Broad Agency Announcement
Call #002

Final Report

697DCK-21-C-00233
UAS Integration Office
Program & Data Management Branch
(AUS-410)

Project Title: Pre-commercialization Effort for Real-Time Transport Protocol UAS Video
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Report Date: 9/19/2022
Contract Period of Performance: 9/20/2021-9/19/2022

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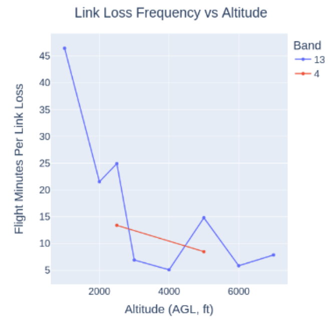
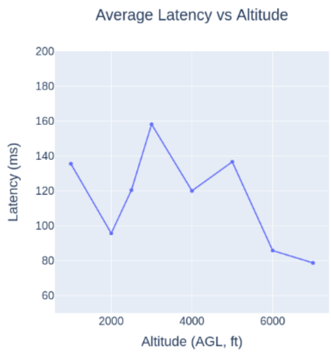
1. EXECUTIVE SUMMARY

Performance evaluation of airborne LTE operation (ALO) was performed to understand the connectivity and reliability of the cellular network at altitudes up to and including 7,000 feet above ground level (AGL). The results of these efforts can be used by regulators for considering the safety and reliability of ALO communications for integration of unmanned aerial systems (UAS) into the national airspace (NAS). Additionally, a real-world use of ALO was demonstrated by integrating a cockpit video recorder (Appareo's AIRS-400) to stream live video data over an ALO enabled device (Appareo's modified ACU-200).

The connection quality of the ALO system tested is sufficient for many use cases, but today ALO alone is not capable of safety critical command and control. The ALO system had a disconnect (link loss) of 20 seconds or greater every 14 minutes of flight on average. Altitude plays a strong role in link loss frequency. Compared 1000ft, link losses were twice as frequent at 2,000 ft and seven times as frequent at 3,000 ft. While altitude does influence the performance of an active link, aside from the frequency of link losses the bandwidth and latency of the link stay within usable levels up to 7000 ft.





The referenced signals received power (RSRQ) measurement, which represents the most useful signal quality measurement showed a 0.8 dB loss of signal per 1,000 feet of altitude which results in a degradation between 1,000 and 5,000 feet of 3 dB (half the signal power). Packet loss showed the worst performance, averaging 13.89% across all data. Latency is usable, averaging 122 ms throughout the testing. Jitter (variation of latency) was excellent as it stayed below 30 ms in 98% of the results.

Video streaming was observed to be qualitatively smooth and stable (720p 30fps) at altitudes up to 5000 ft while the cellular link was active. Full latency from image capture on the camera to display in a web browser was approximately 6 seconds. Multi-second video latency precludes the use of ALO for active visual navigation but is within acceptable ranges for inspection and surveillance operations. Additionally, the high levels of packet loss indicate that the latency is necessary for smooth video.

Ultimately there is a bit more maturity needed in the current ALO solution, but it shows usefulness today in many UAS and other airborne applications. Further refinement and testing of the ALO network, modem, and integration between is recommended.

2. INTRODUCTION

There are several challenges that must be solved before the common and routine operations of Unmanned Aircraft Systems (UAS) beyond the visual line of sight (BVLOS), foremost among them is an acceptable means to detect and avoid (DAA) manned aircraft.

The technical challenges are many. A majority of future BVLOS UAS missions will operate in a low-altitude environment. The low-altitude environment is full of visual and radio detection and ranging (RADAR) clutter sources. It is complicated by terrain features and obstructions to line of sight such as trees and towers. Environmental exposure is also a real concern. People and important systems are exposed to any radiation directed near ground level.

Video streaming over an Airborne Long Term Evolution (LTE) Operations (ALO) modem can demonstrate a real-world operation to gather empirical information on network performance. This will demonstrate the ability of future integration with multiple other communication links to form a commercial infrastructure command and control (C2) device with acceptable connectivity and reliability.

This effort used the combination of the Aircraft Connectivity Units (ACU)-200 with ALO and an airborne cockpit data recorder (AIRS-400) that are currently available from Appareo to demonstrate a high throughput real-world use of the ALO network. Additionally, the ACU-200s with ALO were used to understand the connectivity and reliability of the cellular network at altitudes up to and including 7,000 feet Above Ground Level (AGL) in various scenarios. The results of these efforts can be used by regulators for considering the safety and reliability of ALO communications for future UAS C2 applications. ALO is available in most locations for commercial use without significant infrastructure investments.

The ACU-200 with ALO also has Ground LTE Operations (GLO) connectivity with 3G/2G fallback and global roaming capabilities, an internal Inertial Measurement Unit (IMU) and Global Positioning System (GPS) receiver for generation of information regarding an aircraft's flight without interfacing to aircraft systems. The ALO modem 4G LTE connectivity provides module operation up to and beyond the 5,000 feet AGL operational ceiling imposed by Verizon. This ACU is secure, with an onboard trusted platform module, and it is secure boot enabled. Additionally, the ACU has ultra-low power modes that allow the device to go into a sleep state while the aircraft is off without unduly draining the aircraft battery.

This project demonstrated and validated a pre-commercialization effort to add video streaming capability to the ACU-230 which is currently being commercialized as part of the North Dakota Department of Commerce UAS Test Site BVLOS Vantis UAS network.

Per the funding requirements of this FAA BAA program, a UAS industry leader was required to partner with one of the 7 FAA approved UAS Test Sites. Appareo chose to partner with the Northern Plains UAS Test Site (NPUASTS) who provided test planning and test oversite of manned and unmanned operations in various areas of airspace throughout 4 different testing phases for Appareo to collect the relevant cellular LTE research data. Some tests required advanced UAS operations that were conducted under properly attained airspace approvals through the FAA's Part 107 waiver process. The NPUASTS subcontracted iSight Drones Services to perform the flying and integration of test equipment to both the manned aircraft and the UAS flights in accordance with the Appareo/NPUASTS test plans. Advanced UAS operations in the fourth flight test session included flying a UAS up to 6,000 feet above ground level with the aid of a chase plane in the role of visual observation while collecting data on cellular LTE performance through different altitude environments.

3. APPROACH

The following sections will describe the equipment used, how data was collected, aircraft used, the flight profiles selected by Appareo to exercise ALO, as well as a description of how the video streaming testing was setup.

TEST EQUIPMENT USED

Cellular quality metric collection was performed using Appareo's Aircraft Communication Unit 200[1] with the addition of ALO capabilities via the Quectel EC25[2] modem running firmware version EC25VFAR02A12M4G_ALO. While the ACU-200 with ALO contains a second LTE modem for ground-level operation, only the ALO modem was enabled during testing. For all tests Band 13 was used and Band 4 was used for all manned aircraft tests. Band 13 uses 700 MHz whereas Band 4 uses 1700 MHz or 2100 Mhz. The EC25 used a single SIM card for the Verizon network – handoffs to other carriers were not tested. The cell antennas used in this project include TG.46.8113 (drone) and OMB.6912.03F21 (aircraft). Video was captured using an Appareo AIRS-400 (Airborne Image Recording System)[3]. The ACU-200 with ALO was setup to either collect network information or to stream video data.

DATA COLLECTION METHODS

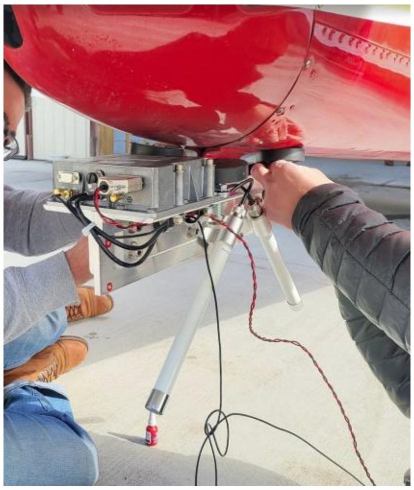
The ACU-200 with ALO collected cell quality metrics from the modem, network performance using iperf[4], and GPS/inertial measurements, logging an aggregate of all metrics once per second and uploading the same aggregate to the cloud via MQTT. Iperf tests were run against Amazon EC2 instances, cycling through a schedule of TCP upload, TCP download, UDP upload, and UDP download for 5 seconds each, for a total cycle time of 20 seconds. TCP tests measure bandwidth and latency, while UDP tests measure packet loss and jitter. Network tests were run serially rather than simultaneously to prioritize accuracy above the area coverage of each metric.

To demonstrate and collect video stream data a web portal was developed to capture and display the video in real time. In addition, this web portal displayed all the metrics collected on the device in real time. This allowed us to more efficiently direct the flight testing. If data stopped flowing in or if something interesting was observed, we were able to react in real time as opposed to finding out after the fact. When an observed outage occurred for long enough a manual power cycle was performed based on the monitoring of the device. After the first week of testing this was automated via a modem disconnect monitor.

1 https://appareo.com/aviation/aircraft-communication-units/
2 https://www.quectel.com/product/lte-ec25-series
3 https://appareo.com/aviation/airs-400/
4 https://iperf.fr/

Aircraft Used

Flights were mainly conducted using a Piper Cherokee carrying 3 ACU-200s with ALO, one under each wing and one mounted under the tail. The tail data was disregarded due to the inability to have similar antennas as well as the unit was programmed to automatically select between Band 4 and Band 13. Due to scheduled maintenance and overland flooding a Mooney was used for one mission. The Mooney lacked a hook to mount on the tail, and the third unit was placed in the cockpit, but the data was not used in this analysis. The UAS used was the Hybrid Project SuperVolo XL which had an ACU-200 with ALO in the equipment bay.



Piper Tail

Piper Wing

UAS

Mooney Wing

Flight Profiles / Methods

The project was setup to have 4 flight test periods of 1 week each. The flight testing across the 4 weeks were setup to collect data in various simulated scenarios as well as capture signal quality gradients across unique regions.

3D Coverage Cube (Area Inspection)

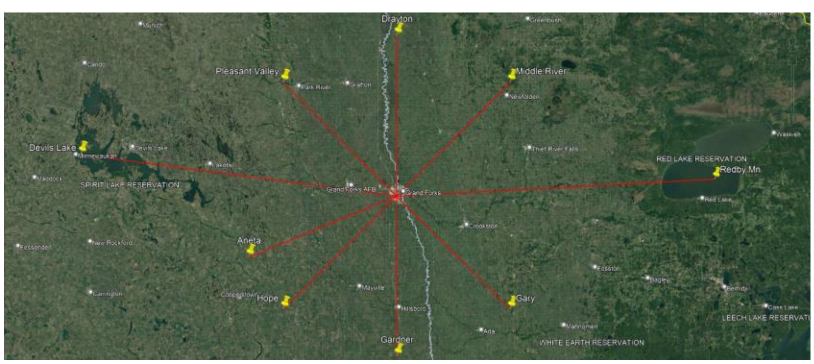
To isolate the influence of altitude on network performance, 3D cubes were flown in Hillsboro (rural) and Grand Forks (suburban). Squares at 1, 3, 5, 7, 9, and 11 miles from center were flown at 1000 – 7000 ft AGL in 1000 ft increments. These flight paths are referred to as Area Inspection in data analysis.

- Plane: Piper Cherokee
- Band Configuration: 1 each of 4, 13, auto
- Altitudes: 1000 – 7000 ft AGL in 1000 ft increments
- Mission Type: Area Inspection
- Environment: Suburban (Grand Forks), Rural (Hillsboro)

Spokes (Linear Inspection)

To cover a wide area of eastern North Dakota and western Minnesota, long lines were flown in a spokes pattern centered in Grand Forks, reaching to Devils Lake in the west and Red Lake in the east. The two altitudes of 2500 and 5000 were flown rather than 7 altitudes due to optimize flight time and budget.

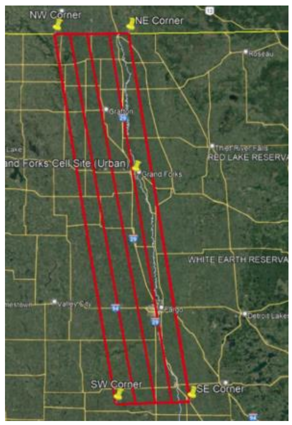
- Plane: Mooney
- Band Configuration: 1 each of 4, 13, auto
- Altitudes: 2500, 5000 ft AGL
- Mission Type: Long Line Linear Inspection
- Environment: Rural crossing over suburban (Grand Forks)



Red River Valley (Linear Inspection)

Mapping the red river valley, long lines were flown at 2500 and 5000 ft AGL. One path covered Grand Forks and Fargo.

- Plane: Piper Cherokee
- Band Configuration: 1 each of 4, 13, auto
- Altitudes: 2500 ft, 5000 ft AGL
- Mission Type: Long Line Linear Inspection
- Environment: Mostly rural with a little suburban (Grand Forks, Fargo)

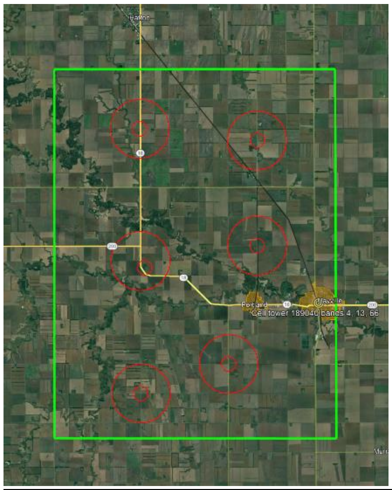


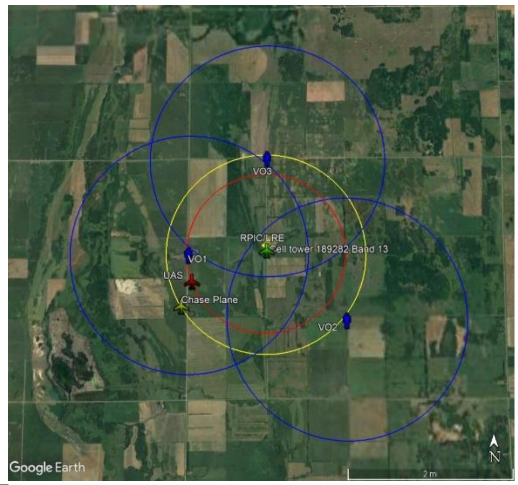
UAS

To test UAS performance, a major constraint was needing to maintain visual line of sight on the UAS. To do that, a combination of ground spotters for 1000 ft and a chase plane for 2000-7000 ft were used. The UAS was flown at two locations: Fertile, MN and Mayville, ND. In Fertile, a single 1-mile ring was flown around a cell tower in a rural area to test the feasibility of maintaining line of sight with a chase plane. Initial tests were promising, with the chase plane maintaining line of sight up to 3000 ft AGL where cloud cover prevented flights at higher altitude.

Mayville was initially planned to have the same 3D cube flight pattern as Hillsboro and Grand Forks, but difficulty acquiring and maintaining visual line of sight at altitude led to an alternative flight plan similar to the successful Fertile flight plan. Specifically, smaller circular patterns were flown to maintain bank and add profile to the UAS. Six sites were chosen distributed across the allowed area, with distinguishable landmarks near center points to aid in acquisition at altitude.

- Plane: Piper Cherokee, UAS
- Band Configuration: 13
- Altitudes: 1000-6000 ft AGL in 1000 ft increments
- Mission Type: Area Inspection, Surveillance
- Environment: Rural





VIDEO STREAMING

The three main components used to achieve in-flight video streaming are the AIRS-400 camera, the ACU-200 with ALO communication unit, and the Amazon Kinesis Video Streams (KVS) managed cloud service. KVS is used to receive, persist, and replay video streams.

While the AIRS-400 can capture and store 4k 30fps video locally, Verizon has stated that ALO upload speed will be throttled to 2Mbps. To fit inside the bandwidth limitation, the AIRS-400 was configured to capture video at 720p 30fps at a constant bitrate of 1.9Mbps, using the h264 video codec. Video was transferred from the camera to the ACU-200 with ALO over Ethernet via the widely used standard Real Time Streaming Protocol (RTSP)[5]. The ACU-200 with ALO streamed the received video to the cloud KVS service via HTTP using the provided GStreamer pipeline element.

The use of a standard video streaming mechanism minimizes the effort needed to integrate alternative cameras with the existing video streaming system. There is no proprietary or nonstandard aspect of the communication or configuration between the ACU-200 with ALO and AIRS-400 camera.

