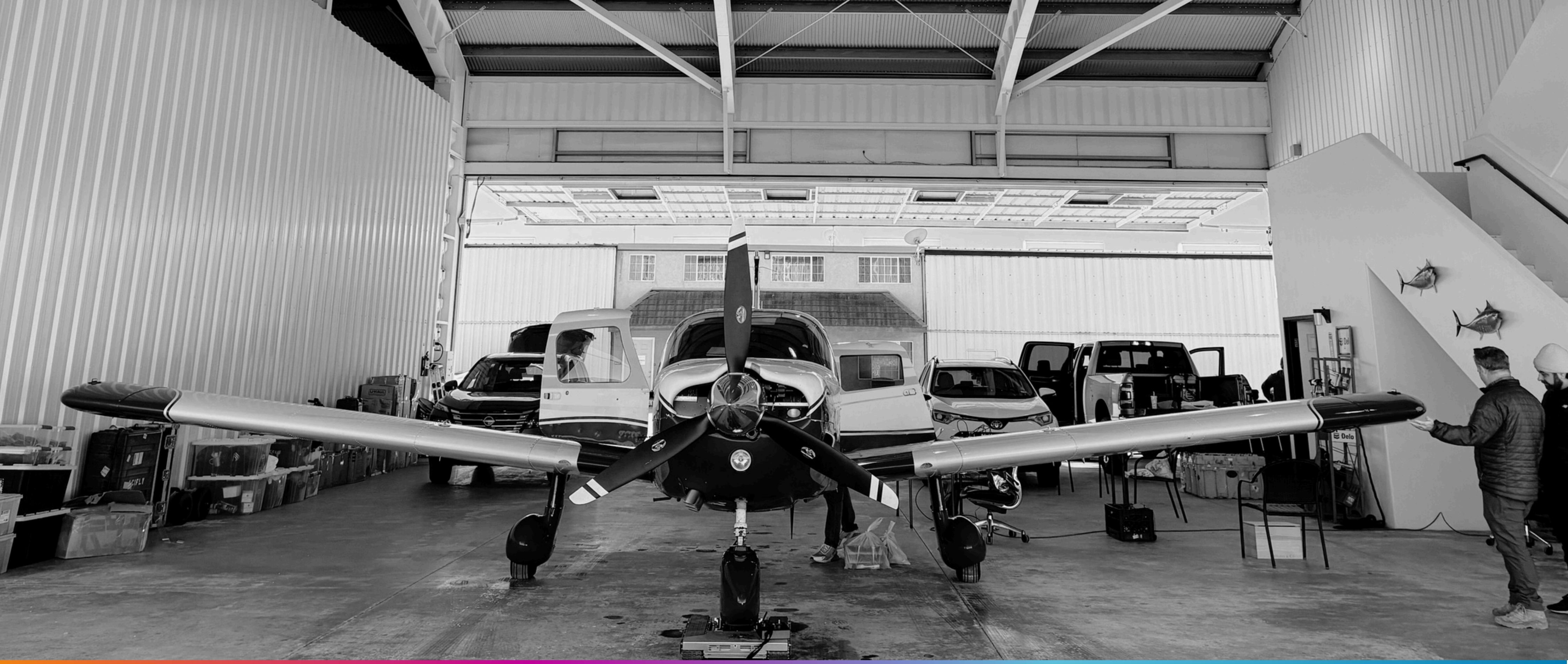

DOODLE LABS

Evaluating Ultra Long-Range Air-to-Ground S-Band Communication

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DOODLE® LABS

1. Introduction

This document details the S-Band airborne testing conducted by Doodle Labs, where an airplane equipped with Optimum Solution's blade antennas linked to a ground-based Optimum Solution tracking antenna located along the coastline in North County San Diego.

The objective of the test was to evaluate the range limits of the Mesh Rider radios and assess the impact of high-gain antennas and bidirectional amplifiers on system performance. NuWaves bidirectional amplifiers were utilized during the experiment to support these assessments.

