C-Band Frequency Assignment Manager (FAM) End-to-End Implementation and Demonstration with Multiple UAS

In Support Of

Federal Aviation Administration
Broad Agency Announcement Call 3

Under
Contract# 697DCK-22-C-00259

Final Report Date: August 11, 2023

Executive Summary

uAvionix and the Northern Plains UAS Test Site (NPUASTS) are proud to have concluded efforts under the Federal Aviation Administration's Broad Agency Announcement Call 3 (FAA BAA Call 3) contract for 2023 in conjunction with the uAvionix Corporation. This effort culminated with 124 Live Flight Demonstrations which demonstrated the end-to-end ability of a C-Band Frequency Assignment Manager (FAM) built by uAvionix to dynamically allocate C-Band frequencies for Command and Control (C2) to multiple UAS platforms, assign those frequencies to RTCA-D0362A compliant radios onboard the UAS, and utilize those radios as the primary C2 radio in multiple flight demonstrations, in a safe manner without interference. The test flights included a single and multi-aircraft demonstration and were performed in Grand Forks, North Dakota in March, and April of 2023.

The FAM, 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 FAM, 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 Command and Control Communications Service Provider management platform's ability, along with the integration of the FAM, 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, have the given CNPC radios receive and operate on assigned frequencies for the designated mission. Tests 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 close proximity.

The project, though limited in scope, successfully conducted 124 flights, without measurable interference with 100% continuity and availability of the C2 links assigned by the FAM.

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.

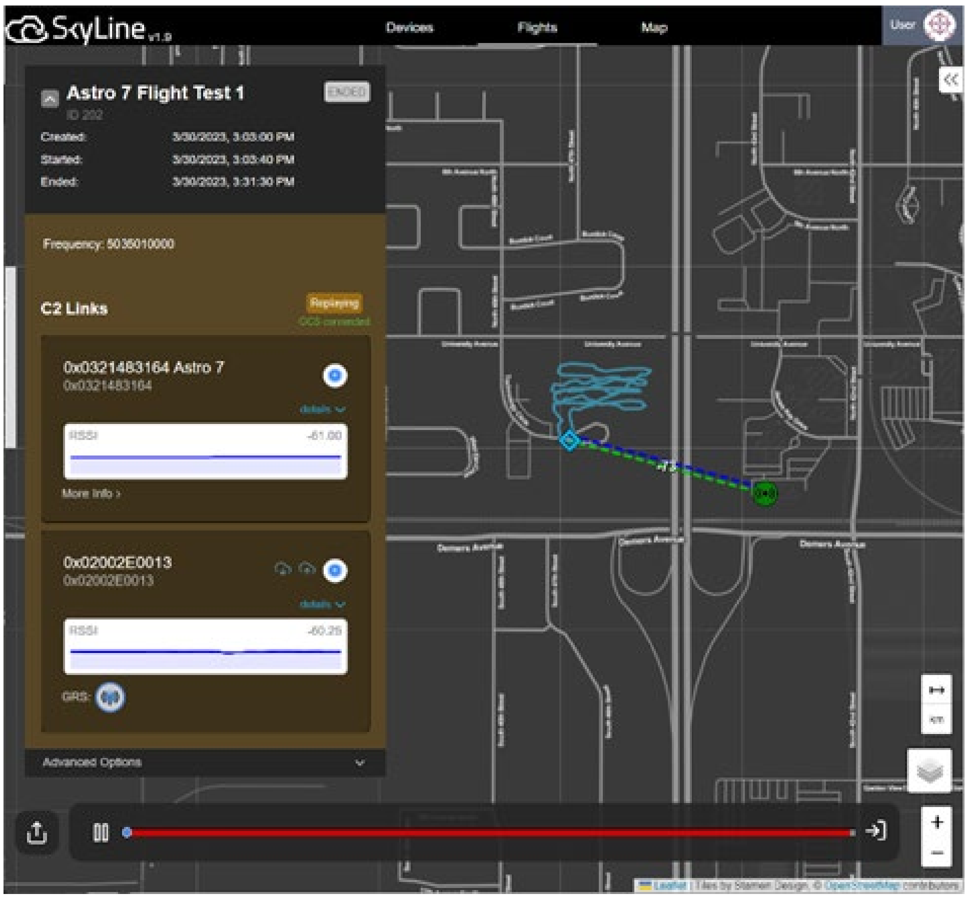

Figure 1: User Display of SkyLine C2CSP with FAM

These field demonstrated results show that the principles of a FAM, designed to ensure the efficient use of available spectrum, can be done safely and without frequency interference. The FAM concept that was developed for this demonstration project still required manual flight creation, however it is anticipated that flight creations are a feature that would ultimately be automated, compatible with other C2 or UTM / USS platforms.

A national FAM 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 FAM 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 FAM to be studied for scalability at a NAS level.

With regards to overall testing of the concept, during the 124 flights split over two major test campaigns, single aircraft, and multiple aircraft, 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 both testing periods. 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 final report is a high-level review of the work that was completed in March and April of 2023.

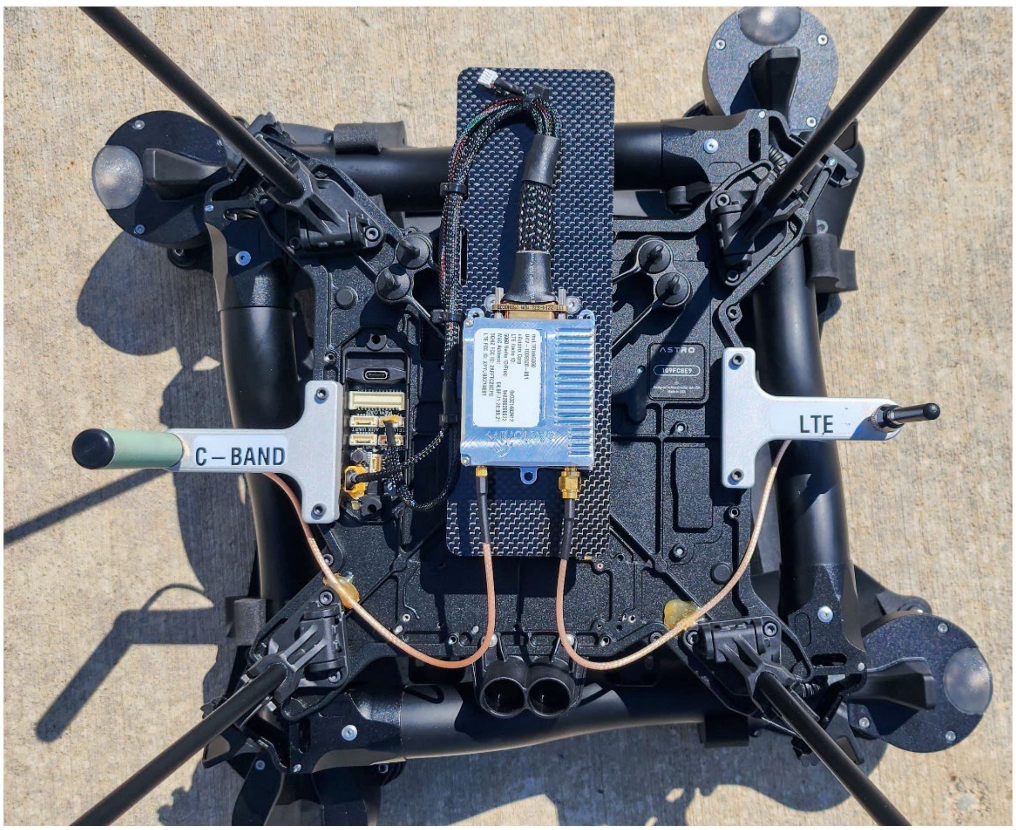

Figure 2: Freefly Astro with muLTElink5060

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1 Background

The goal of this project was to demonstrate and verify real-world operations of dynamically allocated FAA protected spectrum for UAS operations. In doing so, uAvionix and NPUASTS built upon the work of the ITU, ICAO, RTCA, FAA, and FCC in the allocation and establishment of service rules for UAS CNPC protected frequencies, bringing Beyond Visual Line of Sight (BVLOS) operations closer to daily reality.

