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16. ABSTRACT
This is the final report for AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." This research investigated the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communication use cases in existing rural projects as well as existing Caltrans rural operations. The ultimate goal was to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document identifies project interim reports, which are noted in Chapter 1 and provided in appendices; presents the hardware procured or developed in the project; discusses demonstrations and multiple training activities; and presents conclusions and recommendations for future research and deployment of the UAS Repeater.

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Advanced Highway Maintenance and Construction Technology Research Center

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University of California at Davis

Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1

Dave Torick, Kin Yen, Stephen M. Donecker, &
Ty A. Lasky: Principal Investigator

Report Number: CA23-3280
AHMCT Research Report: UCD-ARR-22-11-30-01
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California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

This research investigated the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communication use cases in existing rural projects, as well as existing California Department of Transportation (Caltrans) rural operations. The goal was to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights.

The primary goal of this research project was to develop a prototype unmanned aerial system (UAS) containing a communications payload providing aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi (IEEE 802.11x Wireless LAN) clients. The UAS would allow for deployment within the State highway system right of way, thus extending ubiquitous low-cost network data services further into remote rural areas.

Problem, Need, and Purpose of Research

Communication options in Caltrans rural districts are intermittent and often unavailable. Using satellite technology incurs high equipment and service costs. There is a need to provide enhanced communications availability outside of current cellular offerings without investment in satellite equipment. Based on prior AHMCT research, there is a large cellular network in the rural districts, but the range of these sites is significantly limited by surrounding terrain and foliage. This project aimed to extend the edge of existing cellular infrastructure service boundaries further into rural districts. This research involved developing a UAS and communications payload developed to provide a cellular data service range extension via routing between a cellular modem wireless wide area network (WWAN) and a Wi-Fi base access point interface.

Overview of the Work and Methodology

This research developed concepts for a UAS communications repeater, designed and developed the system hardware and software, sought operator flight training and certification, performed aerial investigations to prove the concept, and analyzed and documented the results.

Major Results and Recommendations

Key results of this research project include:

- Investigation of the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communication use cases in existing rural projects, e.g., the Responder system.

- Implementation of a UAS-based aerial repeater to extend the range of existing wireless communications infrastructure in the rural environment.
- Demonstration of the successful functionality of the UAS-based aerial repeater in both simple and challenging environments, including the steep mountainous canyon areas near Lake Berryessa west of Davis.

Key recommendations include:

- Extensive training is essential for key project personnel to cultivate safe operations and regulatory compliance.
- Key safety issues must be checked prior to and during every flight.
- For safe and proper use of a UAS-based system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skills refresh.

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List of Acronyms and Abbreviations

Acronym	Definition
AGL	Above Ground Level
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
BVLOS	Beyond Visual Line of Sight
Caltrans	California Department of Transportation
CBO	Community-Based Organization
CCTV	Closed-Circuit Television
CFR	Code of Federal Regulations
COTS	Commercial Off-the-Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FAA	Federal Aviation Administration
FPV	First Person View
GPS	Global Positioning System
HMS	Health Management System
IR	Infrared
ITS	Intelligent Transportation Systems
LAN	Local Area Network
LiDAR	Laser imaging Detection and Ranging
LOS	Line of Sight

Acronym	Definition
LTE	Long-Term Evolution
M300	Matrice 300 RTK
NAS	National Airspace System
NIR	Near infrared
NM	Nautical Mile
NDVI	Normalized Difference Vegetation Index
PM	Project Manager
RGB	Red Green Blue
RPIC	Remote Pilot in Command
RPV	Remote-Person View
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RTH	Return-To-Home
SHS	State Highway System
SINR	Signal to Noise and interference ratio
SOP	Standard Operating Procedure
SR	State Route
TFR	Temporary Flight Restrictions
TMC	Transportation Management Center
TRUST	The Recreational UAS Safety Test
UA	Unmanned Aircraft

Acronym	Definition
UAS	Unmanned Aerial System
UASC-R	Unmanned Aerial Systems Communications Repeater
UC	University of California
VLOS	Visual Line of Sight
VO	Visual Observer
WAN	Wide Area Network
Wi-Fi	IEEE 802.11x Wireless LAN

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The authors thank the California Department of Transportation (Caltrans) for their support, in particular Jeremiah Pearce and Keith Koeppen with the Office of Intelligent Transportation Systems (ITS) Engineering and Support, and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

This is the final report for the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." This research, performed for the California Department of Transportation (Caltrans), investigated the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communication use cases in existing rural projects, as well as existing Caltrans rural operations. The ultimate goal was to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights.

This document summarizes previous project interim reports, presents the hardware procured or developed in the project, discusses demonstrations, overviews operator training, provides the collection of flight investigation summaries, and presents conclusions and recommendations for future research and deployment of the UAS Repeater.

The primary goal of this research project was to develop a prototype UAS containing a communications payload providing aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi (IEEE 802.11x Wireless LAN) clients. The UAS would allow for relatively easy deployment within the State highway systems (SHS) right of way, thus extending ubiquitous low-cost network data services further into remote rural areas.

Problem

Communication options in Caltrans rural districts are intermittent and, in some cases, unavailable. Using satellites incurs high equipment and service costs, which typically impact efforts negatively and sometimes preclude use completely. There is a need to provide enhanced communications availability outside of current cellular offerings without investing in satellite equipment. Based on prior AHMCT research, there currently exists a large cellular network in California's rural districts, but the typical range of these sites is significantly limited by surrounding terrain and foliage. The aim of this project was to extend the edge of existing cellular infrastructure service boundaries further into rural districts. This involved an UAS with a communications payload developed to provide a cellular data service range extension via routing between a cellular modem wireless wide area network (WWAN) and a Wi-Fi base access point interface.

Caltrans has continuing interest in the use of technology to improve the safety of workers and the traveling public during highway maintenance operations. This research included various approaches to improve communications for workers in the field to enhance safety while simultaneously improving the effectiveness of maintenance operations and emergency response. Recent Caltrans efforts in this area include the handheld terminal/diagnostic controller research and development of a single hardware kit running specialized apps to control ITS field elements such as changeable message signs (CMS) and closed-circuit TV (CCTV) cameras [1], [2]. Caltrans has also supported a series of projects to enhance maintenance response through its Responder projects, including the Responder development projects [3]-[5], the Responder field testing research [6], and the current Responder research to transition this successful system to a third-party commercial contractor [7].

Objectives

Two of Caltrans' stated goals are:

- Safety First: Provide a safe transportation system for workers and users, and promote health through active transportation and reduced pollution in communities. Double down on what works, accelerate advanced technology, lead safety culture change, and integrate equity.

- Stewardship and Efficiency: Money counts, responsibly manage California's transportation-related assets.

Effective communications are essential for both goals. In order for Caltrans to efficiently and safely manage California's transportation system, Caltrans needs ubiquitous and effective communications. Rural locations sometimes have little or no cellular coverage, and there is often no other means of communications. In some rural sites, Caltrans radios are also ineffective. There is a need to expand communications coverage without the significant expenditure of purchasing satellite communications equipment and service. For safe and proper use of such a system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skills refresher courses.

For safe and proper use of a UAS-based system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skills refresh.

The objective of this research was to investigate the use of UAS to provide an aerial cellular and Wi-Fi communications repeater to expand Caltrans communications coverage in rural areas. AHMCT assessed a UAS cellular and Wi-Fi repeater concept. The purpose was to extend the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Handheld Terminal [1], [2], Responder [3], [6], [7], etc.), as well as for existing Caltrans communications.

By leveraging the results of this research effort, Caltrans can improve the safety and efficiency of its maintenance workers, particularly in rural districts; provide enhanced incident response; dispatch of the right equipment for a given situation in the field; improve the Division of Maintenance's rural capabilities; and ultimately enhance the safety and mobility of the traveling public.

Research Methodology

The research evaluated the potential of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects. The issues addressed include:

- What work has already been done in this area?
- What are currently identified best practices?
- What are Caltrans' desired use cases?
- What commercial UAS options are available to support this application?
- What operator training is required for this system?
- What are the current guidelines or regulations for operating a UAS near state highways? Is there an exemption process for Department of Transportations (DOTs)?
- What range can be provided by the system?
- What bandwidth can be provided by the system?
- How much time does it take to deploy the system?
- How much time does it take to stow the system?
- How much flight time does the system provide?
- What use cases can the system support?

To achieve the goals of this project, the following work was performed:

- Task 1: Project management
- Task 2: Develop research Concept of Operations
- Task 3: Perform literature and product search
- Task 4: Develop system requirements for selected research concept
- Task 5: Develop detailed system design for selected research concept
- Task 6: Procure hardware for aerial repeater research

- Task 7: Demonstrate current research status
- Task 8: Obtain required training and maintain certification for aerial repeater research
- Task 9: Integrate hardware sub-systems for aerial repeater research
- Task 10: Develop software for aerial repeater research
- Task 11: Perform aerial repeater research investigations
- Task 12: Analyze results of aerial repeater research investigations
- Task 13: Submit final report and workshop presentation

The research team for this task was reformed after Task 4. Although the principal investigator and project panel were consistent, the engineers who completed Tasks 5 to13 joined this project in its later stages. This shift presented several challenges that the team was able to overcome; however, it did create a challenge for this project.

Overview of Research Results and Benefits

Table 1.1: Key deliverables

Task	Deliverable	Note
2	Interim report summarizing Concept of Operations	Appendix A and [8]
3	Interim report summarizing literature and product search	Appendix B and [9]
4	Interim report summarizing system requirements	Appendix C and [10]
5	Interim report summarizing detailed system design	Appendix D and [11]
6	Procured hardware	Discussed herein, to be transferred per Project Manager (PM) indications
7	Pertinent demonstration results	Discussed herein
8	Key findings from training	Discussed herein
9	Integrated aerial repeater concept system	Discussed herein, to be transferred per PM indications
9	Integrated lower-cost UAS system to film the aerial repeaters	Discussed herein, to be transferred per PM indications
9	Interim report summarizing the hardware integration	Appendix E and [12]

Task	Deliverable	Note
10	Interim report summarizing the software development	Appendix F and [13]
11	Collection of investigation summaries	Discussed herein
12	Interim report summarizing the aerial repeater research investigation and analysis of investigation results	Appendix G and [14]
13	Final Report	This report

Benefits

This research provides a means to enhance wireless network coverage using existing cellular infrastructure without reliance on satellite communications services. Expanding current systems would provide significant benefits in rural areas with more challenging cellular communications. The system could also provide benefits in urban applications, including the general-purpose Wi-Fi hotspot that is created. Several benefits include:

- Improved daily rural maintenance operations
- Improved maintenance incident response
- Improved ability to dispatch the correct equipment for a given situation based on facts from the field
- Increased safety of the traveling public
- Increased mobility of the traveling public

Culture of Safety

For safe and proper use of a UAS-based system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skill refresher courses. Pilots and team members must develop, use, and continually update checklists. Known useful checklists include mission planning and packing; crew communications; pre-flight systems and site inspections; launch, landing, and post-flight inspections; and final packing. It is critical to document everything to support safe and effective operation and for potential legal purposes. Checklists developed during this research are provided in Appendix H. As noted, checklists should be updated regularly as new items and issues are identified.

Chapter 2:
Project Tasks

Task 1: Project management

The project Principal Investigator (PI) and the team manage the project, including delivery of 15 quarterly reports and 42 invoices to the PM. The team held multiple meetings with the PM in person, via phone, and online. COVID-19 severely impacted this and other project tasks. The COVID-19 shutdown which began in mid-March 2020, soon after project initiation. Several tasks required a significant amount of travel as well as in-person close contact interaction between research team members, often including Caltrans personnel. These tasks included demonstration of research status in the field, aerial platform training, and aerial repeater investigations. The unprecedented and extended COVID measures significantly impacted schedule. This led to request for a no-cost time extension of 18 months to November 30, 2022, including significant revisions to the task schedule. Additional schedule issues occurred due to personnel issues, but AHCMT was able to make adjustments for this and remained on the overall revised schedule. AHCMT appreciates the flexibility provided by the Caltrans PM in this difficult period.

Task 2: Develop research Concept of Operations

This task entailed development of the Concept of Operations for an aerial cellular and Wi-Fi repeater. The effort considered the following elements: aerial platform needs and capabilities, typical use cases, single vs. multiple aerial devices, manual vs. automated flight, hover vs. path following, high-accuracy hover vs. continuous flight pattern, flight time needs and capabilities, vertical take-off and landing vs. runway take-off, communications payload(s), range for envisioned use cases, and weather considerations. This effort led to a viable concept of operations for the UASC-R, as documented in the corresponding interim report,[8] also provided in Appendix A.

Task 3: Perform literature and product search

This task included a literature search concerning UAS use for communications and any reports of existing applications. It also included a search for best practices for use in DOTs and other agencies. The literature and product search considered the following elements: existing research; envisioned use cases;

regulations, including those found at [FAA UAS Policy Document Library (https://www.faa.gov/uas/resources/policy_library)](https://www.faa.gov/uas/resources/policy_library); aerial platform guidance (manual, automatic, hybrid); available aerial platforms (quadcopter, plane, other); aerial platform capabilities; communication needs; existing cellular communication infrastructure; cellular tower/antenna radiation patterns; wireless antennas; wireless communication equipment; aerial platform guidance equipment; software development kits; and hardware development kits. The task deliverable was an interim report,[9] which is also included in Appendix B.

Task 4: Develop system requirements for selected research concept

This task developed system requirements for the research concept selected by the Panel in Task 2. The requirements were divided into the following elements: hardware requirements, software requirements, and operational requirements. The operational requirements provided the overarching project guidance, namely a system capable of supporting a communications payload in extended flight, with the capability of connecting to a (potentially) non-line-of-sight cellular communications tower for Wireless Wide Area Network (WWAN) communications and a wireless interface Wireless Local Area Network (WLAN) for communications to local users. The task deliverable was an interim report,[10] which is also included in Appendix C.

Task 5: Develop detailed system design for selected research concept

Based on the concept (Task 2) and requirements (Task 4), AHMCT developed a detailed system design document for the UAS repeater concept. This design document included the hardware necessary for system take-off, flight, use, landing, and stowage. Due to commercial system evolution in the course of this project, the final design and implementation shifted away from the custom payload implementation of the initial Task 4 requirements and to a more COTS solution. This change provides a more viable long-term solution for Caltrans. The task deliverable was an interim report,[11] which is also included in Appendix D.

Task 6: Procure hardware for aerial repeater research

In this task, AHMCT procured all needed hardware. Hardware included: aerial platforms, additional batteries, storage container for each UAS, communications equipment, guidance equipment, and cameras. Procurement also included training for project staff to provide a culture of safety. The full procurement list, including a mapping to corresponding Task 4 requirements is provided in Appendix K.

Task 7: Demonstrate current research status

Under Task 7, AHMCT provided various demonstrations of the research status to the PM. These demonstrations were typically informal, and generally occurred at the AHMCT Research Center and its related facilities. At the end of Task 7, AHMCT demonstrated the system to Caltrans personnel, along with training for the use of the UAS repeater. This task included completed pre- and post-flight documents as required by the project manager and the Caltrans UAV Handbook. The Task 7 demonstrations are documented in Chapter 4 of this final report.

Task 8: Obtain required training and maintain certification for aerial repeater research

For safety, risk mitigation, and regulatory compliance, training was required for any AHMCT researchers and Caltrans personnel that participated in the aerial repeater investigations. To support the investigative testing phase of the project, as well as facilitating conceptual development and detailed design, at least one AHMCT staff member and one Caltrans Panel member took the training required to fly a UAS based upon current regulations. Throughout the remainder of the project, the trainees followed required actions to maintain their flight certification. The trainees also followed all appropriate regulations (current FAA, state, and local regulations), and the rules set forth in the 2018 Caltrans UAV Website and Handbook. The training is detailed in Chapter 5 of this final report.

Task 9: Integrate hardware sub-systems for aerial repeater research

Based upon the detailed design of Task 5, AHMCT integrated all hardware components, and including the prototype powered aerial repeater systems and repeater payload. AHMCT also integrated a lower-capability and lower-cost UAS to observe and film the UASC-R. Hardware integration will include the following elements: aerial platform, cameras, guidance system, communications system, antennas, power systems, brackets, and enclosures. The task deliverable was an interim report,[12] which is also included in Appendix E.

Task 10: Develop software for aerial repeater research

In the original project plan, based upon the detailed design of Task 5, AHMCT would develop the software needed to support the aerial repeater system and repeater payload(s). Software development would have included the following elements: embedded operating system modifications, hardware driver modifications, wireless networking, and repeater programming.

Based on the maturity of the Commercial Off–The-Shelf (COTS) modem and router market, AHMCT did not need to develop custom communications routing software between the cellular (WWAN) and Wi-Fi (WLAN) networks. There was also no need to develop custom software for the UAS control. Software development within this research was limited to data logging and similar research support activities. The data logging for the wireless modem/router is documented in an interim report, which is also included in Appendix F.