Streaming video from the ACU-200 with ALO to the cloud via the KVS-specific HTTP interface was chosen for reliability and implementation speed in the context of a technology readiness project. For future use cases there is the option to stream video via the standard WebRTC[6] over UDP to minimize latency of live streams and allow the use of alternative cloud backends in addition to KVS, however high packet loss observed during testing predicts poor performance.

[5] https://www.rfc-editor.org/rfc/rfc7826
[6] https://webrtc.org/

4. OBSERVATIONS / RESULTS

This section summarizes the high-level results and observations for the statement of work (SOW) metrics as well as the conclusions determined from the data results which are located in the subsequent section.

FLIGHT TEST PLANNING METRIC RESULTS

The below table provides a key to the rest of the report on how the SOW's flight test planning metrics were addressed.

#	Metric	Report Section(s)
1	CNPC method(s) used	For the UAS the RFD 900 / Silvus MIMO radios were used. Manned aircraft were manually piloted.
2	Frequencies used	Drone control frequencies: - 900 MHz for RFD 900 - 1350/2200 MHz for Silvus MIMO ALO tested band frequencies: - 700 MHz for Band 13 - 1700/2100 MHz for Band 4 Note that the drone control and ALO frequencies were not overlapped.
3	Type of operation	Plots, data tables, maps, and/or discussion when relevant in the report covers the type of operation performed. Area inspection and linear inspections were specifically identified through the maneuvers of the flight test plan.
4	Level of automation	Drone testing used monitored automation after takeoff using the built-in navigation system of the drone. Otherwise, there was no other automation performed.
5	Environment	Plots, data tables, maps, and/or discussion when relevant will mark the environment used. The environments tested through this effort were either rural or suburban. The testing area did not include urban or significant bodies of water.
6	Map of tower distribution	The data analysis section contains a dedicated section to tower distribution. Additionally, the observation section discusses impact of tower distribution.
7	Dual SIM dual standby or Dual SIM dual active	A single ALO SIM on the Verizon network was used for the testing.
8	Operational altitudes	Plots, data tables, maps, and/or discussion when relevant will indicate the altitude (AGL) that the testing was performed. Comparisons across altitude is a focus of many of the results.
9	Handovers per mile of flight	Handovers per mile of flight were addressed in a dedicated section within the data analysis section of the report.

#	Metric	Report Section(s)
10	Latency at altitude	Latency was addressed in dedicated section in data analysis and throughout observations. In general latency was found to be acceptable, however further improvement is expected. Especially for packet loss.
11	Lost link threshold	Lost link was defined as a 20 second timeout on an ICMP ping to 8.8.8.8. After 20 seconds the modem was soft restarted to see if there was a modem issue vs a network issue. It was observed that the modem and/or network has some further improvements to provide a more reliable connection.
12	Lost link occurrence frequency	Lost link occurrence frequency was evaluated in a dedicated section. As noted above, it was observed that lost link performance is not as good as we would like. Further modem and/or network analysis would be needed to isolate the issue if there is one.
13	Signal quality (RSRP, RSRQ, SINR, RSSI)	The cell signal quality metrics were addressed in their own sections in the data analysis and discussed within this observations section. In general, RSRQ is the most trusted indicator and was used to demonstrate the signal quality impact of various environments and scenarios.
14	Interference imposed upon LTE and 5G networks.	This was tested in a round-about way through latency, packet loss, throughput, and jitter. Each of these metrics has a dedicated data analysis section. Additionally, further discussion in this observations section. This was only able to be done from the radios perspective as there was no access to the network side.

Environmental Impact on ALO Observations

This section provides observations on the impact of the environment on the ALO performance.

Rural vs Suburban Impact

When comparing the results between rural and suburban a few key takeaways were observed. The towers are denser in suburban environments and is where band 4 towers are typically located. With band 4 backing up band 13 one would expect good latency performance. Especially with the higher frequency and high throughput of band 4. However, the opposite was observed. The signal quality was equal or higher in the suburban environment, but the latency was worse. The theory is that the network congestion of the suburban environment caused this result. It was noted that higher than normal packet loss could have driven the latency. This further reinforces the theory of network interference. In the data analysis section, the latency, packet loss, and signal quality metric comparison go into further detail to support this observation. It should also be noted that latency or packet loss could just be an issue with the current modem and/or network and as ALO technology matures this will converge to ground based cell performance.

Altitude Impact

In general performance degrades with altitude. The RSRQ, the most useful parameter for determining signal quality shows a 0.8 dB per 1,000 ft degradation. From 1,000 ft to 5,000 ft there is approximately a 3 dB loss in signal (or half the signal power).

Cell Tower Range / Density Impact

There wasn't a strong correlation observed between tower distance and any cellular quality metrics, nor network performance indicators. Note that the data avilable for this report has the locations of the *centers* of LTE cells, not the physical location of towers. With varying LTE cell sizes and range of tower antenna, there isn't a meaningful connection between linear ground distance and cell signal other than the trivial inability to connect from more than ~30 miles away.

ALO Signal Quality Observations

This section provides observations on the ALO signal quality results in the overall effort.

Latency / Jitter / Packet Loss

The biggest weak point of the ALO network tested is high packet loss, averaging 13.89% across all data. Latency is usable, averaging 122 ms. Jitter spikes high around disconnections but stays below 30 ms in 98% of data.

Signal Quality

RSRP is qualitatively near excellent, SINR generally poor (<0), and RSRQ ranging from good to poor linearly with altitude.

Lost Link

At present, a pilot can expect at least one period of 30 second link loss per flight. There were some patterns flown repeatedly, where one pass in an area would lose link, but another time around link would be maintained.

Band 13 vs Band 4 Impact

Note that band 4 isn't officially supported by the modem firmware used in this effort. The higher frequency band 4 consistently has higher throughput than the lower frequency band 13.

ALO Capability Observations

This section provides observations on the capability of ALO to support various use cases.

Video Capabilities

Packet loss likely precludes real-time video streaming, but video streaming is acceptable with a ~6 second delay and periodic outages.

Voice Capabilities

Packet loss predicts poor performance for real-time VOIP use cases. Throughput and latency are sufficient for delayed voice transmissions.

Data Capabilities

The ALO modem has a high throughput but would only work for use cases that accept periodic outages as of today. This technology is sufficient to sufficient to receive non-critical remote commands and offload telemetry data.

Command and Control (C2) Capabilities

The frequency of the link loss precludes the use of ALO for sole C2. A backup link would be required if used for C2.

Video Streaming Performance Observations

Video streaming was observed to be qualitatively smooth and stable (720p 30fps) at altitudes up to 5000 ft while the cellular link was active. Full latency from image capture on the camera to display in a web browser was approximately 8 seconds. Multi-second video latency precludes the use of ALO for active visual navigation but is within acceptable ranges for inspection and surveillance missions. Additionally, high levels of packet loss (averaging above 14%) indicate that the latency is necessary for smooth video. UDP-based real time streaming would likely have poor quality and multiple video artifacts.

5. DATA ANALYSIS

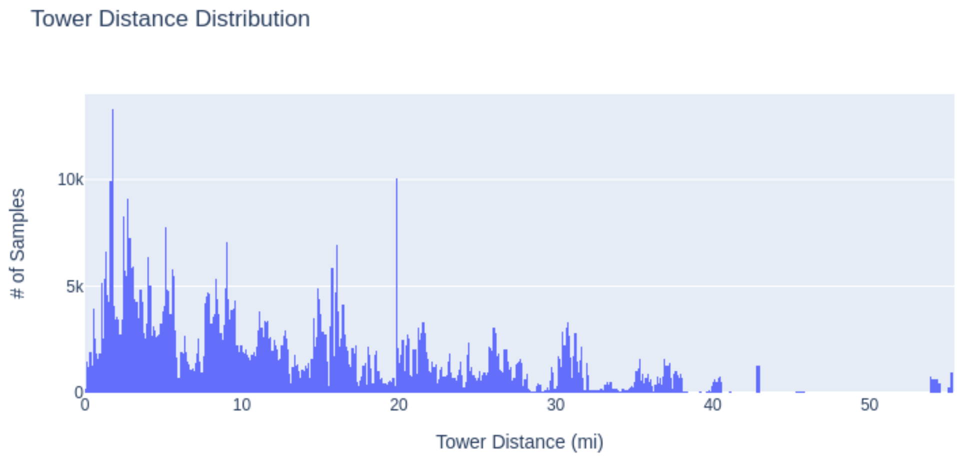
This section provides information for individual scenarios and key metrics analyzed by this effort. This was done via data analysis discussion, plots, maps, and data tables.

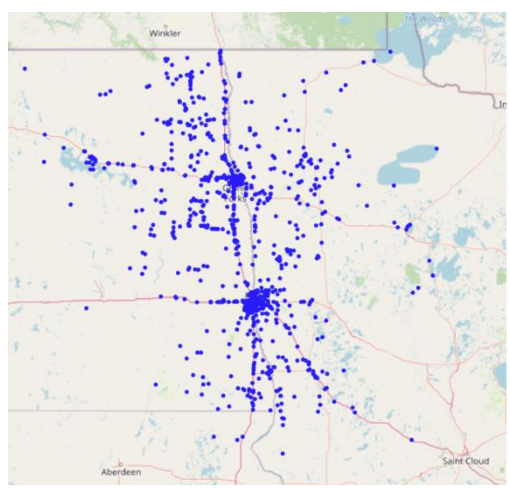
TOWER DISTRIBUTION

This section explores the distribution of cell towers across the area of interest and the behavior of the Quectel EC25V modem managing connections to individual LTE cells.

Tower Distance

The below histogram shows the distribution of the ground distance between the aircraft and the LTE cell. While not shown, the same distribution holds across both altitudes and missions. Note that the cell tower dataset used is incomplete. There were 346 cell IDs (36% of total cell IDs) observed during flight for which location is not available, leaving 20% of flight data without a tower location.





While the average distance to an LTE cell was 13.6 miles, the above figure shows a curious chunk of data with modems connected to towers more than 50 miles away. The modem reporting a cell ID doesn't necessarily mean that it is connected, only that it is trying to connect – flight data from the Red River Valley shows reported cell IDs from all over the US. As part of the modem's start-up procedure, it will attempt to connect to various towers that it knows are distributed geographically in order to gauge its location and narrow down its search. Note that the data in the above figure (and all data in this report) is filtered to a bounding box around the regions flown.

There was no strong correlation between tower distance and any cell signal quality metric or network performance indicator.

Tower Handoffs

This section analyzes how often the cell modem would switch to a different LTE cell. Note that cells most accurately map to antenna – a single physical tower will have multiple antennae pointed in different directions, and so these handoffs are between antennae, not necessarily physical towers. A handoff is a transition from one cell to another, so the number of towers seen in a mile of flight is 1 plus the number of handoffs.

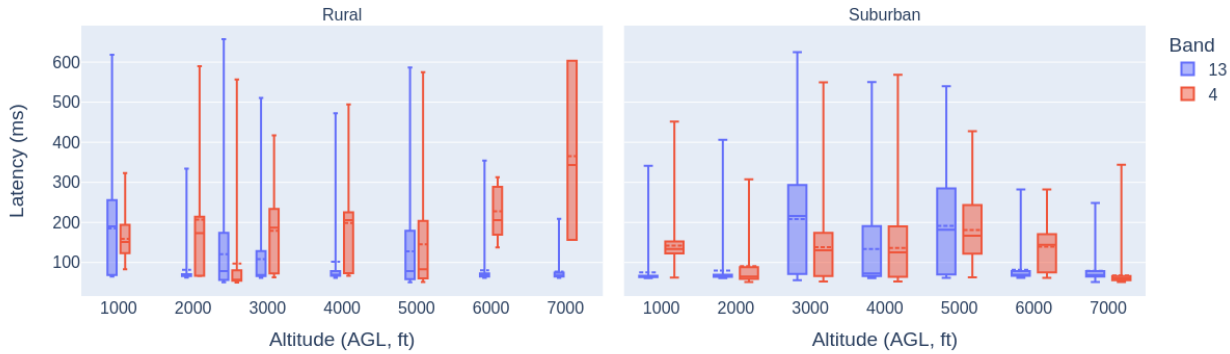
On average, band 13 handed off 1.74 times per mile, with band 4 at 1.33 times per mile. The area inspection. The area inspection missions (Fertile, Mayville) somewhat skew the band 13 data, excluding those missions band 13 averaged 1.46 handoffs per mile. Band 13 still transitions between cells more often than band 4, somewhat counterintuitively as since band 13 is a lower frequency and thus can travel longer distances, one may assume that it would maintain connection to a cell longer than the shorter distance band 4. A possible explanation for band 13 handing off more often than band 4 is that band 4 is technically unsupported by the Quectel EC25 modem, and more tuning work went into the ALO cell switching algorithm for band 13, leading to a difference in behavior.

Latency

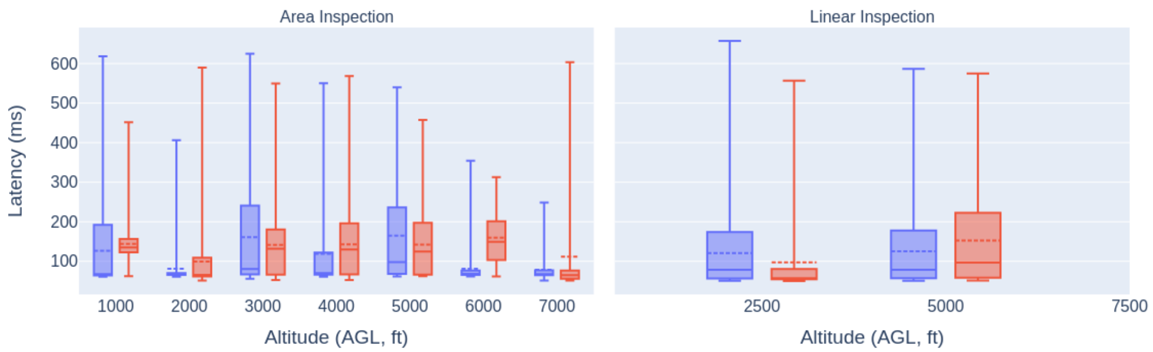
Latency is the amount of time it takes for a packet to travel across the network from source to destination. The lower the latency, the more quickly small command messages can be received and acted upon. Overall cellular band didn't have an outsized effect on latency, with band 13 averaging 114ms and band 4 averaging 115ms. For voice and video use cases, 150ms is about the edge of the acceptable range. Across all data, 77% of band 13 and 74% of band 4 data fell below 150ms latency.

The data analysis section makes heavy use of box-and-whisker plots to present the distribution of data. In these plots, the boxes represent that the middle 50% of data falls within the box, while the whiskers on either side of the box represent the bottom and top 25% of data. The lowest point is the minimum, and the highest point is the maximum. Inside the box, the solid line shows the median, while the dashed line shows the mean.

By environment:



By mission type:

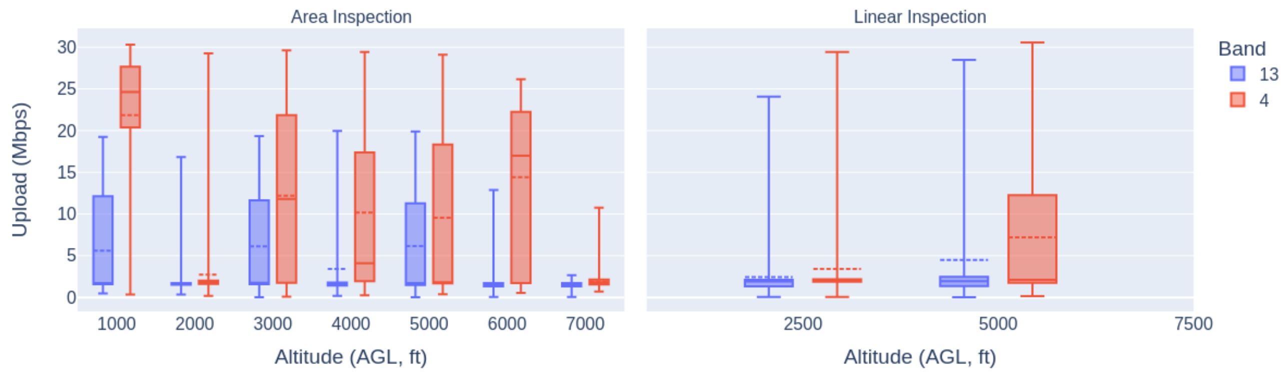


Overall band 13 came away with lower average latency than band 4.