As described in RTCA DO-362 Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial), Appendix I, section I.1:

"*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 does 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 UA will be using the assigned RF channel bandwidth for control from Ground Radio System (GRS) sites at any given time in any area.*

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. Therefore, 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 UA so that other UAs can use the same channel as soon as it is no longer needed."

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.

In December 2020 RTCA published an updated revision of the MOPS (DO-362A) and in February 2021 a revision of the Minimum Aviation System Performance Standards (MASPS) (DO-377A). These documents provide further guidance on the role of a FMO and the FMA process.

Under the FAA Reauthorization Act of 2018 (P.L.115-254), section 374, the FAA and FCC 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 5030-5091MHz 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 FAM infrastructure.

uAvionix is the C2CSP for the Vantis BVLOS Network in North Dakota under subcontract to Thales. In this role, uAvionix has installed 4 GRS at the Key Site in Watford City, ND, all managed by the uAvionix SkyLine enterprise C2CSP platform. 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, NASA, and commercial operators in the US.

1.1 FAM Benefits

Under the current framework, a single operator must obtain access to a limited allocation 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.

The demonstrated FAM solution manages a specified amount of protected spectrum on behalf of many operators in the same area at once, through use of specialized radios equipped on each drone and on the ground to dynamically manage frequency assignments when they are needed for the duration of each flight.

The benefits of a functioning FAM are vast, and span different stakeholder groups, denoted in [brackets] below.

a. [Operators] gain access to protected spectrum free from RF interference, increasing the safety case as compared to the use of unlicensed frequencies.
b. [FAA] and [FCC] are provided with a methodology to manage the protected spectrum asset in finite time slices in defined regional areas. This allows either internal FAM functionality, or delegated authority to authorized FMOs.
c. [FAA] is presented with an option to leverage existing, underutilized spectrum assets to efficiently serve the needs of the UAS industry, meeting the intent and the letter of the Presidential Spectrum Memorandum.
d. [Industry] is presented with a standard model and interface to develop and interface with compatible radios, FMOs and C2CSPs

1.2 New Technology - FAM

The FAM used in the live flight events is a new technology for validation intended to dynamically manage the limited CNPC spectrum and serve out assignments on a per-flight basis. This allows an FMO or C2CSP to manage the protected spectrum more efficiently and enable multiple operators to use this limited asset more effectively and freely than does the current method of obtaining access to this spectrum (STA process). Figure 2 illustrates the workflow sequencing to be demonstrated on this project.

The following technological capabilities were demonstrated and validated:
1. Importing a C-band spectrum allocation (start and end frequencies in MHz) into the FAM module.
2. Automatic channel definitions within allocated spectrum given a DO-362A Data Class
3. Flight planning soft allocation utilizing the window of time and region of operation.
4. Flight initialization, channel assignment to ARS, and relevant GRSs
5. Flight operation moving the active link from one GRS to another in order to support a larger mission coverage area.
6. Flight completion and automatic recovery of channel assignment

The above capabilities were demonstrated through a series of ground and airborne tests. Figure 3 on the following page illustrates the FAM workflow sequencing demonstrated on this project.