Task 11: Perform aerial repeater research investigations

AHMCT personnel performed aerial repeater research investigations with the prototype UAS aerial repeaters in field conditions. The large majority of this task was for internal AHMCT investigations as well as demonstration to the PM. Near the end of Task 11, AHMCT provide demonstration of the system to Caltrans personnel, along with training for the use of the UAS repeater. This training was strictly limited to the use of the UAS as a repeater, i.e. it did not include general UAS operational training, which was acquired by Caltrans personnel as part of Task 8 from a commercial provider. Properly FAA Remote Pilot-certified Caltrans personnel had the opportunity to test the system at the time of this final demonstration. AHMCT solicited feedback from Caltrans regarding the utility and benefit of the UAS repeater, and have documented the results. Investigations were documented, including photos and/or video from the ground, and photos and/or video from the UAS filming system. The investigation summaries are provided in an interim report,[14] which is included here in Appendix G.

Task 12: Analyze results of aerial repeater research investigations

AHMCT analyzed results of aerial repeater research investigations performed and the data gathered in Task 11. AHMCT analyze the data collected in Task 11 and determined the aerial repeater performance with respect to the system requirements. The investigations analyses were documented in an interim report,[14] which is included here in Appendix G. The investigation results guided system modifications, and the final system met the operational requirements. The detailed mapping of performance vs. requirements is provided in Appendix J.

Task 13: Submit final report and workshop presentation

This task .

At the conclusion of the project, the research team deliver a final project report. The final report summarizes the results of the earlier project tasks. This document is the final report of the research project, and documents all deliverables and findings. For future reference, this final report incorporates all previously accepted interim reports in the appendices.

Chapter 3:
System Hardware

The project included several hardware-specific tasks:

- Task 4: Develop system requirements for selected research concept (Appendix C and [10])
- Task 5: Develop detailed system design for selected research concept (Appendix D and [11])
- Task 6: Procure hardware for aerial repeater research (Appendix K)
- Task 9: Integrate hardware sub-systems for aerial repeater research (Appendix E and [12])

As Task 6 did not include an interim report; the results from the procurement are included in Appendix K and are referenced to items from Task 4. The discussion is at a summary level and includes lists of hardware procured.

UAS and Camera Hardware

The UAS is a key subsystem for the research concept developed and tested in the project. The UAS provides the mounting point for the communications payload, allows the payload to be lifted and flown to locations wherein cellular communications can be established, and fundamentally enables the unmanned aerial system communications repeater(UASC-R)to achieve the desired goals. An extended product search was performed [9], leading to the selection of the DJI Matrice 300 RTK (M300) for the UAS (Figure 3.1), in order to satisfy the system requirements [10]. Figure 3.2 shows the M300 in its storage/transport case. The initial procurement list for the M300 and related components is provided in Table 3.1. Each UAS includes a built-in camera. For research purposes and to ensure successful imaging performance, a higher-end Zenmuse H20 camera was also procured, along with a Zenmuse HT20T for situations necessitating thermal infrared (IR) imaging.

Figure 3.1: DJI Matrice 300 RTK for use as the UAS in the concept system

Table 3.1: DJI Matrice 300 RTK and components

Item	Part #	Qty
DJI Matrice 300 RTK	S-DJI-M300	2
GoProfessional Cases Matrice 300 Case	N/A	2
DJI TB60 Intelligent Flight Battery	S-DJI-TB60	12
DJI CrystalSky/Cendence - WB37 Intelligent Battery	S-DJI-CS-CEN-INT-BATT	4
DJI Battery Station	IN2BS	2
DJI Smart Controller Enterprise	S-DJI-SMT-RC-E	1
DJI Zenmuse H20	S-DJI-ZH20	1
DJI Zenmuse H20T Thermal IR Camera	S-DJI-ZH20T	1
DJI Matrice 300 - Dual Gimbal Connector	S-DJI-M300-DGC	2
DJI Matrice 300 - 2110 Propeller	S-DJI-M300-2110P	6
Silver Star Matrice 300 Maintenance	N/A	2
Firmware Upgrade Service	V-NB-FIRM-UPG	2
FREE Lifetime Customer Care & Technical Support Via Phone, Email & Chat	N/A	2
Enterprise Concierge Assist	S-ECA-EUAS	2
DJI Care Enterprise (Basic) Renew	V-DJI-ESR-M300	2
1 Day Free Hardware Training	T-NB-1DF	2

The UAV systems were registered via the FAA Drone Zone (https://faadronezone.faa.gov) site. Registration information for each UAV is included in Table 3.2.

Table 3.2: UAV registration information

Make	Name	Reg	Expire	FAA #	Serial
Matrice 300 RTK	Aggie	4/14/22	4/14/25	FA34XWAPYC	1ZNBJAL00C007D
Matrice 300 RTK	Beaver	4/14/22	4/14/25	FA34XWEM43	1ZNBJ9C00C001J
Mini 2	Camera	4/14/22	4/14/25	FA34XWHH9R	3Q4CJBP3A3G2MH

Figure 3.2: DJI Matrice 300 RTK in case

For flight practice as well as filming the research system during flight, a DJI Mini 2 was procured. This small, low-cost, and lightweight system was ideal for the filming and practice roles. The relative scale of the Mini 2 to the Matrice 300 is portrayed in Figure 3.3.

Figure 3.3: DJI Matrice 300 RTK and DJI Mini2 illustrating scale

Communications Payload Hardware

The communications payload provides the aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi (IEEE 802.11x Wireless LAN) clients. Payload hardware includes communications systems, computing systems, and required support components such as case and mounting. Wherever possible, to expedite research testing and for optimal deployment path, commercial off-the-shelf (COTS) systems were used, including the highest possible level of COTS integration. Custom hardware integration and software development were minimized. Figure 3.4 show the communications payload mounted onto the UAS. Payload components are listed in Table 3.4.

Figure 3.4: DJI Matrice 300 RTK with Communications Payload

Table 3.3: Communications payload components

Item	Qty
Sierra Wireless Airlink MP70 4G LTE-Advanced Router/Gateway	1
Activated Verizon Subscriber Identity Module (SIM) card	1
11.1 V 1500 mAh lithium polymer (LiPo) battery with XT60 plug	1
RP-SMA male to RP-SMA female bulkhead mount RG316 cable 12-inch length	1
5 dB Wi-Fi antenna with Reverse Polarity Sub-Miniature version A (RP-SMA) connector	3
28 dB high-gain Global Positioning System (GPS) active antenna ceramic patch GPS marine navigation antenna with UFL Interface	1
Bingfu 4G LTE antenna 9 dBi SMA male cellular antenna (2-Pack), compatible with 4G LTE	1 set

Table 3.4: Communications ground components

Item	Qty
TP-Link AC1200 Wireless Gigabit access point	1
MikroTik SXTsq 5 high power Wi-Fi Bridge	1

Table 3.5: Miscellaneous hardware

Item	**Qty**
Lenovo Thinkpad X1 Carbon Gen 10 laptop	1
Firman 3200W Dual fuel generator/inverter	1
Hoodman Drone Landing Pad (5-ft diam**eter**)	1
Google Pixel 6 Pro smartphone	1
DJI Mini 2 with fly more combo	1
Anker 521 portable power station	1
Anker 555 portable power station	1
Kestrel 5000 Environmental Meter with Link	1
Uniden Bearcat Handheld Scanner-BC125AT	1

Chapter 4: Demonstrations

At key stages of the research, AHMCT provided informal or formal demonstrations to the PM. Demonstrations included members of the panel as noted in the following sections. Research investigation, which are discussed in Appendix G involved UAS operations that involved only AHMCT members A brief overview of the demonstrations is provided in this chapter.

Demo 1: UAV unpack and inspection

Demo date: April 5, 2022

Attendees: Sean Campbell, Dave Torick, and Ty Lasky

Brief overview

The DJI UAV shipment was received on March 30, 2022. The project team met early afternoon in the AHMCT Robotics Lab and unpacked the six boxes of materials. The key items were the two DJI Matrice 300 RTK UAVs (main systems) and the one DJI Mini 2 UAV to be used for pilot practice and filming. Key elements are shown in Figures 4.1 to 4.6.

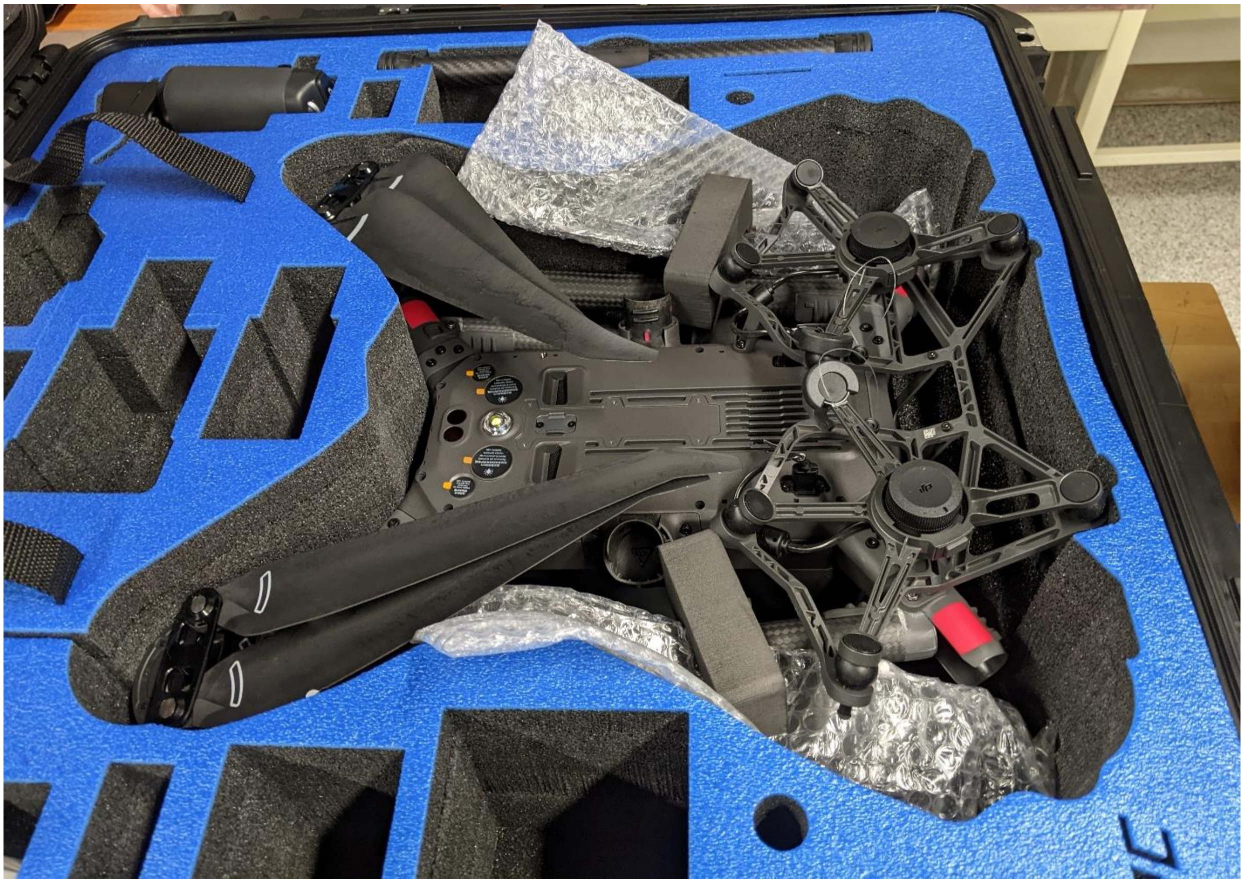

Figure 4.1: DJI Matrice 300 RTK in case with protective foam block removed

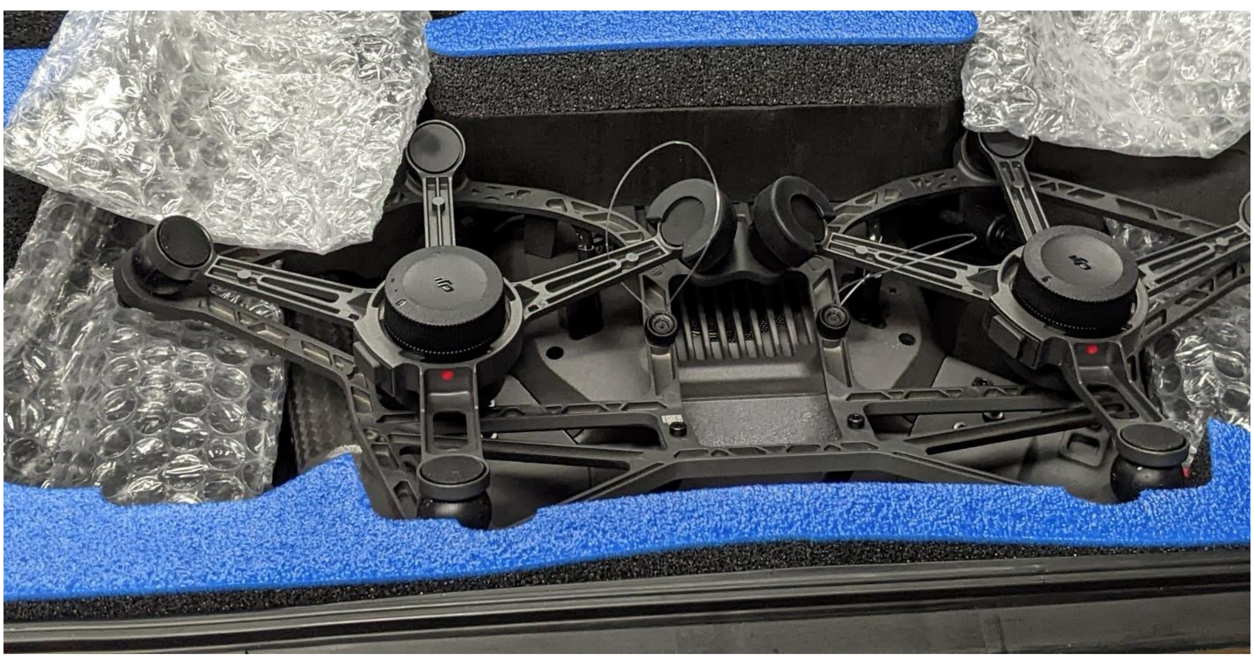

Figure 4.2: DJI Matrice 300 RTK dual gimbal mount, shown in case with protective foam block in place

Figure 4.3: DJI Matrice 300 RTK with legs attached and motor arms and props extended. Here, battery bays are empty.

Figure 4.4: DJI Mini 2 UAV with arms retracted

Figure 4.5: DJI Matrice 300 RTK standard controller

Figure 4.6: DJI Matrice 300 RTK and Mini 2 UAVs illustrating relative size

Significance

Having the UAVs and related materials in hand was very informative. The Matrice UAVs were well packed in hardened cases, which include rugged handles and rolling option. High-density foam with custom cutouts keeps the components tightly packed and protected from impact. One of the Matrice cases included the Zenmuse H20 camera in its own cutout.

The Mini 2 is dramatically smaller and sized to fit in a hand. This UAV comes with a soft case and shoulder strap. Protection is not as significant as for the Matrice systems but appropriate for the size and cost of this UAV.

At the close of this demo, AHMCT put the batteries into the Battery Station to prepare for the pending Matrice-specific training.

Demo 2: Initial UAS Training

Demo date: April 20, 2022

Attendees: Sean Campbell, Keith Koeppen, Ty Lasky, Dave Torick, and Kin Yen

Brief overview

The supplier of the UAS provided a one-day training session that involved in-person class and flight time. The training was provided by a representative of DSLRPros who demonstrated proper unboxing techniques, examples of pre-flight operating procedures, and in-class and field demonstrations of the Matrice M300. The summary of those trainings can be found in Appendix G. Photos from the training day are shown in Figures 4.7 to 4.10, which highlight the tracking and zoom features of the UAS.

