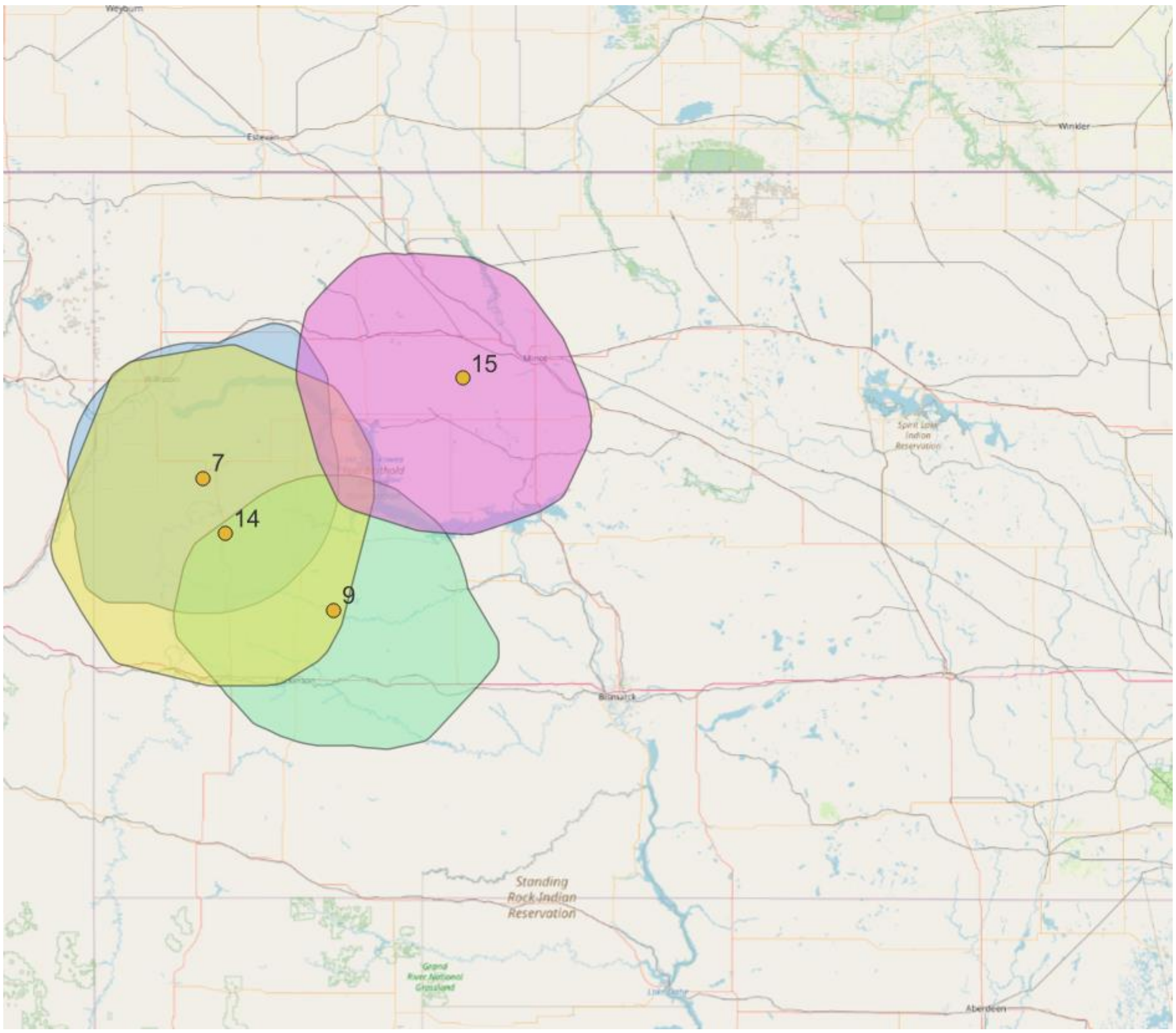
GRS ID	Longitude	Latitude	Frequency
7	-103.3627	47.7333	5.040625 GHz
9	-102.5494	47.1754	5.040875 GHz
11	-102.3916	46.3872	5.040875 GHz
20	-100.7782	48.4937	5.040875 GHz



GRS 7 and 9 were allocated unique frequencies due to viewshed overlap. The small overlap in the viewsheds from GRS 9 and GRS 11 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions. GRS 20 was also able to be allocated to that same frequency.

6.1.1.9 Allocation 9

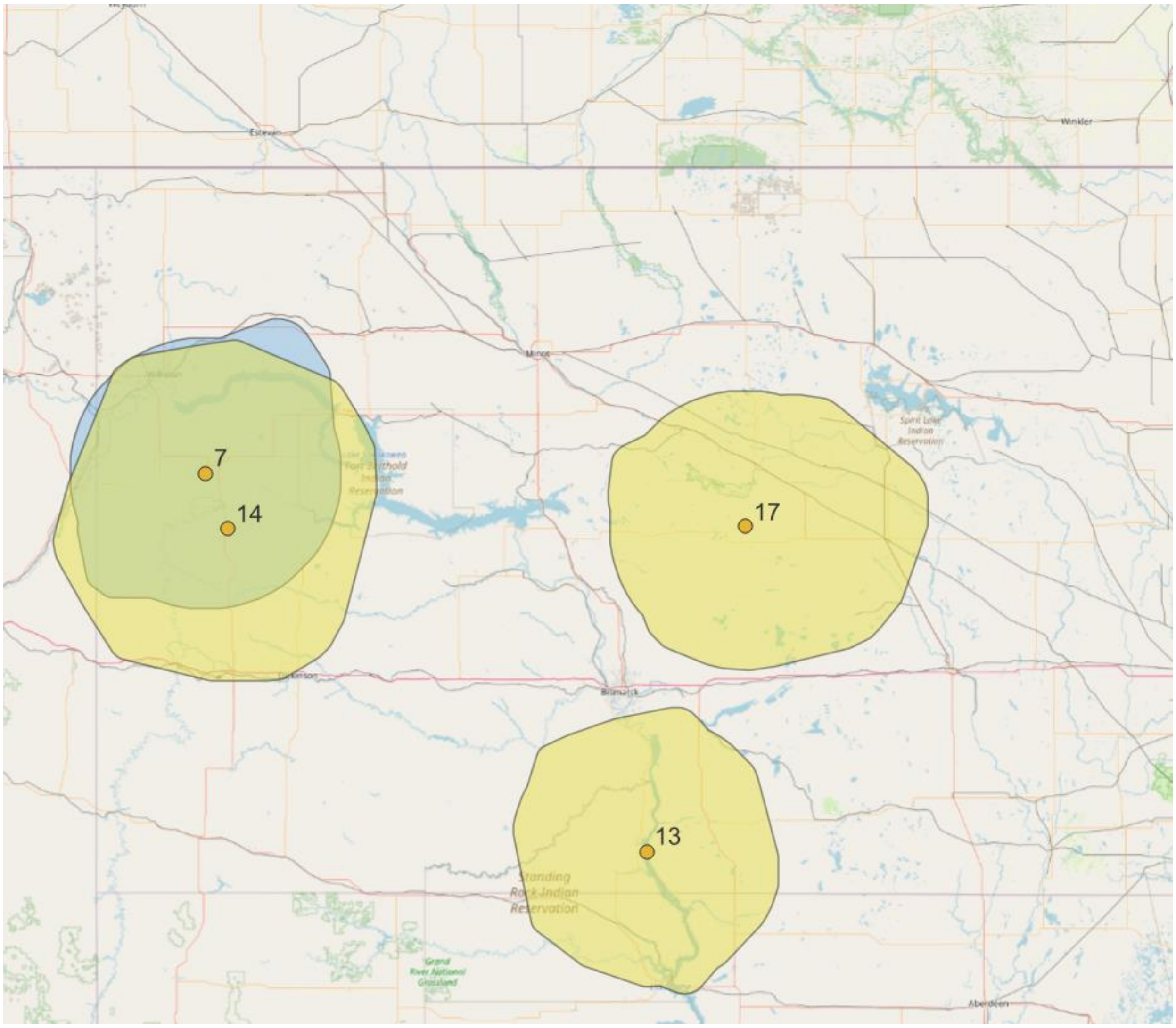
GRS ID	Longitude	Latitude	Frequency
7	-103.3627	47.7333	5.040625 GHz
9	-102.5494	47.1754	5.040875 GHz
14	-103.227	47.5027	5.041125 GHz
15	-101.7416	48.1508	5.041375 Ghz



All GRS are allocated unique frequencies due to viewshed overlap.

6.1.1.10 Allocation 10

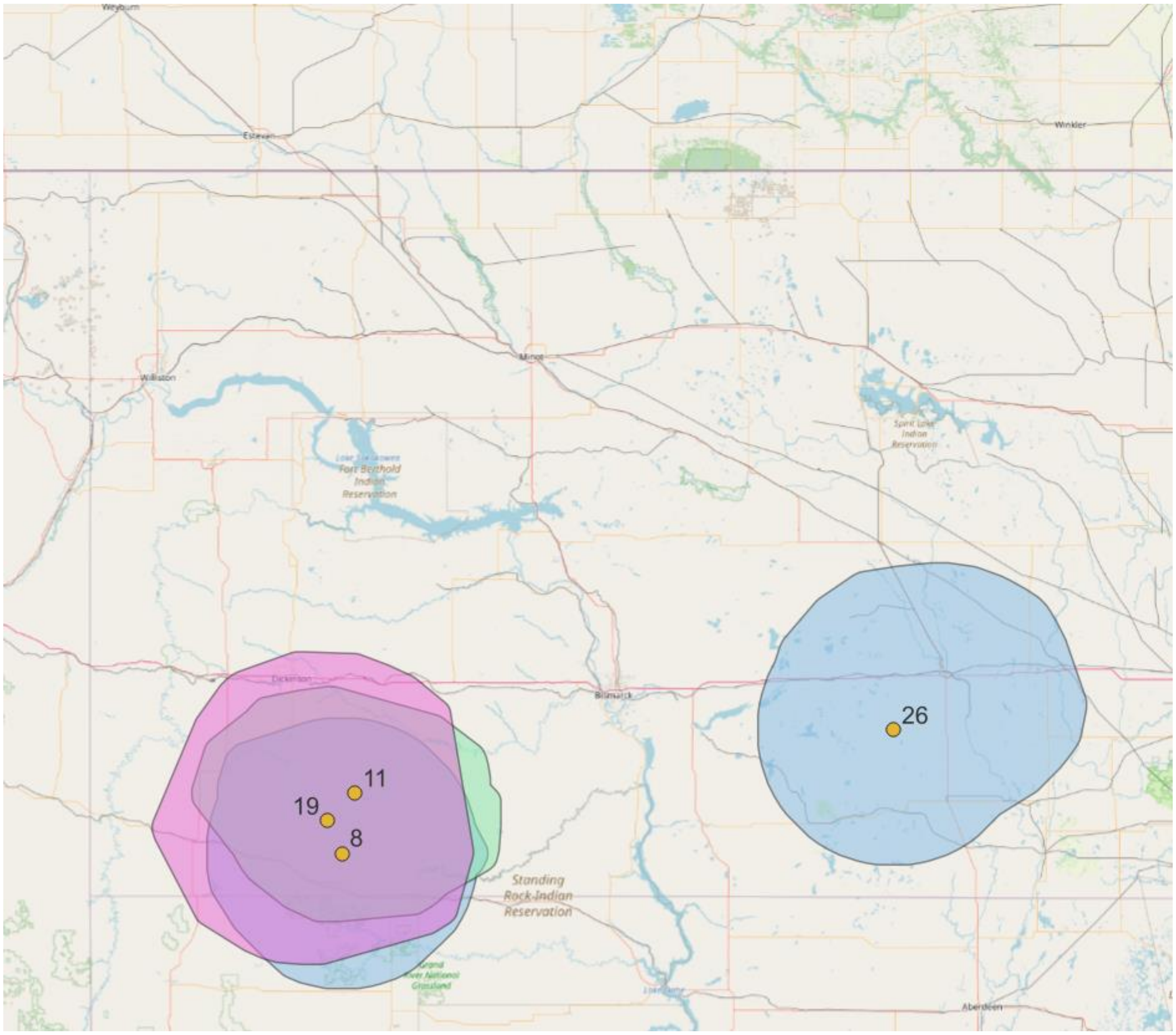
GRS ID	Longitude	Latitude	Frequency
7	-103.3627	47.7333	5.040625 GHz
13	-100.6133	46.1232	5.041125 GHz
14	-103.227	47.5027	5.041125 GHz
17	-100	47.5104	5.041125 GHz



GRS 7 and 14 were allocated a separate frequency due to viewshed overlap.

6.1.1.11 Allocation 11

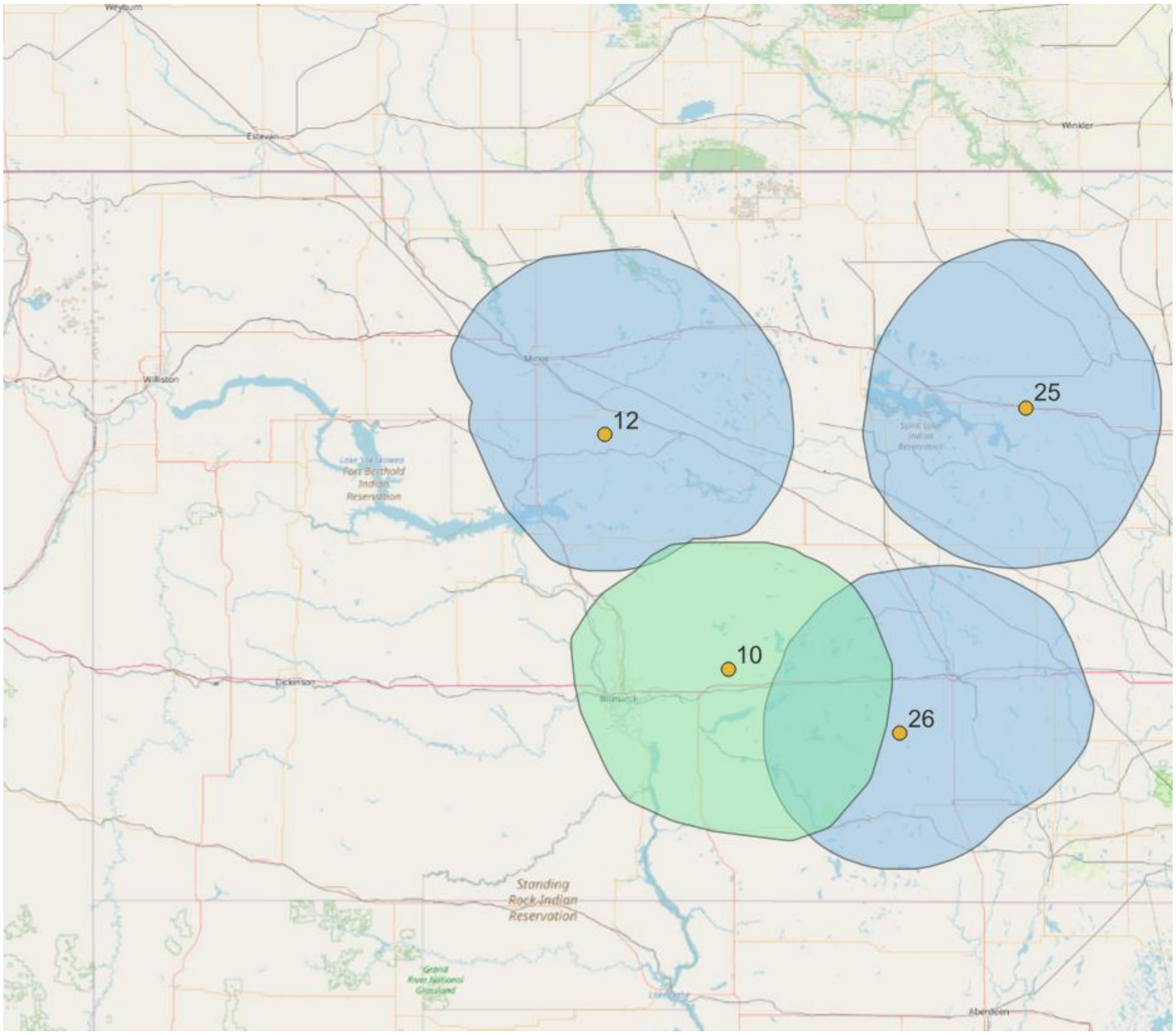
GRS ID	Longitude	Latitude	Frequency
8	-100.1028	46.9325	5.040625 GHz
11	-102.3916	46.3872	5.040875 GHz
19	-102.5627	46.2713	5.041375 Ghz
26	-99.0392	46.6611	5.040625 GHz



GRS 8, 11 and 19 were allocated unique frequencies due to viewshed overlap.