TRANSFER SPEEDS

Upload and download speeds measure the bandwidth of the link – how much data can move across per second. Network speeds are typically measured in megabits per second (Mbps), while typical computer use cases think of data in term of megabytes (MB). 1 byte is 8 bits, so a 2Mbps link is capable of transferring 0.3 MB per second. Mapping to use cases, this was sufficient for streaming 720p 30fps video and uploading telemetry data (health, GPS, attitude, diagnostics).

Upload by mission type:



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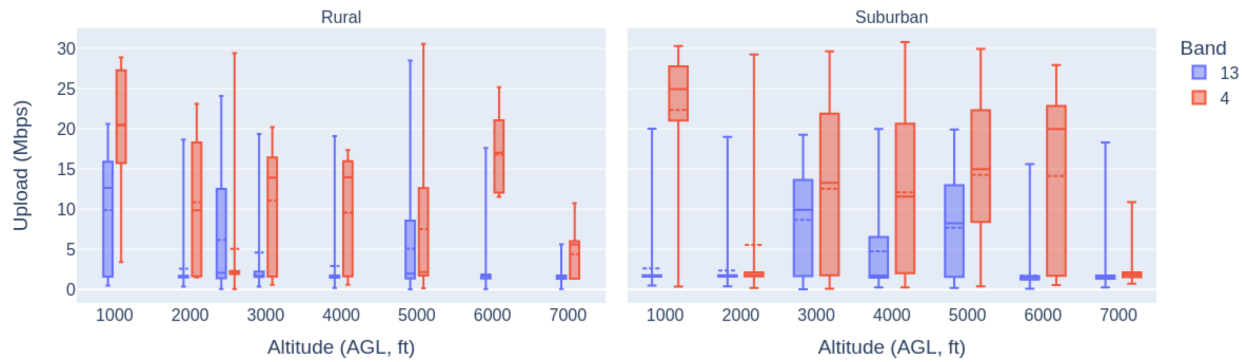

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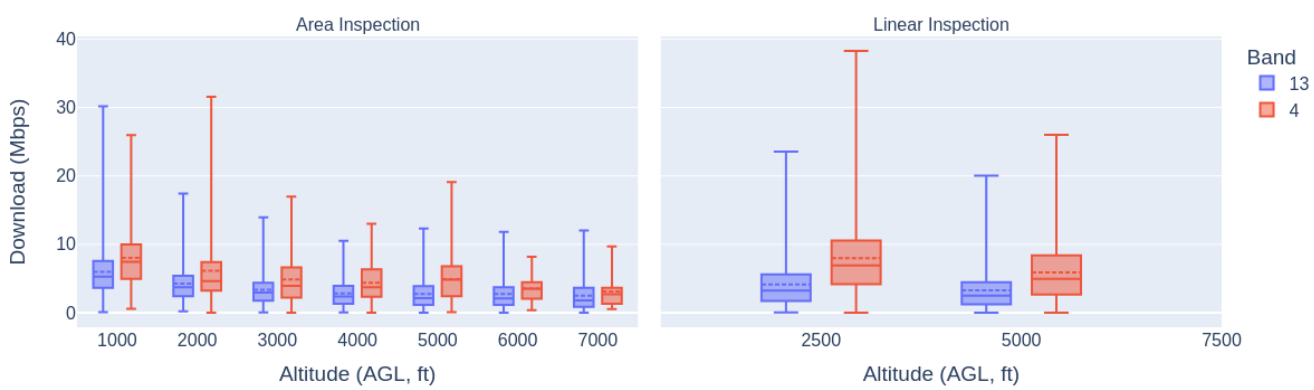

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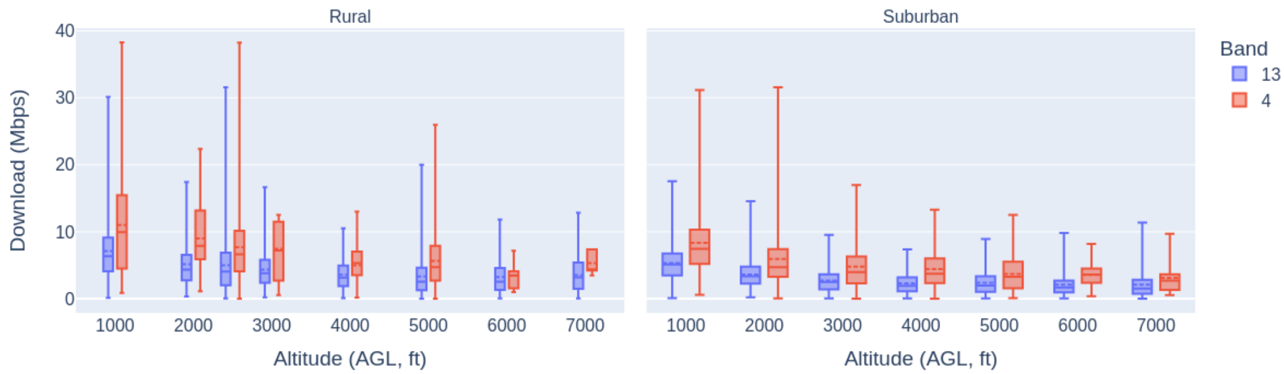


As expected, band 4 (higher frequency) showed higher download and upload speeds than band 13 (lower frequency). Overall, band 13 showed an average of 3.68 Mbps down and 4.08 Mbps up, while band 4 had an average of 6.40 Mbps down and 7.80 Mbps up.

Latency and Transfer Speed Summary Tables

This section contains tables for latency and transfer speeds,

Area Inspection

		Latency (ms)			Upload (Mbps)			Download (Mbps)		
		min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**									
13	**1000**	61.05	618.18	126.84	0.47	20.61	6.03	0.09	30.17	6.17
	2000	60.93	406.05	80.97	0.35	18.98	2.48	0.19	17.41	4.34
	3000	56.04	624.70	160.71	0.03	19.33	6.73	0.04	16.67	3.49
	4000	61.04	550.31	118.68	0.17	19.96	3.89	0.06	10.51	2.87
	5000	61.48	540.01	164.60	0.02	19.89	6.40	0.01	12.33	2.73
	6000	61.67	354.52	81.12	0.04	17.61	1.79	0.02	11.80	2.70
	7000	51.29	248.56	78.42	0.07	18.29	1.62	0.01	12.85	2.70
4	**1000**	62.44	451.88	143.85	0.35	30.29	22.12	0.59	38.29	8.64
	2000	51.44	589.86	99.31	0.17	29.24	5.92	0.02	31.57	6.16
	3000	52.49	549.55	141.66	0.10	29.62	12.42	0.01	16.98	4.98
	4000	52.35	568.26	142.94	0.26	30.78	11.82	0.01	13.30	4.49
	5000	62.05	457.71	142.24	0.39	29.94	10.15	0.09	19.11	4.70
	6000	61.53	312.79	159.41	0.56	27.94	14.72	0.38	8.17	3.52
	7000	51.29	603.52	111.65	0.72	10.86	2.28	0.53	9.68	3.43

Long Line Linear Inspection

		Latency (ms)			Upload (Mbps)			Download (Mbps)		
		min	max	mean	min	max	mean	min	max	mean
Band	Altitude (AGL, ft)									
13	2500	50.40	657.37	120.84	0.04	24.06	6.18	0.03	31.59	4.98
	5000	50.71	586.92	125.34	0.03	28.48	5.05	0.01	20.02	3.35
4	2500	49.98	556.92	97.43	0.04	29.40	5.04	0.01	38.27	7.69
	5000	51.36	574.67	152.45	0.17	30.56	7.96	0.00	25.99	5.55

Rural

		Latency (ms)			Upload (Mbps)			Download (Mbps)		
		min	max	mean	min	max	mean	min	max	mean
Band	Altitude (AGL, ft)									
13	1000	64.69	618.18	184.89	0.47	20.61	9.89	0.14	30.17	7.12
	2000	62.50	334.14	82.09	0.35	18.65	2.60	0.33	17.41	5.14
	2500	50.40	657.37	120.84	0.04	24.06	6.18	0.03	31.59	4.98
	3000	61.35	510.81	108.20	0.35	19.33	4.60	0.22	16.67	4.35
	4000	61.39	472.41	101.91	0.17	19.07	2.93	0.09	10.51	3.54
	5000	50.71	586.92	127.74	0.02	28.48	5.07	0.01	20.02	3.30
	6000	61.81	354.52	80.58	0.04	17.61	1.87	0.04	11.80	3.24
	7000	61.34	209.00	77.38	0.07	5.60	1.48	0.02	12.85	3.52
4	1000	83.23	323.11	158.73	3.40	28.86	20.47	0.85	38.29	11.01
	2000	66.01	589.86	207.30	1.51	23.10	10.84	1.11	22.39	8.98
	2500	49.98	556.92	97.43	0.04	29.40	5.04	0.01	38.27	7.69
	3000	62.65	416.99	179.39	0.58	20.20	11.08	0.53	12.51	7.43
	4000	66.84	494.66	198.83	0.58	17.33	9.56	0.17	13.00	5.01
	5000	51.36	574.67	145.05	0.17	30.56	7.52	0.00	25.99	5.63
	6000	137.80	312.79	228.04	11.54	25.16	16.78	0.97	7.18	3.43
	7000	156.40	603.52	365.58	1.35	10.75	4.40	3.46	7.37	5.33

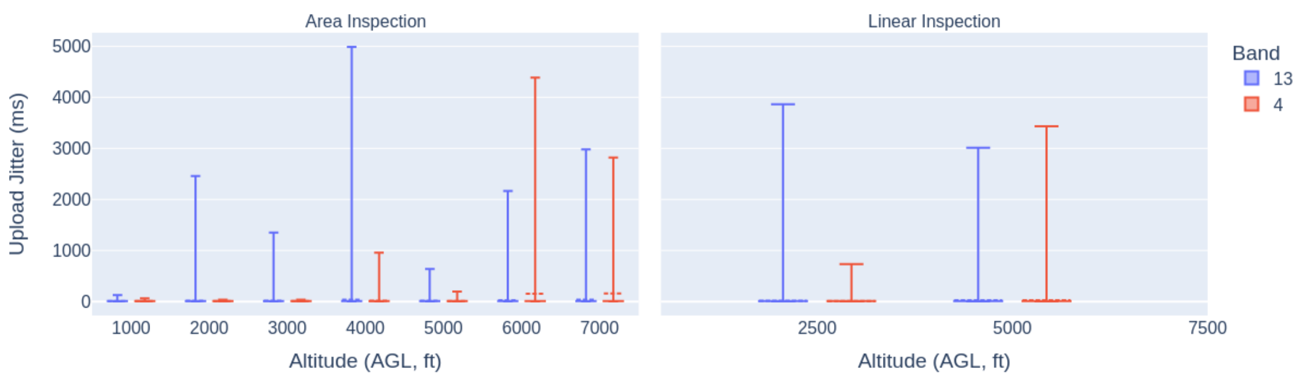
Suburban

		Latency (ms)			Upload (Mbps)			Download (Mbps)		
		min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**									
13	**1000**	61.05	341.06	75.56	0.47	20.01	2.63	0.09	17.57	5.33
	2000	60.93	406.05	79.93	0.37	18.98	2.36	0.19	14.55	3.59
	3000	56.04	624.70	208.54	0.03	19.25	8.66	0.04	9.53	2.71
	4000	61.04	550.31	133.59	0.26	19.96	4.75	0.06	7.35	2.27
	5000	61.48	540.01	191.58	0.19	19.89	7.68	0.06	8.91	2.37
	6000	61.67	282.24	81.73	0.09	15.59	1.69	0.02	9.82	2.08
	7000	51.29	248.56	79.20	0.24	18.29	1.73	0.01	11.36	2.07
4	**1000**	62.44	451.88	141.95	0.35	30.29	22.33	0.59	31.16	8.34
	2000	51.44	307.55	90.97	0.17	29.24	5.54	0.02	31.57	5.94
	3000	52.49	549.55	138.51	0.10	29.62	12.53	0.01	16.98	4.78
	4000	52.35	568.26	136.43	0.26	30.78	12.08	0.01	13.30	4.43
	5000	63.15	427.68	181.24	0.39	29.94	14.26	0.09	12.51	3.68
	6000	61.53	282.32	139.49	0.56	27.94	14.12	0.38	8.17	3.55
	7000	51.29	343.72	67.32	0.72	10.86	1.91	0.53	9.68	3.10

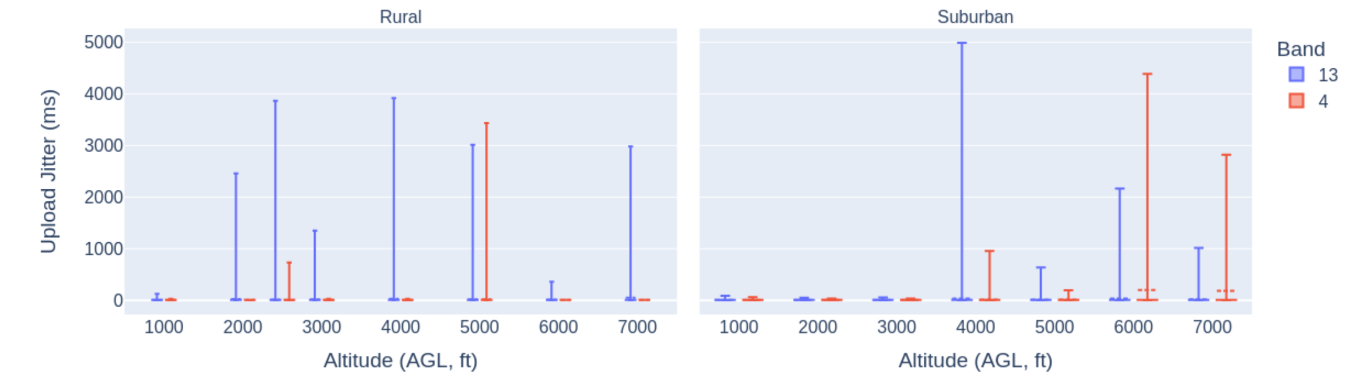
JITTER

Jitter is the variance of latency - latency measures the average time it takes for one packet to arrive, and jitter measures how consistent that average is. Jitter is particularly important in real-time voice and video communication, as even with low latency and high throughput, high jitter can cause degradation in perceived performance. For example, if packets were streamed from a source transmitting every 50 milliseconds, with 0 jitter the destination would receive one packet every 50 milliseconds. In practice, the time between each packet the destination receives will vary – they could arrive at the destination 40ms apart, then 60ms. Packets could be delayed and multiple arrive at once. Jitter measures a spectrum between packets arriving in a consistent stream and packets arriving in bunches of fits and starts

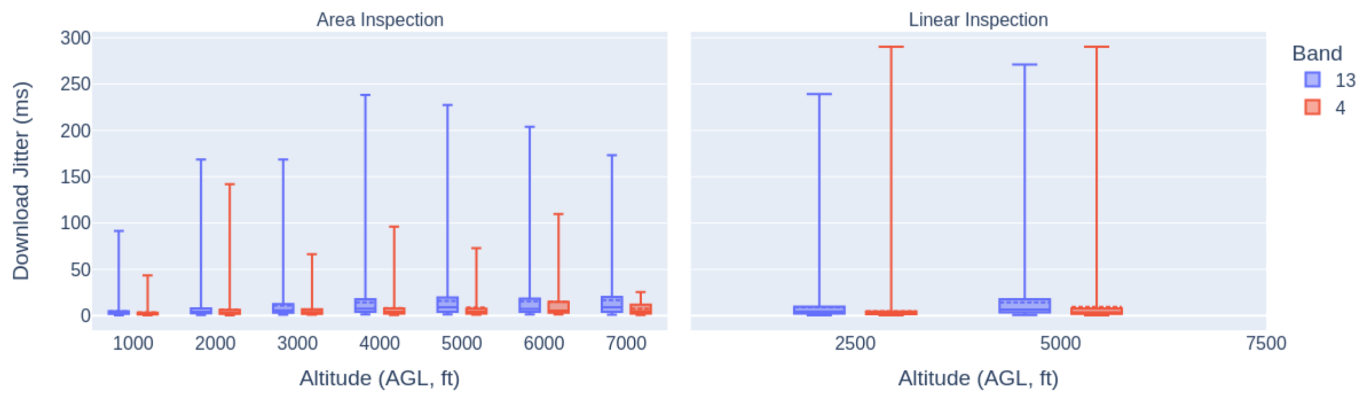
Upload jitter by mission type:



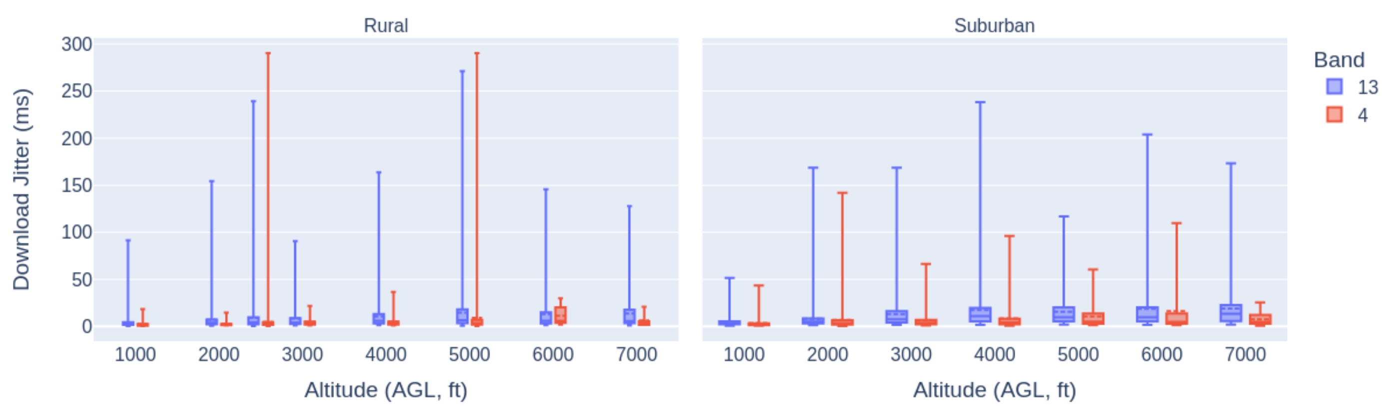
Upload jitter by environment:



Download jitter by mission type:



Download jitter by environment:



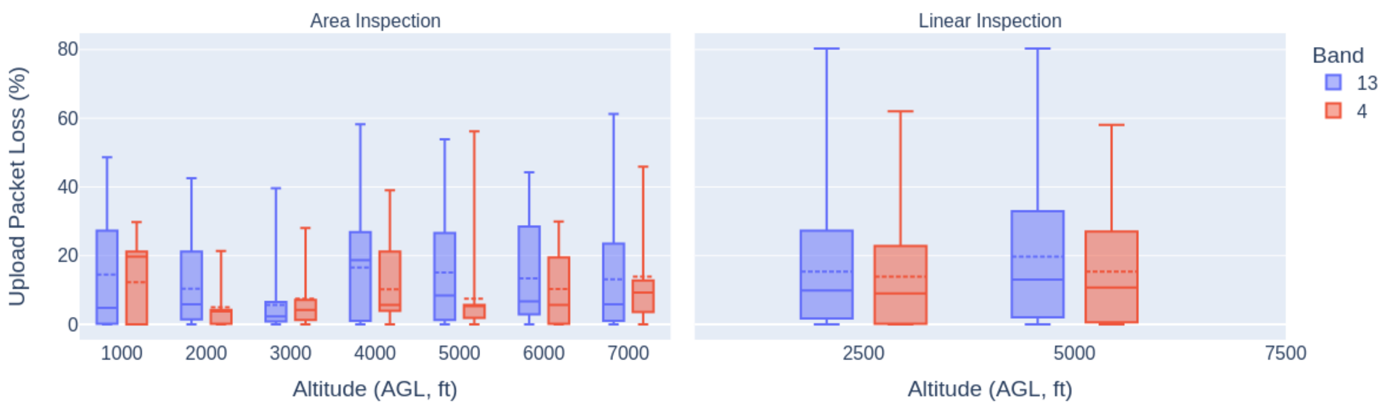
For acceptable levels of jitter, Cisco lists <30ms for voice and 30-50ms for video[7]. The above plots show a high concentration of data at a low threshold, but with outliers reaching into high levels. Overall, 97%/98% of data were below 30ms upload jitter for bands 13/4, and 98%/96% acceptable download jitter.

[7] https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/What_is_Jitter%3F

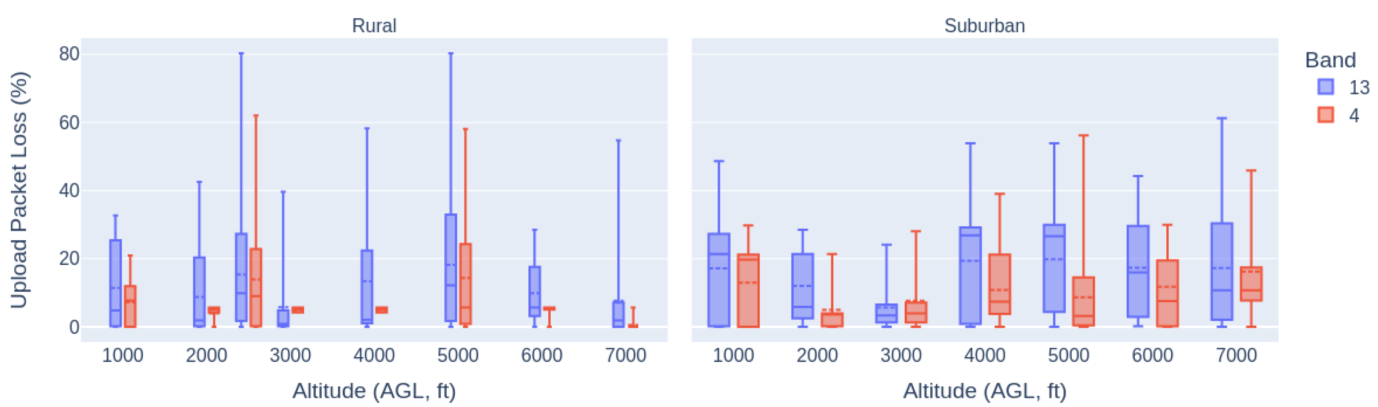
Packet Loss

Packet loss is the percentage of packets that don't reach the destination. Overall, this is the largest weak point of the ALO network measured in this effort. Audible errors in real-time voice communication occur with less that 1% packet loss, but only 14% of data was lower than that mark. Even at 1000 ft, packet loss averaged over 18%.

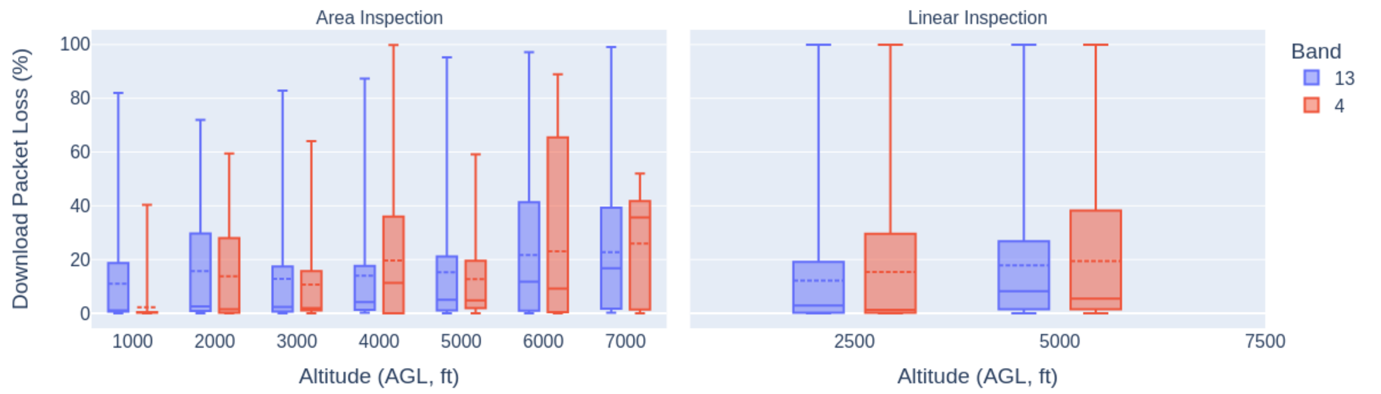
Upload packet loss by mission type:



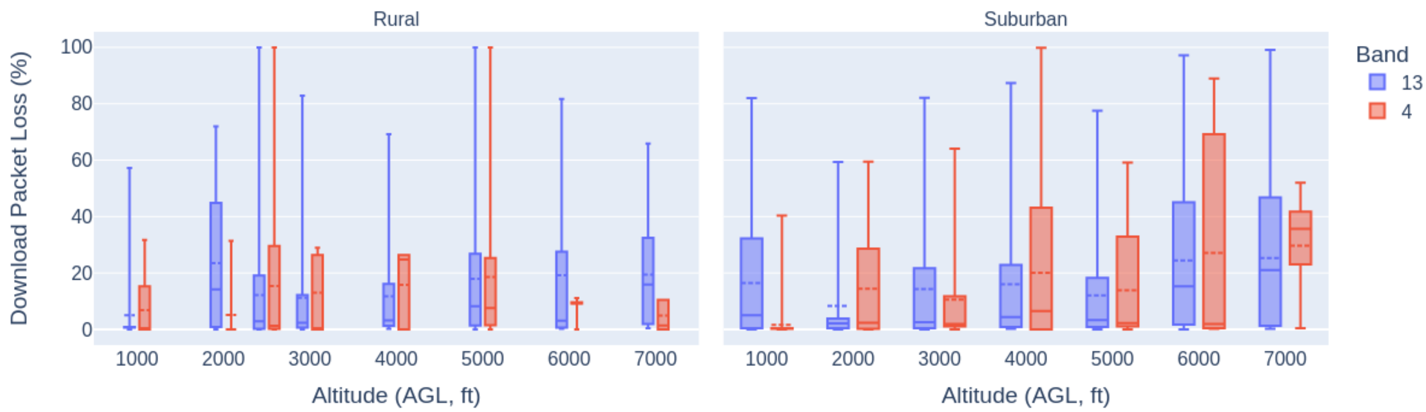
Upload packet loss by environment:



Download packet loss by mission type:



Download packet loss by environment:



Jitter and Packetloss Summary Tables

This section contains summary tables for jitter and packet loss, broken out by mission type, band, and altitude.

Area Inspection

		Upload Jitter (ms)			Download Jitter (ms)			Upload Packet Loss (%)			Download Packet Loss (%)		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	3.72	125.77	7.53	0.43	91.39	4.74	0.00	48.64	14.46	0.00	81.99	11.04
	2000	4.29	2460.40	14.80	0.88	168.66	7.76	0.00	42.56	10.42	0.00	71.98	15.68
	3000	4.34	1350.43	12.29	0.90	168.66	10.95	0.00	39.62	5.70	0.00	82.92	12.86
	4000	3.89	4987.67	34.02	1.42	238.32	14.27	0.00	58.28	16.54	0.21	87.37	14.04
	5000	3.45	637.71	12.49	1.24	227.43	16.02	0.00	53.88	15.11	0.00	95.27	15.28
	6000	3.84	2164.54	23.25	1.26	203.88	15.73	0.00	44.23	13.35	0.00	97.17	21.71
	7000	4.21	2978.75	34.20	0.99	173.29	16.79	0.00	61.22	13.11	0.21	99.12	22.78
4	**1000**	4.88	61.03	7.68	0.54	43.49	3.44	0.00	29.77	12.28	0.00	40.35	2.21
	2000	4.69	36.90	7.64	0.57	142.11	6.72	0.00	21.38	4.94	0.00	59.50	13.74
	3000	4.14	37.65	8.02	1.04	66.38	6.59	0.00	28.09	7.43	0.00	64.02	10.73
	4000	4.74	957.25	15.65	0.88	96.28	8.08	0.00	38.99	10.19	0.00	99.87	19.62
	5000	3.83	195.26	9.94	0.96	72.95	8.76	0.00	56.18	7.44	0.00	59.12	12.76
	6000	5.21	4385.91	155.02	1.28	109.66	15.13	0.00	29.98	10.26	0.00	88.95	23.06
	7000	5.74	2821.07	159.68	0.76	25.65	7.41	0.00	45.91	13.86	0.00	51.96	26.00

Long Line Linear Inspection

		Upload Jitter (ms)			Download Jitter (ms)			Upload Packet Loss (%)			Download Packet Loss (%)		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**2500**	3.54	3864.65	13.55	0.51	239.23	9.21	0.00	80.29	15.38	0.00	99.95	12.13
	5000	3.45	3009.83	22.88	0.66	271.00	14.23	0.00	80.29	19.77	0.00	99.95	17.81
4	**2500**	3.78	732.57	9.32	0.44	290.32	4.68	0.00	62.05	13.91	0.00	99.95	15.34
	5000	3.51	3433.08	22.24	0.58	290.32	9.41	0.00	58.07	15.33	0.00	99.95	19.46

Rural

		Upload Jitter (ms)			Download Jitter (ms)			Upload Packet Loss (%)			Download Packet Loss (%)		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	4.92	125.77	7.71	0.43	91.39	4.20	0.00	32.70	11.41	0.00	57.23	4.99
	2000	4.77	2460.40	22.33	0.88	154.47	7.19	0.00	42.56	8.71	0.00	71.98	23.53
	2500	3.54	3864.65	13.55	0.51	239.23	9.21	0.00	80.29	15.38	0.00	99.95	12.13
	3000	4.36	1350.43	17.67	0.90	90.55	8.48	0.00	39.62	5.72	0.00	82.92	11.26
	4000	5.12	3919.09	32.03	1.42	163.66	10.78	0.00	58.28	13.35	0.21	69.18	11.77
	5000	3.45	3009.83	20.94	0.66	271.00	14.64	0.00	80.29	18.16	0.00	99.95	17.91
	6000	4.43	359.15	14.20	1.26	145.79	12.99	0.00	28.51	9.84	0.21	81.72	19.26
	7000	4.21	2978.75	52.28	0.99	127.58	13.79	0.00	54.72	7.67	0.42	65.85	19.48
4	**1000**	5.69	29.05	7.15	0.54	18.33	2.64	0.00	20.96	7.23	0.00	31.71	6.82
	2000	4.69	10.62	6.96	0.93	14.62	2.89	0.00	5.66	3.99	0.00	31.42	5.17
	2500	3.78	732.57	9.32	0.44	290.32	4.68	0.00	62.05	13.91	0.00	99.95	15.34
	3000	6.08	27.76	8.39	1.04	21.65	4.63	4.19	5.66	4.92	0.00	28.92	12.99
	4000	5.72	27.76	7.48	1.10	36.80	5.11	4.19	5.66	4.99	0.00	26.42	15.80
	5000	3.51	3433.08	20.66	0.58	290.32	9.02	0.00	58.07	14.30	0.00	99.95	18.57
	6000	6.33	8.13	7.58	2.04	29.86	11.16	0.00	5.66	5.17	0.00	11.11	9.26
	7000	6.45	6.92	6.62	1.72	20.84	6.47	0.00	5.66	0.51	0.00	10.48	4.90