The tests successfully spanned 328 km at altitudes reaching 7,500 ft AGL, though the maximum distance was not determined due to hitting restricted airspace and far exceeding expected range. During the flight, throughput data and link metrics were collected to validate the radios' performance at extended ranges.

2. Objectives

- Validate the maximum range and throughput achievable on S-Band while airborne.
- Assess the effectiveness of the Optimum Solution's tracking system and antenna feed for ground-based tracking across a long-range link.
- Evaluate reliability, data transfer rates, and overall link stability of the Doodle Radio RM-2025 Multiband Mesh Rider Radio while using high-gain antennas and NuWaves bidirectional amplifiers.

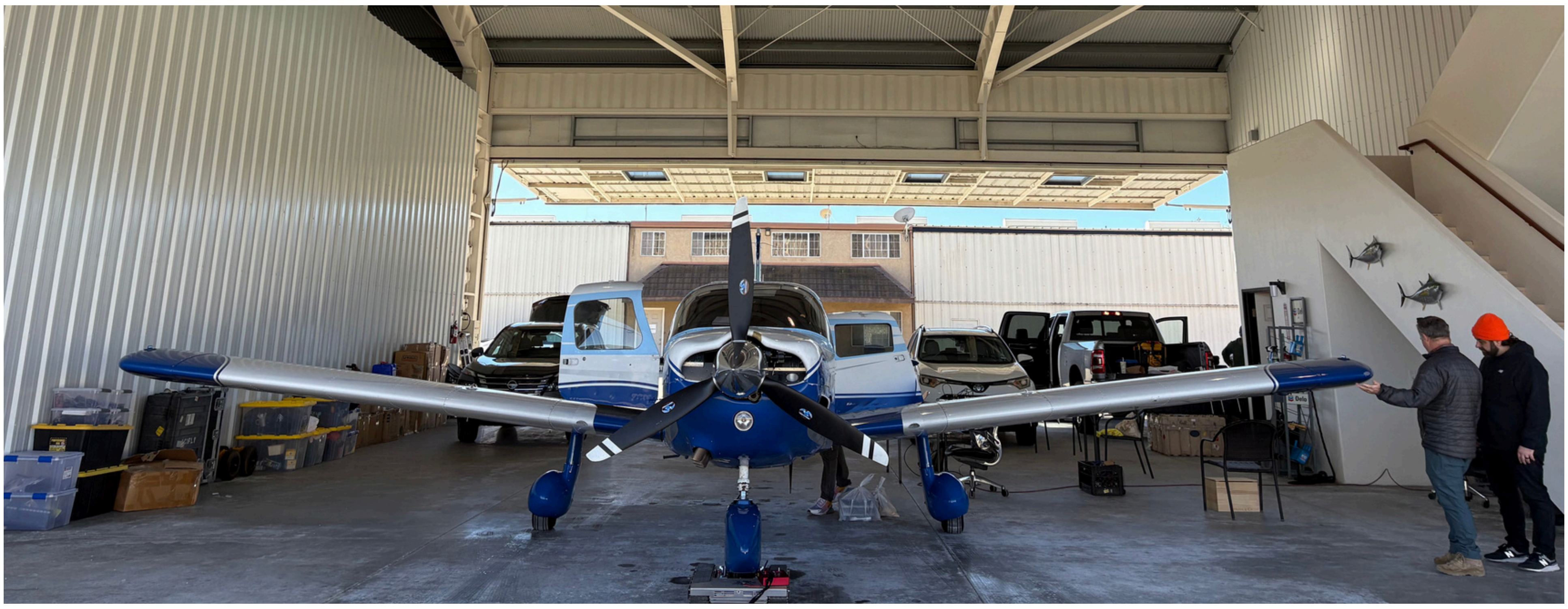

Figure 1 - Set up in the Hangar

3. Test Details & Methodology

3.1. Test Locations and Configuration

Ground Station Details

Antenna: Optimum Solution's PT-100 Tracking System
- Dual Dish Feed 24dBi gain
- Vertical + Vertical Polarization