6.1.1.12 Allocation 12

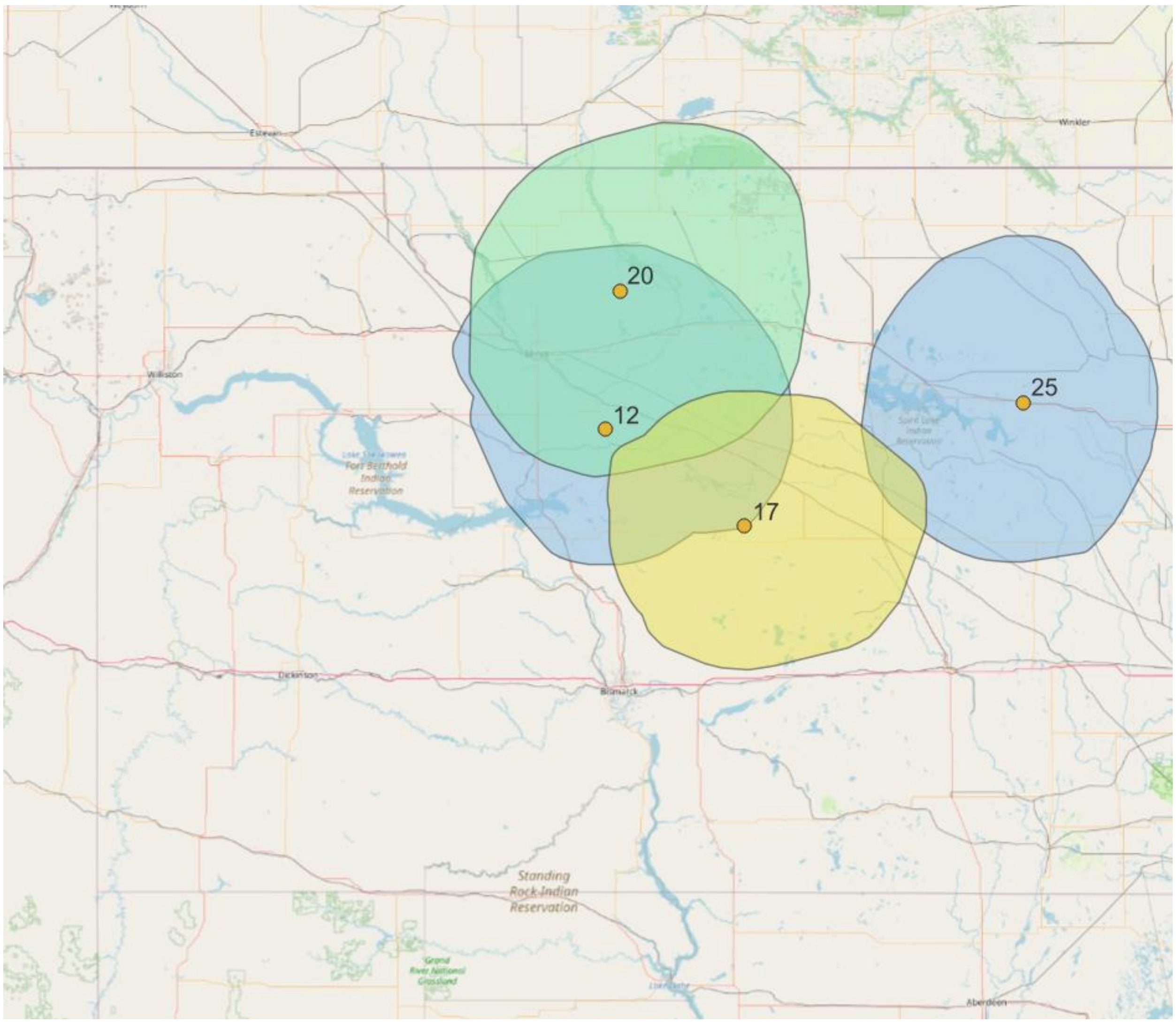
GRS ID	Longitude	Latitude	Frequency
10	-100.1028	46.9325	5.040875 GHz
12	-100.8686	47.9158	5.040625 GHz
25	-98.258	48.0295	5.040625 GHz
26	-99.0392	46.6611	5.040625 GHz



GRS 10 and 26 were allocated unique frequencies due to viewshed overlap. GRS 12, 25 and 26 were allowed to share the same frequency.

6.1.1.13 Allocation 13

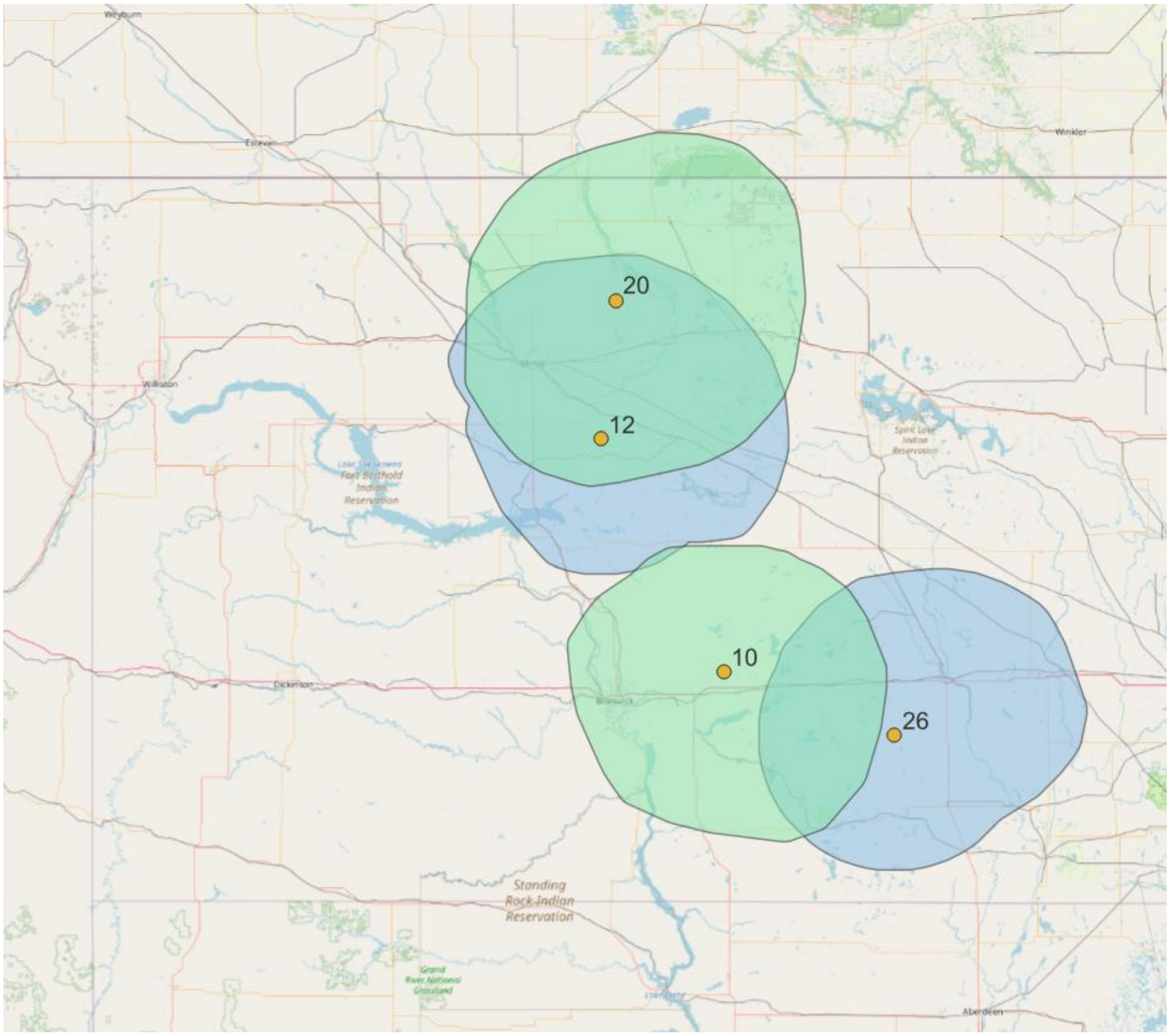
GRS ID	Longitude	Latitude	Frequency
12	-100.8686	47.9158	5.040625 GHz
17	-100	47.5104	5.041125 GHz
20	-100.7782	48.4937	5.040875 GHz
25	-98.258	48.0295	5.040625 GHz



GRS 12, 17 and 20 were allocated unique frequencies due to viewshed overlap. GRS 17 and 25 were also allocated unique frequencies due to viewshed overlap.

6.1.1.14 Allocation 14

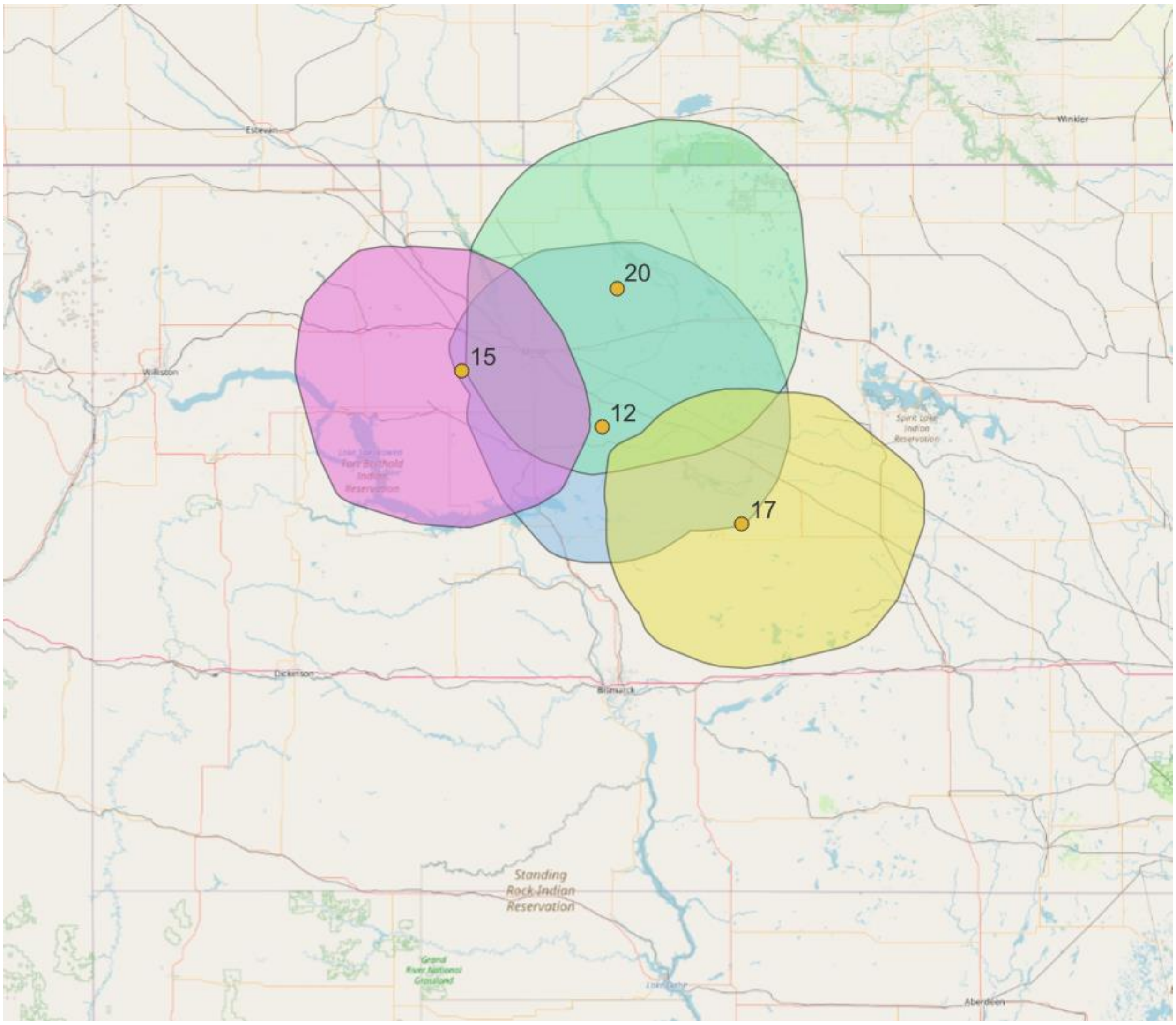
GRS ID	Longitude	Latitude	Frequency
10	-100.1028	46.9325	5.040875 GHz
12	-100.8686	47.9158	5.040625 GHz
20	-100.7782	48.4937	5.040875 GHz
26	-99.0392	46.6611	5.040625 GHz



GRS 12 and 20 and GRS 10 and 26 were allocated unique frequencies due to their viewshed overlap. GRS 12 and 26 and GRS 20 and 10 can share the same frequency.

6.1.1.15 Allocation 15

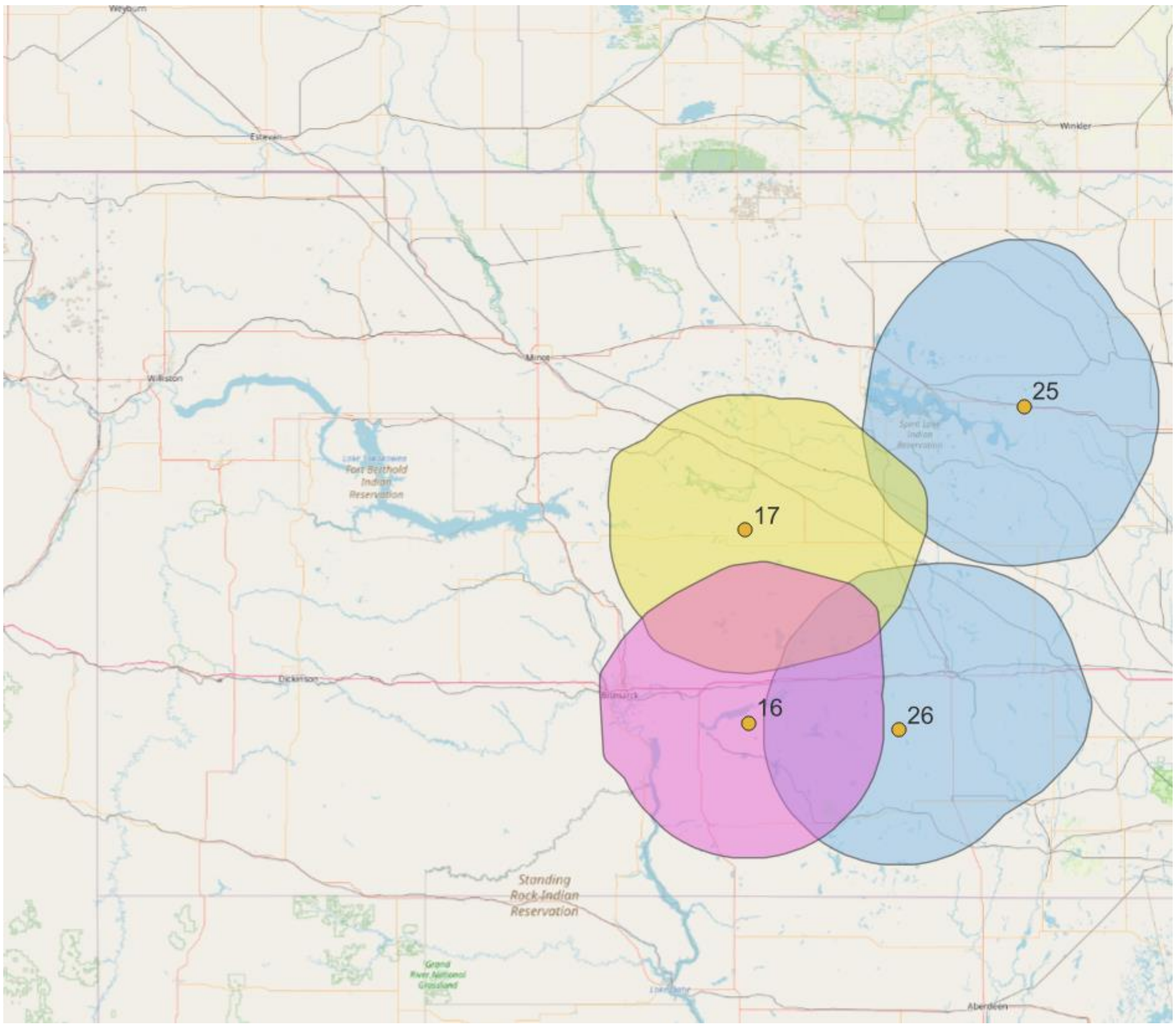
GRS ID	Longitude	Latitude	Frequency
12	-100.8686	47.9158	5.040625 GHz
15	-101.7416	48.1508	5.041375 Ghz
17	-100	47.5104	5.041125 GHz
20	-100.7782	48.4937	5.040875 GHz



All GRS were allocated unique frequencies due to their viewshed overlap.

6.1.1.16 Allocation 16

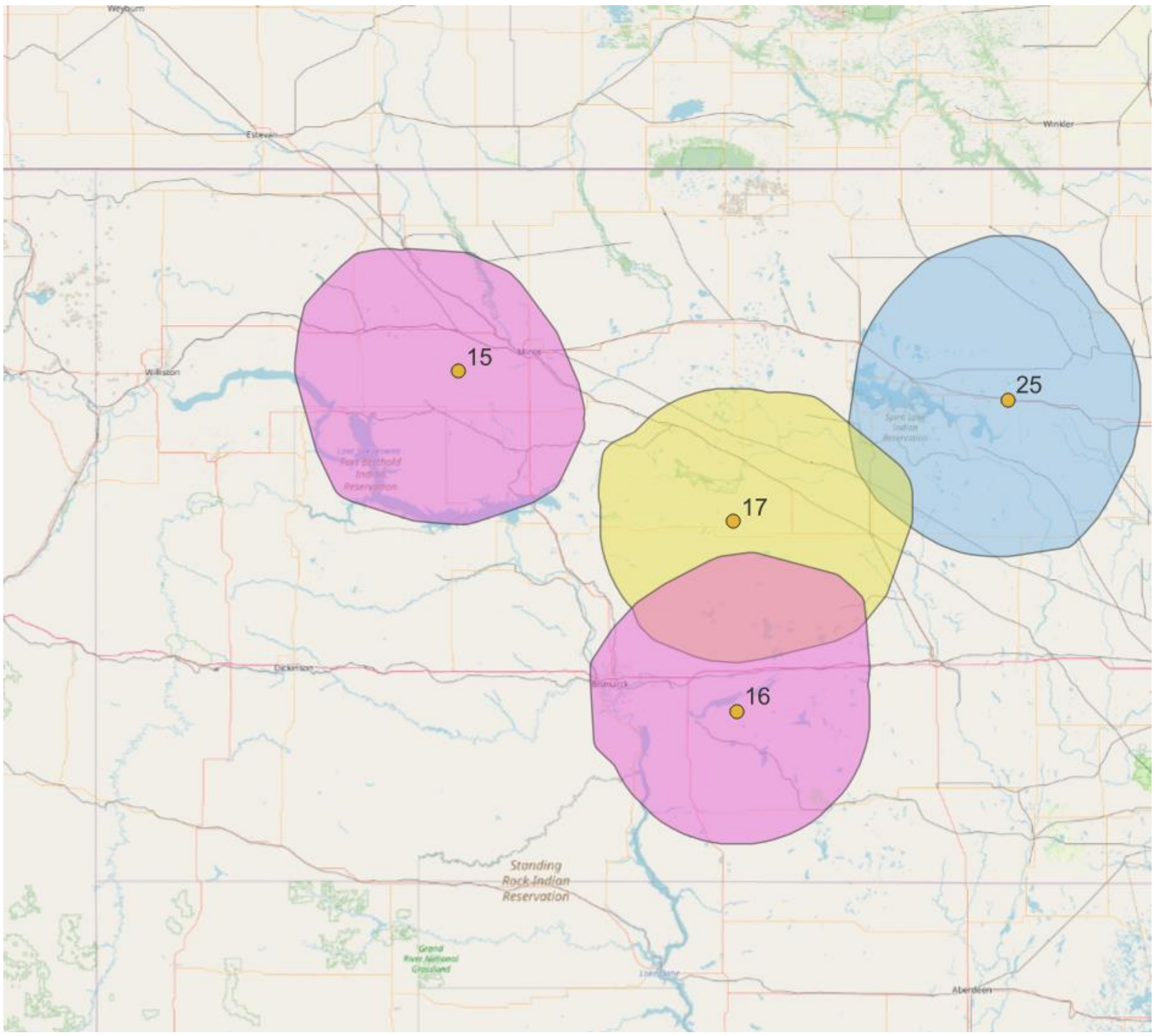
GRS ID	Longitude	Latitude	Frequency
16	-99.9759	46.6902	5.041375 Ghz
17	-100	47.5104	5.041125 GHz
25	-98.258	48.0295	5.040625 GHz
26	-99.0392	46.6611	5.040625 GHz



GRS 16, 17 and 26 were allocated unique frequencies due to viewshed overlap. GRS 25 and 26 can share the same frequency.