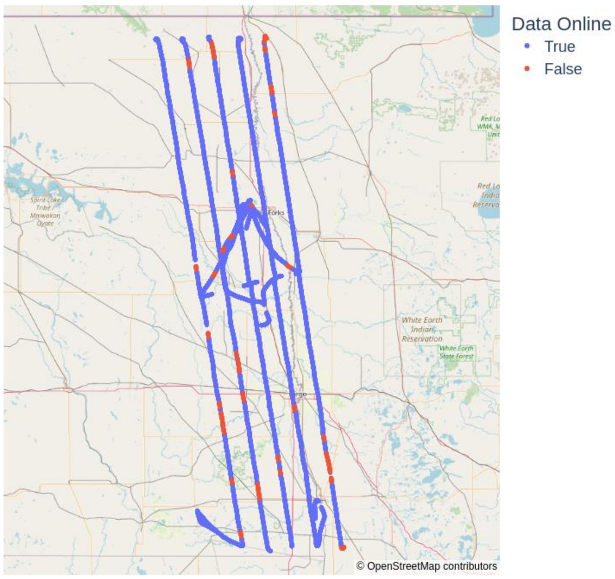
Suburban

		Upload Jitter (ms)			Download Jitter (ms)			Upload Packet Loss (%)			Download Packet Loss (%)		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	3.72	86.89	7.37	0.85	51.60	5.23	0.00	48.64	17.16	0.00	81.99	16.40
	2000	4.29	51.38	7.78	1.33	168.66	8.30	0.00	28.51	12.02	0.00	59.40	8.35
	3000	4.34	54.52	7.38	1.66	168.66	13.19	0.00	24.11	5.69	0.00	82.16	14.32
	4000	3.89	4987.67	35.80	1.58	238.32	17.36	0.00	53.88	19.38	0.21	87.37	16.06
	5000	3.45	637.71	13.10	1.94	116.93	15.49	0.00	53.88	19.80	0.00	77.50	12.06
	6000	3.84	2164.54	33.58	1.57	203.88	18.85	0.21	44.23	17.36	0.00	97.17	24.49
	7000	4.46	1015.92	20.60	1.86	173.29	19.05	0.00	61.22	17.20	0.21	99.12	25.26
4	**1000**	4.88	61.03	7.75	0.61	43.49	3.54	0.00	29.77	12.92	0.00	40.35	1.62
	2000	4.84	36.90	7.69	0.57	142.11	7.02	0.00	21.38	5.01	0.00	59.50	14.41
	3000	4.14	37.65	7.99	1.08	66.38	6.76	0.00	28.09	7.64	0.00	64.02	10.54
	4000	4.74	957.25	16.61	0.88	96.28	8.43	0.00	38.99	10.79	0.00	99.87	20.07
	5000	3.83	195.26	11.63	1.35	60.37	10.78	0.00	56.18	8.63	0.00	59.12	13.88
	6000	5.21	4385.91	197.82	1.28	109.66	16.28	0.00	29.98	11.74	0.21	88.95	27.07
	7000	5.74	2821.07	186.40	0.76	25.65	7.58	0.00	45.91	16.20	0.42	51.96	29.68

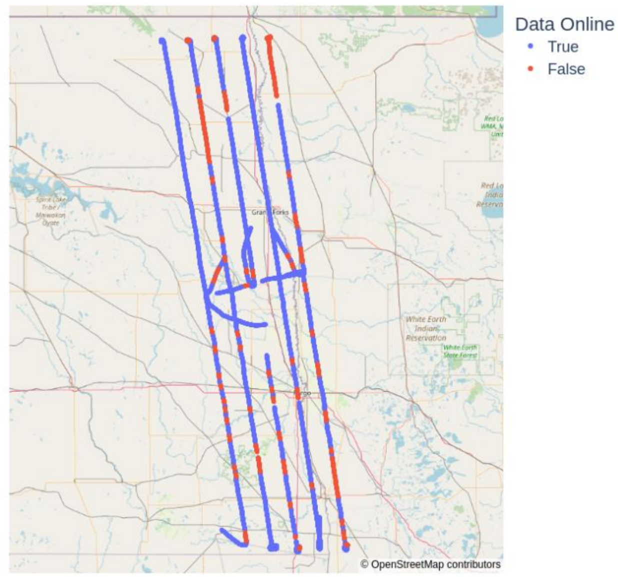
Lost Link

There are two main scenarios for lost link: full disconnection from tower, where the modem reported that it was searching for a tower, and a higher-level disconnection where the modem reported that it was connected, but the ACU was unable to make IP connections. For the latter, this was determined by a 20-second time out on an ICMP ping to 8.8.8.8. Note that the automated aggressive modem restarting only executed for the second scenario – if the modem reported that it was searching for a tower it was left to search. The modem was automatically restarted if it reported that it was connected to a tower, but the 20-second ping timed out, and it had been at least 40 seconds since the last modem restart.

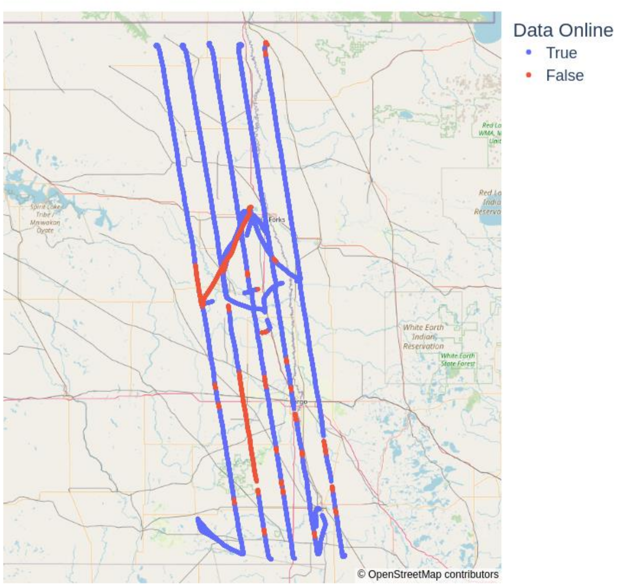
Lost Link - Band 4 - 2500 ft AGL



Lost Link - Band 4 - 5000 ft AGL

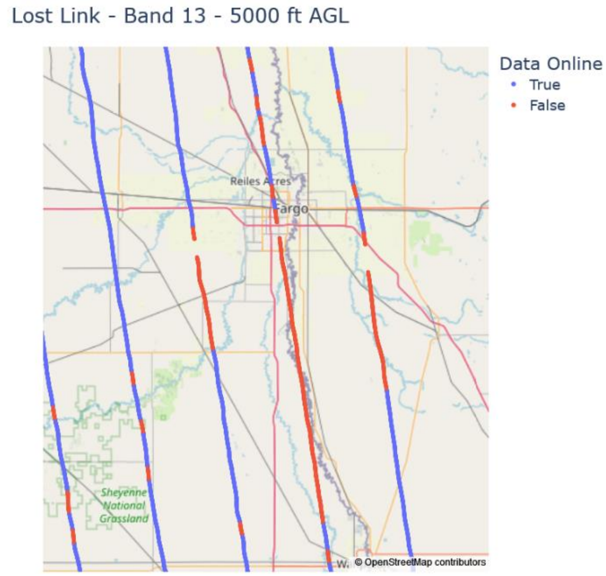


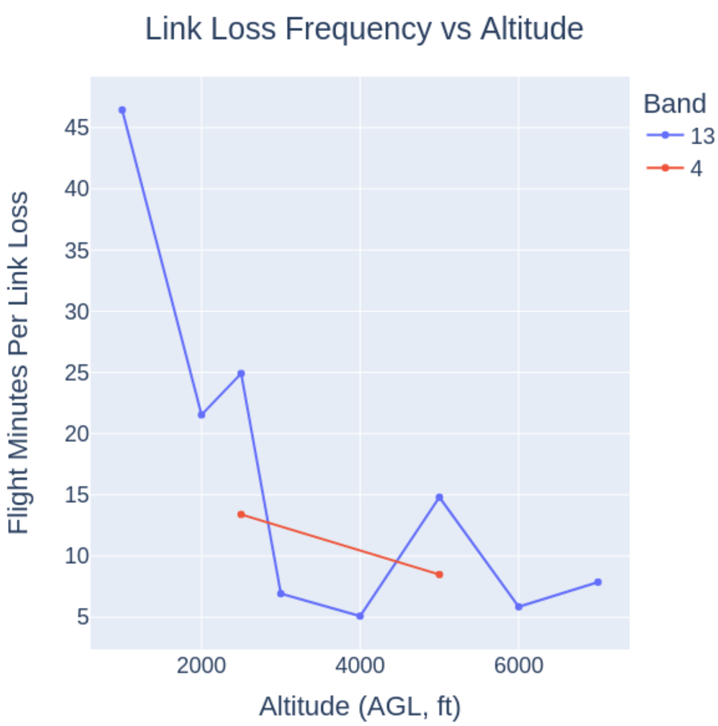
Lost Link - Band 13 - 2500 ft AGL



Lost Link - Band 13 - 5000 ft AGL

Gaps in the lines indicate no data was collected at that location – the whole ACU was manually power cycled by the copilot. Observe in the zoomed-in graph of band 13 at 5000 ft the long periods of disconnection (flying northwards) followed by manual power cycles, and short periods of disconnection while the modem starts up and connects. We suspect that a possible cause for the power cycling working to reconnect the modem is due to the carrier-specified retry schedule in modem firmware prolonging tower search durations. Extrapolating, for example in the north-eastern portion of band 13 at 5000 ft, the disconnection event may have been much shorter had the reconnection attempts been more aggressive.





Link loss was heavily correlated with altitude. The plot to the left shows the average number of minutes flown between link loss events for all missions except Grand Forks and Hillsboro, where the mechanism to collect this data was not yet implemented. For these, band 4 shows a combination of the Valley and Spokes missions, while band 13 shows the linear inspection Valley and Spokes as well as the area inspection Fertile and Mayville.

Over all data, a link loss event would occur every 14 minutes. Missions varied – Spokes had 51 and 31 minutes between link losses on band 13 at 2500 and 5000 ft, while the Valley was more frequent at 16.5 and 11 minutes.

In addition to the lost-link data gathered via ICMP pings, there is also data from at the TCP/UDP level from iperf network performance tests. The table below counts the existing statuses of iperf tests. SERVER_BUSY is somewhat overrepresented by some extended periods of the early Grand Forks and Hillsboro missions where the server process would hang after a client running a test would lose link. After the first week of data was analyzed, an automated process was put in place to mitigate the server hangs. CATCHALL_RUN_FAILED is an upper bound on the percentage of test runs failed due to link loss while an active test was running. Some are due to the link dropping out during the test, and some due to overeager server termination to mitigate hangs. NETWORK_UNREACHABLE indicates that the network was not connected when a test run was started. Note that a backoff schedule of 1, 1, 5, 10, 10, 10... seconds was used after an unsuccessful test run.

iperf Status	Percentage
OK	87.33
CATCHALL_RUN_FAILED	6.01
NETWORK_UNREACHABLE	3.42
SERVER_BUSY	3.25

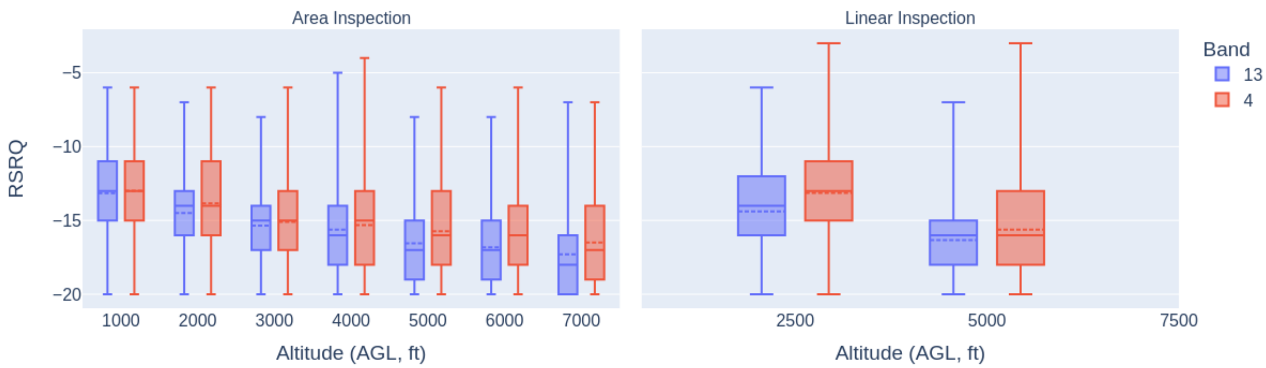
LTE Signal Quality

This section contains cell signal quality metrics broken out by mission type, environment, cellular band, and altitude.

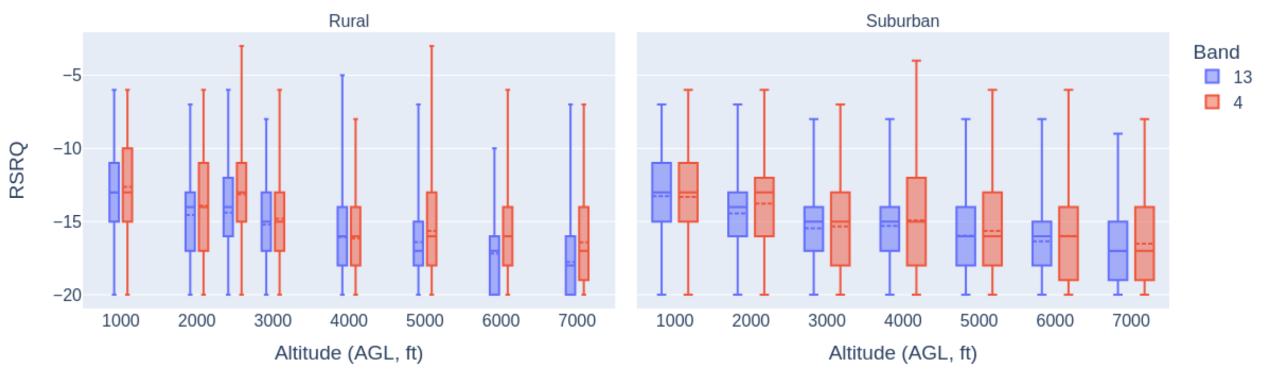
RSRQ

RSRQ is the Reference Signal Received Quality and measures the quality of a cell signal. It ranges from –20 dBm (worst) to 0 (best). Qualitatively, values above -10 dB are normally considered excellent. Overall, band 13 averaged -13.84 dB at 1000 ft, and -16.43 dB at 5000 ft.

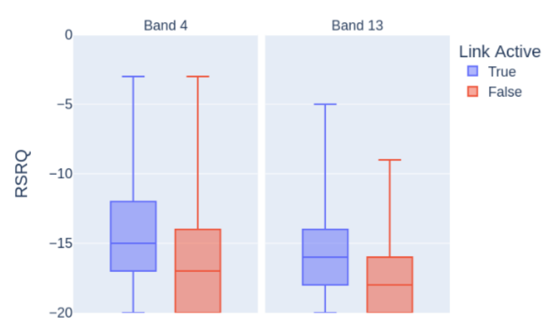
RSRQ by mission type:



RSRQ by environment:

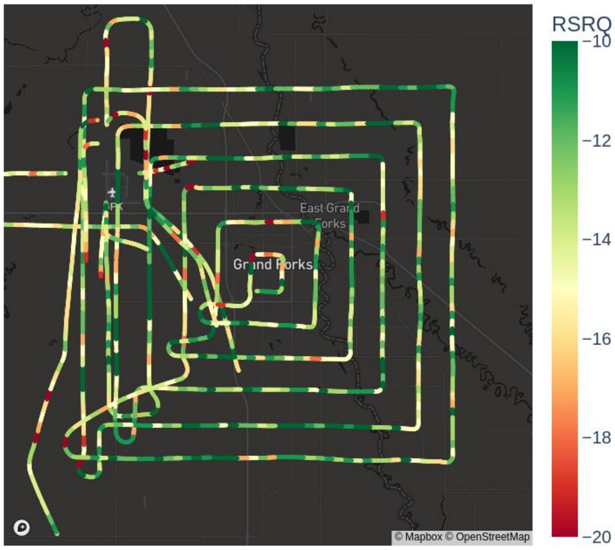


RSRQ during link loss events was slightly lower than during active link, with a difference in median of 2 and 3 dB for bands 13 and 4. However, RSRQ doesn't serve as a good indicator of link loss. Even at the minimum RSRQ of -20, 95% of data points have an established link.