GCS Computer: Windows 11 PC
- Optimum Solution Tracking Software (OST)
- ADS-B Fallback Antennas (1090 MHz ADS-B + 978 MHz UAT) connected to RTLSDR
- GPS USB Receiver

Radio: RM-2025-62M4

BDA: NW-BA-DUAL-LS-20-S01-D30, Dual Channel 25 W

Airplane Details

Antenna: Equipped with Optimum Solution's OS-2025-C Blade Antennas mounted face down on each wing with vertical polarization.

Onboard Computer: Raspberry Pi 4B
- GPS Receiver
- Connected via Ethernet to Doodle Radio

Radio: RM-2025-62M4

BDA: NuWaves NW-BA-DUAL-LS-20-S01-D30, Dual Channel 25 W

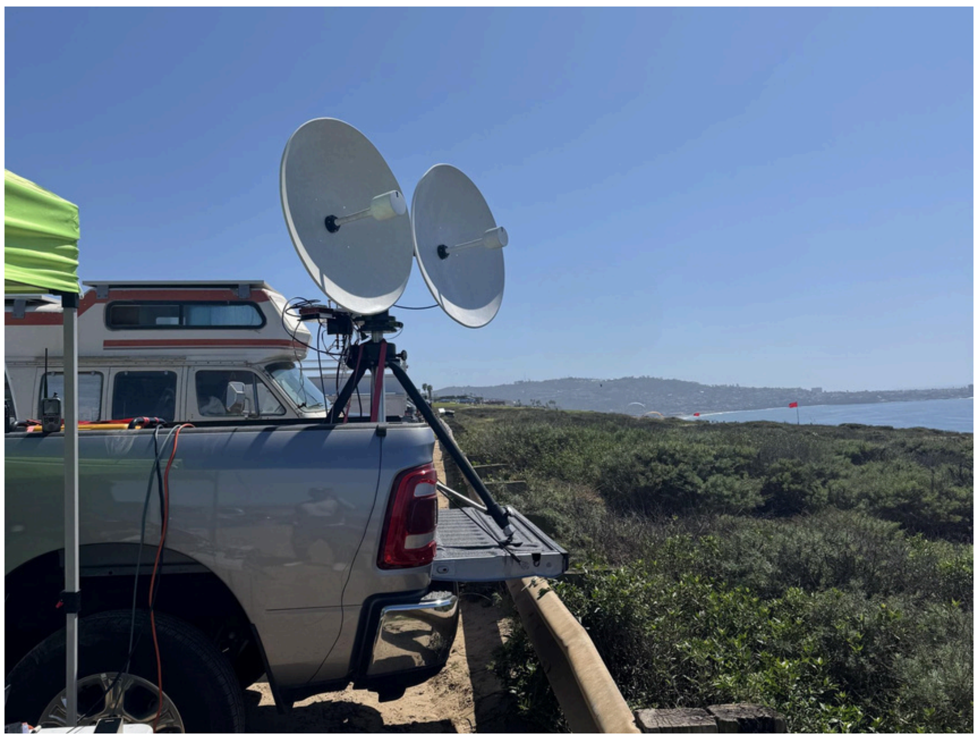

Figure 2 - Ground Station Tracking System

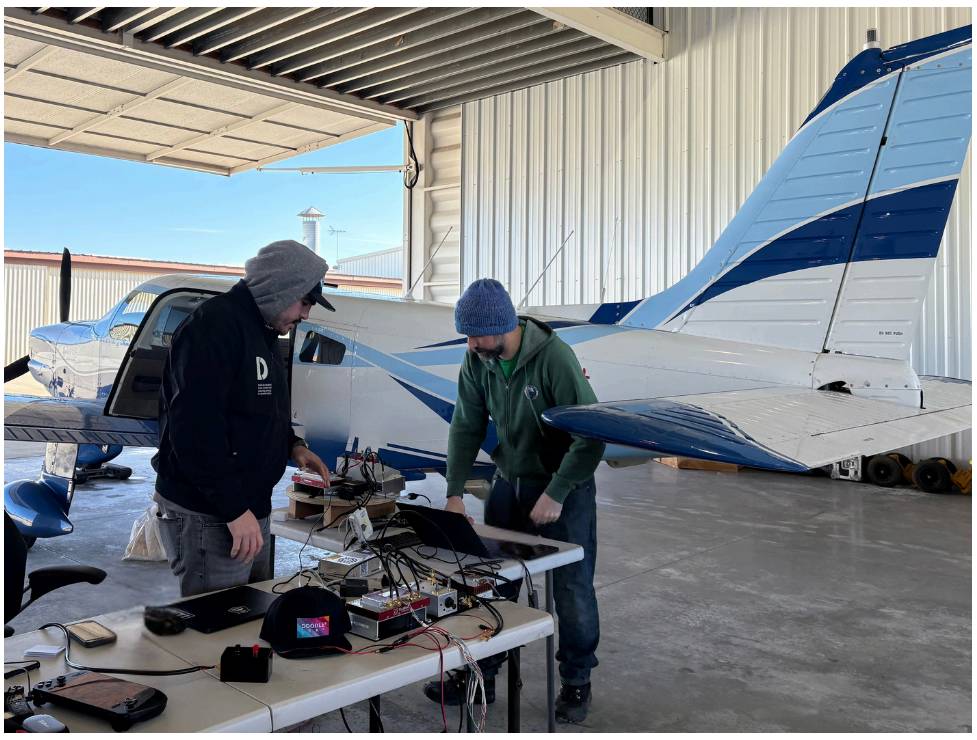

Figure 3 - Airplane Set Up

3.2. Environmental Conditions:

- Clear Skies
- 70 °F
- Light Wind

3.3. Physical Setup Details

Ground Station

The tracking system was installed in the back of a pickup truck, backed up to the bluff along the coastline. Power was delivered to the system and computer via an AC to DC converter, supplied by the truck. An extension cord was run to a table where computers were used to run throughput tests and the tracking software. The Doodle Labs' radio and BDA were powered via an adjustable DC power supply.

Airplane

The radio, BDA, Raspberry Pi, network switch, and a custom-made power control panel were all mounted on a portable prototype platform placed inside the aircraft. Power was supplied via a variable AC to DC power supply. AC was provided by an onboard inverter on the aircraft. Optimum Solution S-Band blade antennas were affixed to the underside of each wing with coax runs to the BDA ports.

3.4. Radio Configuration

- **Firmware Version:** firmware-2024-10.4
- **Center Frequency:** 2250 MHz
- **Channel Bandwidth:** 3/5/10/20 MHz
- **TX Power:** 30dBm
- **Mode of Operation:** AP/Client
- **Distance:** 114750
- **Diversity Rates:** Off