6.1.1.17 Allocation 17

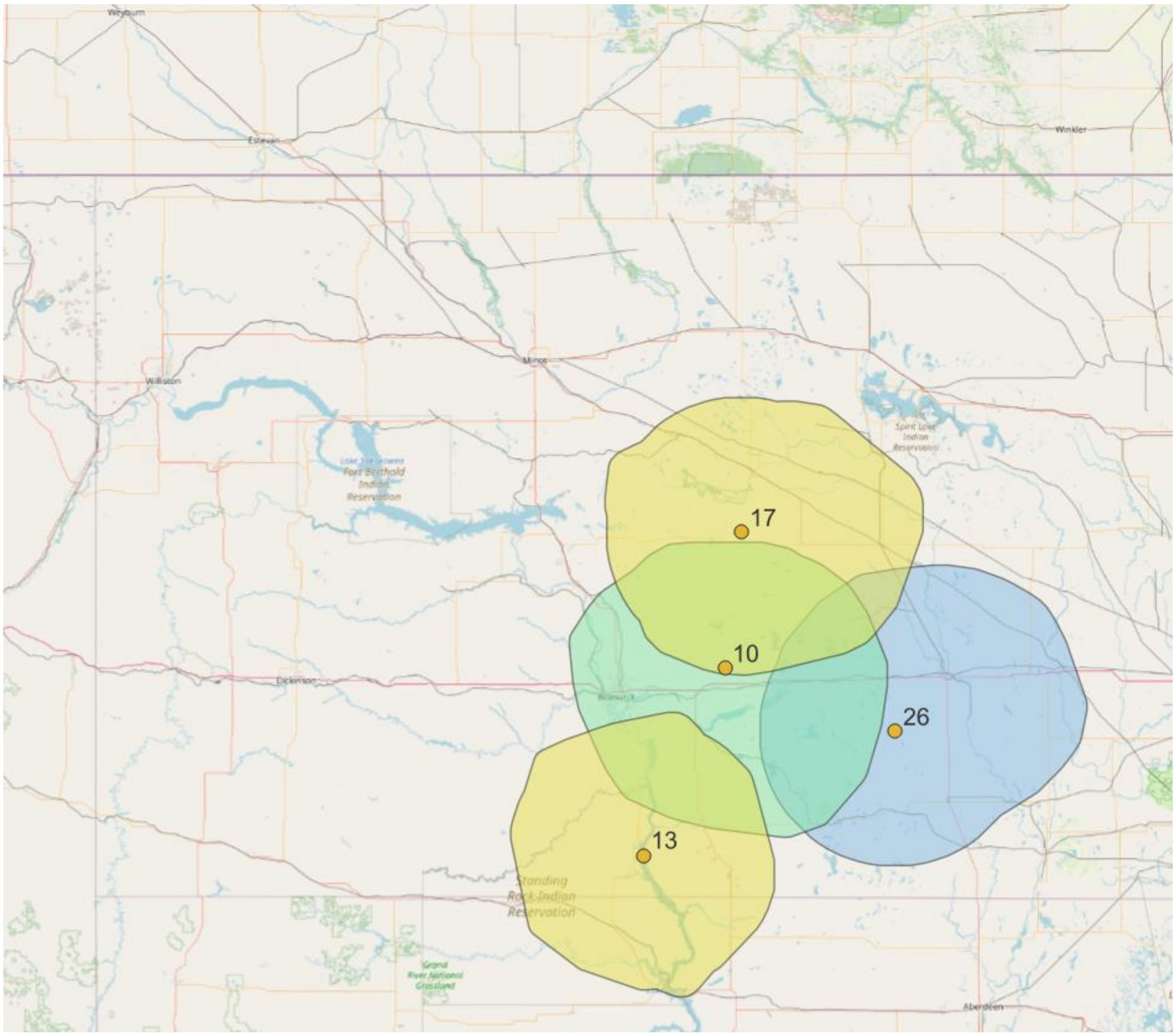
GRS ID	Longitude	Latitude	Frequency
15	-101.7416	48.1508	5.041375 Ghz
16	-99.9759	46.6902	5.041375 Ghz
17	-100	47.5104	5.041125 GHz
25	-98.258	48.0295	5.040625 GHz



GRS 15 and 16 share the same frequency. GRS 16, 17 and 25 were allocated unique frequencies due to viewshed overlap.

6.1.1.18 Allocation 18

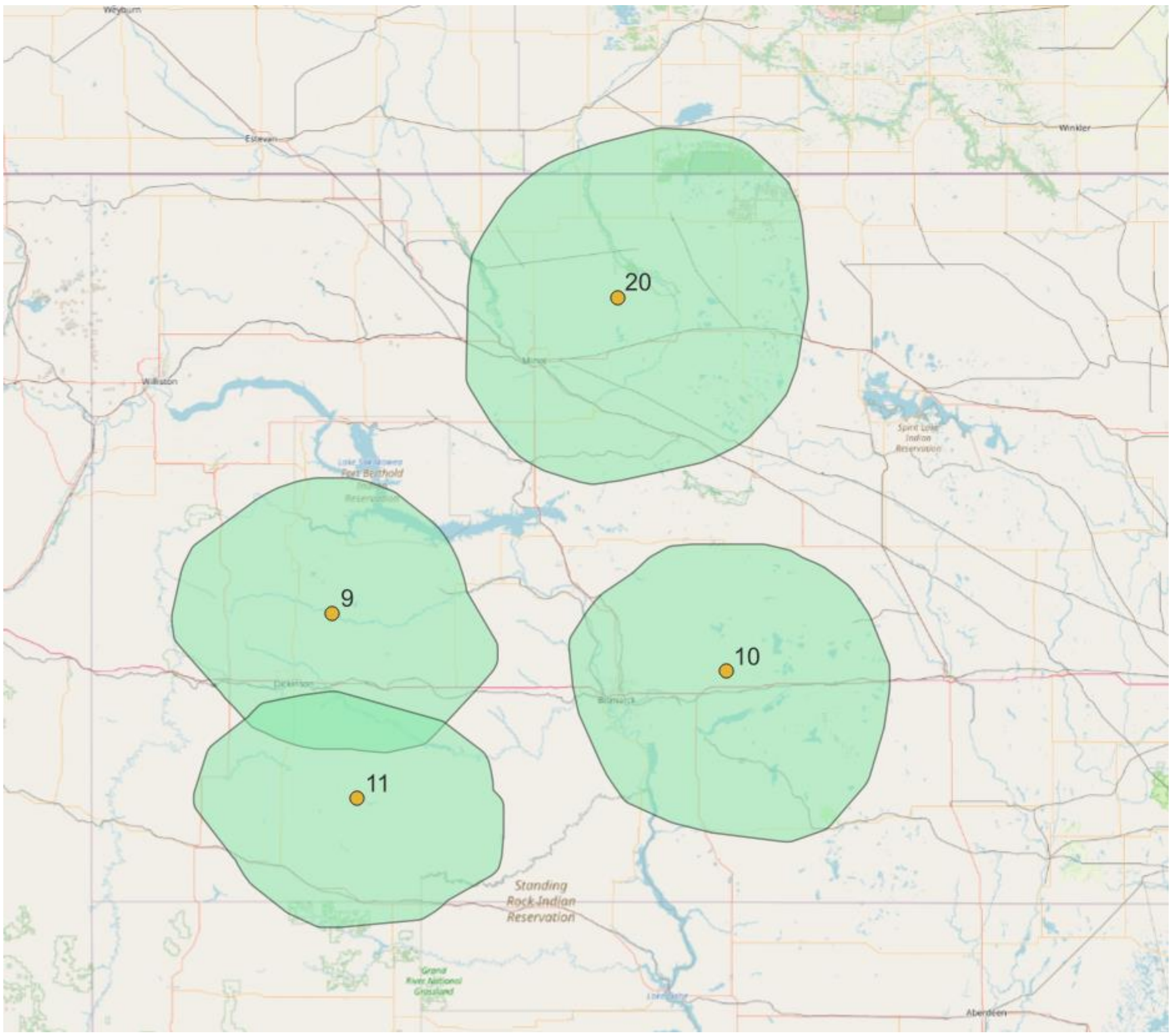
GRS ID	Longitude	Latitude	Frequency
10	-100.1028	46.9325	5.040875 GHz
13	-100.6133	46.1232	5.041125 GHz
17	-100	47.5104	5.041125 GHz
26	-99.0392	46.6611	5.040625 GHz



GRS 10, 13 and 26 were allocated unique frequencies due to viewshed overlap. GRS 13 and 17 can safely share the same frequency.

6.1.1.19 Allocation 19

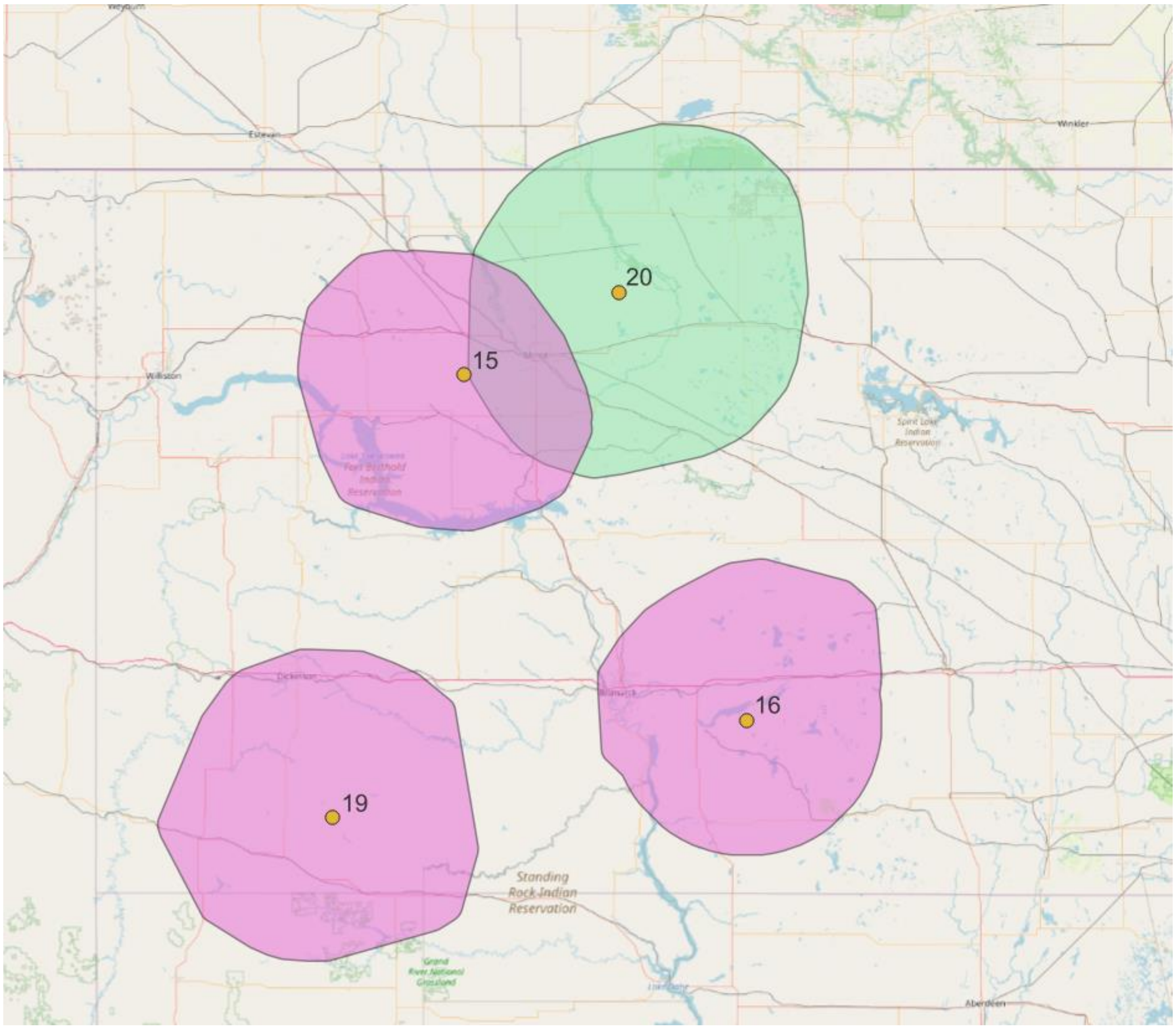
GRS ID	Longitude	Latitude	Frequency
9	-102.5494	47.1754	5.040875 GHz
10	-100.1028	46.9325	5.040875 GHz
11	-102.3916	46.3872	5.040875 GHz
20	-100.7782	48.4937	5.040875 GHz



All GRS can share the same frequency. The overlap in the viewsheds from GRS 9 and 11 were able to be allocated the same frequency after consideration of their specific waypoints and GRS positions.

6.1.1.20 Allocation 20

GRS ID	Longitude	Latitude	Frequency
15	-101.7416	48.1508	5.041375 Ghz
16	-99.9759	46.6902	5.041375 Ghz
19	-102.5627	46.2713	5.041375 Ghz
20	-100.7782	48.4937	5.040875 GHz



GRS 15, 16 and 19 were able to share the same frequency. GRS 15 and 20 were allocated unique frequencies due to their viewshed overlap.

6.2 NFAM Viewshed Validation

Demonstration 2 sought to validate the NFAM generated RF viewshed against real-world observations of RSSI values. A viewshed generated during the NFAM Enhancement Demonstration was validated against real-world measurements to ensure the RF propagation models are accurately reflecting the performance of the SkyLink 5060 equipment. This validation was performed by gathering RSSI from the ARS at various locations within the generated viewsheds and verifying that we did not have signal beyond the viewshed boundaries. Samples were collected by the ARS at a height of 100 ft AGL.

6.2.1 TC-NFAM-DEMO2-001

Tester Name(s)	Alex Logan
Test Event	2
Dates	5/16/2024
Test Facility	Grand Forks, ND
Test Equipment	TC-2
UUT	UUT01 UUT02
Pass/Fail	PASS – The measured RSSI values were the average over the collection period and confirm that the generated viewsheds support a conservative frequency allocation by the NFAM. An “ARS” RSSI of “None” indicates that no connection could be established between the ARS and GRS which occurs when the signal is weaker than approximately -114dBm, which was the threshold used during viewshed generation. All points at which an RSSI measurement was taken were within the generated viewshed, confirmed that there is no interference outside this area. The viewshed is generated using a RLOS (Radio Line Of Sight) propagation model which determines the extents of the viewshed, but not relative RSSI strengths within.
Tester Remarks	(see table below)

PNT	latitude	longitude	ARS RSSI (dBm)
1	47.91981	-97.0915	-66.4532
2	47.91954	-97.0911	-62.6444
3	47.91751	-97.1293	-77.2564
4	47.91385	-97.175	-78.9231
5	47.90414	-97.1968	-81.7978
6	47.91832	-97.2286	-88.5957
7	47.91827	-97.2607	-90.2849
8	47.91843	-97.2937	None
9	47.91865	-97.3304	None
10	47.90506	-97.3648	-96.5
11	47.88928	-97.3813	None
12	47.86067	-97.3922	-89.1053
13	47.84605	-97.42	-90.1481
14	47.88201	-97.4512	None
15	47.90379	-97.5064	None
16	47.90318	-97.5593	None

		17	47.88776	-97.099	-91.3614	
		18	47.84991	-97.0891	None	
		19	47.83621	-97.0883	None	
		20	47.81345	-97.0884	None	
		21	47.79563	-97.0883	None	
		22	47.7809	-97.0884	None	
		23	47.75885	-97.0881	None	
		24	47.73776	-97.0883	None	
		25	47.89045	-97.1534	-84.812	
		26	47.63627	-97.0913	None	
		27	47.49735	-97.0911	None	
		28	47.4973	-97.2146	None	
		29	47.51175	-97.325	None	
		30	47.63502	-97.3254	None	
		31	47.74474	-97.3029	None	
		32	47.97496	-97.6231	None	
		33	48.07917	-97.6007	None	
		34	48.07814	-97.4493	-89.7554	
		35	48.07804	-97.3522	-89.283	
		35	48.078	-97.3522	-89.6101	
		36	48.07809	-97.2456	-90.7794	
		37	48.07676	-97.1758	-87.9891	

Figure 3 represents the NFAM generated viewshed, with the white dot in the center being the GRS location and each green and red dot being a collection point. The green dots are labeled with the average collected RSSI at that point and the red dots indicate no connection was able to be established between the ARS and GRS for comparison. The collection points were taken opportunistically so the real-world heights they were taken from varied from the viewshed generation. An example of this is the southern locations indicated by the series of red dots, which were along a frontage road west of and parallel to the raised highway which blocked the line-of-sight back to the GRS location which was on the east side of the highway in Grand Forks.