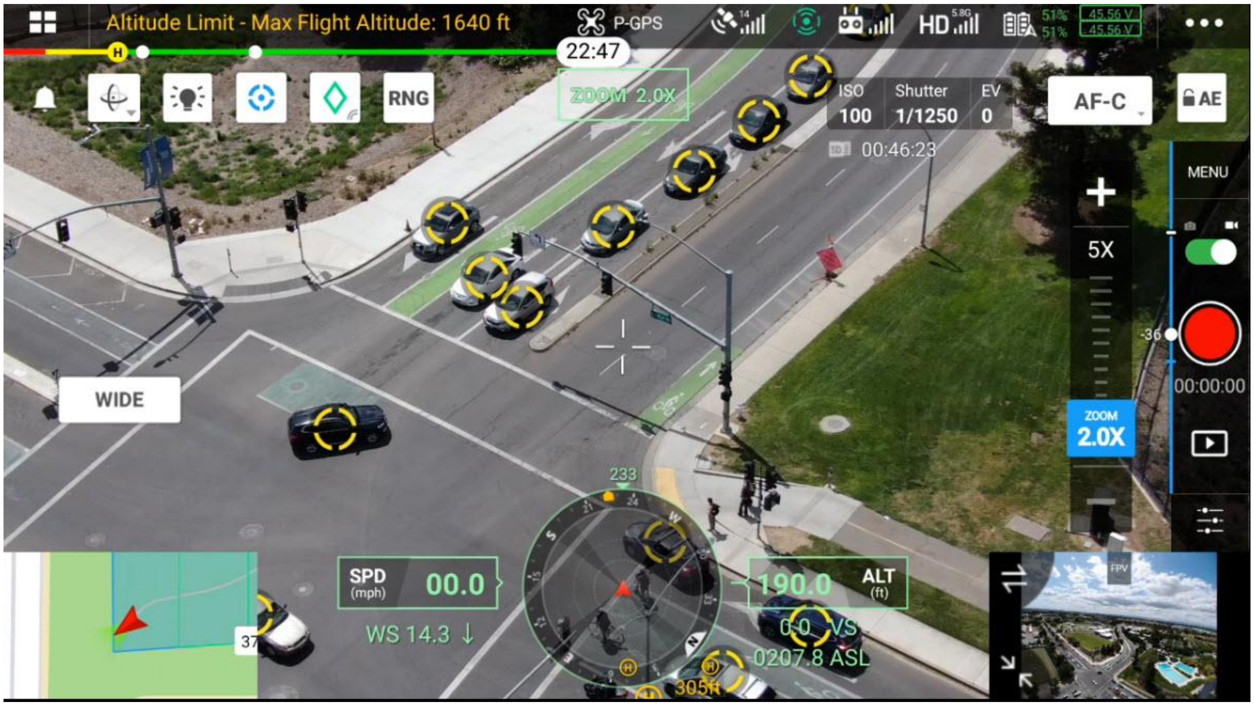

Figure 4.7: M300 Controller screen just before tracking a vehicle

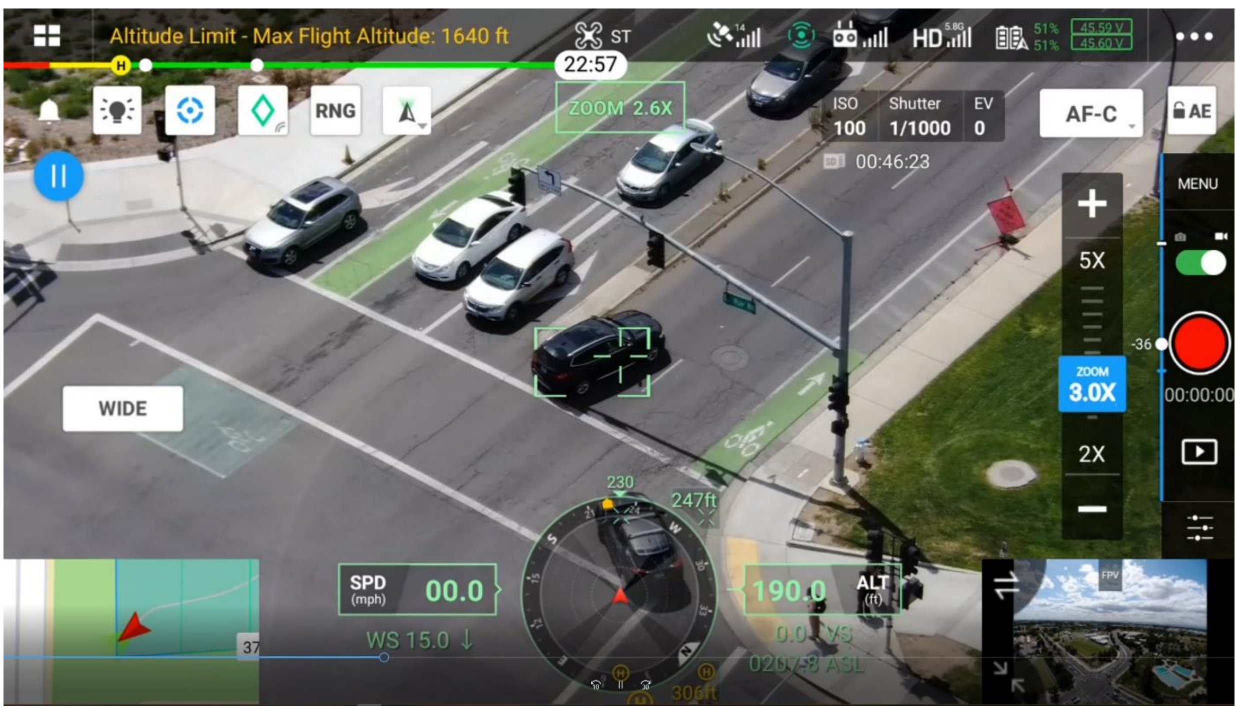

Figure 4.8: M300 Controller screen while tracking a vehicle

Figure 4.9: Photo from H20, area in red box is area of interest that is zoomed onto and shown in Figure 4.10

Figure 4.10: Photo from H20, showing zoom capabilities

Significance

The technical expert who represented DSLRPros was beneficial. They were able to provide a quick overview of good standard operating procedures (SOP)and introduce the UAS, its controller, and the H20 camera payload and its capabilities to the attendees. From this event, the attendees gained an appreciation for the need for checklists, training, and certifications to operate the UAS responsibly and successfully.

Demo 3: Practice flight

Demo date: July 18, 2022

Attendees: Sean Campbell and Dave Torick

Brief overview

A scheduled training flight with the attendees was conducted at the Woodland-Davis Aeromodelers airfield just north of Davis, CA. This field has a specific areas for UAS operations and includes a shade area, limited obstructions, no trees, and several take-off/landing sites. Finding a safe and UAS friendly area is critical to obtaining flight time. The goal of this training session was to further familiarize the attendees with the Matrice M300 and allow the RPIC's to focus on flight controls without needing to be situationally aware of other items, such as trees, buildings, powerlines, and other structures. Figure 4.11 is a satellite image of the airfield, the area in red is the preferred area for UAS operations, the areas in green are the take-off/landing areas, and the area in blue is the shade structure.

Figure 4.11: Satellite image of Woodland-Davis Aeromodelers Airfield

Significance

This was the first of several practice flights that built the attendees familiarity with the system and flight hours. The attendees were able to work together to better understand the controls and operations of the UAS. The airfield was an excellent choice to allow the attendees to primarily be concerned with flight control as it had limited obstacles that could impede flight operations.

Demo 4: Cinematography Practice flight

Demo date: September 15, 2022

Attendees: Sean Campbell and Dave Torick

Brief overview

The attendees in preparation for the final system demonstration utilized the airfield described in Demo 3 to become familiar with video operations using the Matrice M300 and the Zenmuse H20 camera. Through this session, the attendees gained experience with communicating coordinated flight of two UAS and established proper flight speeds to assist in video creation, control of the camera, and methods to reacquire a UAS when it leaves the camera field of view. Figure 4.12 is a picture taken mid-air from the camera UAS.

Figure 4.12: Photo of UAS from the camera UAS

Significance

Moving the UAS in a choreographed fashion proved to be challenging at faster speeds. Through the demo, it became clear that a velocity of no more than 3 ft/sec works well for manual tracking of a UAS. This speed is true for changes in elevation or for level flight. The team was able to successful keep the UAS in the camera view while approaching, ascending, and traveling away from the camera UAS.

Communicating altitude proved to be challenging until a consistent approach was determined. The controllers have a larger numerical display for above ground level(AGL); however, AGL is dependent upon what is right underneath the drone. This proved to cause some errors as the UAS attempted to fly at the same altitude. Once both attendees were aware of the ASL numerical display and used the ASL to coordinate their flight, the coordination improved.

The control of the camera was best performed by utilizing the UAS controls to pan the UAS instead of attempting to pan the camera, which also provided the added benefit of keeping the landing gear or other extensions of the camera UAS from entering the camera's field of view. Further effort can be made in this area to understand the ability of allowing the camera to auto track an object.

High-quality high-speed micro-SD cards were also found to be vitally important. The H20 camera can record wide angle, zoom, and standard feeds simultaneously. Micro-SD cards that are not of sufficient quality or speed do not allow the camera to record to the micro-SD card. The manufacturer suggests a micro-SD card with a UHS speed class rating of 3.

The final significant finding learned from reestablishing the drone in the camera's field of view was developed through trial and error. The most effective method occurred by centering the camera's position, insuring both drones were at the same AGL, attempt to point the camera UAS at the subject UAS, and then slowly fly towards the drone while adjusting the camera's zoom. It was determined that the subject drone should remain stationary throughout this process.

Demo 5: Final system demonstration near Lake Berryessa, California

Demo date: October 6, 2022

Attendees: Sean Campbell, Jeremiah Pearce, Dave Torick, and Kin Yen

Brief overview

A final demonstration site was found near Lake Berryessa. The site was in an area that had no cellular coverage at ground level. While it was in the vicinity of a cell tower, it was apparent that the cellular signal was blocked by the topology of the surrounding hills.

There were two UAS used at this demonstration: a camera UAS with the H20 camera and the unmanned aerial systems communications repeater (UASCR). The objective of this flight was to extend the rural cellular network through a local Wi-Fi network. The camera UAS would record the demonstration of the UASCR taking off and ascending to 100, 200, 300, and 400 ft AGL as shown in Figure 4.14 UAS flight path. Figure 4.13 shows the UASRC was hovering mid-air.

Figure 4.13: View of UASCR from the ground during Demo 5

Figure 4.14: Flight path of UAS for Demo 5

The network download and upload speed at different AGL were measured with both a PC via a Wi-Fi bridge and android device via a Wi-Fi repeater. The quality of the cellular network that the UASRC connected to was also determined through the data logging software that was developed in Task 10 of this project. The communication hardware utilized during this demonstration is shown Appendix D.

Figures 4.15 to 4.20 show the data acquired during the demonstration. The Sierra Wireless MP70 modem can measure and output cell signal performance indicators: Long-Term Evolution (LTE) or 4G, Signal Strength- Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Strength Indicator (RSSI), and Signal to Noise and interference ratio (SINR). Based on the documentation provided by Sierra Wireless, RSRP is the average signal power within LTE channel, indicating whether the modem has a strong connection to the wireless network. An RSRP greater than -105 dBm is good, and an RSRP below -116 dBm is poor or inadequate. RSRQ indicates the quality of the connection to the wireless network. An RSRQ greater than -9 dB is good, and RSRQ below -12 dB is poor. Additionally, an RSSI greater than -78 dBm is good, and an RSSI less than -94 dBm is poor or inadequate. An SINR greater than 6 is good to excellent, and an SINR smaller than 5 is fair to poor.