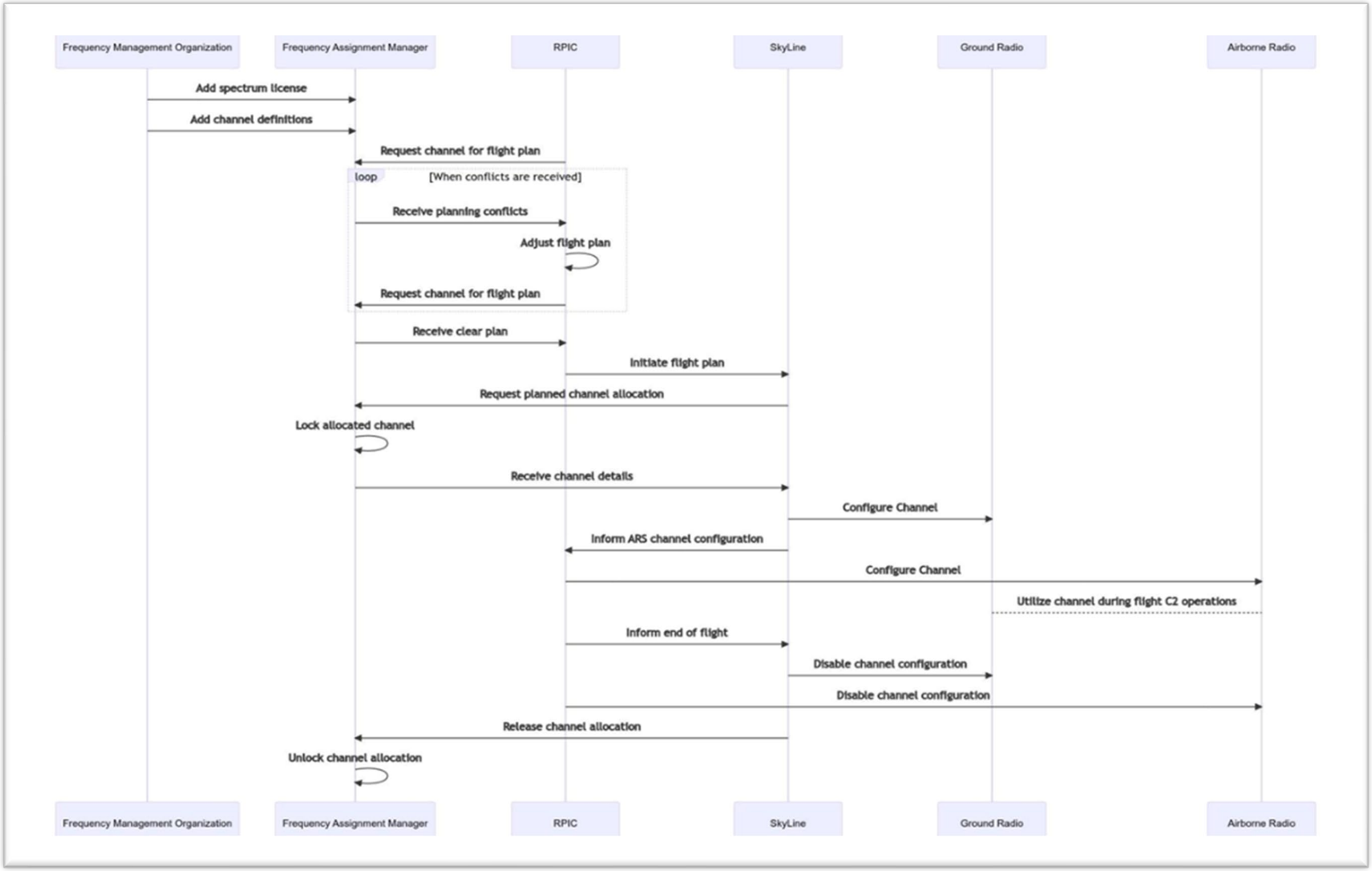

Figure 3: Workflow Sequencing of SkyLine FAM

1.3 Technical Approach

The Frequency Assignment Manager process has two operational phases, planning and allocation. During planning a flight operator generates a request with the minimum parameters including: the location and height of the ground station(s), maximum bounding geographic area of the flight, a time window within which operations will occur, maximum flight duration, and all ground/airborne antenna configurations including maximum transmit power and DO-362A Data Class being used.

The Frequency Manager compiles this information and determines if there is sufficient total capacity for the new plan combined with existing operations. In the case there is not available spectrum for the new plan it will be rejected with an error containing details on the conflict, allowing the flight operator to adjust their new plan or update existing plans to accommodate.

The allocation phase begins when the flight operator is ready to begin the actual flight and must be within the given time window with sufficient time remaining for the maximum flight duration. During allocation, the Frequency Manager will select the next available channel from the larger block of spectrum and assign it to the flight. It is possible for the allocation to still fail when near capacity and another flight has not yet released their allocation and is past the end of their planned window. In this case, the flight operator must wait until notified that a release has happened. Under normal operating conditions, when flight activity is complete the operator is expected to release the allocation.

All functionality is implemented as a web service and operated via a secure API with a simple calling syntax to minimize errors. The API is designed to support simultaneous flight operations from different users and deconflict all access to ensure operational safety of the spectrum allocations. Additional details were submitted to the FAA through the CONOPS.


C-Band Frequency Assignment Manager CONOPS

Concept of Operations
for
C-Band Frequency Assignment Manager (FAM) End-to-End Implementation and Demonstration with Multiple UAS

V1.0 December 2022

uAvionix Corporation
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Figure 4: CONOPS Document

2 Ground Test Overview

The ground test was used to verify use of the FAM to allocate dynamic frequency assignments on multiple frequencies on the 5030-5091 MHz frequency band to paired CNPC radios with a ground-based spectrum analysis tool. C2 continuity of the radio link for each test was measured. In all, two different testing configurations were employed.

Test Configuration 1 is defined below in Figure 5. 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 FAM for frequency allocation and relays the frequency assignment to the GRS and ARS radios. The GRS can be either a SkyStation-5060 POE or SkyStation-5060 LTE. The ARS was a muLTElink-5060. A Pixhawk autopilot was used to terminate the GCS/ARS connection. In this test configuration, the ARS and GRS are connected in a conducted versus radiated fashion and a directional coupler is employed to allow the spectrum analyzer to tap into the ARS/GRS communication. The Spectrum analyzer used the Spectrum view and was configured to monitor a span of 70 MHz with 5.060 GHz as the midpoint. The “Max Hold” and “Marker to peak” values were utilized to determine the frequency measurement.

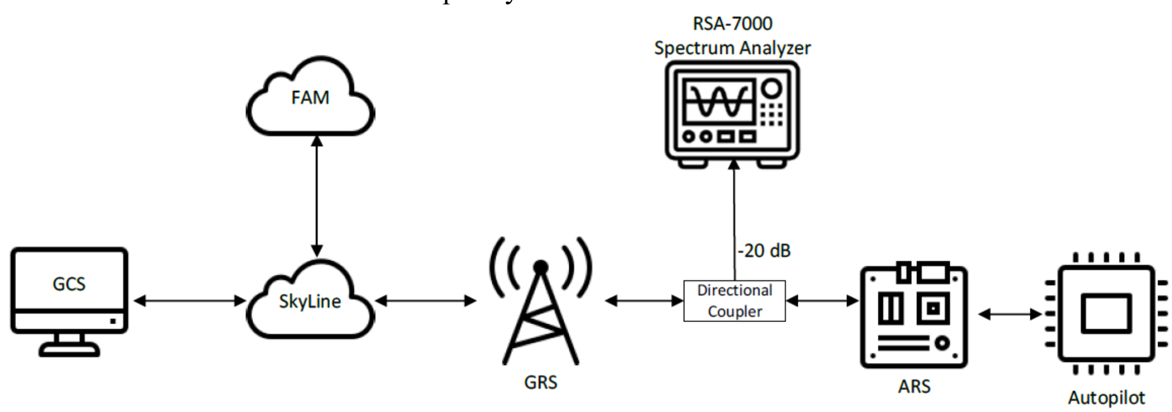

Figure 5: FAM Test Configuration 1

Test Configuration 2 is defined in Figure 6. 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 FAM for frequency allocation and relays the frequency assignment to the GRS and ARS radios. The GRS can be either a SkyStation-5060 POE or SkyStation-5060 LTE. The ARS was a muLTElink-5060. A Pixhawk autopilot is used to terminate the GCS/ARS connection. In this test configuration, the ARS and GRS are connected in a conducted versus radiated fashion and a directional coupler is employed to allow the spectrum analyzer to tap into the ARS/GRS communication.

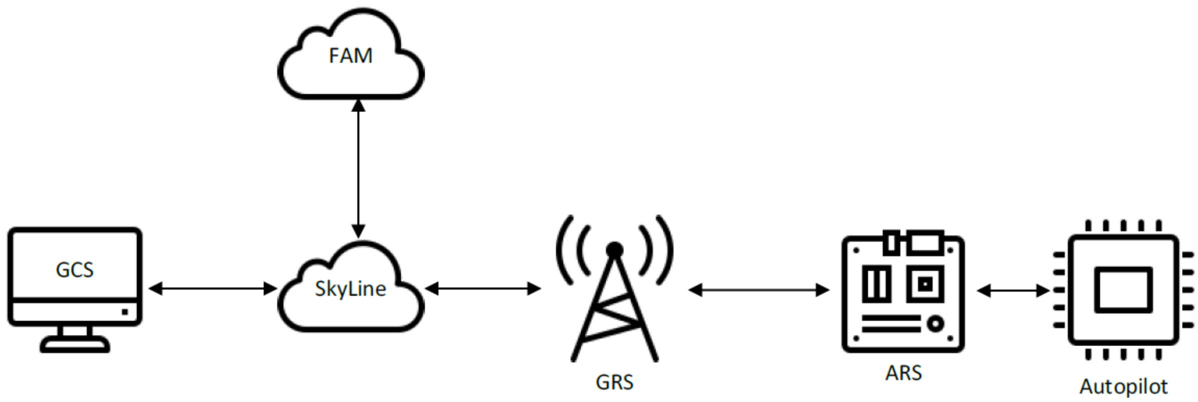

Figure 6: FAM Test Configuration 2

In all, for both test configurations, five flights were successfully created with frequency assignments. Each test was run for 15 minutes. The total number of MAVLink messages transmitted along with the percentage of missed packets (identified by sequence number) and packets which failed CRC check along with the distribution of the MAVLink heartbeat interval, which should be every 1 second were recorded. Overall, all submitted flights met the "PASS" criterion. Results for Test Configuration 1 can be seen below in Table 1 and results for Test Configuration 2 can be viewed in Table 2.