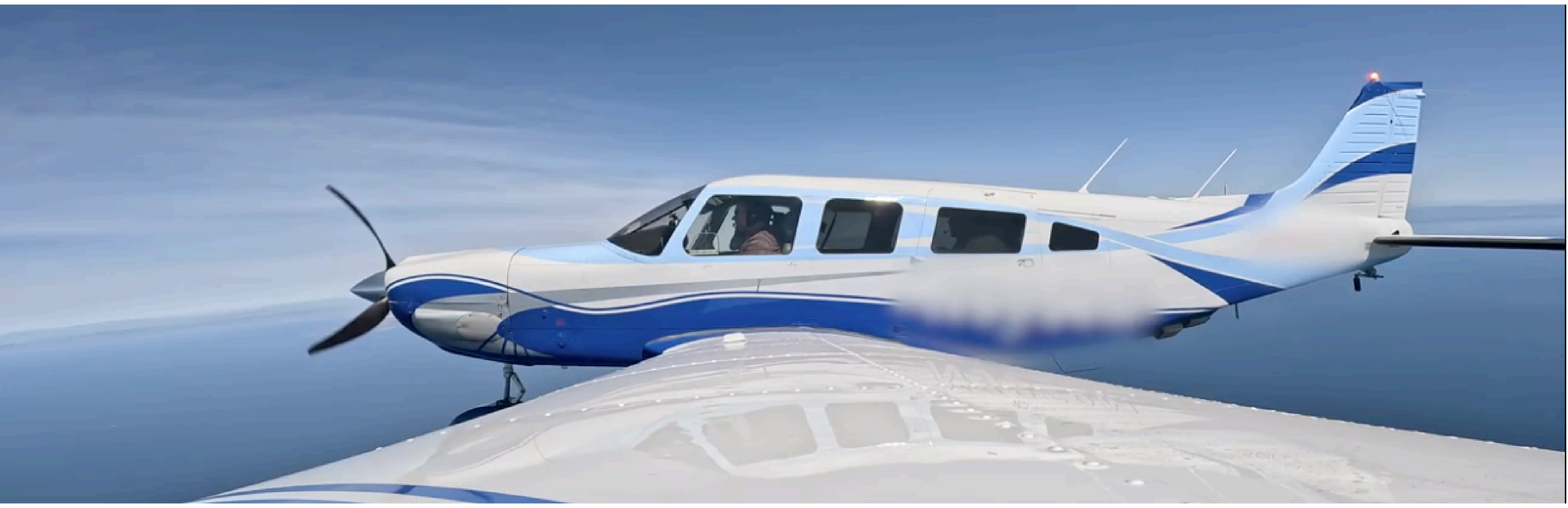

Figure 4 - Airplane in flight

4. Test Procedures

4.1. Plan Summary

The test plan was for the aircraft to depart from an inland airport and proceed toward the coastline, then turn north along the coast to establish the maximum achievable communication range using a 5 MHz channel bandwidth. Immediately after takeoff, the ground station would begin tracking the aircraft upon receiving position data from the plane's onboard transponder. Once the transponder signal was detected and initial aircraft positioning was calculated, the ground-based tracking system was to establish connectivity with the aircraft via the Doodle Labs radios.

With this connection established, GPS data from the aircraft's onboard receiver was transmitted back to the ground station through the link, enabling continuous and precise tracking of the aircraft throughout the flight. After determining the maximum effective communication range using the 5 MHz bandwidth, the intention was for the aircraft to reverse its course. During the return flight, additional throughput testing would be conducted, capturing performance data across multiple channel bandwidths for comprehensive analysis. However, due to hitting restricted airspace and far exceeding expected range, the maximum range was not determined, but we did achieve 328 km.