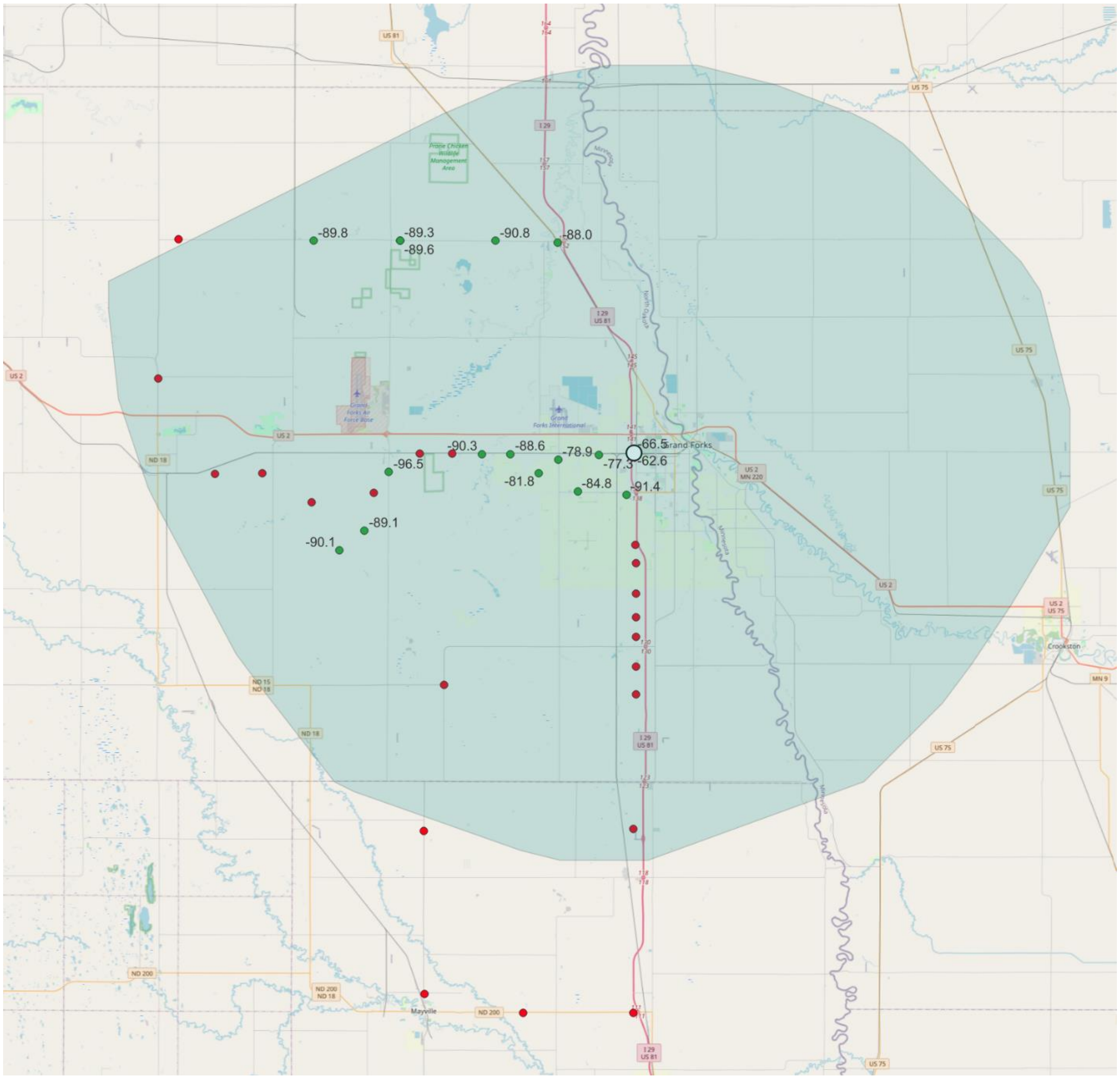


Figure 3 - Demo 3 Viewshed

North Dakota Department of Commerce
Northern Plains Unmanned Aircraft Systems Test Site

In Support Of

Federal Aviation Administration
Broad Agency Announcement Call 4
for
uAvionix Corporation
National Airspace System (NAS) Scaling of C-Band Frequency Assignment Manager (FAM) and Channel Reuse Demonstration with Multiple UAS in Nearby Regions

Under

Contract# 697DCK-23-C-00291

Demo 3 Test Report
Rev C June 2024

Northern Plains Unmanned Aircraft Systems Test Site
North Dakota Department of Commerce

Executive Summary

The Northern Plains UAS Test Site (NPUASTS) has concluded live flight-testing efforts under the Federal Aviation Administration's Broad Agency Announcement Call 4 (FAA BAA Call 4) contract for 2024 in conjunction with the uAvionix Corporation. This effort culminated with 88 Live Flight Demonstrations which demonstrated a national airspace C-Band frequency management application that meets all of the existing and anticipated RTCA specification requirements and informs the potential evolution of FAA TSO C-213a. The test was performed in multiple regions of North Dakota including Grand Forks, Niagara, Mayville, and Carrington North Dakota in May of 2024.

The NFAM, as delivered under this project, operated as a component of the uAvionix SkyLine™ Command and Control Communications Service Provider (C2CSP) management platform. The proof of concept demonstrated through testing shows the ability, through the use of a NFAM, to dynamically assign available frequencies within the internationally recognized UAS C-Band Command and Non-Payload Control (CNPC) range of 5030-5091MHz to Uncrewed Aircraft Systems (UAS) operating with CNPC radios.

As described in RTCA DO-362 Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS):

"*The FAA will hold or have rights to licenses to various safety critical Radio Frequency (RF) spectrum in the United States (U.S.) for PICs to use for these CNPC RF links. […] an assignment scheme must keep the particular frequencies in use clear from interference by other transmitters and the CNPC Link do not interfere with previously approved spectrum users. This CNPC Link Assignment Scheme, implemented by a Frequency Assignment Manager (FAM), shall assign a particular RF channel bandwidth to a particular UA so that only that UAS will be using the assigned RF channel bandwidth for control from Ground Radio System (GRS) sites at any given time in any area.*

As there is only a small amount of RF Spectrum available for a CNPC Link compared with the expected number of UA that it will need to support in the future, the CNPC Link Assignment Scheme must be Dynamic in nature. It must only assign a channel for a short amount of time to any particular UAS so that other UAs can use the same channel as soon as it is no longer needed."

To demonstrate such a link assignment scheme can function safely with multiple simultaneous flights, this project focused on the SkyLine C2CSP's management platform's ability, along with the integration of the NFAM, to manage a pool of allocated (and licensed) frequencies in a designated geographic area, allocate those available frequencies to a specific CNPC radio for a specific mission, and have the given CNPC radios receive and operate on assigned frequencies for the designated mission. Flight Tests also demonstrated the SkyLine C2CSP platform's ability to monitor and perform C2CSP functionality to the SkyLink CNPC radios during the designated missions and also demonstrated non-interference when flying multiple aircraft using uniquely assigned frequencies when operating within geographic proximity.

The project, though limited in scope, successfully conducted 88 flights, without measurable interference with 100% continuity and availability of the C2 links assigned by the NFAM.

The UAS were configured to perform a Return to Land (RTL) upon a C2 lost link, and the lost link threshold parameter was set to 30 seconds as the max Transaction Expiration Time (TET) for all transactions. The GCS and UA were also configured to resend any transactions that were not acknowledged within 1 second, such that multiple transmission attempts are always performed well before the final TET.

When reviewing the project performance as compared to DO-377A, the relevant C2 performance standard, all of the performed flights achieved 100% availability as every transaction was able to be sent before the TET. They also achieved 100% continuity even though some transactions were missed initially, the second retry was able to succeed in all cases as evidenced by the heartbeat graphs associated with each test result. Due to the C2 Link's use of cyclic redundancy checks (CRCs) to reject any transmission errors, 100% integrity was also achieved as the errors were properly detected and handled by resending the dropped transactions.

An example of the SkyLine C2CSP user interface can be viewed below in Figure 1.

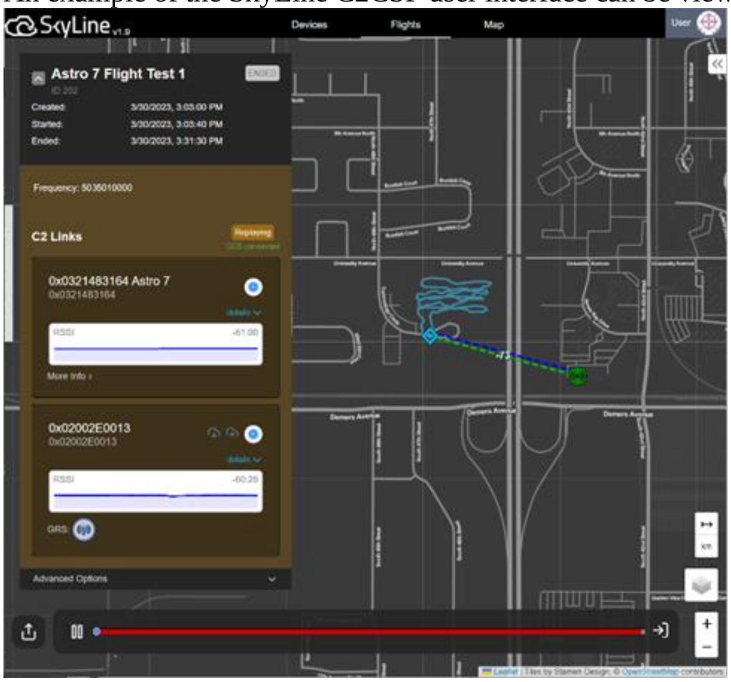


Figure 1: User Display of SkyLine C2CSP with NFAM

These field demonstrated results show that the principles of a NFAM, designed to ensure the efficient use of available spectrum, can be done safely and without frequency interference. The NFAM concept that was developed for this demonstration project required manual flight creation, however it is anticipated that flight creation is a feature that would ultimately be automated, compatible with other C2 or UTM / USS platforms. A NFAM concept that leverages an automated interaction could easily transform into a tool for a Frequency Management Organization (FMO) in a way that encourages commercial build-out of C2CSP infrastructure without limiting competition between providers or depending on exclusive regional lockups. The NFAM functions based on requests from, and assignment to, each operator for individual flights and does not require the participation of, or provide benefits to, any specific C2CSP. As such, we recommend expanded use of automated NFAM to be studied for scalability at a NAS level.

With regards to overall testing of the concept, during the 88 flights as well as during bench testing, no major issues were encountered. The user interface was simple to utilize, and user inputs were minimal for all operators during the testing period. The SkyLine system was easy to connect to and monitor individual UAS signal strength and connection status, allowing flights to be performed efficiently and in a timely manner.

This flight report is a high-level review of the demonstrations completed in May of 2024.

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1 Background

The overall goal of this project is to demonstrate a national airspace C-Band frequency management application that meets all the existing and anticipated RTCA specification requirements and informs the potential evolution of FAA (Federal Aviation Administration) TSO C-213a. This National Frequency Assignment Management (NFAM) application may have the potential to be adopted by the UAS industry in a way that encourages commercial build-out of C2 Communications Service Provider (C2CSP) infrastructure without limiting competition between providers or depending on exclusive regional lockups.

Currently, UAS usage of FAA protected spectrum is by exception only, with the vast majority of operations being conducted with unlicensed frequencies. This increases the overall risk of the operation as compared to usage of licensed, managed, and protected frequencies.

Under the FAA Reauthorization Act of 2018 (P.L.115-254), section 374, the FAA and FCC (Federal Communications Commission) were directed to produce reports on the usage of various spectrum allocations including C-Band for UAS Command and Control. Both entities have provided responses in support of the use of 5030-5091 MHz spectrum. These regulatory actions by RTCA, FAA, and FCC indicate a convergence on the readiness of industry and regulators to move to the next phase of usage of this spectrum, which will require an underlying NFAM infrastructure.

uAvionix SkyLine™ is the first enterprise C2 infrastructure management service built from the ground up to meet aviation design standards for critical UAS and AAM applications – leveraging the DO-377A MASPS as design and architectural guidance. While SkyLine™ is implemented in ND as a component of the Vantis/Thales architecture, it is deployed at numerous FAA test sites, within NASA, and with multiple commercial operators in the US.

1.1 NFAM Benefits

The previous FAM solution by uAvionix, as demonstrated and tested in FAA BAA Call 3, effectively manages a limited amount of protected spectrum for multiple operators in a specific, localized area. This current project aims to demonstrate the NFAM's extended functionality, automating allocations across the entire NAS to prevent interference, and maximizing the spectrum available for concurrent use in multiple regions.

The benefits of a fully functional NAS FAM are numerous and span across various stakeholder groups, as denoted in [brackets] below:

• [Operator] gains access to protected spectrum free from RF interference, enhancing safety compared to using unlicensed frequencies.
• [Operator] can reduce operational costs and complexities by using a standardized FAM system across the entire NAS.
• [FAA] is equipped with a method to efficiently manage protected spectrum assets in finite time slices using a NAS-wide model that ensures no interference.
• [FAA] is presented with an option to utilize existing, underused spectrum assets to serve the C2 needs of the UAS industry now and in the future, in alignment with the Presidential Spectrum Memorandum.
• [FAA] gains better visibility and control over UAS operations, improving overall airspace management and safety.
• [FAA] receives real-world results validating the use of RF modeling to optimize FAM operation.

• [Industry] is provided with a standardized model for the maximum effective density available for DO-362A based C2 links using this spectrum.
• [Industry] can increase the number of concurrent operations in a region through efficient spectrum allocations while maintaining the RF integrity of all links.
• [Industry] is encouraged to innovate and develop new solutions due to more efficient and reliable spectrum access.
• [Public] gains increased confidence in UAS operations as the FAM system ensures the safety and reliability of these flights.

1.2 New Technology – NFAM

The National Airspace FAM (NFAM) is an enhanced innovative technology developed by uAvionix. It builds upon the previous FAM capabilities which dynamically manage geographically limited C-band spectrum. Unlike its predecessor, NFAM is not constrained geography and can safely assign frequencies to multiple regions in general proximity. By analyzing RF parameters using the well-established Longley-Rice propagation model, NFAM ensures that simultaneous assignments pose minimal risk of interference. This enables a Frequency Management Organization or C2CSP to optimize spectrum utilization, allowing multiple operators to reuse occupied channels without causing interference.

The following technological capabilities were demonstrated and validated through the third demonstration in this research effort:

- Collect and store detailed RF parameters for every radio (GRS and ARS) in each planned operation including (but not limited to):
  ▪ GRS positions (lat/long/altitude
  ▪ One or more ARS waypoints
- Perform RF analysis, generating using data from the USGS 3D Elevation Program so that they consider any terrain that would impact performance and build on the open source GDAL tools to perform the terrain calculations. The propagation model used is RLOS (Radio Line of Sight) so that it is always assuming the strongest safety case of non-interference.
- DO-362A only specifies two power levels, 100mW below 1000 feet AGL and 10W above that altitude. The SkyLink radios also only implement these two distinct power levels, which simplifies the RLOS range calculation for the ARS radio when below 1000 feet AGL and given the range of the higher power 10W transmissions it can switch to using the curvature of the Earth as the dominant factor.
- Perform comparisons to detect intersections between stored RF viewsheds.
- All overlapping/intersecting viewsheds then have their specific waypoints and GRS positions loaded and a direct line-of-sight is calculated between each unique ARS-GRS pair of them with the new plan's positions.
- Re-assign channels to other concurrent operations when they are determined to not have any emission intersections.

The above capabilities were demonstrated through a series of three demonstrations, two ground based (Demonstration #1 & #2) and one airborne test (Demonstration #3). The tests developed for Demonstrations 1 & 2 were designed to validate the generated viewsheds against real-world signal quality sampling. For the airborne demonstration (Demonstration #3) uAvionix SkyLink C-band radios were used, although the design of the NFAM ultimately is agnostic to the radio in service. The key metrics from this test are sub-second sampling of the received signal strength from both the ARS and active GRS during the flight.

1.3 Technical Approach

uAvionix aims to build upon the existing FAM capability under the current contract to demonstrate the scalability of an efficient NAS-wide deployment. This expansion involves incorporating RF propagation analysis capabilities into the FAM, enabling the assignment of overlapping channels to different regions without causing interference.

The C-Band spectrum, protected for UAS CNPC usage, is a limited resource that the industry must effectively and efficiently manage. A crucial aspect of adopting C-Band-based solutions involves enabling maximum density allocation schemes without compromising the integrity of other operators.

Solutions for managing shared spectrum in other bands vary widely, often tailored to the specific industry and use-case for which the spectrum is licensed. The work conducted by the RTCA in DO-362A and DO-377A, and the formalized parts in FAA TSO-C213a, establishes the common essential elements for frequency management. uAvionix has implemented these elements and is currently demonstrating a basic Frequency Allocation Manager to validate all specifications.
This current effort involves scaling the management scheme to a national level, optimizing it for the UAS industry while maximizing assignment efficiency without jeopardizing the integrity of any individual C-Band-based C2 Link.

Throughout multiple ground-based tests and the live flight tests completed for this phase of the project, uAvionix has displayed a national airspace frequency management function that meets all existing and anticipated specification requirements. This national FAM can be readily adopted by the industry, promoting commercial build-out of C2CSP infrastructure without limiting competition between providers or relying on exclusive regional lockups. The NFAM operates based on requests from and assignments to each operator for individual flights, independent of any specific C2CSP's participation or benefits.

The overall demonstration for BAA Call 4 has been sectioned into four phases as described below. Phases 1, 2, and 3 close outs are considered "mid-term" exams with their own milestones, while the final Phase 4 close out is considered the "final exam". Details of each phase can be found in the following paragraphs.

NFAM Enhancement Demonstration (Phase 1) – This phase of the demonstration validated the upgrades made to the FAM. In this phase, at least twenty (20) successful frequency assignments were made by the NFAM to at least four (4) regions in close proximity. The assignments were made by the NFAM using the extended request parameters. Generated viewsheds for the requests and the associated regional interference analysis to guarantee that the simultaneous frequency assignments pose minimal risk of interference were captured.

NFAM Viewshed Validation (Phase 2) – The viewsheds generated during the NFAM Enhancement Demonstration were validated against real-world measurements to ensure the RF propagation models are accurately reflecting the performance of the SkyLink 5060 equipment. This validation was performed by gathering Received Signal Strength Indicators (RSSI) at various locations within the generated viewsheds and comparing them to the expected values.

Flight Demonstration (Phase 3) – At least twenty (20) demonstrations of four (4) simultaneous unmanned aircraft flights were executed to demonstrate the use of NFAM to issue deconflicted simultaneous frequency assignments. The Operator created and started four simultaneous missions via SkyLine™ with each mission including a 15-minute flight. Results collected from the mission include regional interference analysis to verify that simultaneous frequency assignments posit minimal risk of interference, attitude and navigation of the aircraft during the test, and all link statistics and analysis per the Data Analysis Plan.

High–Density Model Generation (Phase 4) – Using a simulation tool with the validated NFAM, employing the full 5030–5091 band, at least four high–density models will be created for the national airspace.