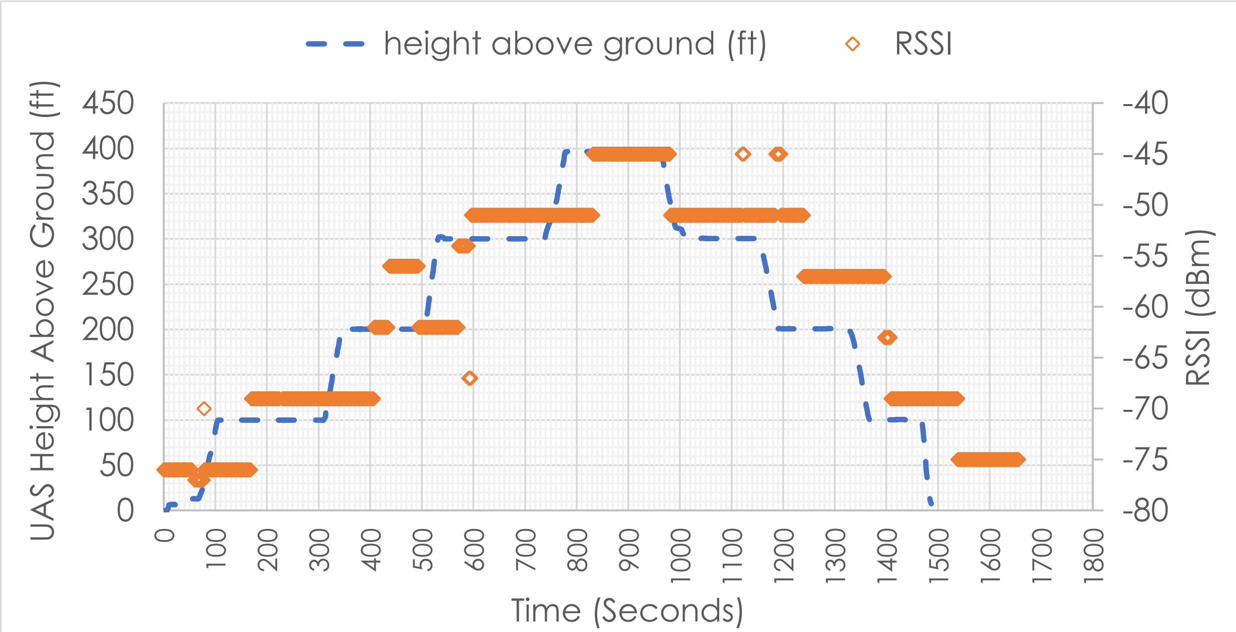

Figure 4.15: UAS height above ground and RSSI values vs Time during Demo 5

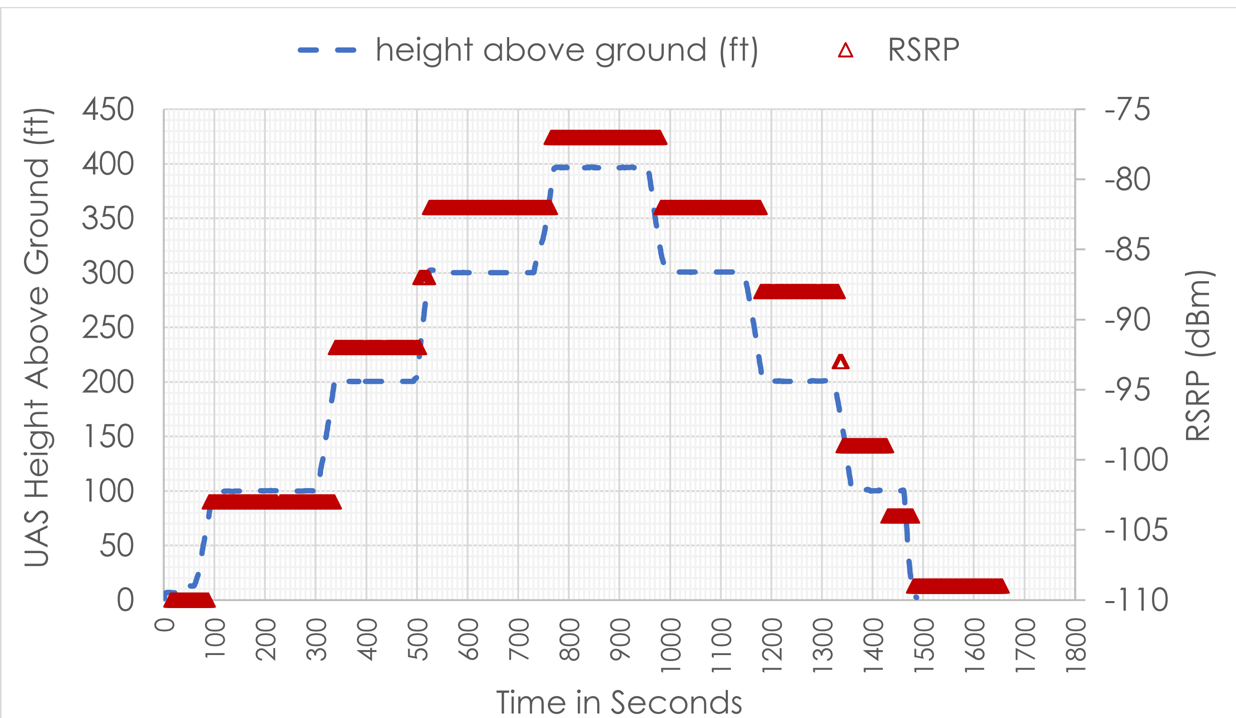

Figure 4.16: UAS height above ground and RSRP values vs Time during Demo 5

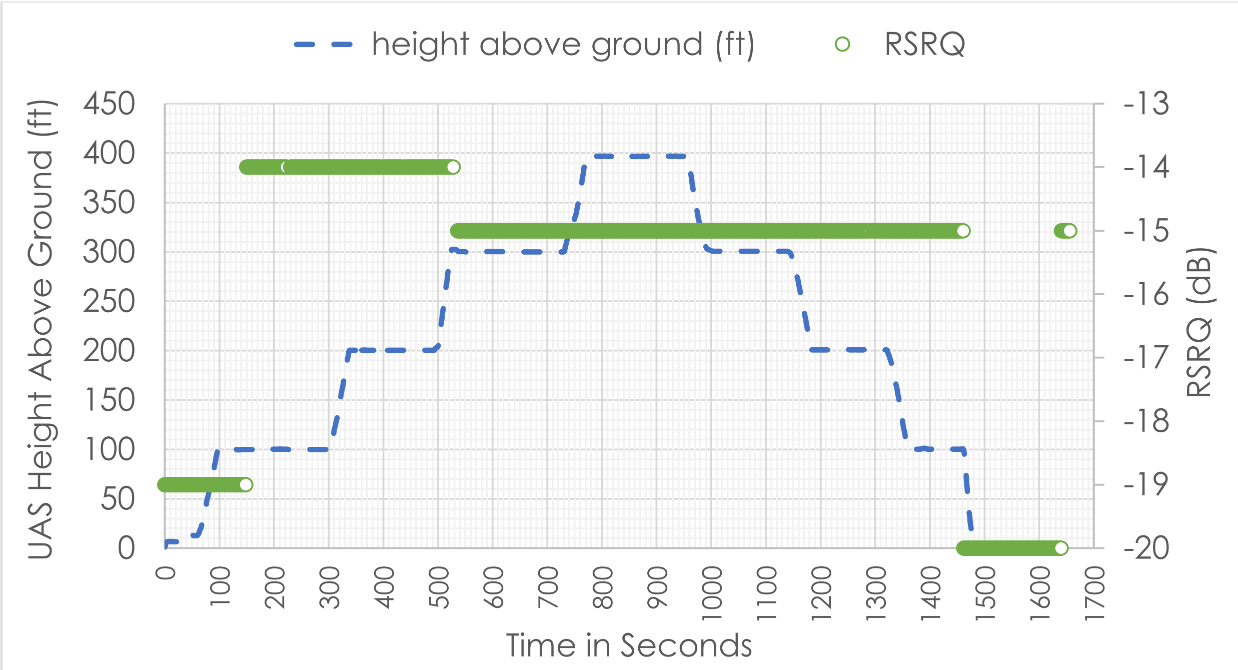

Figure 4.17: UAS height above ground and RSRQ values vs Time during Demo 5

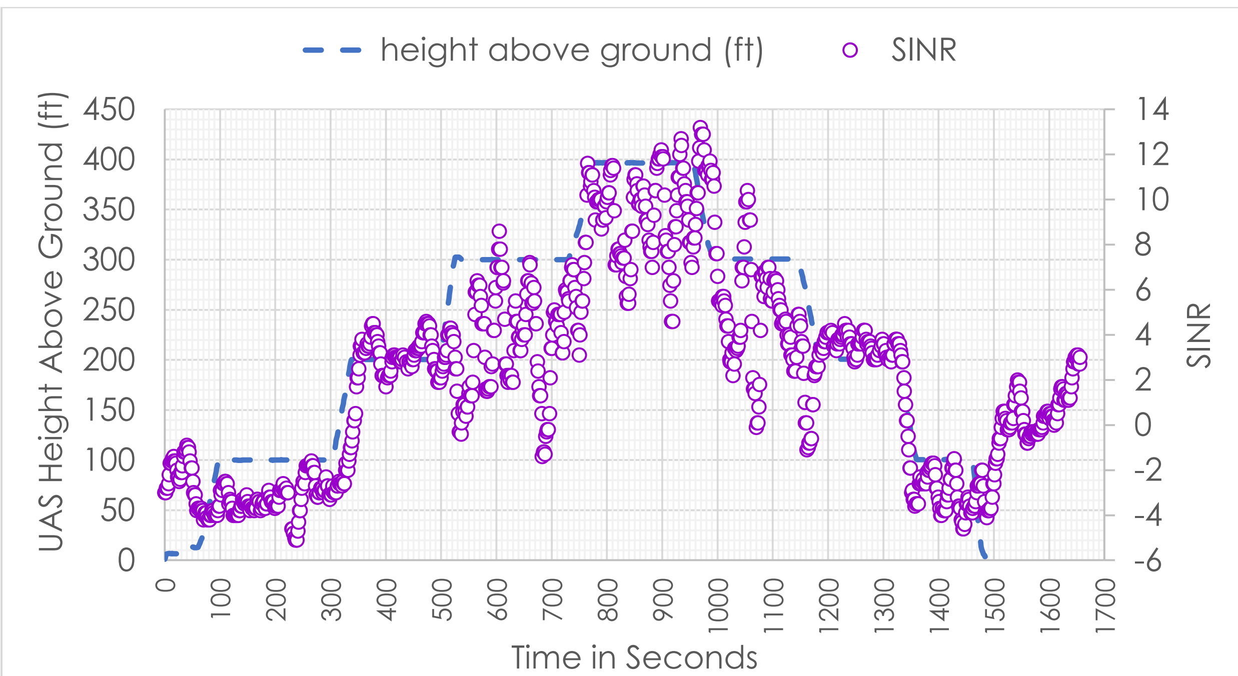

Figure 4.18: UAS height above ground and SINR values vs Time during Demo 5

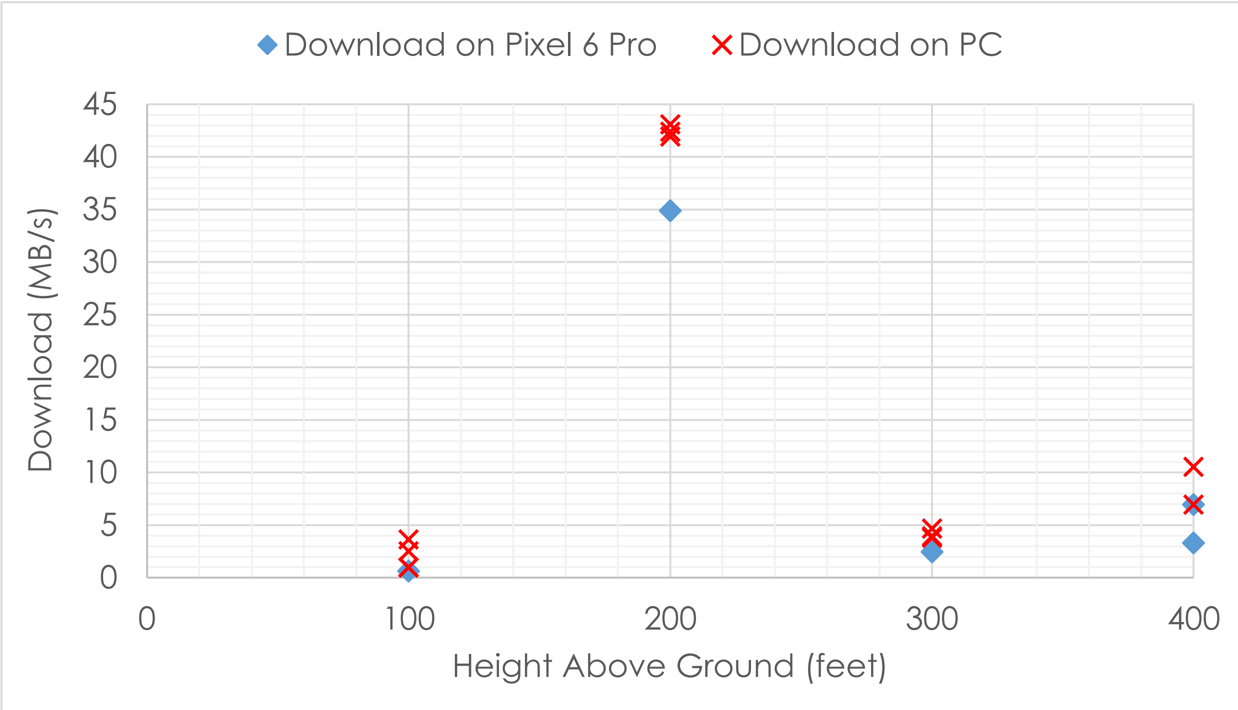

Figure 4.19: Download speed of devices connected to UASCR Wi-Fi network

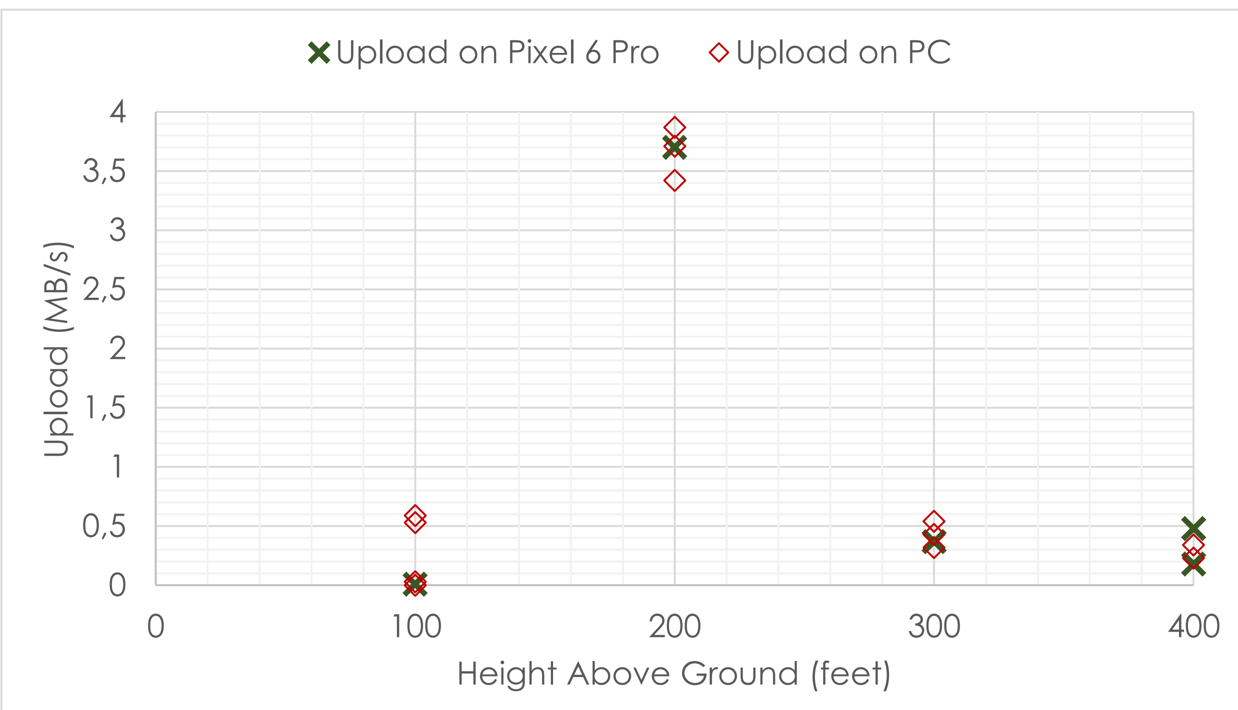

Figure 4.20: Upload speed of devices connected to UASCR Wi-Fi network

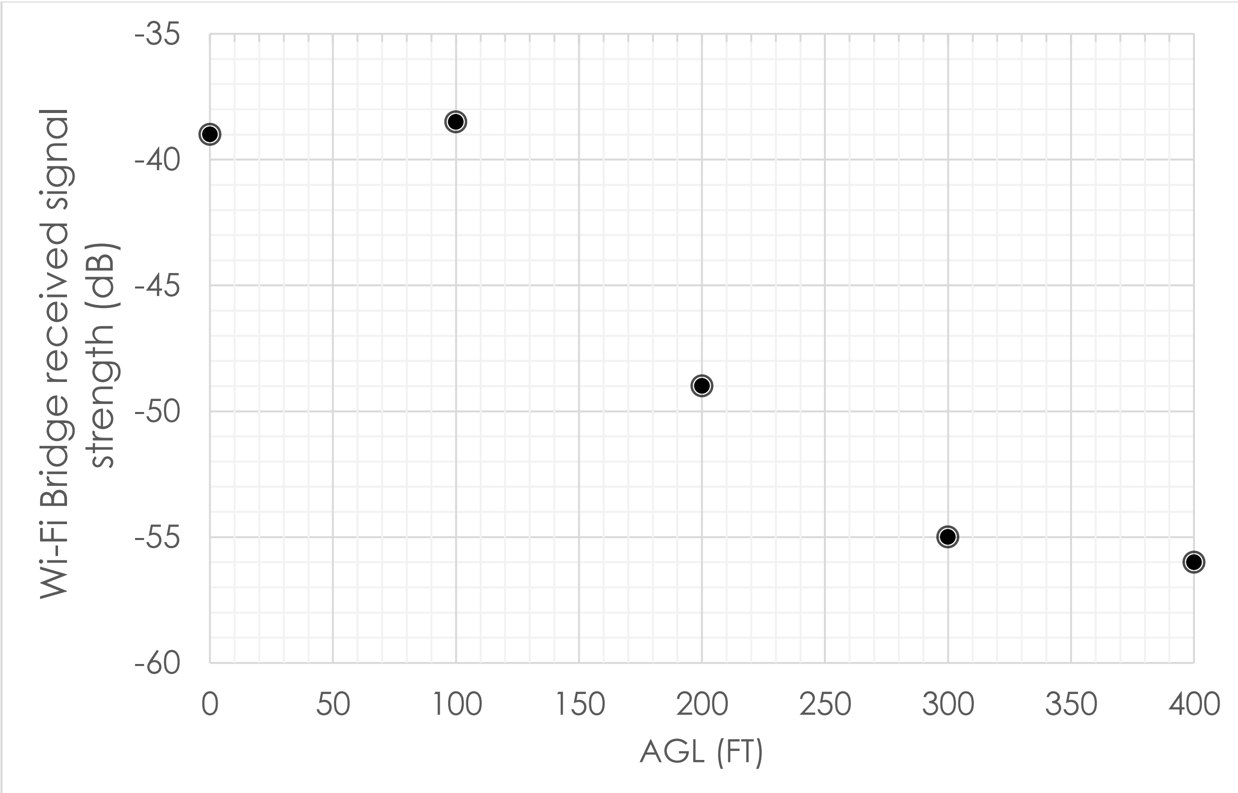

Figure 4.21: Wi-Fi Bridge received Wi-Fi signal strength vs UASCR AGL

Significance

Figures 4.5 to 4.8 show LTE signal indicators (RSSI, RSRP, RSRQ, and SINR) improvement as the UASRC AGL increased. However, the RSRQ measurements was at its maximum at 200 ft AGL. The MP70 was able to establish a slow but reliable LTE connection at 100 ft AGL. Figures 4.9 and 4.10 show that maximum download and upload speed was achieved at 200 ft AGL. Figure 4.21 shows that the Wi-Fi received signal strength from the ground by the Wi-Fi bridge decreased as UASCR AGL increased. A lower Wi-Fi signal strength would lower the Wi-Fi data transfer rate. Therefore, Wi-Fi transfer rate would be lower as AGL or distance from the ground Wi-Fi receiver to the UASRC increases. The relationship between transfer rate and signal strength for both Wi-Fi and LTE is not necessarily linear.

In this particular case, the optimal data transfer rate, or peak performance, was achieved at 200 ft AGL where both LTE and Wi-Fi signal were strong enough to sustain the highest data transfer rate. Further research should be conducted to investigate the impact of different antennas and antenna angles for improved performance at various elevations AGL and distance to the UASRC.

Chapter 5: Training and Key Findings

Project personnel and the PM received varying levels of UAV training, depending on expected roles, in preparation for the flight investigations presented in Appendix G [14]. All personnel completed [The Recreational UAS Safety Test (TRUST) (https://www.faa.gov/uas/recreational_fliers/knowledge_test_updates/)](https://www.faa.gov/uas/recreational_fliers/knowledge_test_updates/) in April 2022. TRUST is required for anyone flying under the [Exception for Recreational Flyers (https://www.faa.gov/uas/educational_users/)](https://www.faa.gov/uas/educational_users/). The team members committed to the project aerial repeater research investigations also obtained the full Federal Aviation Administration (FAA) Part 107 certification, which is required for operation close to the public, public highways, and beyond visual line of sight (BVLOS). The core team members also completed a one-day (April 20, 2022) Matrice-specific training provided by the DJI distributor, DSLR Pros. This training was included in the purchase of the Matrice UAVs and was conducted at UC Davis by a DSLR Pros contractor. The detailed notes for the Matrice-specific training are provided at the end of Appendix G. Training activities and participants are documented in Table 5.1.