Table 1: Test Configuration 1 Results

Flight	FAM Frequency (MHz)	ARS Frequency (MHz)	GRS Frequency (MHz)	Result
1	5035	5035	5035	PASS
2	5082	5082	5082	PASS
3	5040	5040	5040	PASS
4	5072	5072	5072	PASS
5	5055	5055	5055	PASS

Table 2: Test Configuration 2 Results

Flight	Frequency (MHz)	Duration	Result
1	5035	16 min 12 sec	PASS
2	5082	17 min 8 sec	PASS
3	5040	17 min 10 sec	PASS
4	5072	15 min 56 sec	PASS
5	5055	17 min 32 sec	PASS

3 Flight Test Overview

Flight Tests were conducted at the University of North Dakota Technology Business Park, approximately one-half mile west of the NPUASTS headquarters building. This site was selected due to its direct line-of-sight (LOS) between the GRS and ARS as well as its relatively small operational volume, with the intent to investigate any C-Band C2 spectrum interference in a dense operating environment. This series of flight events tested C-Band C2 frequency assignment concepts and connectivity. The focus of the tests was to demonstrate and verify real-world operations of dynamically allocated FAA protected spectrum's for UAS operations. In doing so, uAvionix aimed to demonstrate the ability to build upon the work of the ITU, ICAO, RTCA, FAA, and FCC in the allocation and establishment of service rules for UAS CNPC protected frequencies, with the intent of bringing Beyond Visual Line of Sight (BVLOS) operations closer to daily reality.

Two phases of live flight demonstrations for uAvionix were conducted, with the Single Aircraft Flights occurring in March and April of 2023 and Final Multi-Aircraft Live Demonstration flights occurring in late April 2023. The time range for the Single Aircraft flights was extended primarily due to weather interference. A screenshot of the SkyLine environment and FAM module can be viewed in Figure 7. The overall project schedule including deliverables and dates can be seen in Table 3 below. During these two flights events, the primary objectives were:

- The ability of SkyLine C2CSP platform to manage a pool of allocated (and licensed) frequencies in a geographic area.
- 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 designated mission.
- The ability to demonstrate non-interference when multiple aircraft using uniquely assigned frequencies are operating within close proximity.

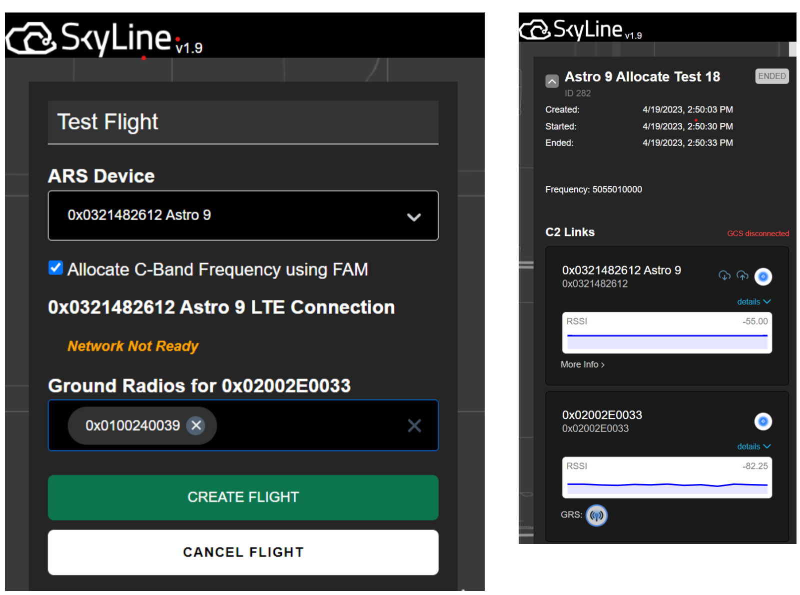

Figure 7: FAM Module in SkyLine

Table 3: BAA Deliverables

Deliverable	Target Completion Dates
Submit Integrated Master Schedule	August 19, 2022
Submit Safety Risk Management Document and CONOPS	November 19, 2022
Submit Ground Test Report	January 19, 2023
Submit Test Plan and Test Cards	April 19, 2023
Submit Flight Test Report Single UAS	May 19, 2023
Submit Flight Test Report Multi UAS	May 19, 2023

uAvionix developed SkyLine as 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 North Dakota as a component of the Vantis/Thales network architecture, it also can also be deployed independently to the field.

In all, 124 total flights were performed, including test flights, repeat flights, and training flights to demonstrate the operability, reliability, and efficacy of the SkyLine platform to perform C2CSP services and the FAM to dynamically allocate C-Band frequencies with minimal interference in densely populated operating volume.

3.1 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 4 below is a list of partnerships and participants that supported the activities in North Dakota.

Table 4: NPUASTS – uAvionix C-Band FAM 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) and Air Radio Systems (ARS). 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 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.

3.1.1 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 for the single and multi-aircraft live flight demonstrations.

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 with Cobra radios. In addition to the Flight Director, the NPUASTS provided the 4 UAS flight teams (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 the uAvionix GRS.

3.1.2 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 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.

3.1.3 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 003 in support of the FAA Unmanned Aircraft Systems Integration Office, UAS Program and Data Management Branch (AUS-410). The FAA also provided project oversight through review of a series of monthly reports and quarterly Project Management Review (PMR) meetings with uAvionix.

3.1.4 Federal Communications Commission (FCC)

The FCC provided Special Temporary Authority (STA) licensing for use of 5 distinct C-Band frequencies in the 5030-5091 MHz band.

3.1.5 UND Aerospace Foundation (UNDAF)

The UNDAF provided access and logistical support to the UND Technology Park and provided airspace access for both single and multi-aircraft demonstrations. The technology park offered a centralized location that supported operations and activates associated with the demonstrations and presented no line-of-sight issues for the uAvionix radios. All flights 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.

3.2 Aircraft

A maximum of four small UAS were flown for the multi-aircraft live flight demonstration and multiple of the same aircraft make and model were flown during the single aircraft live flight demonstrations. Figure 8 on the next page provides basic information about the aircraft used in the flight demonstrations.

3.3 Supporting Equipment

The NPUASTS team used the following assets to support the goals and objectives of this testing. 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 short description is also provided in Table 5.