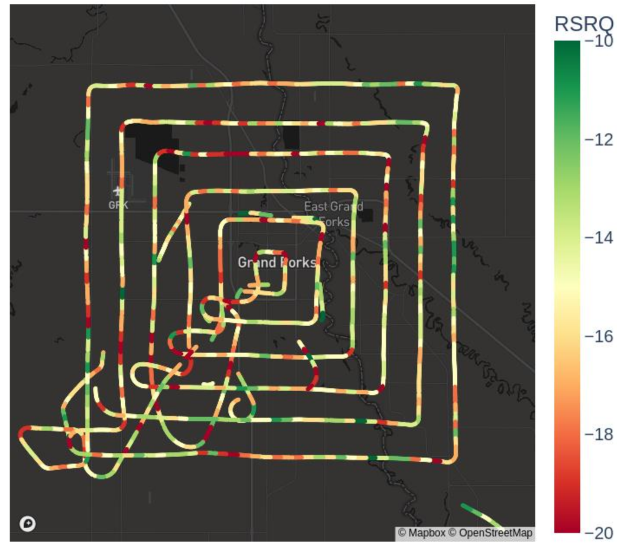


Grand Forks

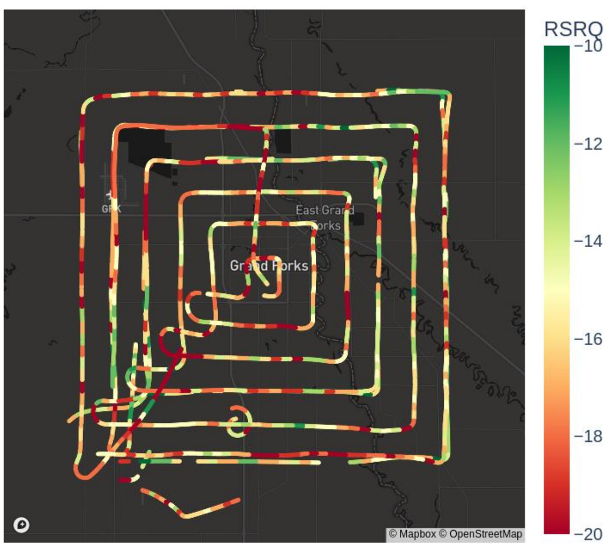
RSRQ - 1000 ft AGL - Band 13



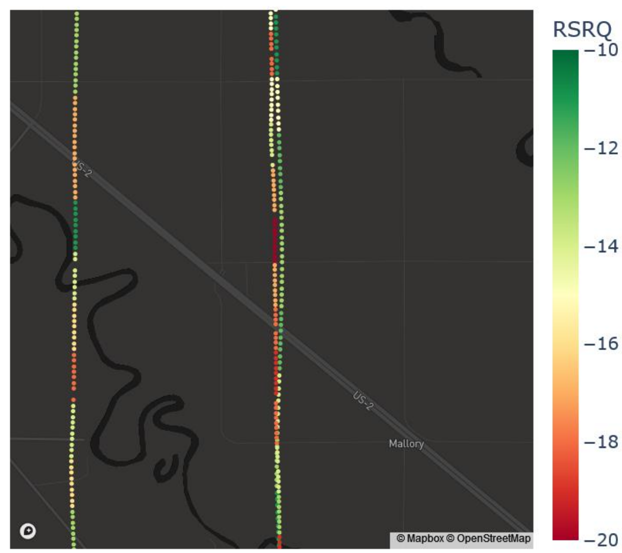
RSRQ - 3000 ft AGL - Band 13



RSRQ - 5000 ft AGL - Band 13



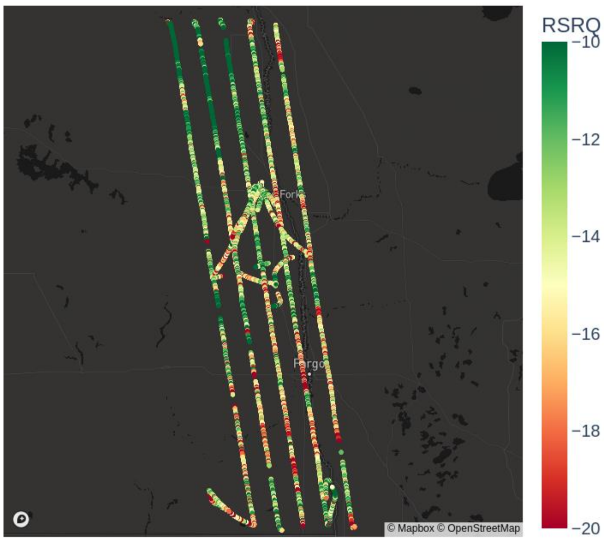
RSRQ - 5000 ft AGL - Band 13



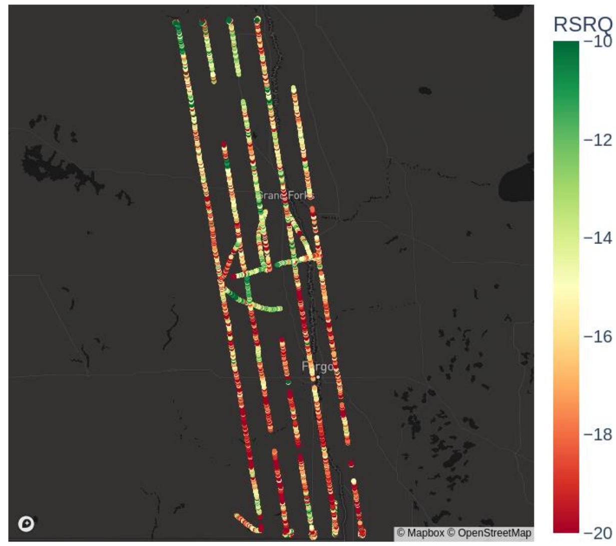
The above maps show RSRQ decreasing with altitude in the Grand Forks mission, from an average of -13.27 dB at 1000 ft to -15.97 dB at 5000 ft, or -0.67 dB per 1000 ft overall. In some of the higher altitudes, flight paths were repeated on a later date due to missing data from extended modem disconnections with band 4. The bottom-right map is zoomed in to the easternmost edge of the 11-mile ring, showing that RSRQ at a location can vary slightly by day.

Valley

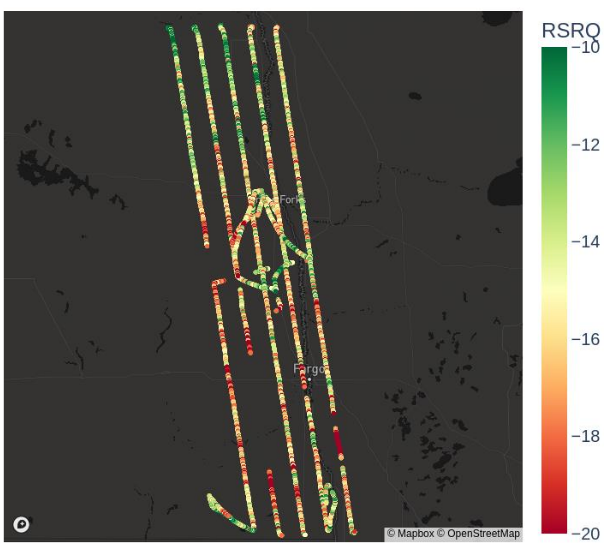
RSRQ - Band 4 - 2500 ft AGL



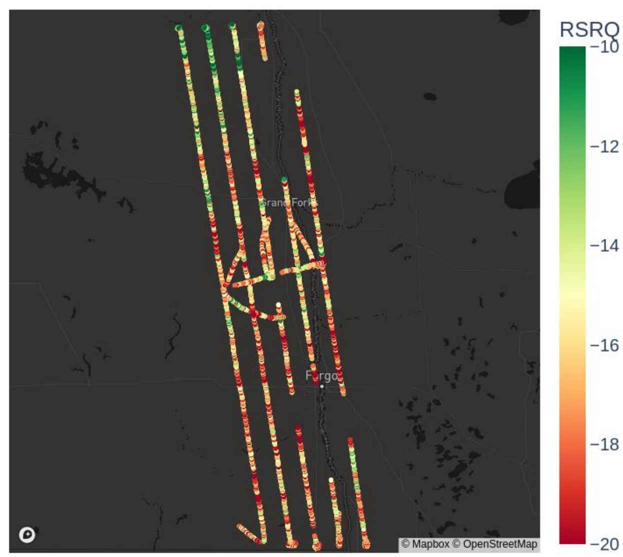
RSRQ - Band 4 - 5000 ft AGL



RSRQ - Band 13 - 2500 ft AGL



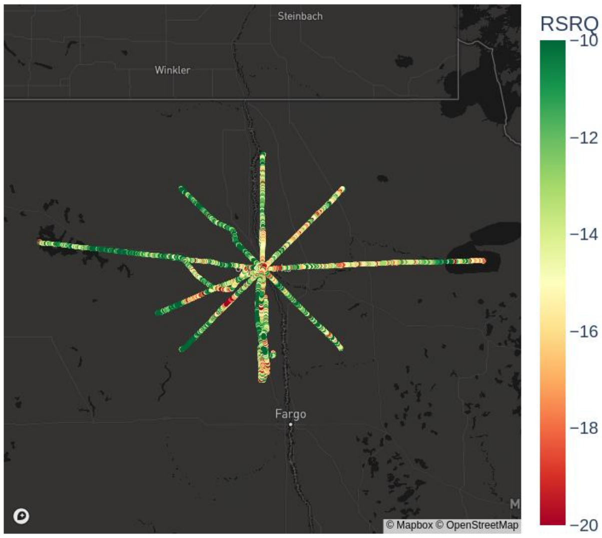
RSRQ - Band 13 - 5000 ft AGL



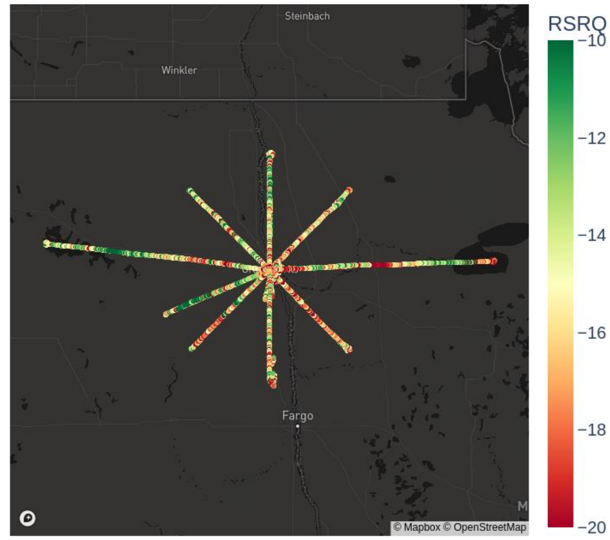
In the Valley mapping mission above, areas of tower disconnection are apparent (see Lost Link section). Grand Forks seems to be a transition point, where RSRQ is generally higher north of Grand Forks than south.

Spokes

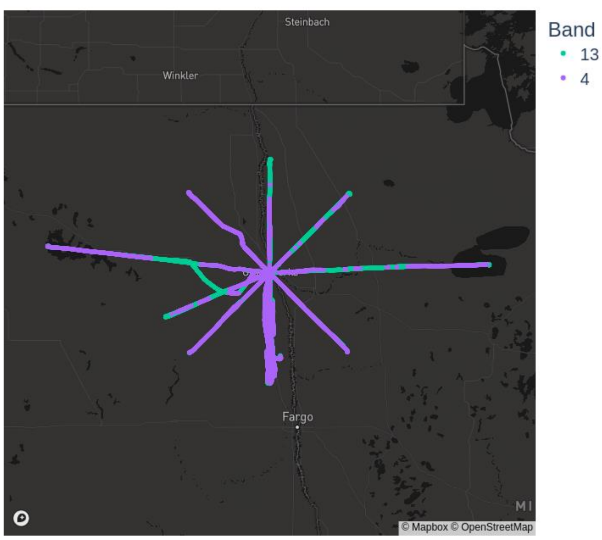
RSRQ - Band Auto - 2500 ft AGL



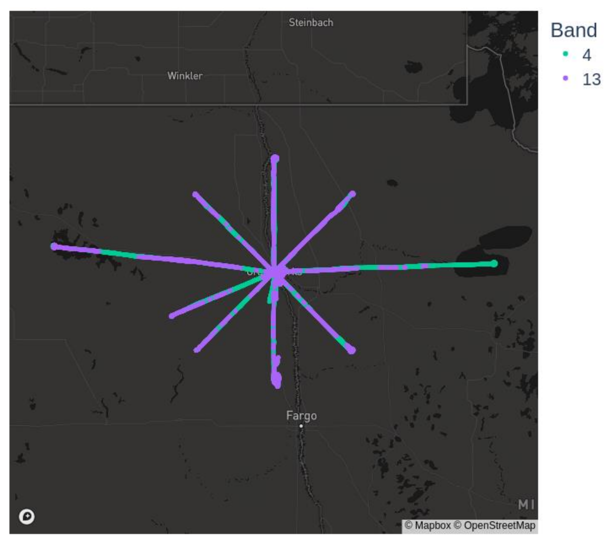
RSRQ - Band Auto - 5000 ft AGL



Flight Path - Band Auto - 2500 ft AGL

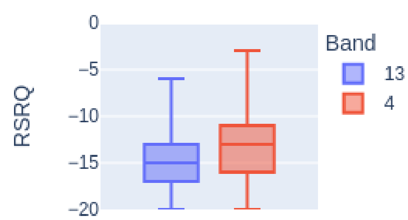


Flight Path - Band Auto - 5000 ft AGL

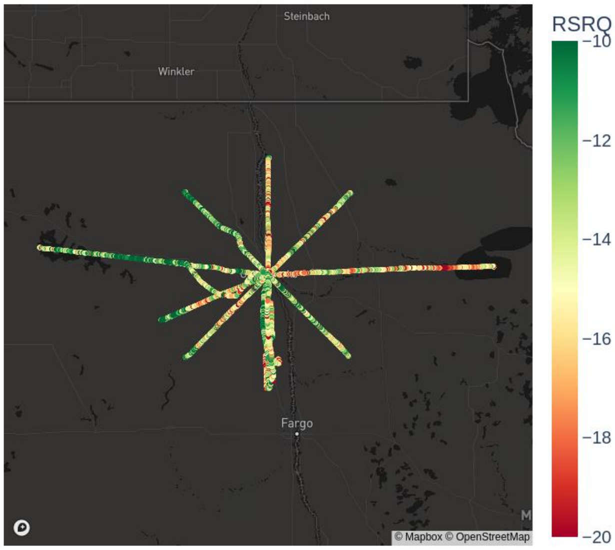


For the Spokes mission, one of the units was configured to band 13, and the other to let the modem switch between band 4 and band 13 as it saw fit. It chose band 4 for 60% of 2500 ft data and 62% of 5000 ft data. RSRQ was similarly higher for band 4 than band 13, with a median of -13 dB vs. -15 dB.

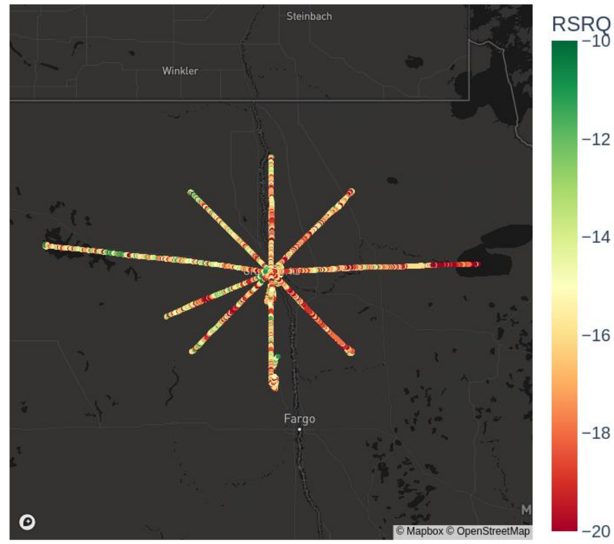
Spokes Auto RSRQ



RSRQ - Band 13 - 2500 ft AGL



RSRQ - Band 13 - 5000 ft AGL

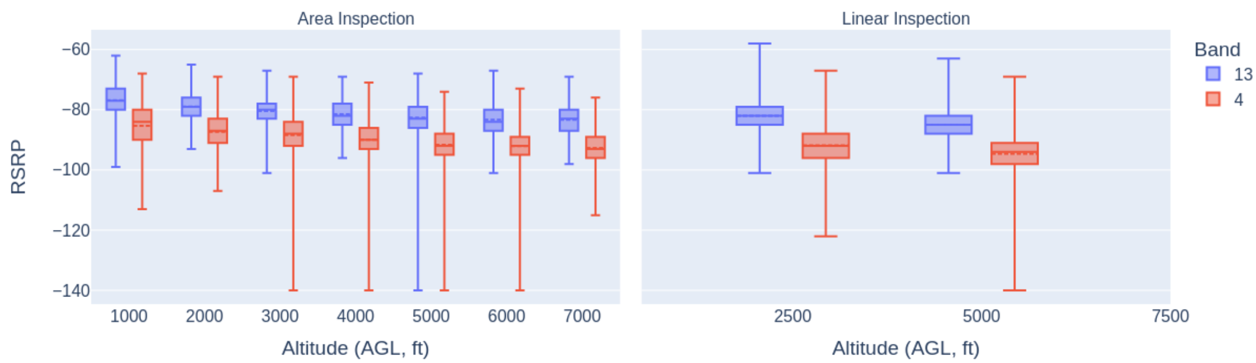


For band 13, the western leg shows much higher RSRQ than the eastern leg, speculatively due to closely following US Highway 2 in the west, while the east is mostly farmland with no major roads.