Table 5.1: Training activities and participants

Training activity	Participant(s)
Recreational UAS Safety Test [TRUST]	Sean Campbell, Ty Lasky, Dave Torick, Kin Yen
Matrice-specific training by DSLR Pros	Sean Campbell, Keith Koeppen, Ty Lasky, Dave Torick, Kin Yen
FAA Part 107 Training and Certification	Sean Campbell, Ty Lasky, Dave Torick
Remote Pilot Certification	Sean Campbell, Ty Lasky, Dave Torick
Advanced Pilot Certification	Sean Campbell, Dave Torick, Ty Lasky
UAS Agriculture Pilot	Sean Campbell, Dave Torick, Kin Yen
UAS Mapping Pilot	Sean Campbell, Ty Lasky, Dave Torick
UAS Cinematography Pilot	Sean Campbell, Ty Lasky, Dave Torick

TRUST Certification

All personnel obtained TRUST certification in April 2022, including Sean Campbell, Dave Torick, Ty Lasky, and Kin Yen. For recreational flyers operating under the exception for limited recreational operations of unmanned aircraft (Title 49 of the United States Code [49 U.S.C.] §44809), this certification is evidence that the holder has passed the aeronautical knowledge and safety test as required by 49 U.S.C. §44809(a)(7). Per the certificate, TRUST operation requirements include:

- Registering the UAV if it weighs more than 55 lbs.
- Flying only for recreational purposes
- Operating in accordance with or within a community-based organization’s (CBO’s) safety guidelines
- Always flying within visual line of sight

- Not interfering with and giving way to any manned aircraft
- Obtaining authorization before flying in controlled airspace
- Not flying higher than 400 ft in uncontrolled airspace

The TRUST certificate supports operation under academic exceptions. However, per indications by the PM and to maximize safety, the aerial repeater research investigations were performed by team members with FAA Part 107 certification.

Matrice-Specific Training

The core team members completed a one-day (April 20, 2022) on-site Matrice-specific training provided by the DJI distributor, DSLR Pros. This training was included in the purchase of the Matrice UAVs. It was conducted at UC Davis by a DSLR Pros contractor.

Part 1 of the training was in the classroom at AHMCT. It included both presentation material and hands-on training with the Matrice 300 RTK. Goals included safe unpacking and packing of the UAV from its case and familiarity with the Matrice hardware, including batteries, UAV, and controller. This process also included a detailed discussion of the controller settings and operation.

Part 2 of the training was Matrice flight demonstration and training. This portion was on campus at the previously reserved Hutchison Field site. Per the UC UAV safety coordinator, flight up to 400 ft is allowed at this site. Dave Torick filed a flight plan via the UC Drone Web App (http://ehs.ucop.edu/drones) in preparation for this portion of the training. Flight training included individual manual operation, testing of vertical ceiling flight limit, testing of vertical obstacle detection and soft landing, testing of the return-to-home (RTH) capability from within 30 m (straight to home) and beyond 30 m (ascend to RTH height, return above home, and descend). The trainer and Dave Torick also executed a mission flight to emulate a photogrammetry mission that covered the Hutchison Field site using a boustrophedon pattern. Once this mission was planned, the operator simply pressed start, and the UAV ascended from the launch site, proceeded to the start point, executed the full scan pattern, and returned to the launch location to land. Key findings from this training and detailed notes are provided at the end of Appendix G.

FAA Part 107 Training and Certification

The team members committed to the project aerial repeater research investigations also obtained full FAA Part 107 certification, which is required for operation closer to the public, public highways, and BVLOS. Sean Campbell (the PM) and Dave Torick (AHMCT flight leader) pursued FAA Part 107 training via online training course at Drone Pilot Ground School (https://www.dronepilotgroundschool.com/). Sean Campbell obtained certification on July 11, 2022, and Dave Torick obtained certification on July 14, 2022. Ty Lasky completed his FAA Part 107 training and obtained certification in October 2022.

Remote Pilot Certification

To further enhance technical capabilities as well as improve mission safety, team members took this and the remaining training courses provided by DroneAviate (https://droneaviate.com/), a UAS training school that operates in Sacramento, San Francisco, and Los Angeles. This course was taken by Sean Campbell (June 25-26, 2002), Dave Torick (August 27-28, 2022), and Ty Lasky (fall 2022). Remote Pilot Certification (https://droneaviate.com/trainings/remote-pilot/) is an online and two-day in-person course providing 12 hours of online instruction followed by a two-day, in-person drone flight training with expert instructors using DroneAviate-supplied training aircraft. DroneAviate guarantees attendees will pass the FAA remote pilot knowledge test on their first attempt. Course registration includes lifetime access to all training materials, remote pilot job resources, and re-currency training. Instruction includes:

- FAA Part 107 Regulations
- Airspace and airport operations
- Authorizations and waivers
- Weather
- Loading and performance
- Emergency procedures
- Night operations
- Aeronautical decision-making
- Crew resource management
- Preventative maintenance
- Preflight inspections
- Insurance
- Privacy and legal considerations

Advanced Pilot Certification

DroneAviate's Advanced Pilot Certification (https://droneaviate.com/trainings/advanced-pilot/) two-day course teaches participants advanced workflow skills required to operate a drone efficiently and safely in the dynamic commercial flight environment. This course was taken by Sean Campbell (July 21-22, 2002). Dave Torick will take this course in fall 2022.

Operating in complex work situations with advanced enterprise UAS equipment was discussed and demonstrated along with an emphasis on safety protocols. Students can attend this class again free of charge for up to one year after graduation. FAA Part 107 Remote Pilot certification or knowledge is required for course enrollment. Instruction includes:

- Complex commercial flight operations
- Enterprise UAS platforms
- Data collection and processing
- Flight site inspection
- Mission planning
- Legal considerations
- Pre-flight inspections
- Mission demonstrations
- Managing your resources
- Human factors
- Emergencies
- Safety Management Systems
- Airspace considerations
- FAA authorizations and waivers
- Insurance

Enterprise Operations - Basic

The Advanced Pilot Certification course has been discontinued. It has been replaced by two courses: Enterprise Operations – Basic and Enterprise Operations – Advanced. This two-day course is the next step for the newer pilot after the Remote Pilot Certification. It includes the introduction of the Enterprise-level UAS ecosystem and flight operations. Using DroneAviate-provided Enterprise entry-level aircraft, hands-on flight skills are introduced and reinforced along with flight application understanding, programming, and operations. Emphasis is on pre-flight, flying, and incorporating the pilot's role in semi-autonomous flight operations required in today's remote pilot field operations. This course was taken by Ty Lasky late in 2022. Instruction includes:

- The Enterprise ecosystem
- Commonly used flight control applications
- Pre-flight and programming of flight control applications

- Pre-flight aircraft inspections
- Hands on enterprise flight skills training
- Advanced flight maneuvering
- Human factors
- Emergencies

UAS Agriculture Pilot

DroneAviate's UAS Agriculture Pilot (https://droneaviate.com/trainings/agriculture-pilot/) one-day course teaches participants how to use drones to optimize agriculture operations, increase production, and monitor crop health using efficient workflows. This course was taken by Sean Campbell, Dave Torick, and Kin Yen on October 10, 2022. Students can attend this course again free of charge for up to one year after completion. Instruction includes:

- How a grower thinks
- Introduction to crop science
- Benefits of UAS in precision agriculture
- Current UAS platforms
- Sensors
- Red/green/blue (RGB), near infrared (NIR), and Normalized Difference Vegetation Index (NDVI) technologies
- Inspection mission planning
- Data processing software platforms
- Deliverables
- Insurance

UAS Mapping Pilot

DroneAviate's UAS Mapping Pilot (https://droneaviate.com/trainings/mapping-pilot/) two-day course teaches participants how to create orthomosaics, elevation, and 3D models using the latest drone mapping technology. This course was taken by Sean Campbell, Ty Lasky, and Dave Torick in fall 2022. UAS equipment, data capture, processing and client deliverable platforms are discussed along with flight planning, project workflows and best practices to create high-quality maps and models for commercial applications. FAA Part 107 knowledge is highly recommended for course enrollment. Students can attend this class again free of charge for up to one year after completion. Instruction includes:

- Aerial photogrammetry
- 3D modeling
- Building information modeling (BIM)
- Current UAS platforms
- Sensors
- Ground control points
- Mission planning
- Data processing software platforms
- Point clouds
- Understanding project scope and costs
- Client deliverables

UAS Cinematography Pilot

DroneAviate's UAS Cinematography Pilot (https://droneaviate.com/trainings/cinematography-pilot/) two-day course teaches participants how to use their own drone to create aerial cinematic videos with hands-on, advanced flight maneuver and post-production film editing training. This course was taken by Sean Campbell, Dave Torick, and Ty Lasky in the fall 2022. In this training, participants learn how to take smooth and difficult shots with expert instructors in the field of drone videography and production. Students can attend this course again free of charge for up to one year after completion. Instruction includes:

- Introduction to aerial videography
- Model and copyright laws
- Privacy
- Story boarding
- Camera settings
- Composing advanced aerial shots
- Advanced aerial maneuver training
- Post-production training with Adobe Premier Pro

Key Findings from Training

The Matrice-specific training yielded the following key findings. Detailed notes are available at the end of Appendix G.

- The only "safety" to prevent the M300 from turning on is the rotating battery catch. If it is horizontal, the batteries are locked in, and operation is possible. If it is vertical, the batteries are not locked, and the M300 will not power up.
- The M300 has extensive obstacle sensing. However, it will not detect small obstacles, e.g., branches or power lines.
- Having a landing/take-off pad is recommended to keep debris away from the M300, particularly the motors.
- The M300 USB port is located on top, near the beacon. The port cover must be securely closed to maintain water resistance.
- The location where the M300 leg attaches can be used for a mounting plate: remove screws, insert a mounting plate, and screw leg back on, just use longer screws.
- The side, top, and bottom of the M300 all have visual and depth of field (DOF) sensors for obstacle detection/avoidance. These work for large obstacles, but not for smaller branches or power lines. There are blind spots, maybe ± 20 degrees near each motor.
- Remove camera covers only when ready to fly to keep lenses protected and cleaner
- Do not take off from a vehicle or other large metal object, this will throw off calibration, e.g., the compass.
- Controller screen and setting information:
    - The sound should be turned all the way up so that audio can be recorded in the field.
    - The M300 Health Management System (HMS) should be checked prior to every takeoff. If a category is yellow, check it, and use caution. If a category is red, M300 cannot takeoff.
- Manual flight:
    - Before operation, set RTH height 50 ft above highest obstacle
    - For all RTH modes: If the UAV is more than 30 m from home, it will rise to RTH height, return above home, and then descend. If closer than 30 m, it flies directly to home. The pilot must watch for intervening obstacles.
    - Maximum altitude should be set at 394 ft due to the FAA’s 400 ft limitation. However, 400 ft is AGL, so if a pilot is working on a hill, the M300 could be at or below 400 ft AGL (the hill), but higher than the controller.
    - To climb a hill, one option is to set the downward distance (obstacle range) somewhat higher than normal (the trainer suggested 50 ft), increase the max height, and fly toward the hill. The UAV should automatically climb up the hill with this

    combination. The pilot still needs to watch for small obstacles, e.g., branches or power lines.
    - Do not take off until a home point has been set. This is essential for RTH.
    - The M300 has a control stick mode, which should be checked before each flight. Only use "2", standard quadcopter mode. Left stick up/down, left right turning.
    - *For new pilots, the suggested maximum wind speed for flying is 15 mph due to takeoff concerns. Small gusts can flip the M300 even at lower wind speeds. The best practice is to have the front of the M300 facing the wind, hammer the throttle on takeoff to get 5 to 10 ft above ground quickly, level out, and then fly. The advanced technique is to pitch forward into the wind on takeoff.*
    - The controller has three modes designated TPS. T is for tripod, stick is less responsive or slow. P is normal operating mode. S is sport, up to 60 mph, which is very responsive and only for racing. Only use P mode.
    - The H20 camera can laser range a target and pin its location. This function may be useful for pinning cell towers.
    - A map can be pre-download for working area and saved to the controller to eliminate the need for a cellular network.
    - Images from the UAS to the controller are set to dual band transmission, leave in dual band if possible. ***Setting transmission to only one band may avoid communications interference.***
- Mission flights:
    - Can create a future mission using a manual flight and gathering waypoints. Every time a camera image is taken, it sets a waypoint. This function could be very helpful if for testing one scenario several times and ensuring the same flight path and actions are taken.
- Batteries:
    - Batteries can be unstable if damaged; they can catch fire or explode.
    - When removing batteries, a fair amount of pressure needs to be applied to disengage them from the UAS. It is recommended that one keeps one hand at the back of battery to keep them from shooting away from the M300 and being damaged when the battery disengages.
    - The batteries should be paired and labelled to keep them paired. This way, they share a common number of cycles and will have similar lifecycles.

    - *Do not leave batteries charging for an extended period. The batteries should be in the charging box, charged, and then unplugged. Leave the batteries in the box for storage and transport. Batteries will slowly discharge, which is normal.*
    - The M300 batteries cannot be transported on a commercial flight. They would have to be shipped.
    - Every 50 cycles, perform a full discharge/charge.
- Controller:
    - The controller charger is a USB-C. Any charger can be used, but it is strongly recommended that only the one shipped by DJI is used. It is a 24 W and probably double the power of a cellphone charger.
    - Ensure the external battery is firmly connected to the controller. Double check this so the external battery is used by the controller and it does not fall out, accidentally.
- Unpacking the M300:
    - Put the legs on first, while M300 is still in the case, and lock the rings (but not too tightly).
    - Do not extend the blades until the M300 is ready to take off. Then them extend most of way. The blades will spin fully out at takeoff.

In addition, the certification trainings yielded the following findings:

- FAA requirements are evolving in conjunction with this rapidly evolving field. For example, the TRUST certification process was not in place at the outset of this project.
- The FAA TRUST Certification process was announced in June 2021 (https://www.aviationtoday.com/2021/06/29/drone-pilots-now-need-faas-trust-fly-nas/). Prior to that, recreational pilots could fly with no certification.
- TRUST review and certification is available online for free. Information is available via the FAA TRUST site (https://www.faa.gov/uas/recreational_fliers/knowledge_test_updates/), including TRUST test administrators (https://www.faa.gov/uas/recreational_fliers/trust_test_administrators/).
- TRUST certification is for personal use as well as flying under academic exception (https://ucdrones.github.io/New_User_Guide/2.1-difference.html). The following situations must be assessed more carefully and may require FAA Part 107 certification:
    - Performing a demonstration
    - Not a US citizen

- Flying above 400 ft AGL
- Flying in fog or with limited visibility
- Flying at night
- Flying internationally

- Recreational flights have fairly strict requirements:
    - Only fly below 400 ft AGL
    - Must stay within visual line of sight (VLOS)
    - Must fly only in safe areas and no closer than 25 ft to any individuals
    - Must use an established safety line to separate all operations from spectators and bystanders
    - Must obtained FAA authorization to fly in controlled airspace
    - Never fly over any person or moving vehicle
    - Never interfere with any manned aircraft or emergency response activity
    - Never fly under the influence of drugs or alcohol
    - Never operate in a careless or reckless manner
- Under FAA Part 107:
    - A drone license is required
    - May fly for any purpose
    - "Fly only when it is safe": The pilot is responsible for determining whether the environment and all conditions are safe for a drone flight. The pilot must use their best judgment to assess whether the proposed flight operation will put anyone at risk.
    - May request special permissions to fly
        - Above FAA facility map altitudes
        - Over people, BVLOS, and more than one drone at a time

Chapter 6: Conclusions and Recommendations

Key contributions of this research project included:

- Investigation of the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects, e.g., the Responder system.
- Implementation of a UAS-based aerial repeater to extend the range of existing wireless communications infrastructure in the rural environment.
- Extensive training for key project personnel to cultivate safe operations and regulatory compliance.
- Demonstration of the functionality of the UAS-based aerial repeater in both simple and challenging environments, including the steep mountainous canyon areas near Lake Berryessa west of Davis.

Items to Monitor

It is essential to monitor for frequency/signal interference between UAS control, video telemetry, and the communications payload modem/Wi-Fi. For initial operations with a new system, perform the first test on the ground. If all is well, i.e., there appears to be no interference, test the system with a low-level flight at less than 10 ft. If there remains no interference, monitor for signs during the initial full-scale flight. If there is interference, one option would be to restrict the UAS control to one frequency. This situation is not ideal, as the UAS will perform better if the controller can automatically switch frequencies for the best signal; however, this may be essential if there is interference with the other sub-systems.

Given the manner that UAS systems receive firmware updates, it is essential to monitor these updates carefully and to test the UAS operation rigorously after any firmware updates. From the experience of the current research, as well as indications from the user community, the vendors do not always sufficiently test functionality when they update system firmware and do not notify users when there are issues. Untested firmware can lead to an inability to fly in a culture of safety. Caltrans operators must place safety first for UAS operation. If an operator identifies an issue that would keep the UAS from flying safely, whether due to software, hardware, or some external factor, the operator must ground the UAS until safety can be reestablished.

Key safety issues must be checked prior to and during every flight. Pilots should always confirm proper communication between the controller and the

UAS and ensure there is sufficient battery power to continue controlled flight operations to a normal landing.

Proper maintenance of the UAS and batteries are essential to safe operations. Utilizing an online drone data and flight management service assists in this process. The UAS flights, total flight time, battery charge cycles, and other information are stored on a website such as Airdata.com. Once the maintenance threshold is reached, the user is alerted and instructed on the next steps.