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

Figure 8: FreeFly Astro General Information and Limitations

Table 5: 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 allows 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, 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 to be positioned based on field measurements
SkyLink ARS	Communications	Omni-directional C-Band (5030-5091 MHz) radio system to be integrated to airframe by uAvionix

3.4 Test Architecture

The test architecture for both single and multi-aircraft flights are provided below in Figures 9 and 10, respectively. For the single flight demonstration, 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 for the multi-aircraft demonstration. The bench test report is displayed below in Figure 11.

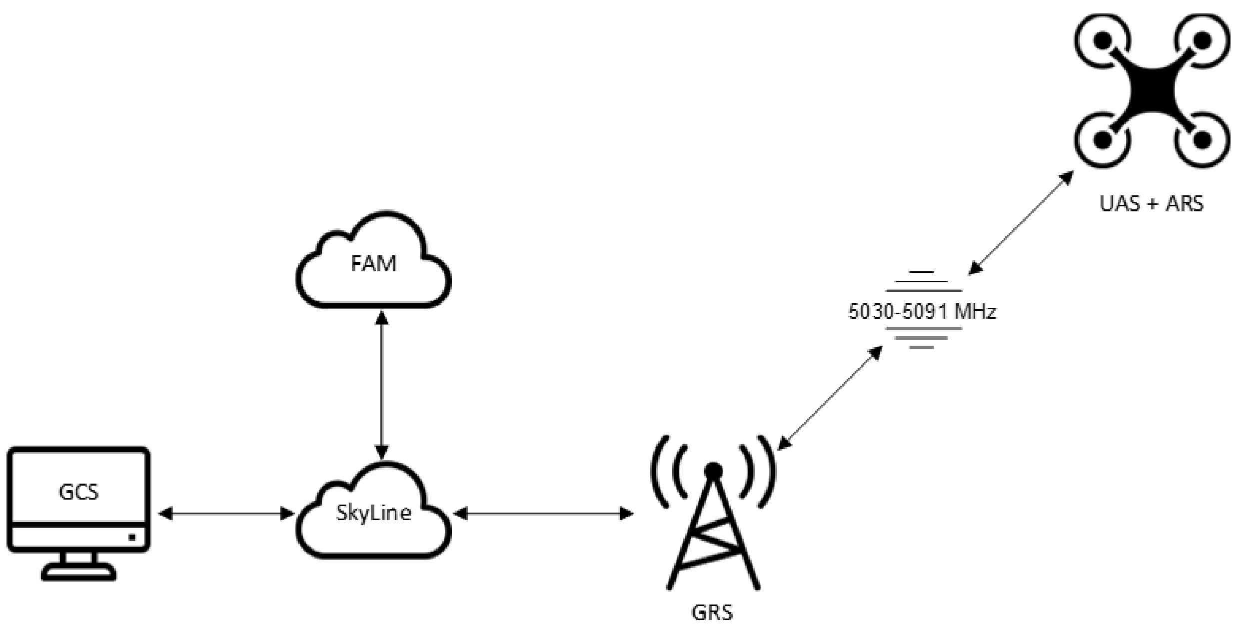

Figure 9: Single Aircraft Test Architecture

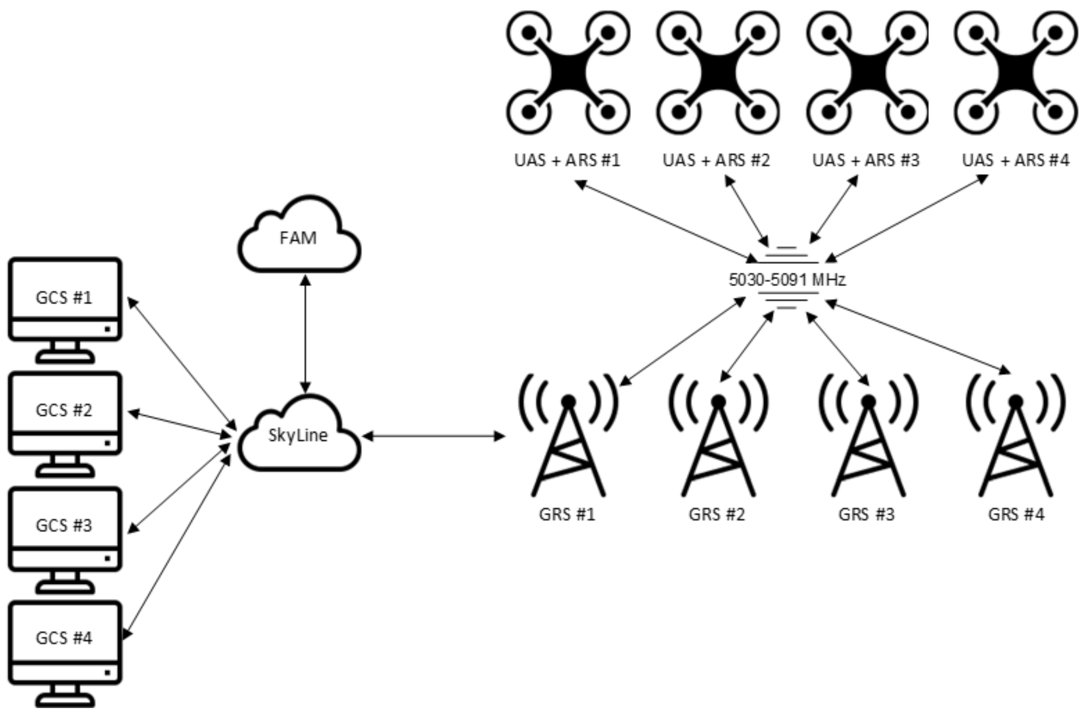

Figure 10: Multiple Aircraft Test Architecture

Figure 11: Bench Test Plan and Report

3.5 Location and Airspace

The operations were conducted in the city of Grand Forks, North Dakota utilizing the airspace above the University of North Dakota Technology Park. The test location is located approximately 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). An Aeronautical chart of the testing location can be seen below in Figure 12.

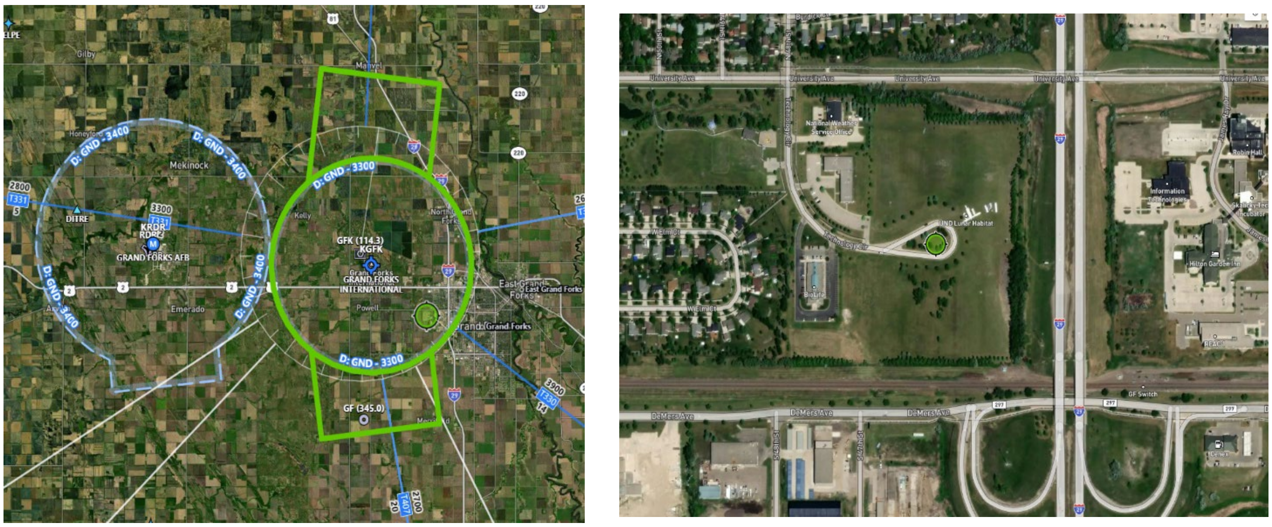

Figure 12: Flight location near Grand Forks KGFK

3.6 Approvals

3.6.1 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.