4.2. Data Collection

The Raspberry Pi had an iperf3 daemon running on it. Periodic throughput tests for forward and reverse TCP and UDP were conducted. Throughout the flight, including times when throughput tests were conducted, the link status log utility remained active on each Doodle radio, capturing all system logs and RF link metrics.

```
perf Done.
ory@Corys-MacBook-Air trackingtest % iperf3 -c 10.223.200.200 -b 4M -u -R  -t 10
onnecting to host 10.223.200.200, port 5201
everse mode, remote host 10.223.200.200 is sending
  5] local 10.223.0.100 port 60425 connected to 10.223.200.200 port 5201
 ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
  5]   0.00-1.00   sec   359 KBytes  2.93 Mbits/sec  1.645 ms  15/269 (5.6%)
  5]   1.00-2.00   sec   546 KBytes  4.47 Mbits/sec  1.437 ms  32/418 (7.7%)
  5]   2.00-3.00   sec   489 KBytes  4.01 Mbits/sec  1.382 ms  0/346 (0%)
  5]   3.00-4.01   sec   485 KBytes  3.97 Mbits/sec  1.541 ms  0/343 (0%)
  5]   4.01-5.01   sec   484 KBytes  3.96 Mbits/sec  1.885 ms  0/342 (0%)
  5]   5.01-6.00   sec   171 KBytes  1.41 Mbits/sec  5.648 ms  12/133 (9%)
  5]   6.00-7.00   sec   260 KBytes  2.13 Mbits/sec  2.438 ms  82/266 (31%)
  5]   7.00-8.01   sec   402 KBytes  3.28 Mbits/sec  2.386 ms  121/405 (30%)
  5]   8.01-9.00   sec   403 KBytes  3.30 Mbits/sec  2.847 ms  174/459 (38%)
  5]   9.00-10.00  sec   406 KBytes  3.33 Mbits/sec  1.631 ms  166/453 (37%)
 - - - - - - - - - - - - - - - - - - - - - - - - -
 ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
  5]   0.00-10.03  sec  4.78 MBytes  4.00 Mbits/sec  0.000 ms  0/0 (0%)  sender
  5]   0.00-10.00  sec  3.91 MBytes  3.28 Mbits/sec  1.631 ms  602/3434 (18%)  receiver
```

Figure 5 - Screenshot of data collection

5. Results and Analysis

5.1. Throughput:

- At short ranges (< 40 km): Up to 9.86 Mbps TCP and 11.6 Mbps UDP.
- At 80–120 km: Sustained 3.9–5.7 Mbps TCP, 7.5–10.1 Mbps UDP.
- At 160–200 km: Up to 3.9 Mbps TCP and 7.6 Mbps UDP, even beyond 200 km.
- Despite minor link interruptions near 198–208 km, likely due to multipath, the connection was largely stable.
- Maximum measured range: 328 km with consistent link stability up to 300+ km.

5.2. Signal Strength (RSSI):

- Excellent RSSI observed throughout the flight — even at 300 km.
- ~-68 dBm at 40 km
- ~-74.5 dBm at 120 km
- RSSI variation (up to 20 dB swings) was noted due to multipath reflections, particularly noticeable around 120 km.
- Maintained better than -80 dBm at furthest distance.

5.3. Latency & Packet Loss:

- Inactive time (i.e., link dropouts) remained low up to 180 km, indicating stable latency and low packet loss.
- Short duration drops occurred briefly at 198 km and 208 km, quickly recovering.

5.4. Video or Data Stream Quality:

- Live video streaming tests from the aircraft to ground confirmed the system's ability to maintain high-quality bi-directional data exchange.
- Real-time GPS data transmission to the tracking system remained uninterrupted for most of the flight.