1.4 Flight Test Overview

Flight Tests were conducted at the University of North Dakota (UND) Technology Business Park, approximately one-half mile west of the NPUASTS headquarters building, at a site in Niagara, ND, at a site NW of Mayville, ND, and at a site SE of Carrington, ND. These sites were selected to give a broad range of geographic locations to test out the features of the NFAM. Each area presented no line-of-sight (LOS) issues between the GRS and UAS and three of the areas, namely Niagara, Mayville, and the UND Tech Park had viewshed results that identified the coverage of each GRS was slightly overlapping the boundary of another geographic location, as would be indicative of real world BVLOS use cases. The Carrington location was chosen, in addition to the other locations, as an outlying volume allowing uAvionix to fully demonstrate the features of the NFAM across distinct geographic regions. Figure 2 shows an initial viewshed model as provided by uAvionix for the various selected flight locations.

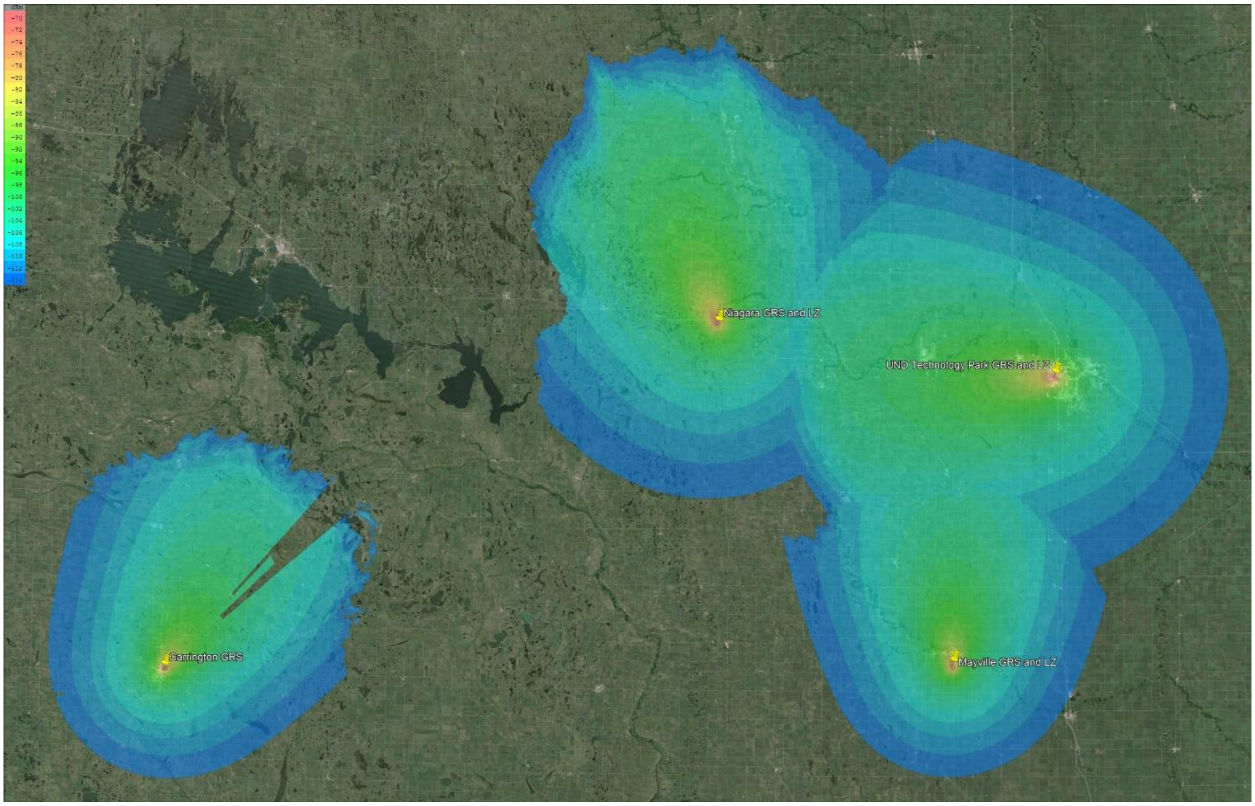

Figure 2. Initial Viewshed Modeling Results from uAvionix NFAM for Selected Flight Locations

Prior to the completion of the live test flight phase of the project, two additional demonstrations were conducted including the generation of three-dimensional viewsheds showing expected transmitter strength over the selected terrain at 95% fault free rate (Demonstration #1), and a manual validation of the NFAM density allocation schemes at a 95% fault free rate (Demonstration #2). The key performance metrics evaluated for Demonstration #2 were the geographically localized viewsheds generated from ground-based assignment requests, as well as regional interference analyses verifying simultaneous spectrum assignments pose a minimal interference risk.

The live test flights (Demonstration #3) were completed to verify the ability of the NFAM to dynamically allocate C-Band spectrum assignments automatically across multiple geographic regions while simultaneously verifying maximum viewshed density allocation schemes without jeopardizing the integrity of any individual C-Band C2 link. In all, a total of 88 test flights were conducted by NPUASTS with 80 test flights of 15-minute minimum duration as required by uAvionix test plan. These flights validated and demonstrated the operability, reliability, and efficacy of the SkyLine platform to perform C2CSP services and the NFAM to dynamically allocate C-Band frequencies with minimal interference across multiple geographically separated operating volumes. NPUASTS gathered flight and weather data (see section 2.7.1.1) while the key metrics evaluated by uAvionix included the sub-second sampling of the received signal strength from both the ARS and active GRS during the flight.

1.5 Partners

To assist with the completion of this effort, the NPUASTS utilized different partnerships to accomplish the specific tasks required for the Live Flight Demonstrations. Table 1 below is a list of partnerships and participants that supported the activities in North Dakota.

Table 1: NPUASTS – uAvionix C-Band NFAM Partners

Partner	Role
NPUASTS	Prime subcontractor. Provided Flight Director, UAS Flight Crews, Data Collectors, Mission Commanders, Project Managers, Safety Oversight, Airworthiness, Range Access & Safety
uAvionix Corporation	Project lead. uAvionix is the world's leader in communications, navigation, and surveillance solutions for unmanned aircraft systems. Provided C-Band Ground Radio Systems (GRS), Air Radio Systems (ARS) and UAS. Provided the SkyLine C2CSP platform, Frequency assignment manager (FAM), Performance Data Analytics, Program Lead, guidance on program development, engineering and technical support, field support.
FAA	Primary stakeholder, guidance on program development, VIP meetings and visits, and financial support
FCC	Federal Communications Commission. Regulates interstate and international communications through cable, radio, television, satellite, and wire. Granted STA (Special Temporary Authority) approval for C-Band frequencies.
UND Aerospace Foundation	UNDAF is a non-profit corporation that develops alternative revenue sources to support core activities of the John D. Odegard School of Aerospace Sciences at University of North Dakota. Provided Technology Park LZ Access and Coordination, Airspace Access.

1.5.1 NPUASTS

The NPUASTS provided project management, subject matter experts, asset procurement, hardware installation and management, flight teams, safety oversight, and facilitated meetings. The Test Site also provided coordination efforts and range access coordination with UND Aerospace Foundation and with the FAA and FCC for the STA's required to utilize the protected spectrum.

The NPUASTS provided the Flight Director who was the primary person leading the execution of the live flight events and oversaw operations using multiple data feeds and communicated directly to the flight crews via Microsoft Teams. In addition to the Flight Director, the NPUASTS provided the 4 UAS flight teams utilizing the FreeFly Astro, and Mission Commanders that assisted and oversaw flights adhering to NPUASTS Standards and Policy for each of the other UAS flight crews. NPUASTS also provided the infrastructure and hardware to install multiple uAvionix GRS.

1.5.2 uAvionix Corporation

uAvionix provided the NPUASTS with subject matter experts, project management and technical support meetings, guidance during test plan development, aircraft, ARS, GRS, and ADSB (Automatic Dependent Surveillance Broadcast) ping station. uAvionix personnel worked in concert with the authority of the NPUASTS Flight Director and flight crews, by advising as needed in the field and helping ensure that relevant test data was collected. uAvionix also provided technical support to NPUASTS technical specialists in the set up and troubleshooting of GRS hardware.

1.5.3 Federal Aviation Administration (FAA)

FAA provided the funding mechanism for this research effort to take place through its Broad Agency Announcement 692M15-19-R-00020 BAA Call 004 in support of the FAA Unmanned Aircraft Systems Integration Office. The FAA also provided project oversight through review of a series of monthly reports and quarterly Project Management Review (PMR) meetings with uAvionix.

1.5.4 Federal Communications Commission (FCC)

The FCC provided Special Temporary Authority (STA) licensing (File Number: 0481-EX-ST-2024) for use of 5 distinct C-Band frequencies in the 5030-5091 MHz band.

1.5.5 UND Aerospace Foundation (UNDAF)

The UNDAF provided access and logistical support to the UND Technology Business Park and provided airspace access for the live flight demonstrations. The technology park offered an ideal location that supported operations and activities associated with the demonstrations and presented no line-of-sight issues for the uAvionix radio installed at the NPUASTS Tech accelerator building. All flights conducted here were flown under part 107 rules. UNDAF has been a longstanding partner of the NPUASTS and supports the University of North Dakota's John D. Odegard School of Aerospace Sciences.

1.6 Aircraft

A maximum of four small UAS, all of the same make and model, were flown for the live flight demonstration. Figure 3 on the next page provides basic information about the aircraft used in the flight demonstrations.

1.6.1 *uAvionix Freefly Astro*

Aircraft – uAvionix Freefly Astro

Size (LxW):	36.1x36.1 inches	Cruise Speed:	34mph
Height:	14.13 inches	UTM/USS:	SkyLine
Weight:	8lbs	UAS Operator:	NPUASTS
Endurance:	30 minutes	GCS Type:	Auterion Mission Control
Visual Line of Site Range:	3	Autopilot:	Skynode
Max Wind Conditions:	30 kts	Temp range	-20C to 50C
Vehicle Hours	Freefly: 3,500+	Pilot Info	Scott Keane Joseph Reilly Hunter Hegel Trevor Hoggatt

NORTHERN PLAINS UAS TEST SITE

Figure 3: FreeFly Astro General Information and Limitations

1.7 *Supporting Equipment*

The NPUASTS team used the following assets to support the goals and objectives of this testing campaign. Several of these assets were reconfigured appropriately to support these efforts. Each asset was categorized as Infrastructure, Sensor, USS/Airspace Display, or Communications and a brief description of each is provided in Table 4.

Table 2: Supporting Test Equipment

Asset	Category	Description
NPUASTS Tech Accelerator Building	Infrastructure	NPUASTS Headquarters. GRS Hardware was installed on the roof of the building and supporting software was ran on the University of North Dakota's network.
University of North Dakota Technology Park	Infrastructure	Flight Testing area is located directly west of the NPUASTS headquarters. Centralized operational center and briefing/debriefing location.
Auterion Mission Control Suite	USS / Airspace Display	The NPUASTS utilized this software for a variety of functions including mission planning and execution.
Cobra Radio Crew Communications	Communications	Cobra Radios allow two-way radio users to take radio communication to greater distances. The NPUASTS utilizes Cobra as the primary source of crew communications during research efforts.

VHF Radios	Communications	VHF Radios (handheld and/or base station) were used for direct GFAFB Air Traffic Control communications as required by the Airspace Manager.
Ping Station	Sensor: ADS-B	Local ADS-B receiver deployed to provide flight crews with additional situational awareness during flight operations. This Ping station was installed on the roof of the NPUASTS building from prior projects.
Internet Network Connectivity	Infrastructure	Network connectivity was provided through Verizon LTE services, and directly through UND network services.
Access Form	Reporting	The UAS Flight data input form is a data collection tool that is used by the flight test director and data collectors to gather pertinent flight data for each mission. This tool includes flight times, durations, weather, and personnel details.
SkyLine	Communications, USS/Airspace Display	CNPC Connection Management System
SkyLink GRS	Communications	Quad-patch dual-dipole, 120-degree directional antennas for C-Band (5030-5091 MHz) radio system positioned based on field measurements and directed at area of operations
SkyLink ARS	Communications	Omni-directional C-Band (5030-5091 MHz) radio system to be integrated to airframe by uAvionix

1.8 Test Architecture

The test architecture is provided below in Figure 4. The Auterion GCS, run on a Windows 10 laptop with Google Chrome as the web browser, was used to connect to uAvionix SkyLine C2CSP, which then handled all interactions with the FAM for frequency allocation and relayed the frequency assignment to the GRS. The GRS then transmitted the frequency to the UAS via the installed ARS. The GRS was a SkyStation-5060 POE. The UAS was a FreeFly Astro with a muLTElink-5060 ARS installed on the airframe. This architecture was repeated in four parallel instances.

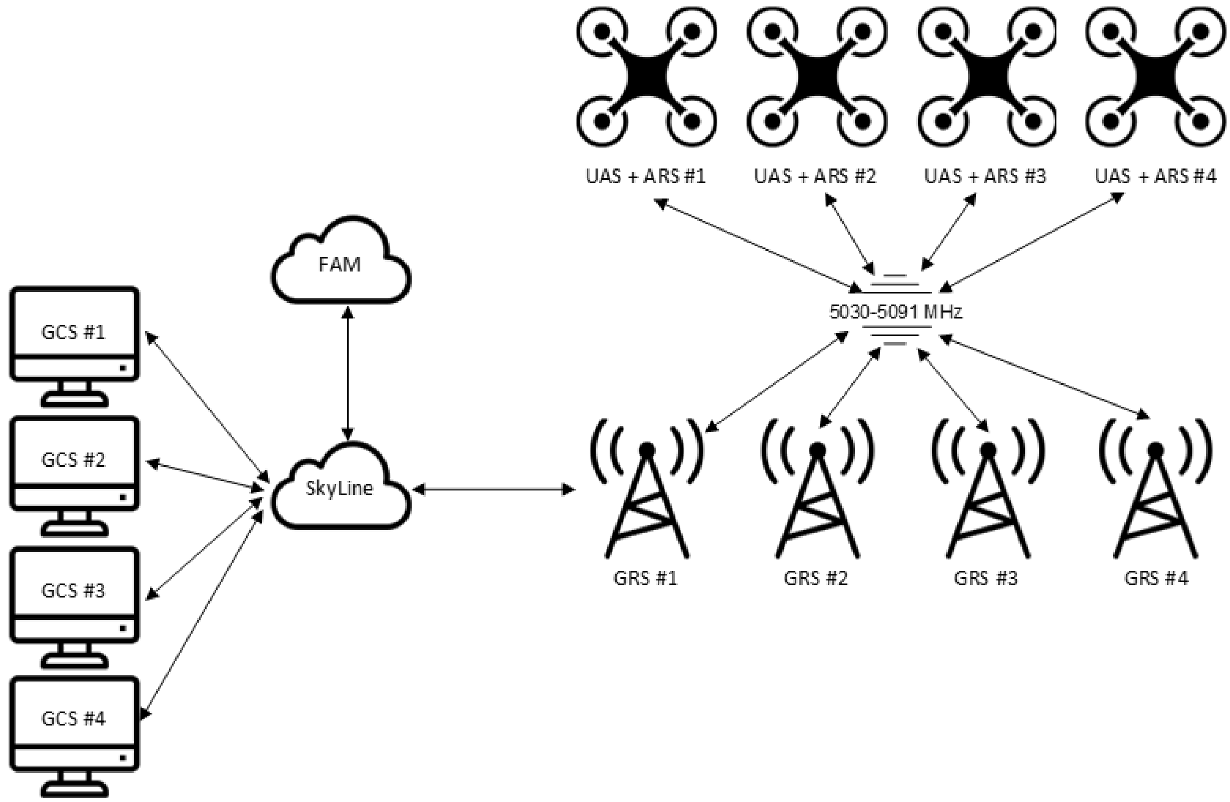

Figure 4: Aircraft Test Architecture

1.9 Location and Airspace

One of the operations was conducted in Grand Forks, North Dakota, using the airspace above the University of North Dakota Technology Park. The test location is located ½ mile due west of the NPUASTS Tech Accelerator headquarters building located on the campus of the University of North Dakota and southeast of the Grand Forks International Airport (GFK).

The second operation was conducted on the eastern side of Niagara, ND, approximately 70 miles west of Grand Forks, ND. The GRS was installed on the NPUASTS command trailer and operations were conducted north of the trailer location.

The third operation was conducted several miles northwest of Mayville, ND where NPUASTS has conducted other flight operations on previous efforts. The GRS was installed on a NPUASTS trailer outfitted with a pneumatic mast.

The fourth and final operation was conducted on a private farm several miles southeast of Carrington, ND. The GRS was installed on a truck-mounted mast and the flights took place south of the farm. The four above locations can be viewed on a sectional chart in figures 5-8 below. All flights were conducted in class G airspace.