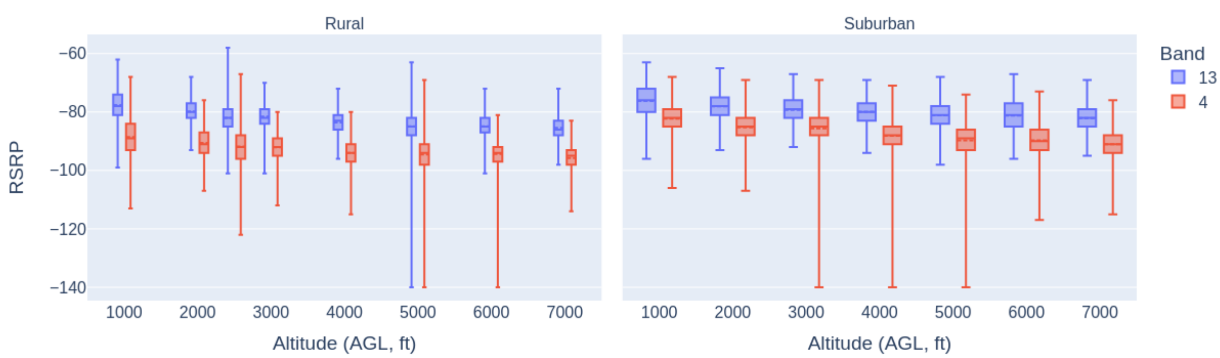
RSRP

RSRP is the Reference Signal Received Power, a measure of the strength of the cell signal. Typically, the bottom of the range is –100 dBm (cell edge), with values above –80 dBm considered excellent.

RSRP by mission type:



RSRP by environment:

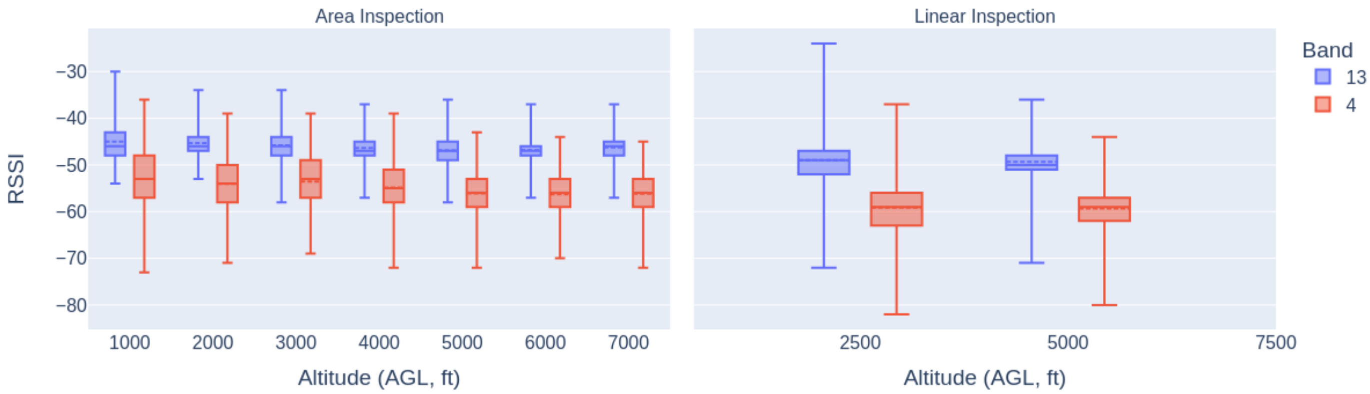


RSRP was consistently higher for band 13 than band 4. RSRP scaled linearly with altitude. The rural environment was slightly lower than suburban.

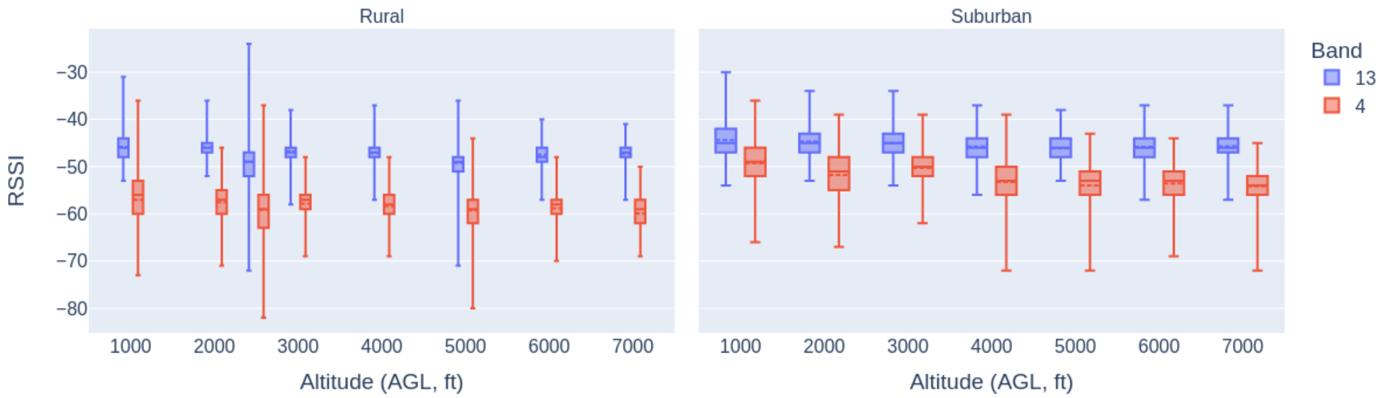
RSSI

RSSI is the Reference Signal Strength Indicator, traditionally used to measure the strength of cell signal for 3G networks. In 4G LTE networks such as the ALO network tested here, RSRP is a better measure of signal power than RSSI.

RSSI by mission type:



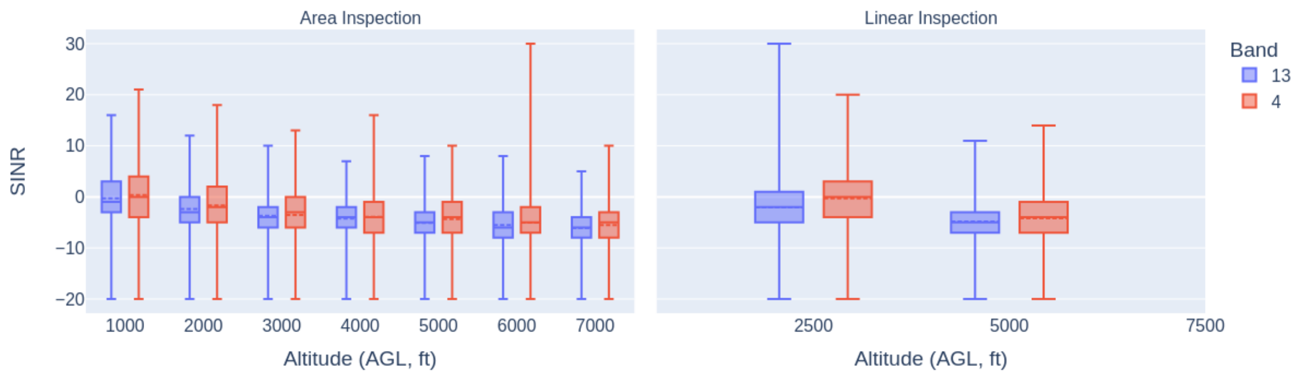
RSSI by environment:



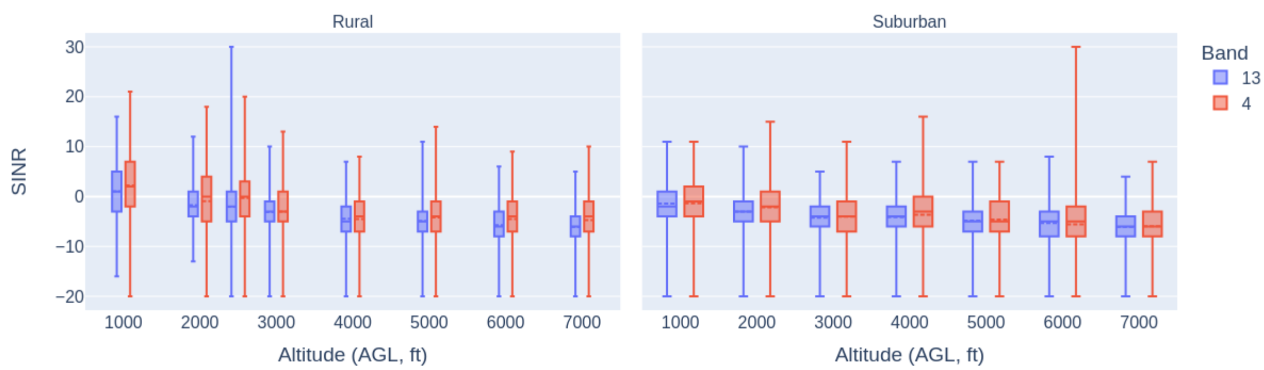
SINR

SINR is the signal to noise ratio of the cell signal. Values above 20 are excellent, with negative values indicating poor signal to noise ratio. With most data below the noise floor, hypothetically this may be the cause of frequent link loss.

SINR by mission type:



SINR by environment:



The best SINR was observed in rural environments at 1000 ft, the only segment showing an average value above 0. Band 4 consistently had higher values of SINR than band 13. Similar to RSRQ, SINR doesn't serve as an indicator of link loss, with only 2% of data points at the minimum value of -20 occurring during link loss.

Cell Signal Quality Metrics Summary Tables

This section contains more in-depth tables showing the same data as graphs above for cell signal quality metrics.

Area Inspection

Cell signal quality metrics for the Area Inspection missions (Hillsboro, Grand Forks 3D cubes):

		RSRQ			RSRP			RSSI			SINR		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	-20.00	-6.00	-13.16	-99.00	-62.00	-76.86	-54.00	-30.00	-45.03	-20.00	16.00	-0.26
	2000	-20.00	-7.00	-14.50	-93.00	-65.00	-78.94	-53.00	-34.00	-45.30	-20.00	12.00	-2.37
	3000	-20.00	-8.00	-15.35	-101.00	-67.00	-80.40	-58.00	-34.00	-45.84	-20.00	10.00	-3.70
	4000	-20.00	-5.00	-15.62	-96.00	-69.00	-81.49	-57.00	-37.00	-46.34	-20.00	7.00	-4.25
	5000	-20.00	-8.00	-16.55	-140.00	-68.00	-82.66	-58.00	-36.00	-46.88	-20.00	8.00	-5.11
	6000	-20.00	-8.00	-16.82	-101.00	-67.00	-83.32	-57.00	-37.00	-46.78	-20.00	8.00	-5.55
	7000	-20.00	-7.00	-17.29	-98.00	-69.00	-83.33	-57.00	-37.00	-46.25	-20.00	5.00	-6.10
4	**1000**	-20.00	-6.00	-12.99	-113.00	-68.00	-85.30	-73.00	-36.00	-52.98	-20.00	21.00	0.36
	2000	-20.00	-6.00	-13.84	-107.00	-69.00	-87.37	-71.00	-39.00	-54.05	-20.00	18.00	-1.65
	3000	-20.00	-6.00	-15.10	-140.00	-69.00	-88.41	-69.00	-39.00	-53.56	-20.00	13.00	-3.57
	4000	-20.00	-4.00	-15.31	-140.00	-71.00	-89.98	-72.00	-39.00	-54.87	-20.00	16.00	-3.93
	5000	-20.00	-6.00	-15.73	-140.00	-74.00	-91.60	-72.00	-43.00	-56.09	-20.00	10.00	-4.33
	6000	-20.00	-6.00	-16.00	-140.00	-73.00	-92.11	-70.00	-44.00	-56.29	-20.00	30.00	-5.04
	7000	-20.00	-7.00	-16.49	-115.00	-76.00	-92.66	-72.00	-45.00	-56.17	-20.00	10.00	-5.54

Long Line Linear Inspection

Cell signal quality metrics for the Long Line Linear Inspection missions (spokes, valley):

		RSRQ			RSRP			RSSI			SINR		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**2500**	-20.00	-6.00	-14.38	-101.00	-58.00	-82.01	-72.00	-24.00	-48.96	-20.00	30.00	-2.06
	5000	-20.00	-7.00	-16.34	-101.00	-63.00	-84.99	-71.00	-36.00	-49.37	-20.00	11.00	-4.81
4	**2500**	-20.00	-3.00	-13.14	-122.00	-67.00	-91.79	-82.00	-37.00	-59.12	-20.00	20.00	-0.28
	5000	-20.00	-3.00	-15.62	-140.00	-69.00	-94.60	-80.00	-44.00	-59.34	-20.00	14.00	-4.19

Rural

Cell signal quality metrics for rural environments (Hillsboro, spokes, valley):

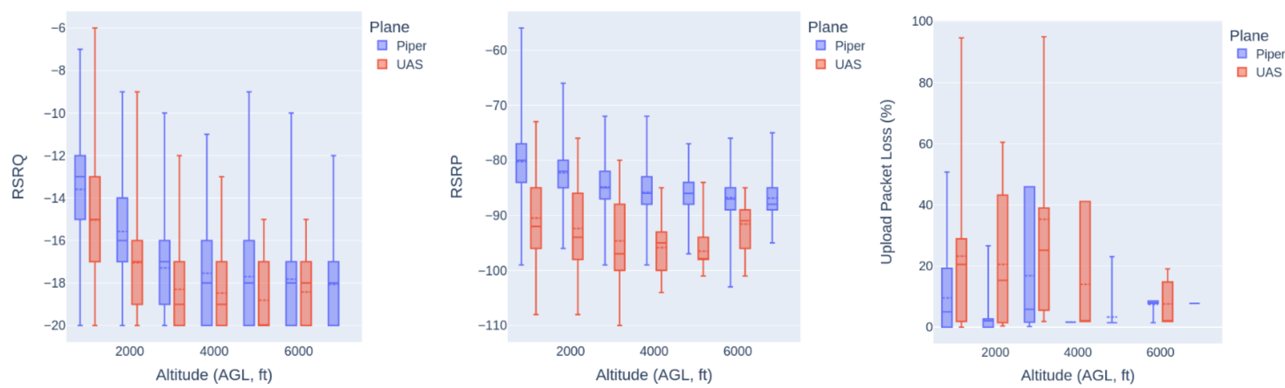
		RSRQ			RSRP			RSSI			SINR		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	-20.00	-6.00	-13.03	-99.00	-62.00	-77.63	-53.00	-31.00	-45.79	-16.00	16.00	1.06
	2000	-20.00	-7.00	-14.55	-93.00	-68.00	-79.81	-52.00	-36.00	-45.91	-13.00	12.00	-1.74
	2500	-20.00	-6.00	-14.38	-101.00	-58.00	-82.01	-72.00	-24.00	-48.96	-20.00	30.00	-2.06
	3000	-20.00	-8.00	-15.21	-101.00	-70.00	-81.61	-58.00	-38.00	-46.74	-20.00	10.00	-3.10
	4000	-20.00	-5.00	-16.06	-96.00	-72.00	-83.59	-57.00	-37.00	-47.10	-20.00	7.00	-4.43
	5000	-20.00	-7.00	-16.41	-140.00	-63.00	-84.94	-71.00	-36.00	-49.23	-20.00	11.00	-4.86
	6000	-20.00	-10.00	-17.18	-101.00	-72.00	-84.88	-57.00	-40.00	-47.49	-20.00	6.00	-5.71
	7000	-20.00	-7.00	-17.77	-98.00	-72.00	-85.46	-57.00	-41.00	-47.24	-20.00	5.00	-6.12
4	**1000**	-20.00	-6.00	-12.63	-113.00	-68.00	-88.61	-73.00	-36.00	-57.02	-20.00	21.00	2.21
	2000	-20.00	-6.00	-13.92	-107.00	-76.00	-90.63	-71.00	-46.00	-57.54	-20.00	18.00	-0.91
	2500	-20.00	-3.00	-13.14	-122.00	-67.00	-91.79	-82.00	-37.00	-59.12	-20.00	20.00	-0.28
	3000	-20.00	-6.00	-14.81	-112.00	-80.00	-92.07	-69.00	-48.00	-57.84	-20.00	13.00	-2.99
	4000	-20.00	-8.00	-16.15	-115.00	-80.00	-93.97	-69.00	-48.00	-58.34	-20.00	8.00	-4.52
	5000	-20.00	-3.00	-15.64	-140.00	-69.00	-94.53	-80.00	-44.00	-59.28	-20.00	14.00	-4.16
	6000	-20.00	-6.00	-16.01	-140.00	-81.00	-94.33	-70.00	-48.00	-58.84	-20.00	9.00	-4.53
	7000	-20.00	-7.00	-16.43	-114.00	-83.00	-95.77	-69.00	-50.00	-59.94	-20.00	10.00	-4.70