Culture of Safety

For safe and proper use of a UAS-based system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skills refresh. Pilots and team members must develop, use, and continually update checklists. Known useful checklists include mission planning and packing; crew communications; pre-flight systems and site inspections; launch, landing, and post-flight inspections; and final packing. It is critical to document everything to support safe and effective operation and for potential legal purposes. Checklists developed during this research are provided in Appendix H. As noted, checklists should be updated regularly as new items and issues are identified.

Future Work

Future work may include further hardening the prototype system in preparation for wider deployment in Caltrans. Deployment could begin in District 2, which is a rural area with a challenging terrain. Additional experiments are needed to optimize Wi-Fi antenna configuration for different scenarios.

The UAS platforms, training, and capabilities developed in the current research could be leveraged for multiple unrelated, UAS-based research projects, including ones on UAS-based photogrammetry, UAS-based Laser imagining Detection and Ranging (LiDAR) surveying, and UAS-based flood-flow sensing and estimation. Discussions with various Caltrans subject area experts should begin to develop research projects and expand application of the UAS system.

The UAS platform and the cameras that have already been purchased can be utilized to assess the maintenance needs of microwave communication systems in Caltrans. Through the addition of a real-time kinematic (RTK) positioning solution, the UAS can be utilized to inspect the structural components of microwave towers and determine the need for vegetation management to reduce Fresnel zone obstructions. The RTK removes the need for reliance on GPS positioning, which can be impacted by microwaves.

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Appendix A:
Interim Report Summarizing Concept of Operations

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TECHNICAL REPORT DOCUMENTATION PAGE

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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document provides the Operational Concepts for the UAS repeater.

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Unmanned Aerial Systems Communications Repeater Prototype System Operational Concepts

Stephen M. Donecker &
Ty A. Lasky: Principal Investigator

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June 25, 2020

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
14 CFR	Title 14 of the Code of Federal Regulations
1xRTT	Single carrier (1x) Radio Transmission Technology
AGL	Above Ground Level
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ARFCN	Absolute RF Channel Number
ATC	Air Traffic Control
BER	Bit Error Rate
BGAN	Broadband Global Area Network
BID	Basestation ID
BSIC	Base Station Identity Code
BVLOS	Beyond Visual Line of Sight
Caltrans	California Department of Transportation
CCTV	Closed-Circuit Television
CDMA	Code Division Multiple Access
CFR	Code of Federal Regulations
CI/CID	Cell Identity
CQI	Channel Quality Indicator
DHCP	Dynamic Host Configuration Protocol
DRISI	Caltrans Division of Research, Innovation and System Information

Acronym	Definition
EARFCN	Evolved UTRA Absolute RF Channel Number
ECIO	Energy per Chip to Interference power ratio
EDGE	Enhanced Data rates for GSM Evolution
EIRP	Equivalent Isotopically Radiated Power
EVDO_0	Evolution Data Optimized release 0
EVDO_A	Evolution Data Optimized release A
EVDO_B	Evolution Data Optimized release B
FAA	Federal Aviation Administration
FPV	First Person View
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPAP	High Speed Packet Access Plus
HSUPA	High Speed Uplink Packet Access
LAANC	Low Altitude Authorization and Notification Capability
LAC	Location Area Code
LAN	Local Area Network
LEO	Low Earth Orbit
LOS	Line of Sight
LTE	Long Term Evolution

Acronym	Definition
MCC	Mobile Country Code
MNC	Mobile Network Code
NAS	National Airspace System
NID	Network ID
NOTAM	Notices to Airmen
ORC	Office of Radio Communications
PCI	Physical Cell Identity
PSC	Primary Scrambling Code
QOS	Quality of Service
RF	Radio Frequency
RPIC	Remote Pilot in Command
RPV	Remote-Person View
RSCP	Received Signal Code Power
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SATCOM	Satellite Communications
SHS	State Highway System
SID	System ID
SINR	Signal to Interference plus Noise Ratio
SR	State Route
TAC	Tracking Area Code

Acronym	Definition
TFR	Temporary Flight Restrictions
TMC	Transportation Management Center
Tx/Rx	Transmit / Receive
UA	Unmanned Aircraft
UARFCN	UMTS Absolute RF Channel Number
UAS	Unmanned Aerial System
UC	University of California
UE	User Equipment
UMTS	Universal Mobile Telecommunications Service
UTRA	Universal Terrestrial Radio Access
VLOS	Visual Line of Sight
VO	Visual Observer
VSAT	Very Small Aperture Terminal
WAN	Wide Area Network
Wi-Fi	IEEE 802.11x Wireless LAN

Referencing Supporting Documents

For a typical research report, the reference section and the related in-text citations are self-explanatory. For the current report, the citations are in some cases more complex, and a brief overview of the approach is provided here, based on representative sample citations.

- A simple numerical citation such as [6] refers to the entire reference, for example the research report by Donecker, *et al*. [6].
- The § symbol represents "Section" per standard usage. Hence §101 of [7] would be Section 101 of Federal Aviation Administration, Department of Transportation, CFR Title 14 Chapter I [7].
- Subsections and similar are represented by decimal points. For example, §101.13 of [7] would be Subsection 13 of Section 101 of [7].
- Federal UAS operational regulations are found primarily in §107 of the Code of Federal Regulations (CFR) Title 14 Chapter I [7].

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Jeremiah Pearce with the District 2 Office of ITS Engineering and Support, and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

1 Introduction

The primary purpose of this document is to discuss current cellular data service availability within rural sections of the State Highway System (SHS), present coverage shortcomings within these areas, provide mitigating and system concepts, outline key operational and/or business constraints, and propose a prototype system that will significantly extend the usable range of existing cellular infrastructure data services.

This document forms the basis for the understanding between the California Department of Transportation (Caltrans) and the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California (UC), Davis with respect to the overall project scope and direction of the prototype system development.

The primary goal of the encompassing research project is to develop a prototype Unmanned Aerial System (UAS) containing a communications payload providing aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi (IEEE 802.11x Wireless LAN) clients. The UAS would allow for relatively easy deployment within the SHS right of way thus extending ubiquitous low-cost network data services further into remote rural areas.

1.1 Assumptions

It is assumed that all consumers of this document are aware of the communications systems deployed or deployable within Caltrans rural districts for use in day-to-day and emergency scenarios within the rural district sections of the SHS. Specifically, it is assumed that readers have sufficient knowledge of existing mobile radio high-band/low-band (point-to-point and repeater-based), satellite (vehicle, modem, and phone), and cellular (voice and data) systems with respect to operational use cases, costs, performance, and availability throughout rural service areas.

1.2 Objectives

The high-level primary objectives of this document and subsequent associated research and development of a prototype system are to:

- Demonstrate understanding of the scope of the existing cellular data services availability, or lack thereof, within rural sections of the SHS
- Demonstrate understanding of a class of possible mitigations that would fundamentally enhance the usable range of cellular data services within rural sections of the SHS

- Discuss the general concepts of operation of a proposed prototype system that would allow use of existing cellular data services beyond current usable range and/or within existing dead zones within the rural regions of the SHS
- Discuss operational scenarios outside of the scope of this project, specifically hypothetical future deployment within rural sections of the SHS, which are instrumental in understanding key system operational boundaries required for analysis, design, proposal, and subsequent selection of various operational concepts

The proposed prototype system shall be

- Capable of carrying a communications payload with the ability to extend/enhance the usable range of existing cellular data services
- Capable of carrying a video camera payload with the ability to relay video in real-time to the ground users
- Capable of carrying modular payloads
- Comparatively easily deployable and operable within and near the SHS right of way
- Capable of flight within the full range of the legally allowable air space
- Capable of self-flight (i.e. hold position). Self-flight beyond stationary positioning is dependent on existing regulations and current commentary.

Key components of the proposed prototype system, including the flight vehicle, shall be considered and selected such that they may be considered multi-use within Caltrans for the purposes of aiding in early adoption and hypothetical subsequent deployment.

Prototype systems under consideration shall be discussed, analyzed, and proposed such that hypothetical deployment of said system would follow all Federal, State, Local, and Caltrans regulations.

This concept document is intended for the Caltrans project panel to assess the AHMCT Research Center's understanding of Caltrans' needs related to this research project and aid the panel's selection of all or some of the proposed system concepts. This document will assist the AHMCT project team in developing the subsequent functional requirements (Task 4) and system design (Task 5) documentation.

2 Current system or situation

This chapter aims to document and discuss the current state of cellular network coverage from major providers in a few representative areas of rural districts. We begin by discussing the cellular service coverage maps from several major providers and will then follow with a general discussion of AHMCT Research Center detailed on-site cellular measurements throughout many of the rural SHS routes. We will then conclude the initial analysis of overall cellular coverage within rural environments and will note the preferred cellular service providers.

Following the initial cellular coverage analysis, we will examine a representative group of three example on-site locations within District 2 (D2). For each example site we will begin by discussing the cellular measurements in the local area, mapping the known location of the nearest cellular towers, and follow with a view of the tower locations with respect to the local terrain in an effort to explain lack of local cellular signal coverage.

2.1 Cellular Provider Coverage

As a baseline reference point, the cellular provider coverage maps, shown in Figures 2.1-2.4, represent the vendor claimed service availability surrounding the Lassen National Forest. In each of the following figures, note the area bounded by State Route 44 (SR44) to the east and SR89 to the west. Although the coverage maps are not very detailed at this zoom level, it can be easily seen that coverage along SR44 and portions of SR89 are sparse.

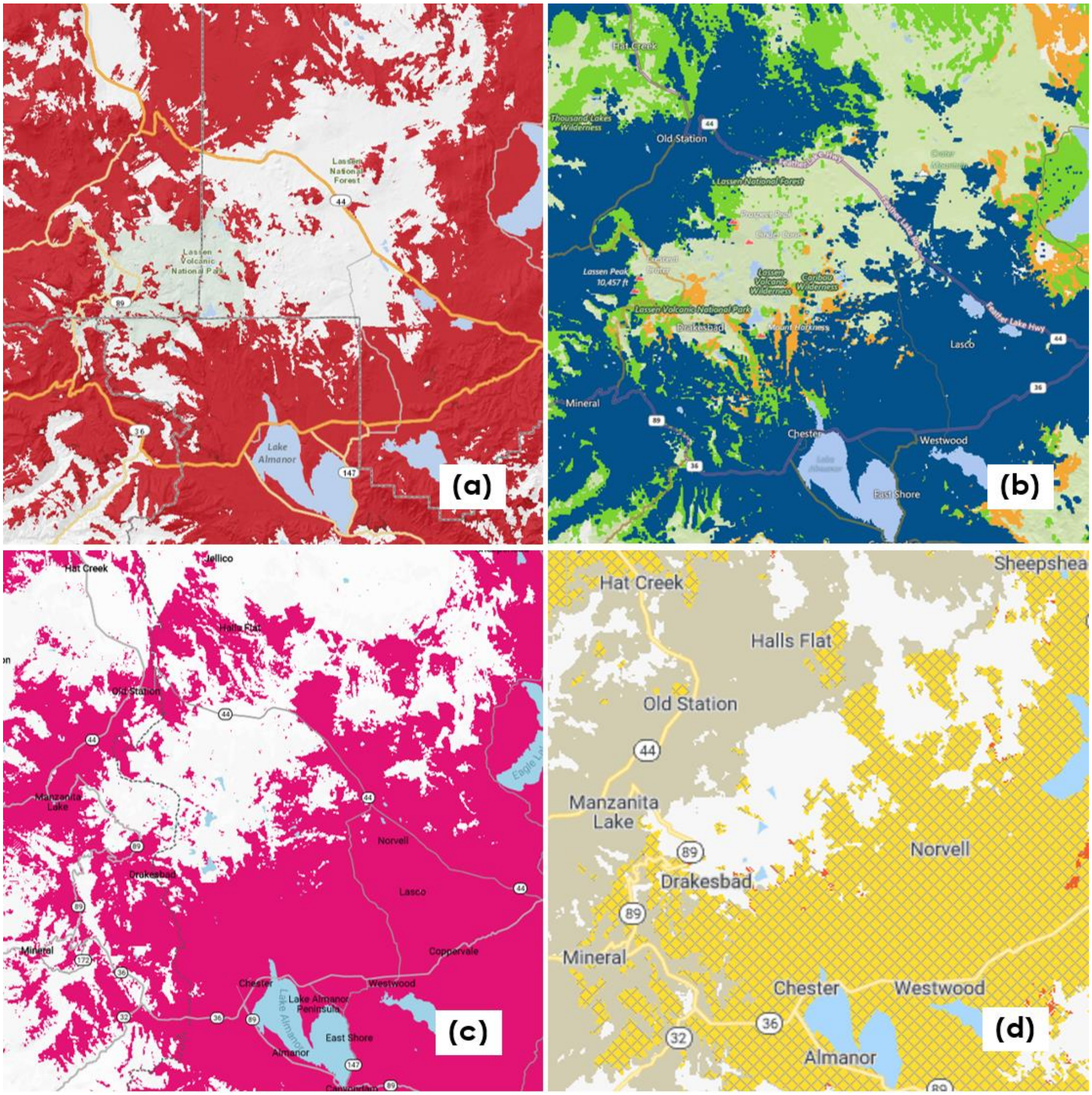

Figure 2.1: Cellular network coverage map. (a) Verizon, (b) ATT, (c) T-Mobile, (d) Sprint (images courtesy of respective providers)

Figure 2.1 is a composite of several leading cellular network data service providers' coverage within the Lassen area. Figure 2.1(a) shows the Verizon cellular service coverage along SR44 to the east. Notice that the cellular coverage is weak to non-existent from Bogard northwest towards SR89, and further north of SR44 along SR89. Note that the Verizon coverage map suggests that outside of this area the cellular coverage is relatively quite good along many of the surrounding routes.

Figure 2.1(b) shows the ATT cellular service coverage along SR44 to the east. Notice that the cellular coverage is also weak to non-existent from Bogard northwest towards SR89, and further north of SR44 along SR89. Note that the ATT coverage map suggests that outside of this area the cellular coverage is reasonably good along many of the surrounding routes with the exception of a few areas to the southwest of the Lassen area. In this particular coverage map the dark blue represents 4G LTE, the green represents other ATT coverage, and the orange represents off-net coverage. The light green and the white represent no coverage areas.

Figure 2.1(c) shows the T-Mobile cellular service coverage along SR44 to the east. Notice that the cellular coverage is also weak to non-existent from Bogard northwest towards SR89, and further north of SR44 along SR89. Note that the T-Mobile coverage map suggests that outside of this area the cellular coverage is spotty along many of the surrounding routes.

Figure 2.1(d) shows the Sprint cellular service coverage along SR44, not shown, to the east between Norvell and Old Station. Notice that the cellular coverage is close to non-existent from Bogard northwest towards SR89 at Old Station and further north. Note that the Sprint coverage map suggests that outside of this area the cellular coverage is relatively poor along many of the surrounding routes.

Note that cellular coverage maps provided by cellular providers have been historically overly generous in service availability coverage estimates. Good engineering judgement, due diligence and caution should be used any time these maps are referenced for planning and installation purposes.

2.2 Detailed Service Availability Estimates

Knowing that the vendor provided service availability coverage maps are historically inaccurate, we further investigate detailed service availability [1], [2], [3], and estimated locations of service provider tower locations [3], [4]. In general, the service availability coverage services provide reasonably detailed estimates compared to those of the vendor coverage maps in highly traveled areas.

In general, we found that for the example areas discussed below in sections 2.5.1 and 2.5.2 there was very little usable service availability coverage estimates, as seen in Figure 2.2(a). However, for the example areas discussed below in 2.5.3 we found a high degree of correlation between the service availability estimates, as seen in Figure 2.2(b), and the AHMCT measurements.