Figure 5. Flight location UND Technology Park on VFR Sectional Chart

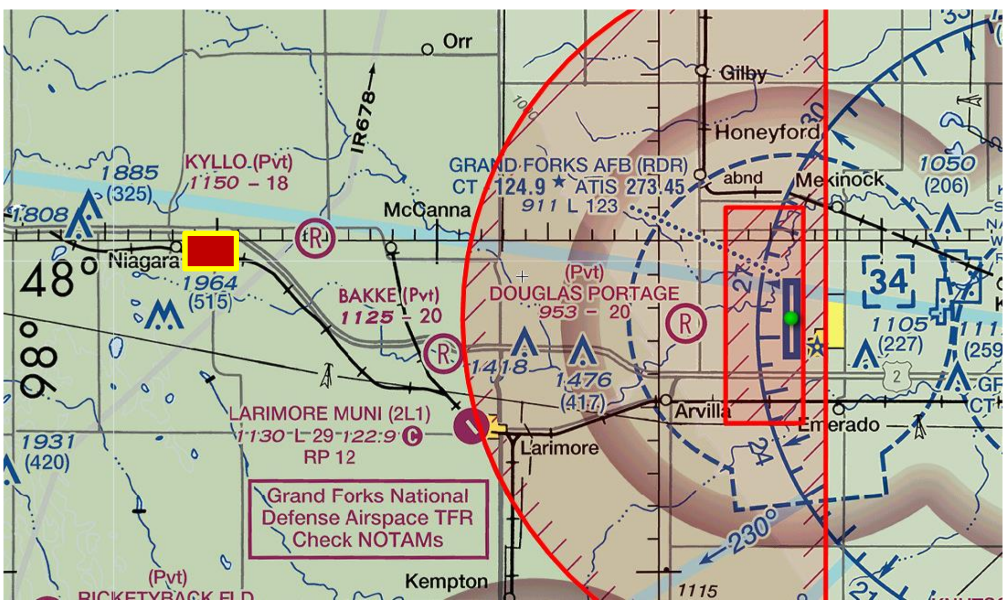

Figure 6. Flight location Niagara, ND on VFR Sectional Chart

Figure 7. Flight location Mayville, ND on VFR Sectional Chart

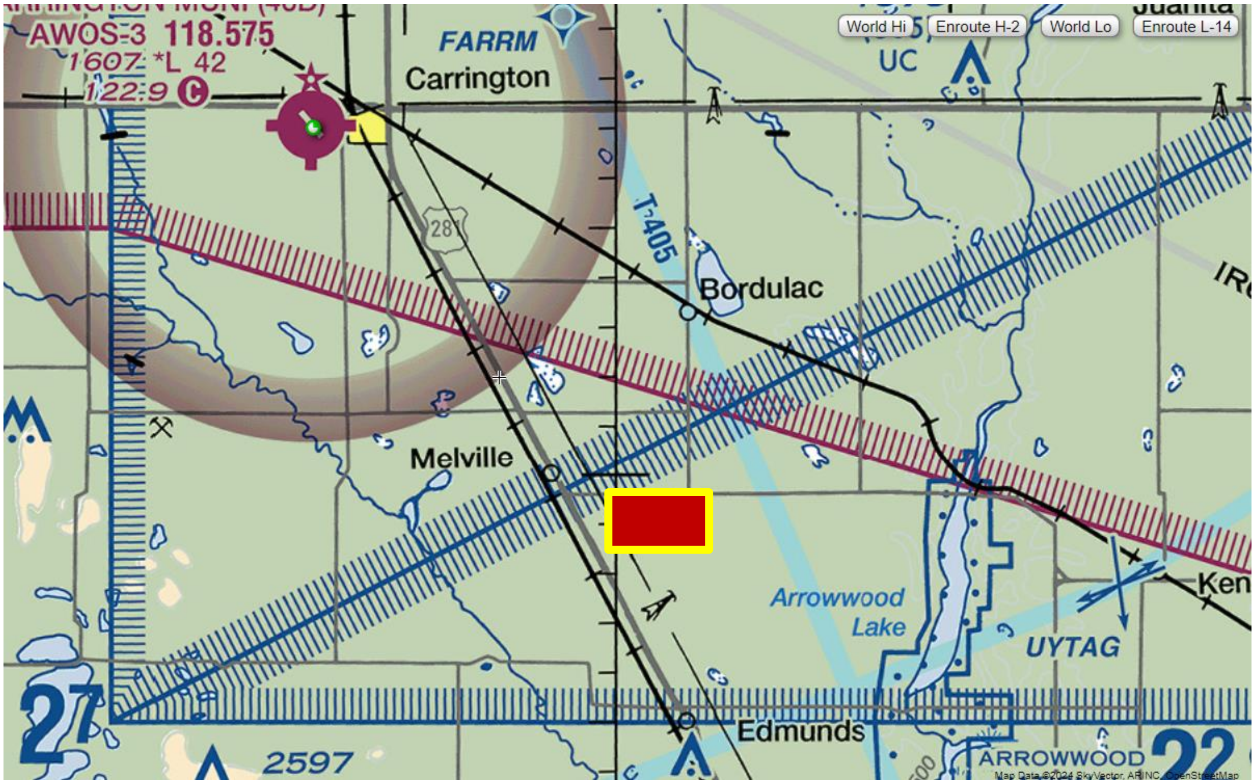

Figure 8. Flight location Carrington, ND on VFR Sectional Chart

1.10 Approvals

1.10.1 Operational Site Use Approvals

An agreement was put in place between NPUASTS and UNDAF for use of the UND Technology Park facilities and airspace. NPUASTS has a long history of supporting UNDAF in their UAS efforts and values the partnership. The remaining operations were conducted from public areas while the Carrington, ND location was approved by verbal agreement of the landowner.

1.10.2 Flight Approvals

All live UAS operations were flown under part 107 rules and no additional approvals or waivers were required for flight operations, other than the STA's provided by the FCC for C-Band frequency allocation. The specific frequencies allocated for this research effort are provided below in Table 3. Each frequency was approved for use within 111 km centered in Kloten, ND (N:47-42-55, W: 98-04-30) with an authorized power of 96.6 Watts Effective Radiated Power (ERP).

Table 3: Frequencies Approved for Use with SkyLine NFAM

Frequency (MHz)	Authorized Power (Watt) ERP
5040.925	96.6
5041.140	96.6
5041.785	96.6
5042.860	96.6

LAANC requests were submitted during days of flight operations for operations occurring in the UND Tech Park as the testing location is near the approach flight path for GFK. The remaining operating sites did not require LAANC approval.

1.10.3 Frequency Deconfliction

Given the testing location and no additional UAS or manned flights in the area, the NPUASTS team did not have to take any additional steps to address frequency deconfliction.

1.11 Test Description and Results

1.11.1 Flight Statistics

Different flight volumes were created for each flight team based on the parameters set forth by uAvionix. Specifically, three of the aircraft flew missions involving orbital patterns, both clockwise and counterclockwise, while the fourth aircraft flew a raster pattern. There was no additional need for vertical or horizontal deconfliction due to the aircraft flying in separate geographic locations with no additional UAS or crewed aircraft operating in the vicinity.

A breakdown of total flight time and number of flights by aircraft for the Live Flight Demonstration are provided in the following sections.

1.11.2 Test Flight Data

Table 4 below shows Data from the Flight Test Demonstrations that occurred on May 8th and 9th of 2024 in support of uAvionix NFAM. Per the test plan, a minimum of 20 flights, each with a minimum duration of 15 minutes of flight time, were required by uAvionix. The reader will note a total of 22 flights performed by each aircraft with a grand total of 1385 minutes of total flight time amongst the four aircraft. This was due to a field identified need to reposition the GRS in the Mayville testing location after the first two flights on May 8th. Those flights were subsequently made up at the end of the day on Thursday, May 9th.

Additionally, the latitudinal/longitudinal coordinates of the take off and recovery areas as well as the location of the GCS can be seen in Table 5. Given the localized nature of the mission profile, the GCS was located concurrently with the operations.

Table 4: Flight Time and Number of Flights by Aircraft for Astros During Live Flight Demonstrations

Aircraft	Number of Flights	Flight Time (minutes)
Astro #6	22	333
Astro #7	22	352
Astro #8	22	347
Astro #9	22	353
Total	88	1385

Table 5. Launch, Recovery, and GCS Coordinates for Flight Teams during Live Flight Testing

8-May	Launch Latitude	Launch Longitude	Recovery Latitude	Recovery Longitude	GCS Latitude	GCS Longitude
uavionix_Astro6_050824	47.91998	-97.09613	47.91998	-97.09613	47.91998	-97.09613
uAvionix_Astro7_050824	47.59227	-97.36783	47.59227	-97.36783	47.59227	-97.36783
uavionix_Astro8_050824	48.00029	-97.86148	48.00029	-97.86148	47.99842	-97.86240
uavionix_Astro9_050824	47.32537	-99.00611	47.32537	-99.00611	47.32537	-99.00611
9-May						
uavionix_Astro6_050924	47.91998	-97.09613	47.91998	-97.09613	47.91998	-97.09613
uAvionix_Astro7_050924	47.59227	-97.36783	47.59227	-97.36783	47.59227	-97.36783
uavionix_Astro8_050924	48.00029	-97.86148	48.00029	-97.86148	48.00029	-97.86148
uavionix_Astro9_050924	47.32537	-99.00611	47.32537	-99.00611	47.32537	-99.00611

Tables 6 and 7 on the following pages depict the remainder of flight data for the research effort, detailing the flight length, distance, number of flight crew, and if the flights took place in a rural or urban setting. As noted above, 10 test flights were executed on May 8th and twelve test flights were executed on May 9th, as the GRS in the Mayville location was reoriented following the first two test flights on May 8th. See section 2.7.2 for additional details on the flight test schedule.

Table 6: Flight Test Data for Wednesday, May 8th, 2024

Flight Name	Flight Duration (mins)	Number of Flight Crew	Max Altitude	Max Altitude Unit	Flight Distance	N-Number	Population Density
uavionix_Astro6_050824_F3	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F4	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F5	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F6	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F7	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F8	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F9	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050824_F10	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uAvionix_Astro7_050824_F3	0:16:32	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F4	0:16:50	3	250	AGL	0.5	FA3EH9WWKA	Rural

uAvionix_Astro7_050824_F5	0:16:39	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F6	0:16:50	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F7	0:16:36	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F8	0:16:33	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F9	0:16:34	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050824_F10	0:16:35	3	250	AGL	0.5	FA3EH9WWKA	Rural
uavionix_Astro8_050824_F3	0:16:32	3	350	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F4	0:16:23	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F5	0:16:11	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F6	0:16:19	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F7	0:16:15	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F8	0:16:22	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F9	0:16:23	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050824_F10	0:16:15	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro9_050824_F3	0:16:16	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F4	0:16:47	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F5	0:16:43	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F6	0:17:00	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F7	0:16:41	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F8	0:16:40	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F9	0:17:35	3	400	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050824_F10	0:16:39	3	150	AGL	0.3	FA3EHA4LPN	Rural

Table 7: Flight Test Data for Thursday, May 9, 2024

Flight Name	Flight Duration (mins)	Number of Flight Crew	Max Altitude	Max Altitude Unit	Flight Distance	N-Number	Population Density
uavionix_Astro6_050924_F1	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F2	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F3	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F4	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F5	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F6	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F7	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F8	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F9	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F10	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F11	0:16:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uavionix_Astro6_050924_F12	0:17:00	3	100	AGL	0.3	FA3EH9T3FF	Urban
uAvionix_Astro7_050924_F1	0:12:59	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F2	0:16:32	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F3	0:16:48	3	250	AGL	0.5	FA3EH9WWKA	Rural

uAvionix_Astro7_050924_F4	0:16:38	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F5	0:16:37	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F6	0:16:32	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F7	0:17:02	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F8	0:16:35	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F9	0:16:39	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F10	0:16:34	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F11	0:16:37	3	250	AGL	0.5	FA3EH9WWKA	Rural
uAvionix_Astro7_050924_F12	0:16:31	3	250	AGL	0.5	FA3EH9WWKA	Rural
uavionix_Astro8_050924_F1	0:16:16	2	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F2	0:15:39	2	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F3	0:16:56	2	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F4	0:15:41	2	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F5	0:16:19	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F6	0:16:06	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F7	0:16:04	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F8	0:16:01	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F9	0:16:10	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F10	0:16:04	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F11	0:16:01	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro8_050924_F12	0:15:54	3	150	AGL	0.2	FA3EH9YPMX	Rural
uavionix_Astro9_050924_F1	0:17:10	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F2	0:16:59	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F3	0:19:00	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F4	0:17:12	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F5	0:16:13	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F6	0:15:34	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F7	0:16:30	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F8	0:15:47	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F9	0:16:31	3	250	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F10	0:16:30	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F11	0:16:30	3	150	AGL	0.3	FA3EHA4LPN	Rural
uavionix_Astro9_050924_F12	0:14:55	3	150	AGL	0.3	FA3EHA4LPN	Rural

Finally, the weather data reported by each flight crew can be viewed below in Table 8. Some flight crews had access to real time weather data via the NPUASTS Davis Weather Station, while others reported local METARS and still others used local weather data as provided by public weather stations located throughout North Dakota. The main weather impact was wind, specifically wind gusts, which were approaching the wind limitations of the Astro's toward the end of flight day number 2 (Thursday, May 9th), however the gusts never exceeded the wind limits of the aircraft and testing was able to proceed.

Table 8. Daily Weather Data for Flight Testing Demonstrations

8-May	Local Cloud Cover	Local Precipitation	Local Wind Direction	Local Wind Speed (kts)	Local Wind Gusts (kts)	Local Visibility (SM)	Local Ambient Temperature (F)
uavionix_Astro6	Few	None	90	6	0	>7 SM	52
uAvionix_Astro7	Few	None	90	6	0	>7 SM	52
	Scattered	None	100	8	0	>7 SM	52
	Scattered	None	100	8	0	>7 SM	61
	Scattered	None	100	7	17	>7 SM	63
	Scattered	None	110	10	16	>7 SM	64
	Scattered	None	110	10	16	>7 SM	64
	Scattered	None	110	10	16	>7 SM	64
	Scattered	None	92	8		>7 SM	64
	Scattered	None	110	6	16	>7 SM	70
	Scattered	None	110	6	16	>7 SM	70
uavionix_Astro8	Few	None	120	5	0	>7 SM	52
	Few	None	80	7	0	>7 SM	61
	Few	None	80	7	0	>7 SM	61
	Scattered	None	100	12	0	>7 SM	63
	Scattered	None	100	12	0	>7 SM	64
	Scattered	None	100	12	0	>7 SM	64
	Scattered	None	100	12	0	>7 SM	64
	Scattered	None	120	10	0	>7 SM	66
	Scattered	None	120	10	0	>7 SM	66
	Scattered	None	130	8	16	>7 SM	68
uavionix_Astro9	Clear	None	110	10	0	>7 SM	50
9-May							
uavionix_Astro6	Few	None	10	11	0	>7 SM	70
uAvionix_Astro7	Clear	None	350	8	0	>7 SM	52
	Clear	None	350	8	0	>7 SM	52
	Clear	None	340	7	0	>7 SM	55
	Clear	None	350	7	0	>7 SM	55
	Clear	None	350	7	0	>7 SM	55
	Clear	None	360	10	0	>7 SM	63
	Clear	None	360	10	0	>7 SM	63
	Clear	None	10	13	18	>7 SM	66
	Clear	None	36	11	17	>7 SM	68

	Clear	None	360	11	17	>7 SM	68
	Clear	None	10	11	0	>7 SM	70
	Clear	None	10	11	0	>7 SM	70
uavionix_Astro8	Few	None	350	8	0	>7 SM	52
	Few	None	350	8	0	>7 SM	52
	Few	None	350	8	0	>7 SM	52
	Few	None	350	8	0	>7 SM	52
	Clear	None	350	8	0	>7 SM	59
	Clear	None	350	9	0	>7 SM	64
	Clear	None	350	9	0	>7 SM	64
	Clear	None	350	9	0	>7 SM	64
	Clear	None	30	15	0	>7 SM	66
	Clear	None	360	13	19	>7 SM	68
	Clear	None	360	13	19	>7 SM	68
	Clear	None	360	12		>7 SM	70
uavionix_Astro9	Clear	None	360	7	0	>7 SM	50

1.11.3 Flight Test Demonstration System Data

The live flight aircraft demonstrations consisted of twenty (20) flight demonstrations at four locations for a total of 80 flights, with each flight 15-minutes or longer, showing four aircraft flying as outlined in Sections 1.8 and 1.11.2. All tests were completed successfully and flow on the same frequency without radio interference. The total number of MAVLink packets, percentage of CRC error, percentage of missed packets and average RSSI over the entire length of flight as measured at the ARS are included for each flight in Table 9 below.

Table 9: Skyline System Data for Demonstration Test Flights

Flight Name	Flt	Astro/Site	Freq	Flt ID	Total Packets	CRC %	Missed %	ARS RSSI (dB)
uavionix_Astro6_050824_F3	3	6/TechPark	5035	485	115054	0.22	4.16	-64.08
uavionix_Astro9_050824_F3	3	9/Carrington	5035	487	93237	0.11	4.16	-59.57
uAvionix_Astro7_050824_F3	3	7/Mayville	5035	489	96006	0.11	3.5	-46.36
uavionix_Astro8_050824_F3	3	8/ Niagara	5035	491	75643	0.26	4.05	-71.68
uavionix_Astro9_050824_F4	4	9/Carrington	5035	492	84008	0.12	3.41	-58.70
uavionix_Astro6_050824_F4	4	6/TechPark	5035	494	79033	0.1	4.45	-58.20
uavionix_Astro8_050824_F4	4	8/ Niagara	5035	495	82088	0.27	4.65	-49.43
uAvionix_Astro7_050824_F4	4	7/Mayville	5035	496	82076	0.31	5.12	-64.68
uavionix_Astro6_050824_F5	5	6/TechPark	5035	497	89125	0.11	3.52	-58.94
uavionix_Astro9_050824_F5	5	9/Carrington	5035	498	84628	0.1	4.2	-58.53
uAvionix_Astro7_050824_F5	5	7/Mayville	5035	499	78560	0.33	6.83	-63.50

uavionix_Astro8_050824_F5	5	8/ Niagara	5035	501	65105	0.05	3.09	-51.32
uavionix_Astro6_050824_F6	6	6/TechPark	5035	502	80303	0.11	3.11	-57.72
uAvionix_Astro7_050824_F6	6	7/Mayville	5035	503	78554	0.28	5.69	-63.43
uavionix_Astro8_050824_F6	6	88/ Niagara	5035	504	75630	0.06	2.75	-50.57
uavionix_Astro9_050824_F6	6	9/Carrington	5035	505	71713	0.14	3.01	-58.66
uAvionix_Astro7_050824_F7	7	7/Mayville	5035	506	82095	0.3	5.48	-62.33
uavionix_Astro6_050824_F7	7	6/TechPark	5035	507	76011	0.11	2.39	-56.20
uavionix_Astro8_050824_F7	7	8/ Niagara	5035	508	75112	0.06	1.9	-50.31
uavionix_Astro9_050824_F7	7	9/Carrington	5035	509	74437	0.15	3.8	-57.48
uAvionix_Astro7_050824_F8	8	7/Mayville	5035	510	76362	0.22	6.25	-63.26
uavionix_Astro9_050824_F8	8	9/Carrington	5035	511	75579	0.15	5.53	-58.97
uavionix_Astro8_050824_F8	8	8/ Niagara	5035	512	74919	0.09	3.42	-50.17
uavionix_Astro6_050824_F8	8	6/TechPark	5035	513	69646	0.1	3.2	-55.81
uAvionix_Astro7_050824_F9	9	7/Mayville	5035	514	74078	0.31	5.38	-64.29
uavionix_Astro6_050824_F9	9	6/TechPark	5035	515	74462	0.24	4.17	-58.46
uavionix_Astro8_050824_F9	9	8/ Niagara	5035	516	67289	0.07	3.1	-51.12
uavionix_Astro9_050824_F9	9	9/Carrington	5035	517	71757	0.1	4.9	-58.60
uavionix_Astro6_050824_F10	10	6/TechPark	5035	518	78871	0.11	4.2	-59.34
uAvionix_Astro7_050824_F10	10	7/Mayville	5035	519	76799	0.29	5.07	-63.81
uavionix_Astro8_050824_F10	10	8/ Niagara	5035	520	72621	0.04	3.82	-51.10
uavionix_Astro9_050824_F10	10	9/Carrington	5035	521	71434	0.16	2.65	-58.40
uavionix_Astro9_050924_F1	11	9/Carrington	5035	522	72508	0.13	3.46	-65.93
uAvionix_Astro7_050924_F1	11	7/Mayville	5035	523	113324	0.36	6.16	-66.18
uavionix_Astro8_050924_F1	11	8/ Niagara	5035	524	120557	0.06	1.98	-48.85
uavionix_Astro6_050924_F1	11	6/TechPark	5035	525	73095	0.12	2.61	-58.43
uAvionix_Astro7_050924_F2	12	7/Mayville	5035	526	79411	0.26	5.05	-66.05
uavionix_Astro9_050924_F2	12	9/Carrington	5035	528	71891	0.14	5.08	-62.74
uavionix_Astro6_050924_F2	12	6/TechPark	5035	529	71582	0.1	2.53	-57.35
uavionix_Astro8_050924_F2	12	8/ Niagara	5035	530	62085	0.07	3.45	-47.76
uavionix_Astro9_050924_F3	13	9/Carrington	5035	531	86427	0.09	4.84	-62.97
uavionix_Astro8_050924_F3	13	8/ Niagara	5035	532	78077	0.07	3.34	-46.90
uAvionix_Astro7_050924_F3	13	7/Mayville	5035	533	75480	0.19	4.07	-65.60
uavionix_Astro6_050924_F3	13	6/TechPark	5035	534	74340	0.13	3.87	-57.02
uAvionix_Astro7_050924_F4	14	7/Mayville	5035	535	79141	0.25	5.88	-64.48
uavionix_Astro9_050924_F4	14	9/Carrington	5035	536	78138	0.16	4.54	-62.34
uavionix_Astro8_050924_F4	14	8/ Niagara	5035	537	74777	0.06	3.34	-47.37
uavionix_Astro6_050924_F4	14	6/TechPark	5035	538	68535	0.16	3.79	-56.02
uavionix_Astro9_050924_F5	15	9/Carrington	5035	540	81760	0.14	3.28	-64.24
uavionix_Astro6_050924_F5	15	6/TechPark	5035	541	74522	0.13	5.02	-57.46