3.6.2 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 6. Each frequency was approved for use within 37 km centered in Grand Forks, ND (N:47-51-37, W: 97-03-27) with an authorized power of 96.6 Watts Effective Radiated Power (ERP).

Table 6: Frequencies Approved for Use with SkyLine FAM

Frequency (MHz)	Authorized Power (Watt) ERP	Frequency Tolerance (+/-)
5035.01	96.6	0.00005%
5055.01	96.6	0.00005%
5065.01	96.6	0.00005%
5075.01	96.6	0.00005%
5085.01	96.6	0.00005%

LAANC requests were submitted during days of flight operations as the testing location is near the approach flight path for GFK.

3.6.3 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.

3.7 Test Description and Results

3.7.1 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. The aircraft were vertically deconflicted during the multi-aircraft live flight demonstration.

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

3.7.1.1 Single Aircraft Demonstration

Table 7 below shows statistics from the Single Aircraft demonstration flights performed in March and April of 2023.

Table 7: Flight time and number of flights by aircraft for Astro during the single aircraft demonstrations.

Aircraft	Number of Flights	Flight Time (minutes)
Astro #6	7	96
Astro #7	14	221
Astro #8	3	48
Astro #9	2	32
Total	26	397

3.7.1.2 Multiple Aircraft Flight Demonstration

Table 8 below shows statistics from the Single Aircraft demonstration flights performed in April of 2023.

Table 8: Flight time and number of flights by aircraft for Astro during the multiple aircraft demonstrations.

Aircraft	Number of Flights	Flight Time (minutes)
Astro #6	25	368
Astro #7	25	365
Astro #8	23	358
Astro #9	25	358
Total	98	1449

3.7.1.3 Single Aircraft Test Summary

A detailed summary of the single aircraft demonstration flights can be found in the Flight Test Report provided to the FAA. All twenty flights had minimal CRC errors and missed packets, ranging from 0.05 to 0.65% and 1.33 to 11.43% respectively. Additionally, there was minimal deviation or jitter from the expected 1 second heartbeat interval. This is indicative of good C2 performance on the link for each flight. The performance metrics from the single aircraft demonstrations set a performance baseline for non-interference of the frequencies in the multiple aircraft demonstrations. A passing result indicates that the mission was flown successfully for a duration of at least 15 minutes with 100% Continuity and Integrity. All corrupted and missed packets due to typical RF conditions were automatically detected by the flight control protocol's built-in CRC and sequence error detection, allowing the impacted messages to be retransmitted and received well within their Transaction Expiration Time (TET) such that all transactions were 100% successful.

3.7.1.4 Multiple Aircraft Test Summary

A summary of the multiple aircraft demonstration flights can be found in the Flight Test Report provided to the FAA. All twenty flights had minimal CRC errors and missed packets, ranging from 0.05 to 0.36% and 1.14 to 6.40% respectively. Additionally, there was little deviation or jitter from the expected 1 second heartbeat interval. This is indicative of good C2 performance on the link for each flight, demonstrating non-interference of the concurrent flights on different frequencies, when compared to the same metrics for the single aircraft flight demonstrations. A passing result indicates that the mission was flown successfully for a duration of at least 15 minutes with 100% Continuity and Integrity.

3.7.1.5 Flight Crew Feedback

Overall feedback from the flight crews regarding the performance of the FAM via SkyLine was favorable. Based on the manual provided by uAvionix and without the addition of dedicated training time, 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 being a mission allocation volume that was outside the pre-defined C-Band volume set in the program. Once identified, uAvionix was able to quickly make the correction allowing for flights to resume successfully.

One additional take away was the installation of the uAvionix GRS's onto the University of North Dakota's (UND) network. There were several issues related to firewalls that NPUASTS and uAvionix support staff had to work through prior to getting the GRS's operational. This included issues with the University firewall and also utilizing an underpowered POE++ switch that was provided by UND IT department. Once these issues were identified and rectified, the GRS's functioned very well. Going forward, it is recommended to perform due diligence during project planning phases when looking to connect GRS's to network infrastructure instead of operating stand alone in the field.

3.7.1.6 Scenario 1: Single Aircraft Demonstration

This scenario was created to test how the C2 signal is maintained throughout the flight. The UAS performed a quarter mile orbit flight profile at 250 ft AGL which consisted of yawing, rolling and pitching. The flight profile and additional scenario information can be seen in Figure 13 and Table 9, respectively.

Figure 13: Single Aircraft Flight Profile

Table 9: Single Aircraft Demonstration Scenario Information

Test Card #	1
Location	University of North Dakota Technology Park
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	250 ft AGL
Repetitions	20 minimum
Flight Profiles	Clockwise orbit of approx. 325 ft diameter. (47.920301° -97.095997°)
Test Objective	The series of flight events will test the ability of the FAM to issue a deconflicted spectrum assignment through the C2 Communication Service Provider (C2CSP).

3.7.2 Multi-Aircraft Live Flight Demonstration

NPUASTS conducted the Multi-Aircraft Live Flight Demonstration at UND Technology Park approximately ½ mile west of the NPUASTS headquarters on Monday, April 24, 2023, and Tuesday, April 25, 2023. In all a total of 102 flights, including all test flights and repeat flights, were completed within 48 hours. This is a great testament to the NPUASTS flight crews and uAvionix seamless performance of the SkyLine system and FAM operation.

Successful flight criteria included a successful dynamic frequency assignment by the FAM once requested through SkyLine, a minimum 15-minute flight duration, constant communication to the Auterion Mission Control software and with the SkyLine platform. Issues such as % CRC Errors and % Missed packets were analyzed by the uAvionix team following the flights, guided by DO-377A metrics. Issues that were encountered that led to requiring repeat flights were largely confined to pedestrians too close to the operational area, loss of hotspot LTE signal to connect the GCS to the SkyLine software, and one PIC utilizing a previous version of the Auterion software, which was rectified after the first day of multi-Aircraft testing. If one aircraft encountered issues the remaining aircraft were instructed to RTL in accordance with the multi-aircraft testing objectives.