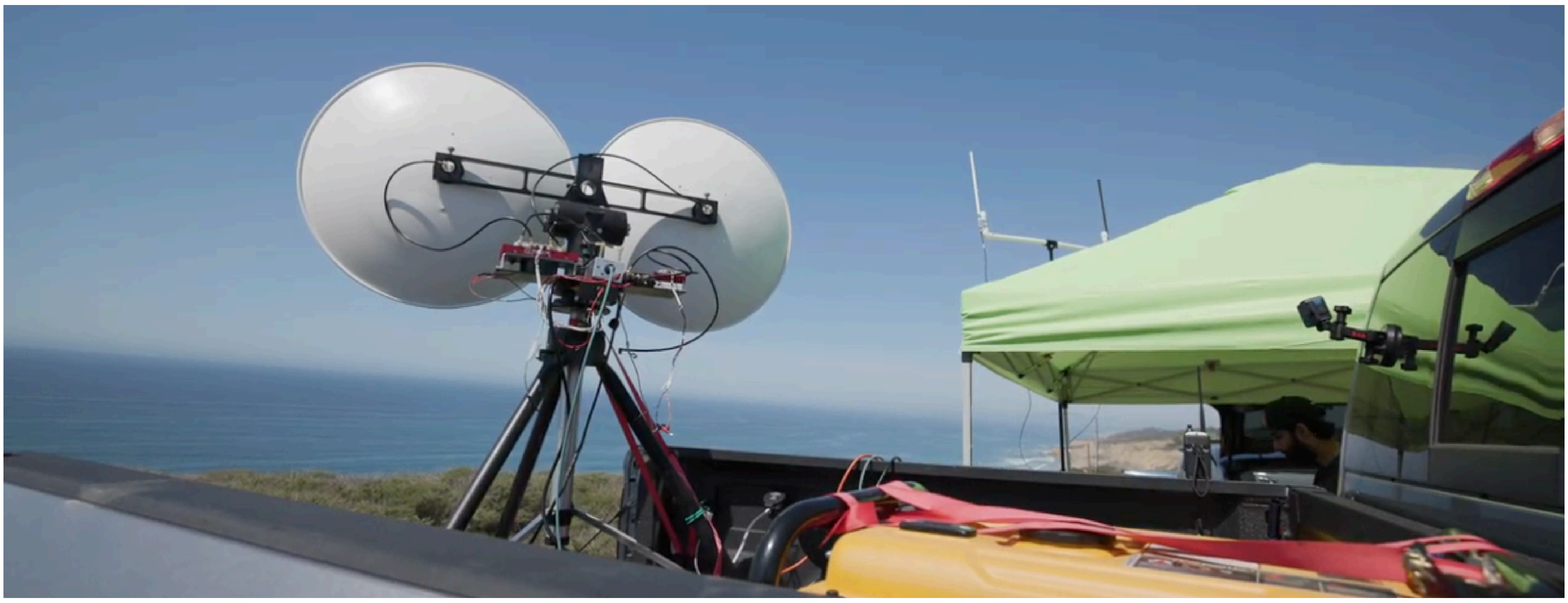

Figure 6 - Ground control tracking system

6. Observations

6.1 Range Limitations and Link Margins:

- Aircraft altitude shifts had noticeable effects: a climb to 8500 ft around 112 km helped maintain line-of-sight past the Earth’s curvature.
- Multipath interference ("ground bounce") from ocean surface reflections contributed to some signal fluctuations.

6.2 Tracking Antenna Performance:

- Optimum Solution’s tracking system successfully maintained lock throughout the flight, even beyond 300 km.
- Slight upward tilt of the antenna improved multipath mitigation.

6.3 Blade Antenna Performance (Air Side):

- Blade antennas with vertical polarization performed effectively when mounted on the underside of the wings.
- Minimal degradation during banking or maneuvering observed.

7. Conclusion

The Ultra Long-Range S-Band flight test conducted by Doodle Labs successfully validated the capabilities of the RM-2025 Multiband Mesh Rider Radio, achieving a remarkable range of 328 km with stable data links and reliable throughput. Throughout the test, stable TCP and UDP throughput was maintained, notably achieving up to 9.86 Mbps (TCP) and 11.6 Mbps (UDP) at short ranges, and reliably providing sustained throughput up to 3.9 Mbps (TCP) and 7.6 Mbps (UDP) beyond 200 km. The RSSI consistently stayed better than -80 dBm even at the furthest distance, with minor signal variations primarily attributed to multipath interference.

The Optimum Solution’s ground-based tracking antenna demonstrated exceptional performance, dynamically tracking the aircraft beyond 300 km. Airborne blade antennas with vertical polarization performed robustly, maintaining consistent link quality.
This test confirms the suitability of this configuration for demanding long-distance aerial applications. Altitude adjustments naturally improved line-of-sight connectivity and helped mitigate multipath interference.

Future testing recommendations include evaluating performance under with alternative antenna configurations (different polarization combinations), and increased payload demands. Further long-duration flight testing will provide additional insight into the long-term stability and reliability of Doodle Labs' communication solution.