uavionix_Astro8_050924_F5	15	8/ Niagara	5035	542	68760	0.08	2.03	-48.11
uAvionix_Astro7_050924_F5	15	7/Mayville	5035	543	66790	0.34	6.16	-64.55
uavionix_Astro9_050924_F6	16	9/Carrington	5035	547	74720	0.14	5.25	-62.68
uavionix_Astro8_050924_F6	16	8/ Niagara	5035	548	68791	0.08	1.87	-48.13
uAvionix_Astro7_050924_F6	16	7/Mayville	5035	549	68582	0.32	6.37	-65.77
uavionix_Astro6_050924_F6	16	6/TechPark	5035	550	69649	0.08	1.99	-53.90
uAvionix_Astro7_050924_F7	17	7/Mayville	5035	551	80690	0.3	4.67	-65.71
uavionix_Astro9_050924_F7	17	9/Carrington	5035	552	79365	0.16	2.38	-62.37
uavionix_Astro6_050924_F7	17	6/TechPark	5035	553	67460	0.07	2.39	-54.36
uavionix_Astro8_050924_F7	17	8/ Niagara	5035	554	61072	0.04	1.66	-48.50
uAvionix_Astro7_050924_F8	18	7/Mayville	5035	555	95230	0.15	5.22	-63.73
uavionix_Astro6_050924_F8	18	6/TechPark	5035	556	83165	0.1	2.4	-57.52
uavionix_Astro9_050924_F8	18	9/Carrington	5035	557	81845	0.14	6.23	-64.06
uavionix_Astro8_050924_F8	18	8/ Niagara	5035	558	74480	0.07	4.3	-48.03
uavionix_Astro9_050924_F9	19	9/Carrington	5035	559	80879	0.21	4.18	-63.77
uAvionix_Astro7_050924_F9	19	7/Mayville	5035	560	70171	0.18	5.85	-64.94
uavionix_Astro6_050924_F9	19	6/TechPark	5035	561	70963	0.1	2.74	-55.28
uavionix_Astro8_050924_F9	19	8/ Niagara	5035	562	66389	0.11	6.99	-47.69
uavionix_Astro6_050924_F10	20	6/TechPark	5035	563	76246	0.1	2.81	-56.79
uAvionix_Astro7_050924_F10	20	7/Mayville	5035	564	78043	0.18	2.69	-63.94
uavionix_Astro9_050924_F10	20	9/Carrington	5035	565	76533	0.11	3.72	-63.93
uavionix_Astro8_050924_F10	20	8/ Niagara	5035	566	69659	0.05	1.9	-47.82
uavionix_Astro9_050924_F11	21	9/Carrington	5035	567	74960	0.13	5.71	-63.13
uavionix_Astro6_050924_F11	21	6/TechPark	5035	568	70302	0.12	3.32	-55.60
uAvionix_Astro7_050924_F11	21	7/Mayville	5035	569	69716	0.2	3.94	-65.14
uavionix_Astro8_050924_F11	21	8/ Niagara	5035	570	62846	0.08	3.23	-48.19
uAvionix_Astro7_050924_F12	22	7/Mayville	5035	571	102799	0.14	5.54	-64.17
uavionix_Astro6_050924_F12	22	6/TechPark	5035	573	88798	0.1	3.39	-59.08
uavionix_Astro8_050924_F12	22	8/ Niagara	5035	574	81923	0.06	3.01	-48.04
uavionix_Astro9_050924_F12	22	9/Carrington	5035	575	74105	0.22	6.47	-64.67

1.11.3.1 Flight Test Summary

A detailed summary of the demonstration flights can be found in the following sections. Section 1.9.1.4 provides a summary of the NFAM performance for this demonstration and the following section details feedback from the flight crews.

1.11.3.2 NFAM Performance Summary

A summary of the aircraft demonstration flights can be found in Section 1.11.3. All twenty flights had minimal CRC errors and missed packets, ranging from 0.04 to 0.36% and 1.66 to 6.99% respectively.

Additionally, all flights exhibited a good RSSI signal strength on the ARS for the GRS radio. This is indicative of good C2 performance on the link for each flight, demonstrating non-interference of the concurrent flights on different frequencies. A passing result indicates that the mission was flown successfully for a duration of at least 15 minutes with 100% Continuity and Integrity.

1.11.3.5 Flight Crew Feedback

Overall feedback from the flight crews regarding the performance of the NFAM via SkyLine™ was favorable. Based on the manual provided by uAvionix and with additional guidance provided by uAvionix as required, the flight teams were able to successfully plan and execute missions utilizing the Auterion Mission Control software and the SkyLine™ platform. As this technology is still under development, there were several minor issues identified during testing, the most noteworthy of which was alternating connection coloring for the C2 C-Band link in the SkyLine™ platform itself. See Figure 9 below in the SkyLine™ interface window. Some operators experienced the green and blue lines changing colors throughout the flight without any indications from the system on what was transpiring. It's important to note that while these changing colors did not impact C2 during flight testing, it did provide some confusion to the flight crews that encountered it.

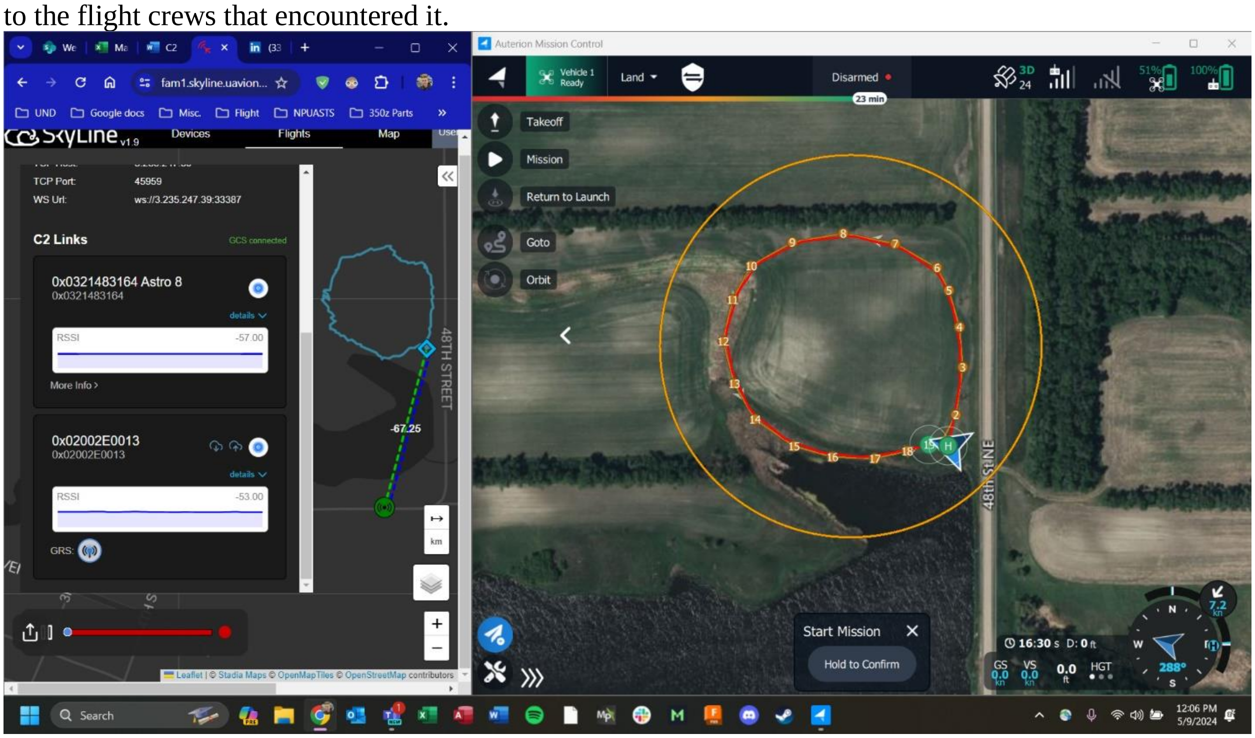

Figure 9. Pilot In Command Interface Window with Skyline and Auterion Mission Control

1.11.3.6 Scenario 1: UND Technology Park

This scenario was created to allow for the operation of a UAS on C-Band C2 with a nearby radio positioned on the top of a building, as might be encountered for mission cases in an urban setting. The UAS performed a raster pattern simulating multiple "touch and go's" at low altitude. The flight profile and additional scenario information can be seen in Figure 10 and Table 10, respectively.

Figure 10: Scenario 1 Aircraft Flight Profile

Table 10: Scenario 1 Aircraft Demonstration Scenario Information

Test Card #	1
Location	University of North Dakota Technology Park
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	100 ft AGL
Repetitions	20 minimum
Flight Profiles	UAS #1 Raster Pattern at 100 ft AGL
Test Objective	Fly Raster Pattern at 100 ft AGL for minimum of 15 minutes, repeat for 20 repetitions.

1.11.3.7 Scenario 2: Mayville, ND

This scenario was created to test how the C2 signal is maintained throughout multiple UAS in flight with UAS flying in adjacent geographic regions, with each region deploying a localized GRS. This type of use case is indicative of an agricultural inspection as might be required outside of city limits. This UAS performed a clockwise orbit of .15-mile diameter at approx. 250 ft AGL which consisted of yawing, rolling and pitching. The flight profiles and additional scenario information can be seen in Figure 11 and Table 11, respectively.

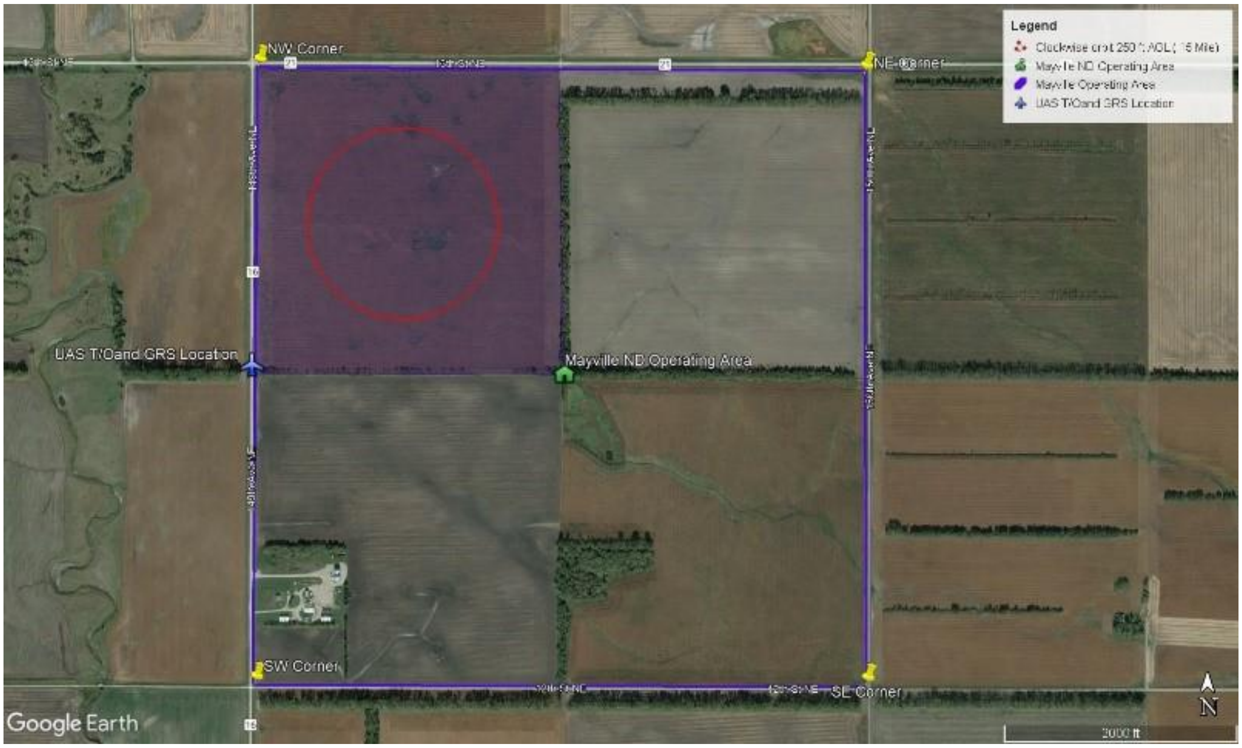

Figure 11: Scenario 2 Aircraft Flight Profile

Table 11: Scenario 2 Aircraft Demonstration Scenario Information

Test Card #	**2**
Location	Mayville, ND
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	250 ft AGL
Repetitions	20 minimum
Flight Profiles	UAS #2 Clockwise Orbit at 250 ft AGL (.15-mile orbit)
Test Objective	Fly Clockwise Orbit Pattern at 250 ft AGL (.15-mile orbit) for minimum of 15 minutes, repeat for 20 repetitions.

1.11.3.8 Scenario 3: Niagara, ND

This scenario was created to test how the C2 signal is maintained throughout multiple UAS in flight with UAS flying in adjacent geographic regions, with each region deploying a localized GRS. This type of use case is indicative of an agricultural inspection or inspection of public land, such as a public boat ramp as might be required within smaller communities. This UAS performed a counterclockwise orbit of .05-mile diameter at approx. 350 ft AGL which consisted of yawing, rolling, and pitching. The flight profiles and additional scenario information can be seen in Figure 12 and Table 12, respectively.

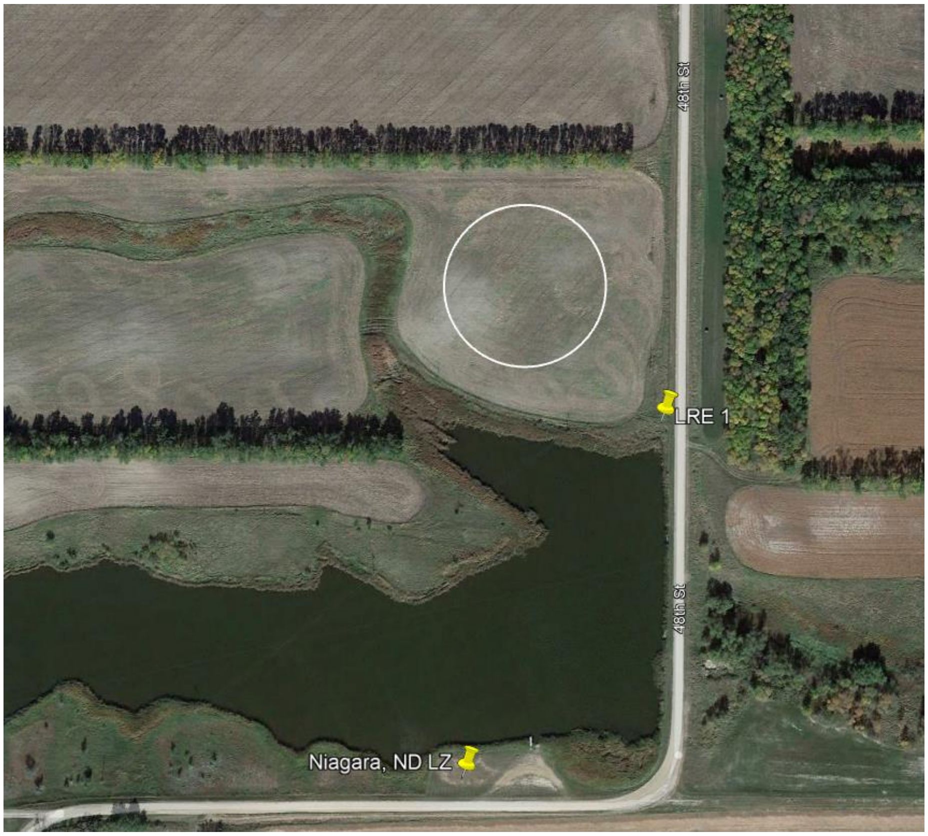

Figure 12. Scenario 3 Aircraft Flight Profile

Table 12: Scenario 3 Aircraft Demonstration Scenario Information

Test Card #	3
Location	Niagara, ND
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	100 ft AGL
Repetitions	20 minimum
Flight Profiles	UAS #3 CCW orbit at 350 ft AGL (.05-mile orbit)
Test Objective	Fly Counterclockwise Orbit (.05 Mile Orbit) Pattern at 350 ft AGL for minimum of 15 minutes, repeat for 20 repetitions.

1.11.3.9 Scenario 4: Carrington, ND

This scenario was created to test how the C2 signal is maintained and allocated across multiple UAS in flight with UAS flying in geographically distinct regions, separated from this region, with each region deploying a localized GRS. This type of use case is indicative of a private infrastructure inspection. This UAS performed a counterclockwise orbit of .10-mile diameter at approx. 150 ft AGL which consisted of yawing, rolling, and pitching. The flight profiles and additional scenario information can be seen in Figure 13 and Table 13, respectively.