3.7.2.1 Scenario 2: Multi-Aircraft Demonstration

This scenario was created to test how the C2 signal is maintained throughout multiple UAS in flight. Three of the UAS performed either a clockwise or counterclockwise orbit at approx. 150 ft in diameter with one UAS having flown a raster pattern simulating multiple “touch and go’s” at low altitude. The flight profiles and additional scenario information can be seen in Figure 14 and Table 10, respectively.

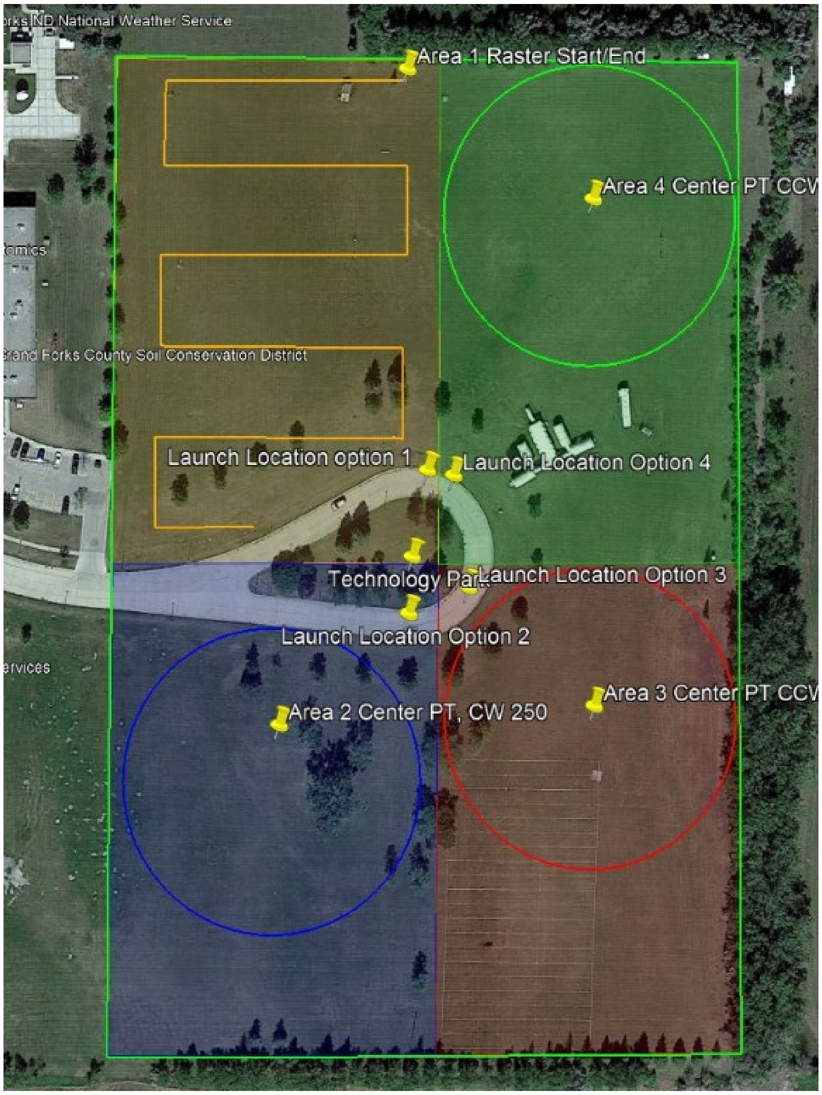

Figure 14: Multi-Aircraft Flight Profiles

Table 10: Multiple Aircraft Demonstration Scenario Information

Test Card #	2
Location	University of North Dakota Technology Park
UAS	FreeFly Astro
Target Scenario Time	15 minutes minimum
Altitude	100/150/250/350 ft AGL
Repetitions	20 minimum
Flight Profiles	UAS #1 Raster Pattern at 100 ft AGL UAS #2 Clockwise Orbit at 250 ft AGL (150 ft orbit) (47.853808° -97.064216°) UAS #3 CCW orbit at 350 ft AGL (150 ft orbit) (47.853784° -97.058956°) UAS #4 CCW Orbit at 150 ft AGL (150 ft orbit) (47.857363° -97.058914°)
Test Objective	The series of flight events will test the ability of the FAM to issue a deconflicted spectrum assignment through the C2 Communication Service Provider (C2CSP).

3.7.2.2 Day 1: Monday April 24, 2023

- 0800 Flight teams met at Tech Accelerator
- 08:30 Mobilization to Technology Park
- Conducted Morning Briefing in Field
- Successfully conducted 13 flights for Astro #6, with 10 successful test flights
- Successfully conducted 13 flights for Astro #7, with 10 successful test flights
- Successfully conducted 11 flights for Astro #8, with 10 successful test flights
- Successfully conducted 13 flights for Astro #9, with 10 successful test flights
- In all conducted 50 flights with 40 successful test flights according to the criteria in 3.7.2. Unsuccessful flights are attributed to pedestrians in the area, low LTE signal strength, and an issue for one PIC with a previous version of the Auterion Mission Control software.
- 17:00 End of day

3.7.2.3 Day 2 Tuesday April 25, 2023

- 0800 Flight teams met at Tech Accelerator
- 08:30 Mobilization to Technology Park
- Conducted Morning Briefing in Field
- Successfully conducted 13 flights for Astro #6, with 10 successful test flights
- Successfully conducted 14 flights for Astro #7, with 10 successful test flights
- Successfully conducted 13 flights for Astro #8, with 10 successful test flights
- Successfully conducted 12 flights for Astro #9, with 10 successful test flights
- In all conducted 52 flights with 40 successful test flights according to the criteria in 3.7.2. Unsuccessful flights attributed to pedestrians in the area and low LTE signal strength. Included in the numbers, the uAvionix team also requests four repeat tests of the single aircraft test flights to verify performance of a single GRS. No additional issues were encountered.
- 18:00 End of day

3.7.2.4 Demonstration Photographs

Figures 15 through 18 in the following pages showcase several photos from the multi-aircraft testing demonstration as well as the GRS installation at the NPUASTS headquarters building.

Figure 15: Group Picture of Four Astro aircraft in Flight During the April Multi-Aircraft Testing

Figure 16: Multiple UAS Taking Off While Utilizing SkyLine for C-Band Command and Control

Figure 17: FreeFly Astro with uAvionix muLTElink-5060 ARS Installed Waiting for Launch

Figure 18: uAvionix SkyStation-5060 POE GRS Installed on the Roof of the NPUASTS Tech Accelerator Building.

3.8 Self-Assessment NPUASTS

3.8.1 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 102 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 the on-site uAvionix engineering support staff. The uAvionix staff was very receptive to pilot feedback and took several product improvement ideas away from the conversation.

3.8.2 General Self-Assessment

The NPUASTS' overall self-assessment for meeting the objectives of uAvionix for BAA Call 3 is a highly positive one. NPUASTS ultimately 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 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 FAM.

NPUASTS flight crews were able to successfully demonstrate C2 while utilizing C-Band spectrum frequencies and were able to conduct multiple flights in a small operational volume without incident.