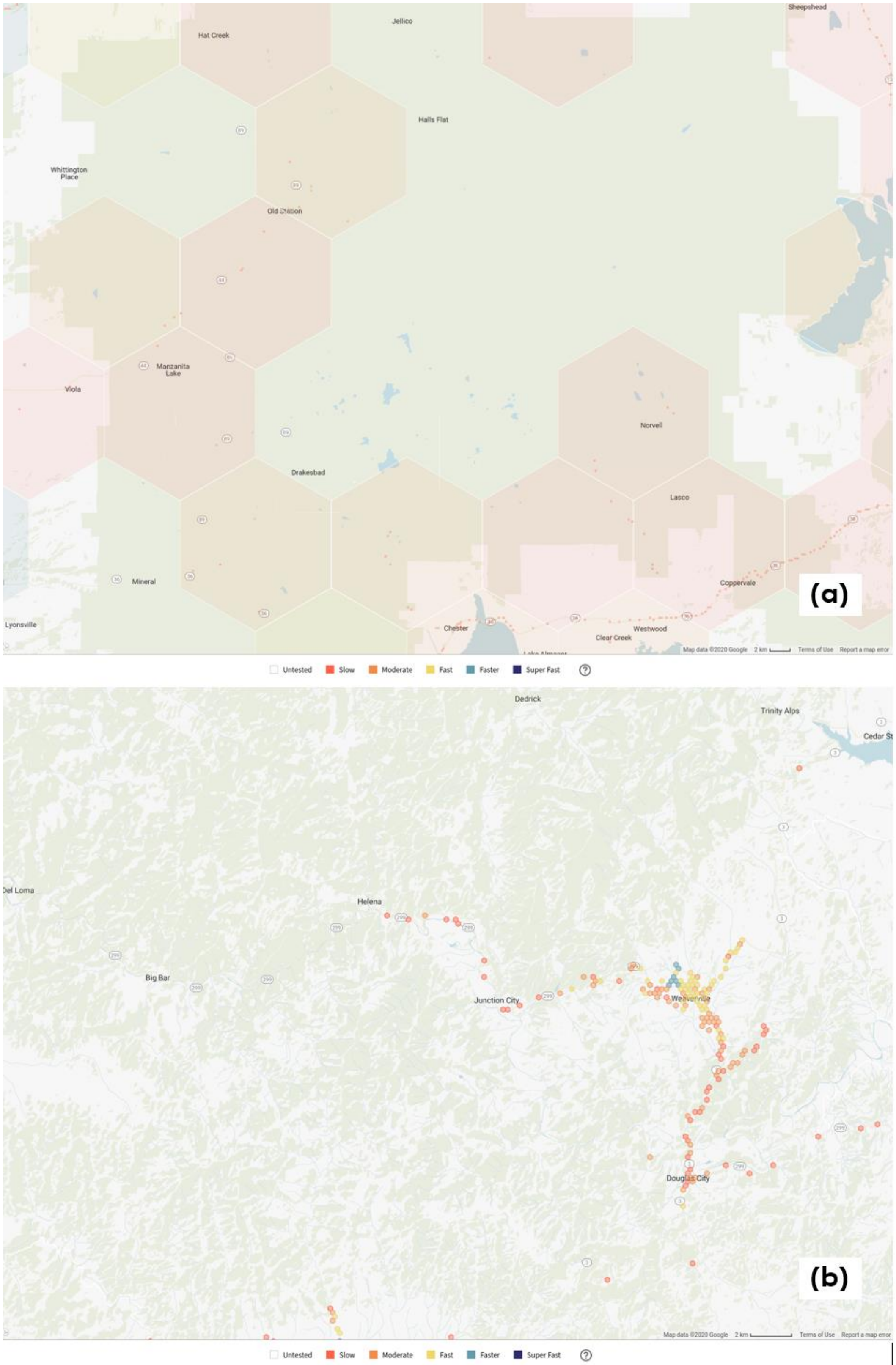

Figure 2.2: The cellular coverage map estimate for Verizon using fastest speed found (a) SR44 and SR89, (b) SR299W (images courtesy of RootMetrics)

As for the tower location estimates we found that [3] provided a set of useful cell tower data, beyond location, by sector, including type, identification, channel, reference signal received power maximum, direction, bandwidth, up/down frequencies, and band. However, as discussed in detail [5] using the FCC service [4] is very cumbersome and requires a significant amount of effort and ingenuity to ferret out current cell sites. Although the FCC would be considered the gold standard, this route is certainly not a feasible solution for end users of a UAS to easily research cell tower locations and sector directions for a given operational environment. Further research on this subject is warranted.

When requesting nearest cellular site data, from the major service providers, the typical responses are that the information is proprietary, irrelevant, or a concern of homeland security, according to [5]. The recommendation is to perform "do-it-yourself" measurements. Therefore, for the analysis of the following example sites we rely on the measurements conducted in [6].

2.3 AHMCT Cellular Field Measurements

The AHMCT Research Center developed an application to collect cellular service availability measurements over all Caltrans mountain pass snow routes [6].

Cellular measurements include:

- Cell location (lat/lon)
- Mobile location (lat/lon)
- Network identification
    - BSIC/BID (GSM/CDMA) – basestation identity
    - CI/CID (GSM/UMTS/LTE) – cell identity
    - LAC (GSM/UMTS) – location area code
    - MCC (GSM/UMTS/LTE) – mobile country code
    - MNC/NID (GSM/CDMA/UMTS/LTE) – mobile network code
    - PCI (LTE) – physical cell id
    - PSC (UMTS) – primary scrambling code
    - SID (CDMA) – system identity
    - TAC (LTE) – tracking area code
- Cell signal strength
    - RSSI (GSM/CDMA/LTE) – received signal strength indicator
    - RSCP (UMTS/LTE) – received signal code power

- Cell signal quality
    - BER (GSM) – bit error rate
    - ECIO (CDMA/UMTS) energy per chip to interference power ratio
    - CQI (LTE) - channel quality indicator
    - RSRP (LTE) – reference signal received power
    - RSRQ (LTE) – reference signal received quality
    - SINR (LTE) – signal to interference plus noise ratio
- Cell channel
    - ARFCN (GSM) – absolute RF channel number
    - UARFCN (UMTS) – UMTS absolute RF channel number
    - EARFCN (LTE) – evolved UTRA absolute RF channel number
- Network type
    - GSM – GPRS, EDGE
    - CDMA - 1xRTT, EVDO_0, EVDO_A, EVDO_B
    - UMTS – HSPA, HSDPA, HSUPA, HSPAP
    - LTE

Note that the non-exhaustive list of measurements are collected if/when reported by the particular embedded user equipment (UE) communications hardware/firmware. This means that some of the measurements are reported periodically, others as states change, while some measurements, based on vender firmware implementation, are unavailable altogether.

The application was installed in several phones and configured to operate on Verizon, AT&T, and T-Mobile cellular networks. These phones were all in operation during the data collection process. The resultant data from the measurement effort was synthesized into cellular service availability heat maps.

Measurements and analysis over all mountain pass snow routes show a high degree of correlation, and suggest that in rural areas with sparse coverage there are performance leaders between the various cellular providers in rural sections of the SHS. Additionally, AHMCT's measurement and analysis findings and those advertised by the leading cellular providers, shown in Figure 2.1, correlate reasonably well. The results show that, depending on the area, one service provider may perform better than the others depending on location. For the purposes of this document, we will use Verizon cellular tower locations and AHMCT data measurements when discussing service availability in the selected example rural sections of the SHS within District 2.

2.4 Quality of Service

Many factors can affect both signal strength and signal quality between a cellular basestation and UE and thus affect the overall quality of service (QOS).

Some typical factors affecting general signal strength and quality:

- Distance between cell tower and mobile user locations
- Sector traffic load (i.e. interference from other users of same sector)
- Interference from nearby sectors
- Near-far problem (i.e. imbalance of power between the basestation, nearby mobile users, and faraway mobile users)
- Fading due to multi-path
- Sector antenna height, directivity, direction, and tilt with respect to mobile location
- Significant obstructions

Many times, in very rural areas of the SHS, significant LOS obstructions are one of the primary causes of little to no service, that is if the free space path loss between the basestation and the UE does not exceed system requirements. In this case, it is interesting to note that attempting to mitigate loss of service by moving the cellular UE from a ground based location to an aerial based location above a significantly tall obstruction at distance, while not suffering from excessive path loss due to the LOS distance from the basestation, may degrade QOS due to sector antenna tilt.

Additionally, while in remote rural areas of the SHS, it is likely that a mobile user could run into the near-far problem when at a significant distance from the targeted basestation. This issue arises when an imbalance of Tx/Rx power between the basestation, nearby mobile users, and faraway mobile users results in significant interference to the weaker signal at the basestation. To combat the problem, basestation and mobile power control is employed. However, power control may not be able to sufficiently mitigate the various imbalances resulting in a significantly degraded QOS or altogether prohibit initiation of or an ongoing connection.

A primary goal of this research is to see what QOS achievements can be made by moving around/above significant obstructions, moving towards cell sites just out of reach, and/or moving/orienting in such a way that connection with a higher QOS basestation is achieved. Each of these possibilities requires an aerial solution that has the ability to establish LOS with a chosen cellular tower with the stated goal of significantly opening up the opportunity to potentially usable regions of existing cellular infrastructure in rural environments.

The purpose of the following sections is to explore real world lack of service due to significant LOS obstacles.

2.5 Example Site Analyses

Two different rural areas within District 2, one more flat-land and the other mountainous, will be investigated. In each area, we will provide a set of figures, including cellular service availability measurements, topographic maps, cellular tower locations, site locations, and 3D views of the local terrain, and discuss why cellular service availability is lacking at each of the example site locations.

2.5.1 Bogard Buttes SR44

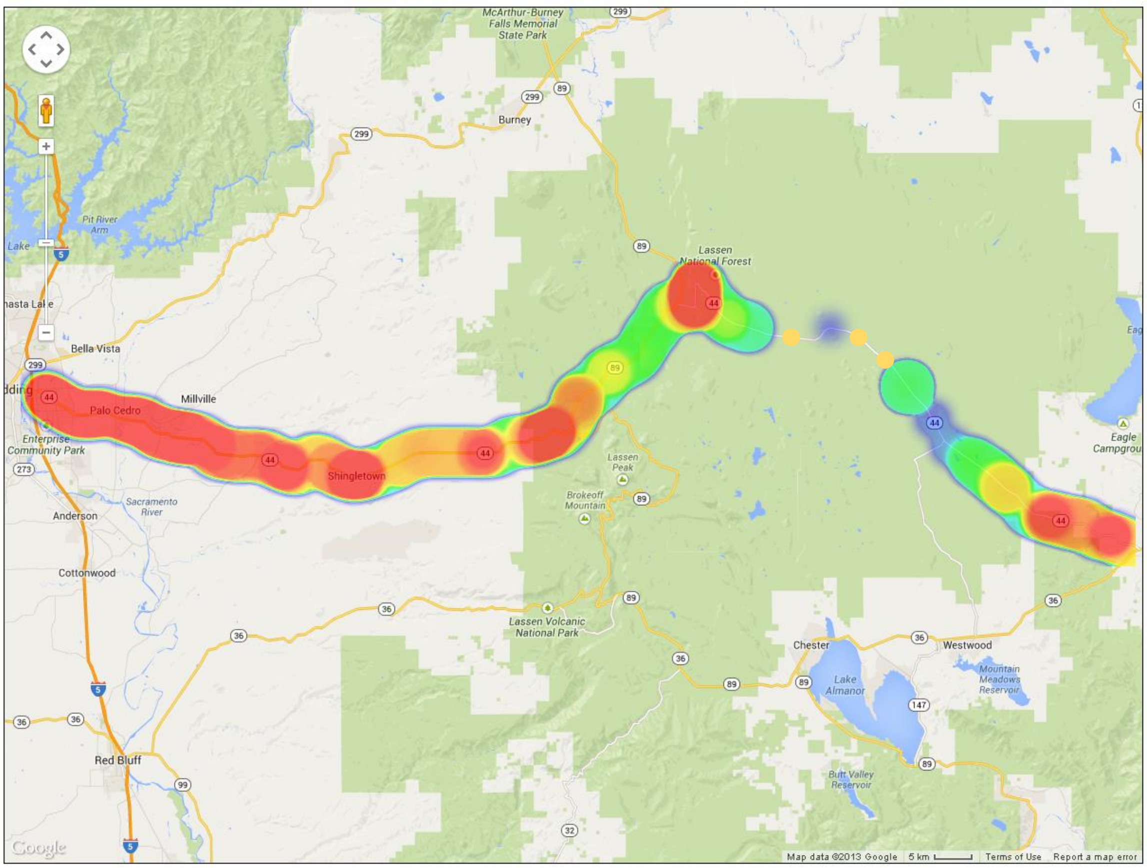

Figure 2.3: SR44 Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure 2.3 shows the Verizon cellular service availability measurements along SR44. The yellow markers represent three example analysis sites. Notice that the cellular coverage is weak to non-existent from Bogard northwest towards SR89. The AHMCT Research Center on-site measurements correlate well with the Verizon coverage map shown in Figure 2.1(a).

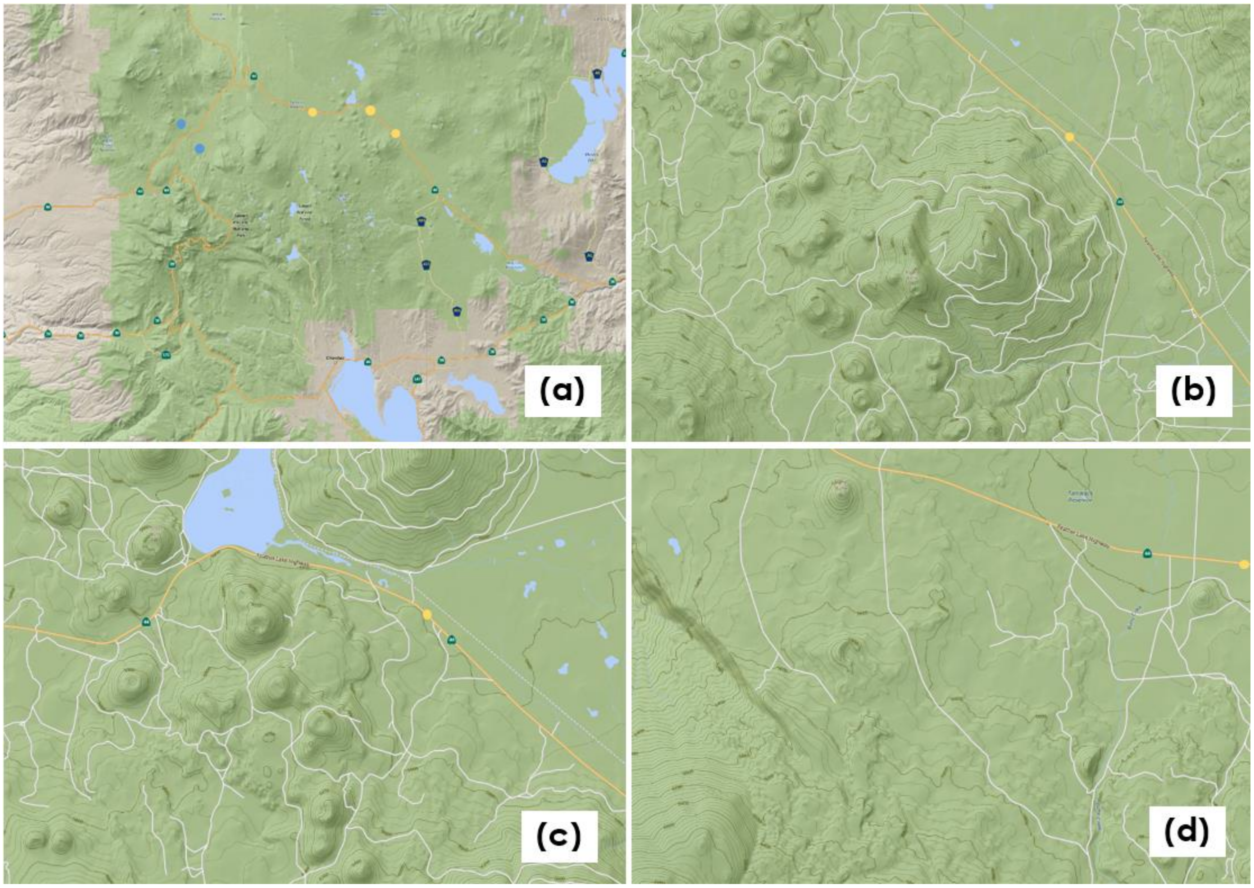

Figure 2.4: SR44 Topographic map with select cellular tower and example site approximate locations near Bogard Buttes (a) Verizon cellular tower and site locations, (b) Site 1, (c) Site 2, (d) Site 3 (images courtesy of AHMCT Research Center)

Figure 2.4(a) shows the approximate locations of two nearby Verizon cellular towers [3] represented by blue markers, along with example Site 1, 2, and 3 locations represented by yellow markers. Looking at the tower locations with respect to the section of SR44 surrounding the example site locations, there is likely a significant chance of occluding geography between the two. Furthermore, looking at Figure 2.4(b)-(d) it can be seen that in each case there is indeed local topography between the cellular towers and the respective example site.