Suburban

Cell signal quality metrics for suburban (Grand Forks) environment:

		RSRQ			RSRP			RSSI			SINR		
		min	max	mean	min	max	mean	min	max	mean	min	max	mean
Band	**Altitude (AGL, ft)**												
13	**1000**	-20.00	-7.00	-13.27	-96.00	-63.00	-76.19	-54.00	-30.00	-44.36	-20.00	11.00	-1.42
	2000	-20.00	-7.00	-14.45	-93.00	-65.00	-78.09	-53.00	-34.00	-44.70	-20.00	10.00	-2.99
	3000	-20.00	-8.00	-15.47	-92.00	-67.00	-79.31	-54.00	-34.00	-45.04	-20.00	5.00	-4.23
	4000	-20.00	-8.00	-15.30	-94.00	-69.00	-79.94	-56.00	-37.00	-45.78	-20.00	7.00	-4.11
	5000	-20.00	-8.00	-15.97	-98.00	-68.00	-81.12	-53.00	-38.00	-46.11	-20.00	7.00	-4.85
	6000	-20.00	-8.00	-16.36	-96.00	-67.00	-81.25	-57.00	-37.00	-45.83	-20.00	8.00	-5.33
	7000	-20.00	-9.00	-17.02	-95.00	-69.00	-82.08	-57.00	-37.00	-45.67	-20.00	4.00	-6.09
4	**1000**	-20.00	-6.00	-13.31	-106.00	-68.00	-82.25	-66.00	-36.00	-49.28	-20.00	11.00	-1.34
	2000	-20.00	-6.00	-13.78	-107.00	-69.00	-85.22	-67.00	-39.00	-51.75	-20.00	15.00	-2.14
	3000	-20.00	-7.00	-15.33	-140.00	-69.00	-85.57	-62.00	-39.00	-50.25	-20.00	11.00	-4.01
	4000	-20.00	-4.00	-14.91	-140.00	-71.00	-88.14	-72.00	-39.00	-53.26	-20.00	16.00	-3.65
	5000	-20.00	-6.00	-15.63	-140.00	-74.00	-89.74	-72.00	-43.00	-54.00	-20.00	7.00	-4.63
	6000	-20.00	-6.00	-15.99	-117.00	-73.00	-89.74	-69.00	-44.00	-53.58	-20.00	30.00	-5.58
	7000	-20.00	-8.00	-16.52	-115.00	-76.00	-91.02	-72.00	-45.00	-54.19	-20.00	7.00	-5.98

UAS VS MANNED CELL PERFORMANCE



The UAS with its smaller antenna showed poorer cell signal reception than the manned aircraft. The above plot shows the distribution of RSRQ, RSRP and packet loss for the Fertile and Mayville missions, colored by whether the aircraft was the manned Piper with large antennae or the UAS with smaller antennae. The UAS with its smaller antenna showed poorer cell signal reception than the manned aircraft. The above plot shows the distribution of RSRQ and RSRP for the Fertile and Mayville missions, colored by whether the aircraft was the manned Piper with large antennae or the UAS with smaller antennae.

6. LESSONS LEARNED

Technology and Integration Lessons Learned

This section covers lessons learned with the ALO technology and how things could be different a second time around.

Cell Modem Maturity

ALO is relatively new technology, so new in fact that the cell modem firmware on the cell modem used was being developed at the same time as Appareo was adding it into the ACU-200. The maturity of this firmware is still being improved upon. As of today, the cell modem does not officially support band 4, and band 4 was prone to falling into a permanent disconnect state, where the modem would say that it had established a tower connection, but no internet link was available to the operating system. Band 13 also had a few issues when it came to being able to re-establish a lost connection, and the aggressive measure of restarting the modem to force a reconnection used in this testing to maximize data collection would certainly fail certification by carriers. In retrospect it would have been good to spend more time up front with the cell modem manufacturer addressing some of these issues before this testing, however, non-flight testing performed did not indicate a disconnect issue was present. As such it should be assumed that the results collected provide a lower bound for the capability of the ALO network, and that better performance is likely.

Network Constraints

During the testing, Verizon constraints on how ALO is integrated were key drivers of performance, retry logic and upload data rate limiting.

Retry logic limits the number of times the modem would try to reconnect to the network. During an outage, this can cause additional outage time as the modem waits for the retry timer to expire. It is understood that this is in place to keep modems from constantly trying to connect when there is an issue and overloading a tower. However, for ALO in challenging signal environments, allowing more aggressive reconnect attempts could be a major factor in decreasing link loss frequency and duration.

Verizon has indicated the intent to cap data upload rate for ALO modems at 2 Mbps. Data gathered in this effort shows higher values as the cell-network side throttling had yet to be implemented by Verizon. A motivation for the 2 Mbps cap is to limit the amount of data being transmitted by modems which have access to more cell towers than normal while being up in the air. This cap limits the video streaming quality and general throughput capabilities.

While there were early indications that tower location data would be provided by the network provider, this did not come to fruition and crowd-sourced data was used instead.

Video Quality

The cockpit video recorder (AIRS-400) is tightly tuned for specific mounting locations in aircraft. This ideal mounting location was not able to be used given it would have physically altered aircraft to install it in that location. When aiming the camera directly out the window it resulted in a washed-out image, looking like sunlight with a small sliver of visible ground at the bottom, and wasn't useful for demonstrating motion in video. This was ultimately overcome by aiming the camera at an iPad playing a video in the back seat to test smoothness of motion.

MANNED AND DRONE FLIGHTS LESSONS LEARNED

This section covers lessons learned in the planning and execution of the manned and drone flights.

Flight Planning Scope Definition

While Appareo, the test site, and drone/aircraft operator were able work together to collect the data desired, it became apparent that there were different expectations on what 1 week of flight testing consisted of. More clarity and definition would have helped avoid this such as defining a minimum number of flight hours or minimum number of data collection objectives. The different organizations could then scope the assumptions and expectations so that in the case that those assumptions were broken, then there could be a discussion about further funding or change in scope in the effort. We were lucky to have such a great group of people and organizations working on this effort that were able to be flexible in achieving the goals set out for this testing.

Manned Flights Near Major Flight Training Center and Air Force Base

As the flight provider, the Northern Plains UAS Test Site's (NPUASTS) primary challenges were to assist Appareo in their collection of Cellular LTE data at various altitudes and distances. Manned test flights were completed by mounting Appareo ALO radios to a manned Piper Cherokee that then flew different scenario patterns at different altitudes and environments for the different Flight Test events. Manned Piper Cherokee flights were piloted by iSight Drones Services personnel; The NPUASTS test directed and oversaw all of the manned flight scenarios for this effort.

The manned Piper Cherokee flights required an extra level of coordination with the Grand Forks International Airport (GFK) and tower communications with the Grand Forks Air Force Base (RDR), depending upon the scenario flights. At times this required flights to occur at special times when local air traffic would be its lowest to reduce the airspace risk in areas of high-volume aviation student and training traffic. The scenario segments that were flown directly over or near GFK were mostly relegated to operations occurring the in the early hours of Sunday mornings when student air traffic is at its lowest. Any future three-dimensional mapping of ALO signal coverage area efforts will have to strictly coordinate with local airports and air traffic control in order to safely collect the ALO data at specific sampling distances and altitudes.

Drone Flight Approvals

An unforeseen challenge to the Northern Plains UAS Test Site's (NPUASTS) ability to provide and enable advanced UAS operations was the FAA's reinterpretation of access to public Certificate of Authorization (COA) airspace approvals that was declared several months after the FAA BAA awards were first issued. The timing of this declaration put Appareo's entire BAA award and associated work at risk, when a grandfather clause or transition timeline would have been a more acceptable strategy to redefine the type of flights that qualify for public COA guidelines. This caused the NPUASTS to pivot to the Part 107 waiver approval process, thus causing unplanned delays and extra contractual work to extend the period of performance with Appareo.

Due to the Part 107 process being a long and protracted effort when applying for approval to perform advanced UAS operations, the NPUASTS had to create two sequential waiver application packages to allow for daisy-chained visual observers, in a safely coordinated airspace, up to an altitude of 6,000 feet above ground level. This means this Appareo FAA BAA research effort was put at risk while waiting for two Part 107 waiver application queues which added months to the period of performance. Both Appareo and the NPUASTS were able to pivot and perform to the research required under the stricter and lesser scope of the approved Part 107 operations but not necessarily to the data sampling level that both parties would have preferred and originally envisioned. Despite the reduced scope of UAS operations flying and testing the ALO payload, Appareo and the NPUASTS were able to safely perform some advanced UAS flight tests that allowed Appareo to collect ALO data at altitudes above the typical part 107 ceiling of 400 feet above ground level.

Drone Flight Execution

UAS flights were flown under Part 107 rules and waivers with oversight conducted by the NPUASTS. The SuperVolo UAS is large for a under 55-pound UAS with nearly a 9.8-foot wingspan, but even at that size care and strategy was needed to conduct chase plane activities for these altitude scenarios up to 6,000 feet AGL as allowed per the waiver.

To achieve safe chase plane operations, the Piper Cherokee would orbit the SuperVolo UAS launch site at 1,000 ft AGL so that the manned aircraft could witness the launch of the UAS. The UAS would then enter a smaller orbit offset from the Cherokee orbit until the Cherokee could maneuver into a formation flying pattern. The SuperVolo UAS pilot would then coordinate with the Test Director and manned Cherokee pilot to climb in altitude in coordinated 200-foot increments. This method was the most efficient and least stressful for the Cherokee pilot and visual observer. With the SuperVolo UAS always in a circular orbit or in a circular spiral while climbing or descending, this kept the UAS at an offset visual angle was that easier for the chase plane to see or quickly reacquire if the sightline was lost. These circles and spirals for the formation flying were flown counter-clockwise; if the chase plane visual was loss, the Cherokee pilot would turn right, and the SuperVolo UAS would turn left, with visual handed over to the ground-based observers. Then the UAS would reestablish its scenario orbit, with the chase plane following at an offset distance to require visual and then continue with the flight scenario. Challenges to this method would come from the weather conditions; if it was noticeably hazy at altitude then the teams would fly below that altitude to maintain clearer visual tracking and maintain safe operations.

7. RECOMMENDATIONS

Future Project Setup

This section covers recommendations that may allow smoother BAA projects based on observations throughout this effort.

Drone Flight Approvals

Ensure the applicant of the program is made aware of any potential rule changes within the FAA that may impact the program. Likewise, the applicant(s) should be encouraged to review the recent FAA rules or similar for any changes prior to starting the program. If possible, a grandfather clause of sorts would be ideal to ensure minimal disruption and a more successful execution of the program. This may be an infrequent type of event, but it was one the most disruptive to the program. Fortunately, it was resolved without impacting the budget or the completion of the effort.

Flight Planning Constraints / Definitions

As noted in the lessons learned, there may be benefit to ensuring the applicant has a clear set of definitions on what a period of flight testing consists of to ensure there isn't confusion. This also didn't cause an issue with this program as the team was able to work through the different expectations of the parties involved, but if this advice was provided to future BAA efforts that could help avoid an unfortunate situation.

Cell Tower Locations

Consider including the network provider or arranging the ability for network providers to provide key data such as cell tower data that may be protected information. While this effort was able to produce good results, it would have been better with more accurate cell tower location data.

Network and Modem Integration Recommendations

This section covers recommendations that may allow better ALO performance in future BAA projects based on the observations throughout this effort.

Network Provider Retry Logic

Consider suggesting to network providers to allow alternate retry logic in challenging signal environments. Possibly by using a lookup table via GPS to allow more frequent connection retries in remote areas, under supported areas, or challenging signal environments.

Network Upload Throttling

Consider suggesting to network providers that the limitation is adjusted or removed for specific use cases that require higher throughput such as critical video surveillance activities. Possibly a waiver system with the network(s) to request additional throughput.

Band 4

Given that Band 4 is not officially supported on the modem used, it is recommended that the modem and the platform that the modem is integrated in are certified for Band 4 and both organizations fix any issues that may be occurring on this frequency. Additionally, it appears there may be another modem or two now on the market as of today that support Band 13 and Band 4. A switch to another modem or comparison of modems for a future test effort would be recommended as well.

ALO Modem Performance

It is recommended that further work with the modem supplier to improve the modem performance or the resulting performance of the integration of the modem be further refined to ensure optimal results.

Other Networks / Modems

It is also recommended that future efforts consider other networks as they add ALO capabilities and other modems as more become available on the market. The ALO options available were and still are fairly limited.

Further Testing and Data Analysis

This section covers recommendations for further testing and data analysis to enhance the performance understanding of ALO in future BAA (or equivalent) efforts.

Demonstration of VOIP Testing

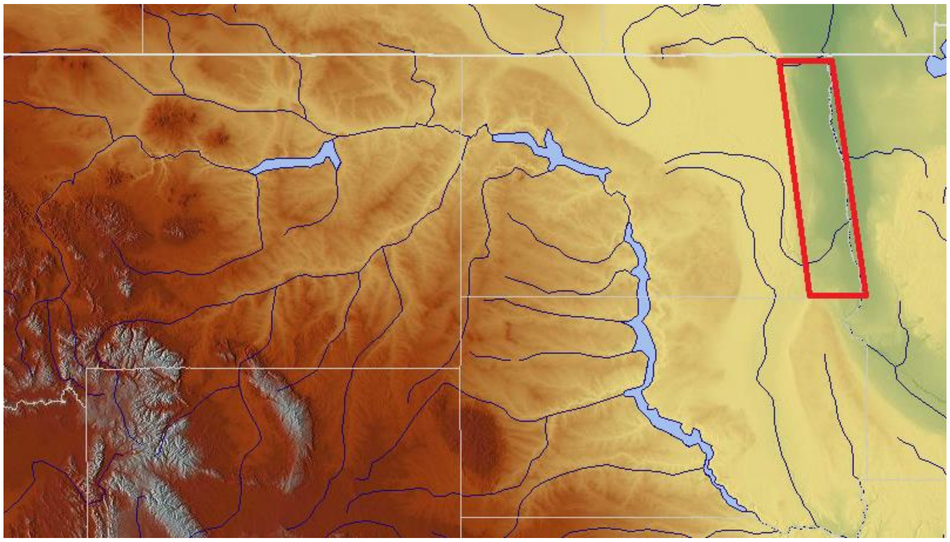
Voice over IP (VOIP) initial results were speculatively provided in this report however real-world testing of voice performance should be considered for qualitative analysis. This technology would be useful for relaying audio from pilots broadcasted near the UAS.

After Further ALO Maturity

Since ALO is fairly new, there were some issues discovered during this test. After those issues are resolved further testing is suggested. Those issues may be resolved via further modem, modem integration, and network refinement to ensure optimal ALO performance

Varied Terrain

Testing was done in a very flat area which is a great way to test the ALO performance without having terrain impact the results. However, it would be good to do a reality check in more challenging terrain environments that result in cell towers being blocked, to see if ALO outperforms ground-based LTE modems in those areas. Additionally, this could discover if there are any signal blocking or reflection concerns in those types of terrains. As shown in the below picture highlighted in red, the region that this effort tested in is extremely flat compared to the rest of the country.



Elevation Map of North Central US
(Montana / North Dakota / South Dakota)
Red highlighted region was general testing area.

Data Analysis

Further data analysis could be performed in the future on the data collected or via another test collection effort to further utilize IMU (roll/pitch/heading) and GPS data to evaluate arrival angle of signals relative to the cell tower and impact of different antennas. At this time the current data is unlikely to produce meaningful results in this area without further refinement of the connection and by also being able to obtain accurate cell tower location data.