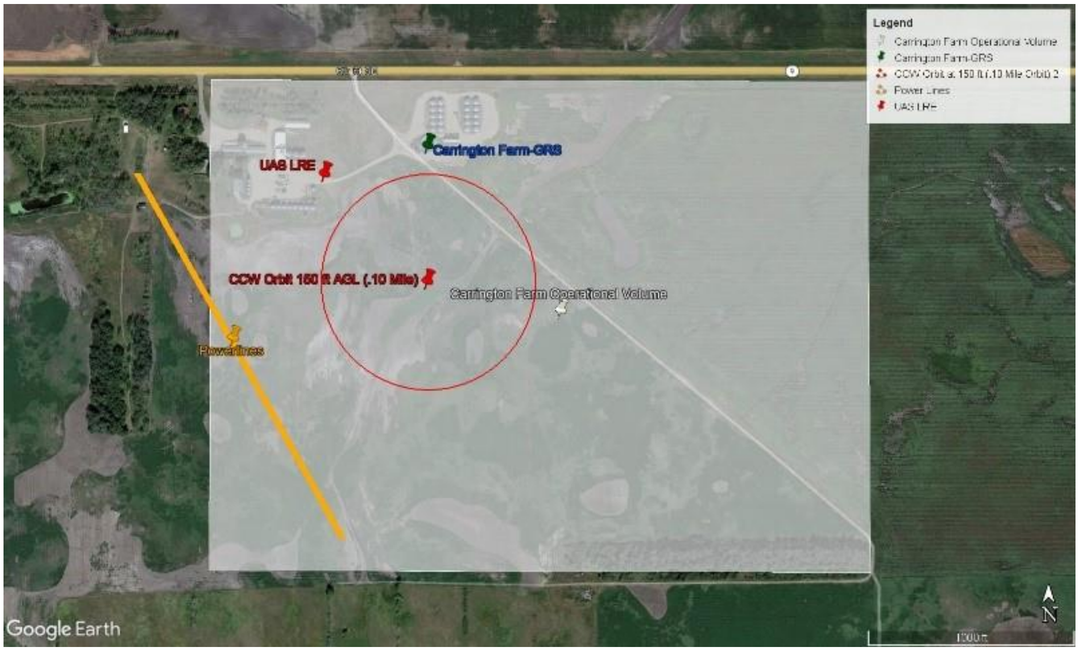

Figure 13. Scenario 4 Aircraft Flight Profile

Table 13: Scenario 4 Aircraft Demonstration Scenario Information

Test Card #	4
Location	Carrington, ND
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	150 ft AGL
Repetitions	20 minimum
Flight Profiles	UAS #4 CCW Orbit at 150 ft AGL (.10-mile orbit)
Test Objective	Fly Counterclockwise Orbit (.10-Mile Orbit) Pattern at 150 ft AGL for minimum of 15 minutes, repeat for 20 repetitions.

1.11.4 Live Flight Demonstration Schedule

NPUASTS conducted the Live Flight Demonstrations at each of the above outlined locations over the period of Monday, May 6, 2024, through Friday, May 10, 2024. In all, 88 flights, including all test flights and repeat flights, were completed within 48 hours, including one duty day for flight crews of 10 hours and the second of 11 hours. The reason operations were conducted in this fashion was due to wind and weather constraints encountered by the flight crews on Monday, Tuesday, and Friday of the week. This is a great testament to the NPUASTS flight crews and uAvionix seamless performance of the SkyLine™ system and NFAM operation.

1.11.4.1 Day 1: Monday May 6, 2024

- Crews were delayed due to high winds.

1.11.4.2 Day 2 Tuesday May 7, 2024

- Crews were delayed due to rain.

1.11.4.3 Day 3 Wednesday May 8, 2024

- 0800 3 of 4 Flight teams met at Tech Accelerator. The fourth flight team departed Carrington.
- 08:30 Mobilization to Technology Park, Niagara, Mayville, and Carrington
- Conducted Morning Briefing in Field
- Successfully conducted 10 flights for Astro #6, with 8 successful test flights
- Successfully conducted 10 flights for Astro #7, with 8 successful test flights
- Successfully conducted 10 flights for Astro #8, with 8 successful test flights
- Successfully conducted 10 flights for Astro #9, with 8 successful test flights
- 18:00 End of day

1.11.4.4 Day 4 Thursday May 9, 2024

- 0700 3 of 4 Flight teams met at Tech Accelerator. The fourth flight team departed Carrington.
- 07:30 Mobilization to Technology Park, Niagara, Mayville, and Carrington
- Conducted Morning Briefing in Field
- Successfully conducted 12 flights for Astro #6, with 12 successful test flights
- Successfully conducted 12 flights for Astro #7, with 12 successful test flights
- Successfully conducted 12 flights for Astro #8, with 12 successful test flights
- Successfully conducted 12 flights for Astro #9, with 12 successful test flights
- 18:00 End of day

1.11.4.5 Day 5 Friday May 10, 2024

- 0800 Finalized Demobilization efforts from Carrington Flight location
- 1500 End of Day

1.11.4.6 Demonstration Photographs

Figures 14 through 22 in the following pages showcase several photos from the testing demonstration as well as the GRS installations at the multiple deployment sites.

Figure 14. FreeFly Astro Awaiting Mission Launch in Carrington, ND

Figure 15. FreeFly Astro Awaiting Launch on Landing Pad

Figure 16. FreeFly Astro Executing RTH following a Test Flight

Figure 17. FreeFly Astro Launching from Landing Pad for Test Flight

Figure 18. FreeFly Astro RTH for Landing Following Test Flight

Figure 19. uAvionix SkyLink GRS Installed at Carrington, ND

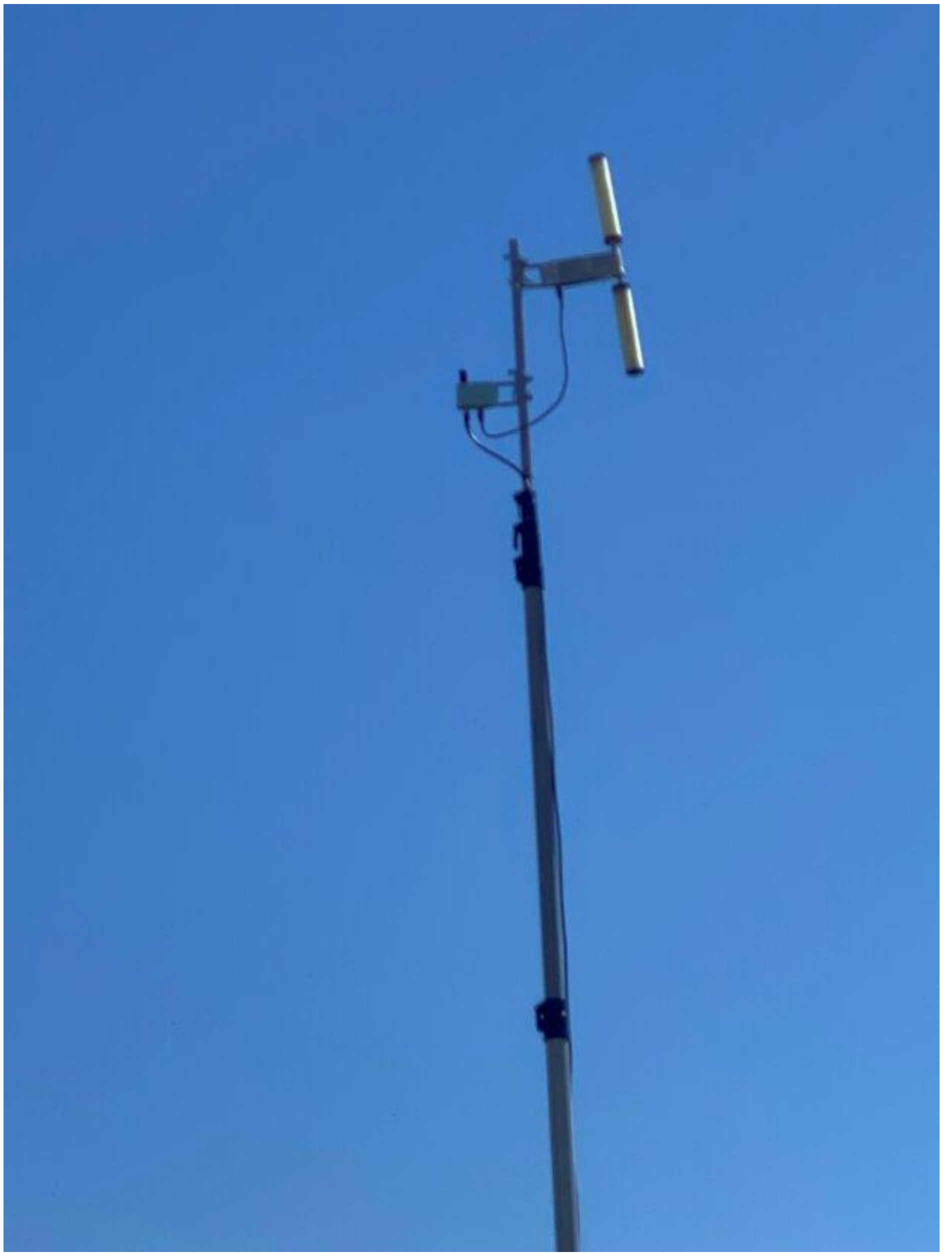

Figure 20. Close up of uAvionix SkyLink GRS in Operation

Figure 21. uAvionix SkyLink GRS Installed on NPUASTS Mobile Command Trailer at Niagara, ND

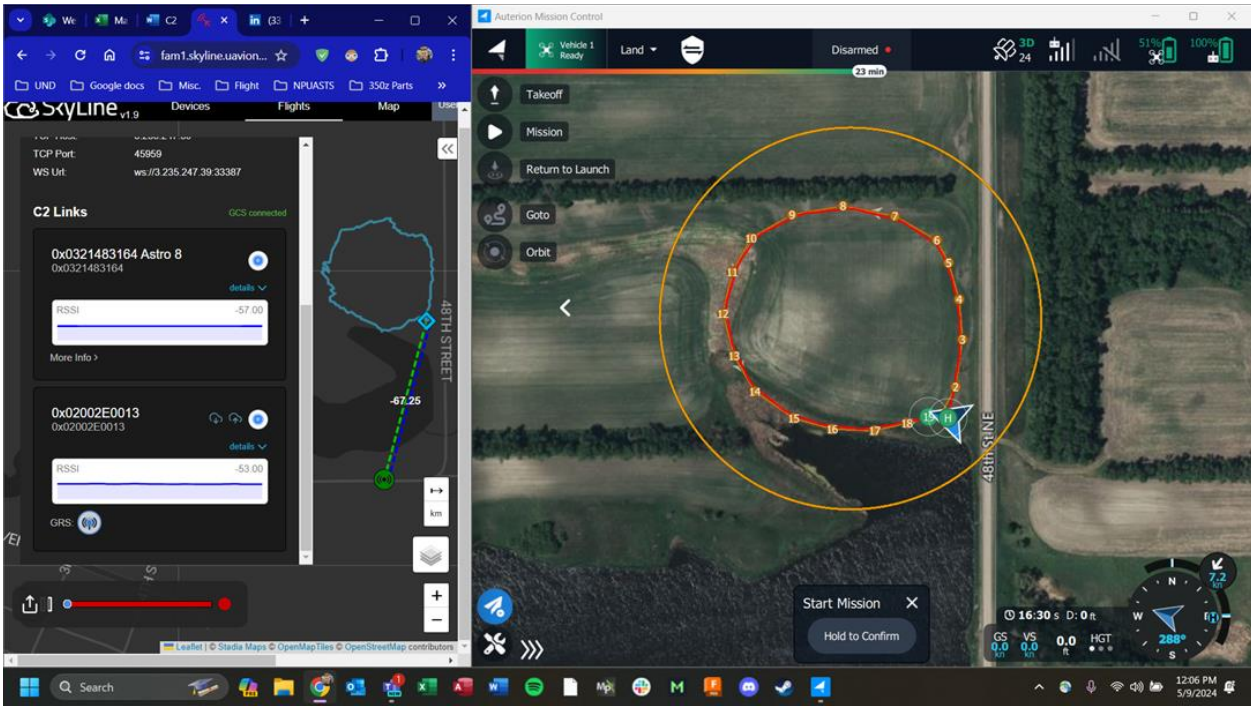

Figure 22. Skyline and Auterion PIC Interface for Niagara, ND Test Flights

1.11.5 Flight Efficiency

The NPUASTS embraces its ability to safely and efficiently carry out flight events pursuant to the research goals of our partners. NPUASTS flight crews were able to safely execute 88 UAS missions within a 48-hour period, efficiently gathering data and providing the uAvionix team with valuable information and insight into the performance of SkyLink with the newly incorporated FAM.

The ability to efficiently and safely execute these many missions while deployed live in the field brought additional value to the human factors research component. Flight crews were able to get real, hands-on experience operating the SkyLine™ system and were able to provide feedback on the product to uAvionix engineering support staff real time via Microsoft Teams. The uAvionix staff was very receptive to pilot feedback and helped to evaluate data quality and solutions in real time during the testing efforts.

1.11.6 General Self-Assessment

The NPUASTS' overall self-assessment for meeting the objectives of uAvionix for BAA Call 4 is a positive one. NPUASTS provided valuable guidance and project steering through the test planning phase which enabled repeatable operations performed at a complex level. NPUASTS was able to deliver the scenarios as planned and improvise on demand to adapt to weather considerations and accommodate uAvionix testing needs, also ensuring all safety and airworthiness protocols were met. NPUASTS' ability to repeat and adapt ended up being an integral component to this success. The feedback from uAvionix team indicated that they were very happy with NPUASTS' performance and data collected on the SkyLine™ system and NFAM.

NPUASTS flight crews successfully demonstrated C2 while utilizing C-Band spectrum frequencies and conducted multiple flights across multiple geographically distinct mission volumes without incident.

2 Suggestions

Throughout this effort, the NPUASTS identified a list of items that would have increased efficiency and redundancy within its team on executing tasks. This list is provided below in Table 14 with short descriptions.

Table 14: NPUASTS Feedback Recommendations for Future Testing

Suggestion	Comment
Strategic Placement of STA Request	Filing the STA permits with a common location at Kloten, ND which encompassed each of the geographically distinct operational areas was a good strategic move that cut the amount of paperwork required and streamlined the approval process to one STA submission, instead of 4 separate approvals.

3 Conclusions

NPUASTS and uAvionix provided the concepts of their National Frequency Assignment Manager for use in UAS Command and Control. The uAvionix NFAM technology proved it could manage a limited amount of protected spectrum on behalf of many operators in multiple geographically distinct regions for the duration of each flight without interference. The combination of ground and live flight testing demonstrated the following capabilities of SkyLine™ with incorporation of the NFAM:

- That the FAM upgrades provided by uAvionix enable nationwide C-Band frequency management via the NFAM. This includes FAM upgrades like allocation planning interface, storage of multiple viewshed results, and regional interference analysis.
- The ability of SkyLine C2CSP platform to allocate available frequencies (frequencies which are both allocated and not in use) to a specific CNPC radio for a specific mission.
- The ability of the SkyLink CNPC radios to receive assigned frequencies for the designated mission.
- The ability of the SkyLink CNPC radios to operate on the assigned frequencies for the designated mission.
- The ability of the SkyLine C2CSP platform to monitor and perform C2CSP functionality to the SkyLink CNPC radios during the duration of the designated mission.
- That the NFAM viewshed and interference analyses are validated by real world flights including 20 flights of at least 15-minute duration across four different UAS located in geographically separate regions.

This next step in technology is extremely important in leveraging C-Band C2 in current UAS VLOS and BVLOS operations. Under the current existing framework for operations with C-Band, a single operator must obtain access to a limited slice of aviation protected spectrum. This involves coordination with both the FAA and FCC and typically takes about 3 months to receive an operationally and time-limited (typically 6 months) Special Temporary Authority (STA) to operate on the desired frequency. This also “locks out” other nearby operators from using that same spectrum during that time even if it is not in actual use. Standard STA approvals are typically in effect for six months. While implemented for this project under the SkyLine™ infrastructure, the NFAM will be architected as an API service layer, allowing any FMO (whether operating as a C2CSP or not) to perform the FAM function using a common implementation scheme. Commonality across federated FMOs may be an important feature of scalability without creating interference across boundaries between FMOs. In short, this National Frequency Allocation Management

(NFAM) application has the potential to be adopted by the UAS industry in a way that encourages commercial build-out of C2 Communications Service Provider (C2CSP) infrastructure without limiting competition between providers or depending on exclusive regional lockups. This application is a plausible, available option to manage the entire 5030-5091MHz band (C-Band), inclusive of interference modeling regionally.

It is the conclusion of the research team that the next step in the development of the NFAM is to provide results to the FAA in furtherance of the development of FAA TSO C-213a. The results from this testing campaign will provide regulators with meaningful feedback as this and future standards are developed.

NPUASTS was able to successfully help uAvionix demonstrate the ability of their NFAM to dynamically allocate protected C-Band frequencies to multiple UAS across geographically distinct volumes, without spectrum interference and in validation of the NFAM viewshed modeling tool, as discussed above. Throughout the research effort, the NPUASTS was also able to successfully execute all deliverables, each with its own extensive list of goals and requirements. The aircraft demonstrations were successfully performed and provided the research teams with valuable data. Each set of flight events ended without incident, and flight teams efficiently flew many missions in a short time. Overall, the tests were considered a success and the uAvionix team was able to gather valuable data as well as user feedback for continued development of SkyLine™ as a C-Band C2CSP provider.

4 Appendix A: Reference Documentation

Please refer to Table 15 below for supporting documentation for this final report.

Table 15: Supporting Reference Documentation

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
UAV-1007035-001 Rev A	uAvionix Freefly Astro UAS Operation Manual
UAV-1004752-001 Rev M	uAvionix Service Layer API ICD
UAV-1004775-001 Rev M	uAvionix Link Event WebSocket ICD
UAV-1007074-001 v1.0	uAvionix Frequency Allocation Manager API Reference
4/10/2023	FAA BAA C3-Uavionix C2 FAM Test Plan
12/16/2022	SRMD FAA BAA C-Band uAvionix
C-Band FAM Test Report697DCK-22-C-00259 UAVION-ND Rev 1.0	Flight Test Report Including SkyLine FAM performance and other testing details.