4 Future Opportunities

The NPUASTS continues to push the boundaries with uAvionix exploring the full capabilities for C-Band use in C2 application and is highly interested in further testing concepts and technologies to move C-Band command and control forward. The NPUASTS is currently working hard on a statewide networked infrastructure that would support not only commercial and state UAS operations but could also support federal agency activities and initiatives. As a close partner with the FAA through the Test Site program, as well as the BEYOND program, the NPUASTS is actively supporting integration efforts on a wide scale. The NPUASTS is working with standards bodies to define standards for UAS, as well as the FAA by supporting aviation rulemaking committees. Throughout these efforts, there are opportunities that arise for continued testing and the NPUASTS is interested in supporting these activities.

The C-Band spectrum protected for UAS CNPC usage is a constrained resource that our industry must demonstrate it can manage effectively and efficiently. A key part of adopting C-Band based solutions is doing so in a way that can enable a maximum density allocation scheme without impacting the integrity of other operators.

Management of shared spectrum in other brands has a wide variety of solutions that are often unique to the industry and use-case that the spectrum is licensed for. The work done by the RTCA in DO-362A and DO-377A and parts that have been formalized in FAA TSO-C213a all establish the common essential elements for frequency management. This project has implemented these common essential elements and is demonstrating a basic Frequency Assignment Manager to validate all the specifications.

What remains for future efforts is scaling the management scheme to a national level with an approach that is optimized for the UAS industry while maximizing the efficiency of the assignments without compromising the integrity of any individual C-Band based C2 Link.

uAvionix plans to demonstrate a national airspace frequency management function that meets all the existing and anticipated specification requirements. This national FAM could be easily adopted by the industry in a way that encourages commercial build-out of C2CSP infrastructure without limiting competition between providers or depending on exclusive regional lockups. The FAM will function 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. The anticipated demonstration would occur in four phases as described below.

Phase 1 – Plan to extend the existing FAM allocation planning interface to require the additional details of all antenna configurations such as max EIRP, radiation pattern, mounting height, and orientation, etc. These details will be required from every GRS and ARS that will be used in a planned flight. Additional flight parameters such as max altitude and geographic bounds will also be required. The FAM would then perform a detailed viewshed analysis for a given set of these inputs.

Phase 2 – The FAM would then add the capability to store multiple viewshed results and perform an interference analysis to determine if an already assigned channel in one region can be re-assigned concurrently in a nearby region without any impact to performance.

Phase 3 – The FAM would be used to manually generate multiple real allocation requests for the designated test range. Test flights would then be conducted using those assigned channels and the actual measured performance to validate the viewshed and interference analysis would be recorded.

Phase 4 – Finally, creation of an allocation request simulation tool that would use the now validated FAM to generate many planned test scenarios to evaluate the density characteristics in different regions. Finally use the simulation tool with the validated FAM to create multiple high-density models for the entire national airspace.

In conjunction with the phases outlined above, the next steps in the progression of the FAM would be to demonstrate the following capabilities to advance the overall Technology Readiness Level (TRL) of this C-Band C2 solution:

- Demonstrate FAM upgrades that enable nationwide C-Band frequency management. This includes FAM upgrades including but not limited to an allocation planning interface, storage of multiple viewshed results, and a regional interference analysis. To showcase this ability plan to perform twenty (20) successful frequency allocations, fault free, in the FAM application; it is anticipated the count would restart if faults are encountered. These demonstrations can be executed at the contractor's facility.
- Demonstrate the Nationwide FAM (NFAM) by manually generating multiple allocation requests for the designated test range and Prime Contractor facility. Plan to perform 20 successful frequency allocations, fault-free, in the FAM application and restart the count if faults are encountered.
- Demonstrate the NFAM by performing 20 live test flights at the ND UAS Test Site using the assigned channels and record the actual measured performance to validate the viewshed and interference analysis. Each required flight should have a duration of no less than 15 minutes.
- Demonstrate the simulation tool with the live flight validated NFAM to create multiple high-density models for the entire national airspace. Plan to simulate:
    - 10 allocations
    - 100 allocations
    - 10,000 allocations
    - Potential maximum density of the NFAM (stress test)

The NPUASTS is very interested in continuing efforts with uAvionix to support further development of the next phase of this important research utilizing C-Band in Command-and-Control capacities for UAS. NPUASTS believes the next phase of this research should build on the work presented here and use these results to help uAvionix build out a larger, nationwide C-Band frequency management tool, while also providing valuable feedback to the FCC for use in their RTCA specifications development.

5 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 11 with short descriptions.

Table 11: NPUASTS Feedback Recommendations for Future Testing

Suggestion	Comment
Evaluate Network Infrastructure Prior to GRS Installation	Ensure POE++ switches are at the proper power levels and network firewall requirements have been identified prior to GRS installation if installing on a network
GRS Spectrum Management When Transferring between single and multi-UAS flights	When using multiple UAS, ensure each GRS on a given frequency is linked with a specific UAS. Identified an issue when switching from multi-to single UAS where a single GRS was sending signals to 2 unique UAS providing C2 for one aircraft and causing the other to arm, but not launch
Providing Handheld RF Controllers	Auterion Mission Control in conjunction with SkyLine functioned well, but the PIC's requested an additional layer of control in the form of a hand-held RF controller to be incorporated in conjunction with the Auterion suite for additional control should an emergency situation arise.

6 Conclusions

The uAvionix FAM technology proved it was capable of managing a limited amount of protected spectrum on behalf of many operators in the same area concurrently and only for the duration of each flight. The combination of ground and live flight testing demonstrated the following capabilities of SkyLine with incorporation of the FAM:

- The ability of SkyLine C2CSP platform to manage a pool of allocated (and licensed) frequencies in a geographic area.
- 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.
- The ability to demonstrate non-interference when multiple aircraft using uniquely assigned frequencies are operating within close proximity.

This proof of 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.

There are multiple benefits of a functioning FAM across different stakeholder groups including operators, industry partners and Original Equipment Manufacturers (OEM), the FAA, and the FCC. A functional FAM allows operators to gain access to protected spectrum free from RF interference often encountered using ISM bands. This dramatically increases the safety case as compared to the use of unlicensed frequencies. Second, industry partners and OEMs are presented with a standard model and user interface to develop and interact with compatible radios, Frequency Management Organizations (FMO) and C2CSPs. Additionally, the FAA, as well as the FCC, are both provided with a methodology to manage the protected spectrum asset in finite time slices and in defined regional areas. This ability allows for either internal FAM functionality, or delegated authority to an authorized FMO. Finally, the FAA is also presented with an option to leverage existing, underutilized spectrum assets to efficiently serve the needs of the UAS industry, meeting the intent and the letter of the Presidential Spectrum Memorandum.

It is the conclusion of the research team that the next step in the development of the FAM is to demonstrate 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. This national Frequency Allocation 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. This application is an available option to manage the entire 5030-5091MHz band (C-Band), inclusive of interference modeling regionally.

NPUASTS was able to successfully help uAvionix demonstrate the ability of their FAM to dynamically allocate protected C-Band frequencies to multiple UAS in a small volume without spectrum interference 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 single and multiple aircraft demonstrations were successfully performed and provided the research teams with valuable data. Each set of flight events concluded without incident and flight teams were able to efficiently fly a large number of missions in a short time frame. 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.

7 Appendix A: Reference Documentation

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

Table 12: 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.