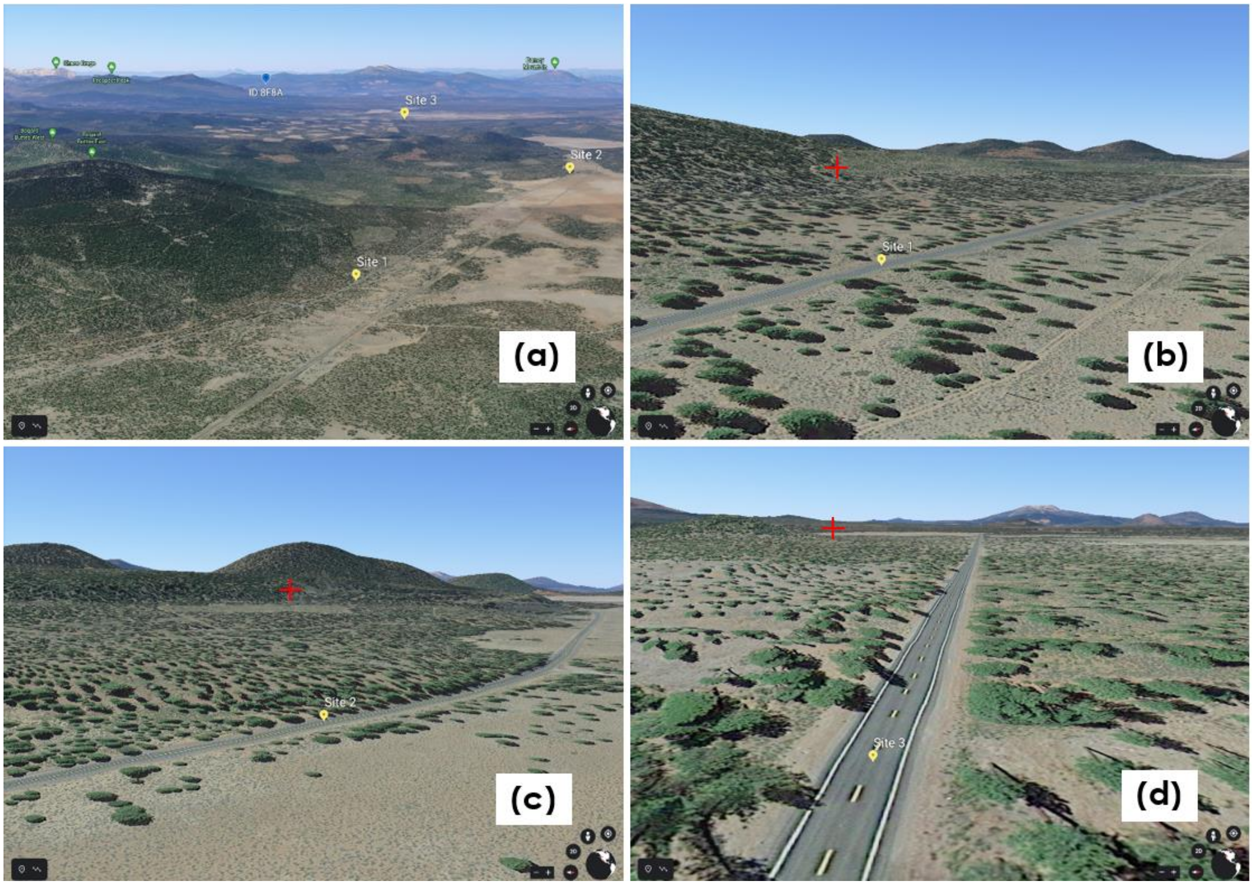

Figure 2.5: SR44 3D map with select cellular tower and example site approximate locations near Bogard Buttes (a) Verizon cellular tower and site locations, (b) view towards the cellular tower from Site 1, (c) view towards cellular tower from Site 2, (d) view towards cellular tower from Site 3 (images courtesy of Google Earth)

Figure 2.5 represents the cellular tower and example site approximate locations shown in the topographic maps of Figure 2.3 from the perspective of the example site locations.

Figure 2.5(a) shows a high-altitude view of the Verizon cell tower location with ID 8F8A, represented by a blue marker, visible to the north of Bogard Buttes East in the foreground, and Prospect Peak in the background. Sites 1, 2, and 3 along SR44 are represented by yellow markers.

Figure 2.5(b) shows the view of Site 1 on SR44 in the foreground, Bogard Buttes East to the left, and mountains in the background obscuring the view of Verizon cellular tower ID 8F8A. The red plus marker represents the approximate Line-Of-Sight (LOS) of the cellular tower from Site 1, which is clearly blocked by local terrain.

Figure 2.5(c) shows the view of Site 2 on SR44 north of Bogard Buttes East and a mountain in the background also obscuring the view of Verizon cellular tower

ID 8F8A. The red plus marker represents the approximate LOS of the cellular tower from Site 2, which is also clearly blocked by local terrain.

Figure 2.5(d) shows the view of Site 3 on SR44 west of Bogard Buttes and a mountain range in the background also obscuring the view of Verizon cellular tower ID 8F8A. Similarly, the red plus marker represents the approximate LOS of the cellular tower from Site 3, which is blocked by terrain across the valley towards the cellular tower location.

Figure 2.5 represents directional views towards the local Verizon cell tower and shows a clear rationale for the lack of cellular coverage along SR44 near Bogard. Although the area is surrounded by what appears to be slowly sloping short hills, each is capable of shielding these sections of SR44 from cellular reception.

2.5.2 Sugarloaf Peak SR89

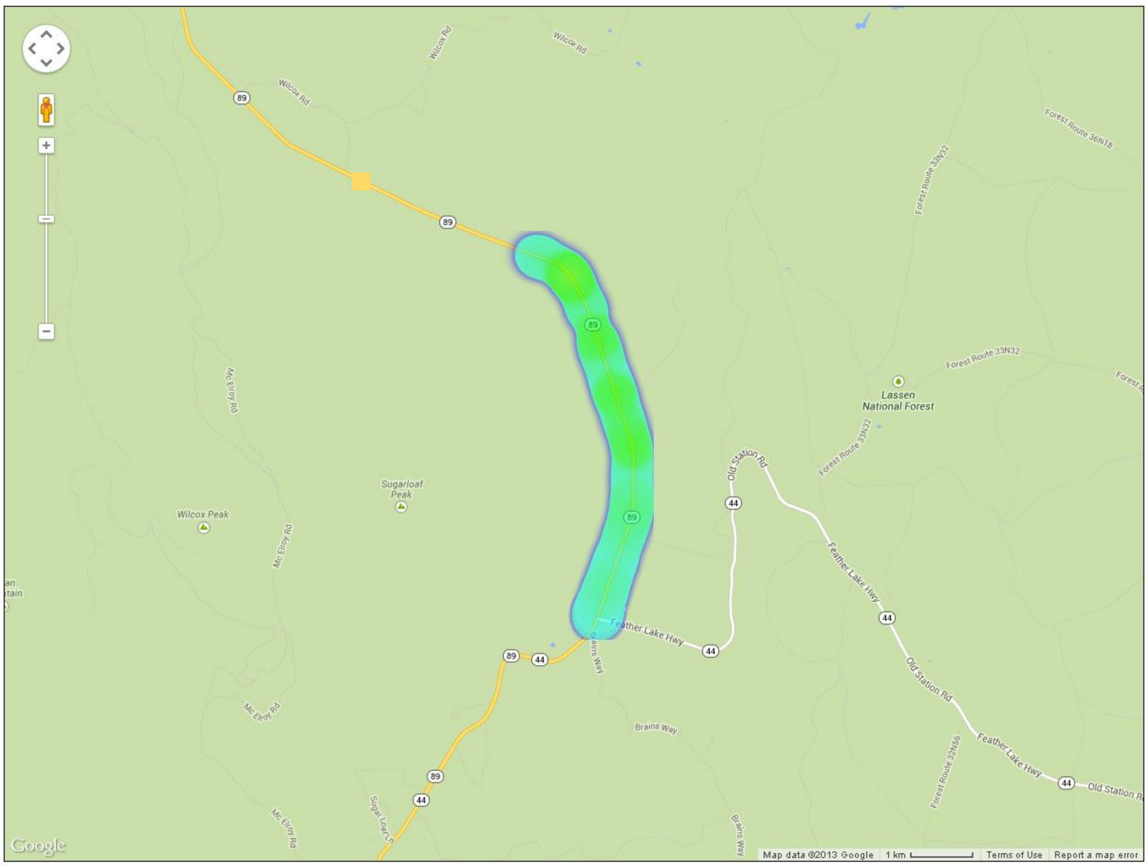

Figure 2.6: SR89 Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure 2.6 shows the Verizon cellular service availability measurements along SR89 north of SR44. The yellow marker represents an additional example analysis site. The cellular coverage is reasonably good just north of the intersection of

SR44 and SR89, but falls off immediately following the turn in the northwest direction. The AHMCT Research Center on-site measurements correlate well with the Verizon coverage map show in Figure 2.1(a).

Figure 2.7(a) shows the approximate locations of two nearby Verizon cellular towers [3] represented by blue markers, along with the example Site 4 location represented by a yellow marker. Looking at the tower locations with respect to the section of SR89 surrounding the example site location, there is also likely a significant chance of occluding geography between the two. Furthermore, looking at Figure 2.7(b) it can be seen that there is indeed local topography between the cellular towers and the example site.

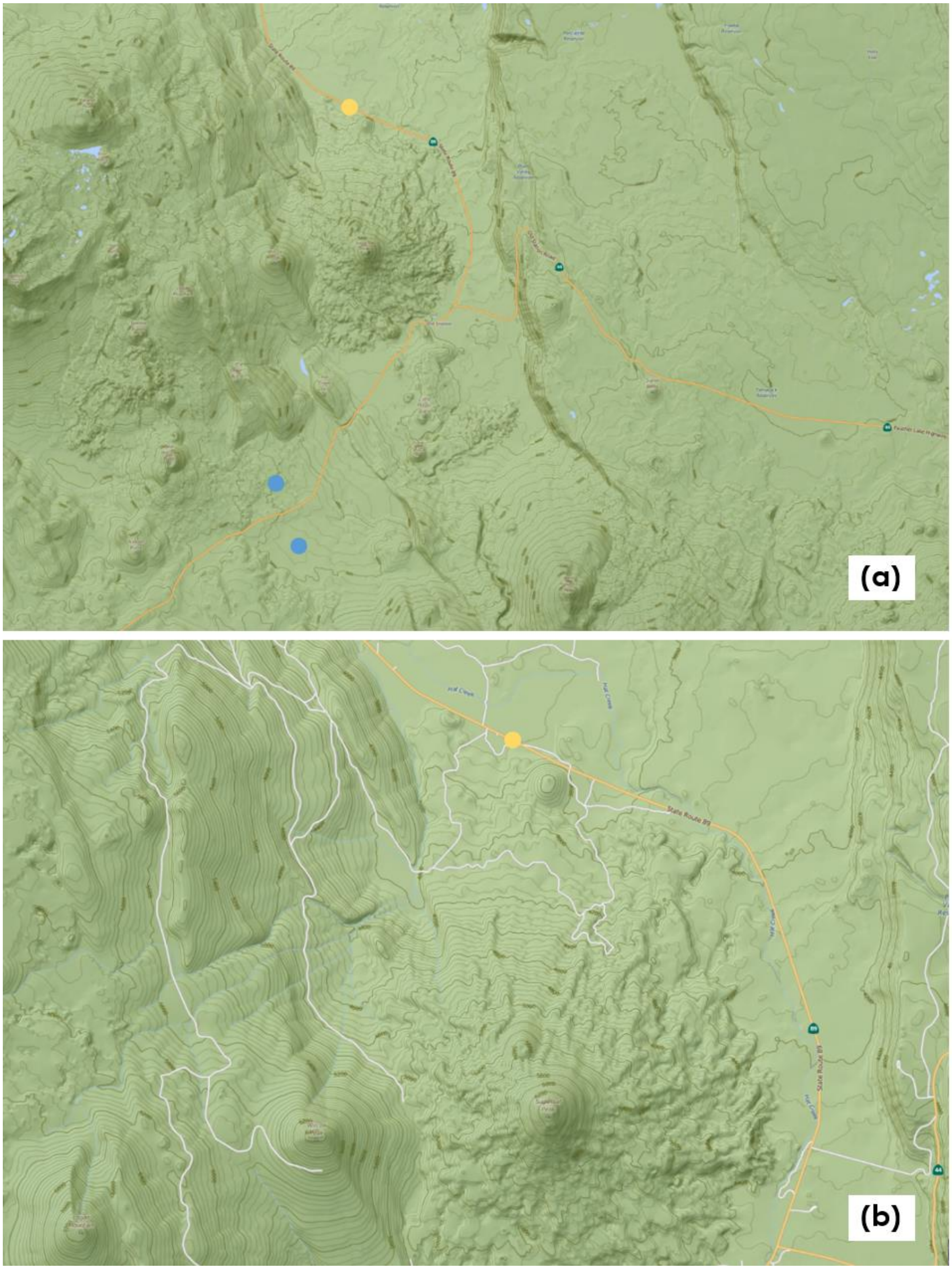

Figure 2.7: SR89 Topographic map with select cellular tower and example site approximate locations near Sugarloaf Peak (a) Verizon cellular tower and site locations, (b) Site 4 (images courtesy of AHMCT Research Center)

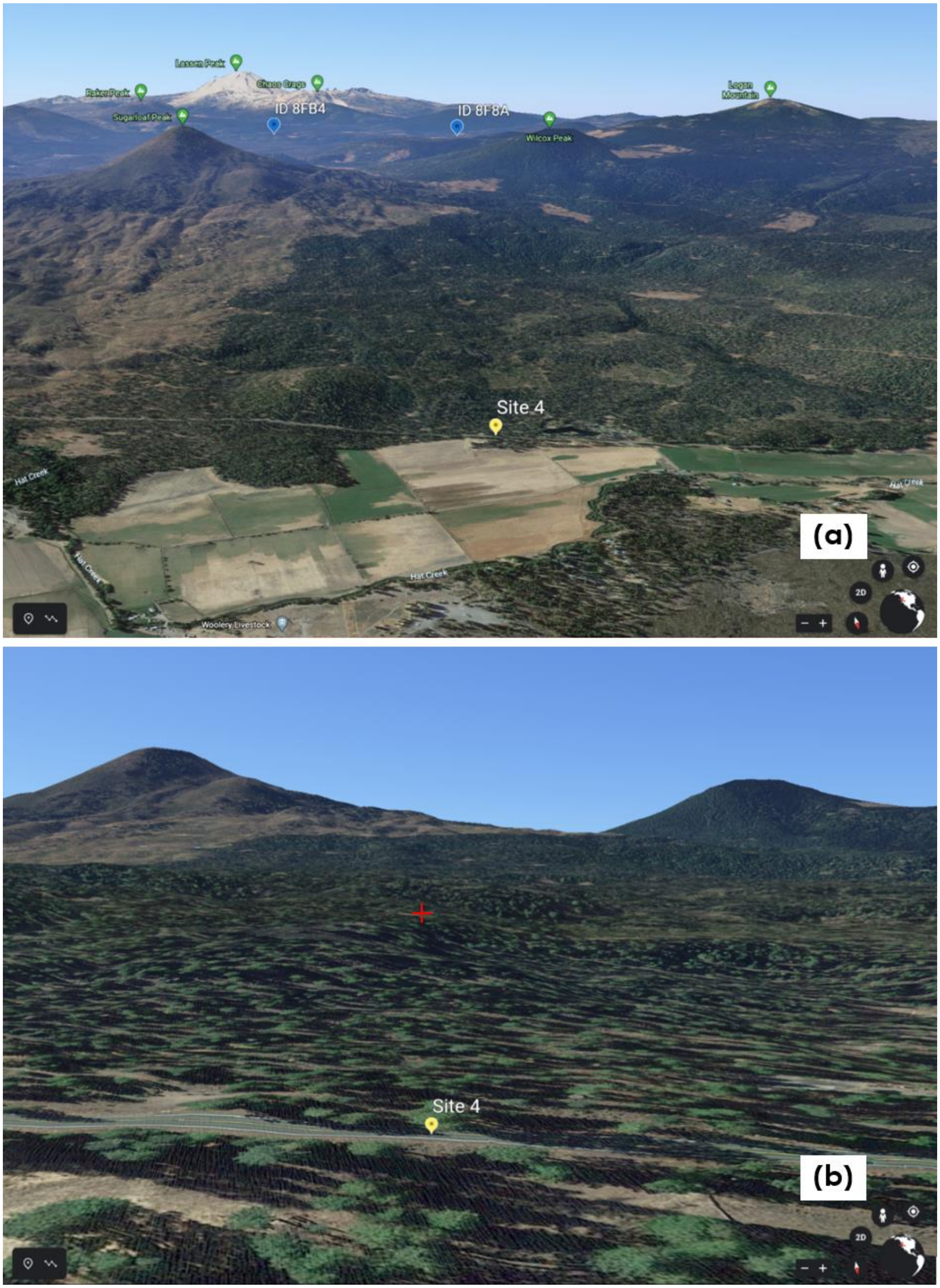

Figure 2.8: SR89 3D map with select cellular tower and example site approximate locations near Sugarloaf Peak (a) Verizon cellular tower and site locations, (b) view towards the cellular tower from Site 4 (images courtesy of Google Earth)

Figure 2.8 represents the cellular tower and example site approximate locations shown in the topographic maps of Figure 2.6 from the perspective of the example site location.

Figure 2.8(a) shows a high-altitude view of the Verizon cell tower locations with ID 8FB4 and ID 8F8A, represented by blue markers, visible to the southwest of Sugarloaf Peak in the background. Site 4 along SR89 is represented by a yellow marker.

Figure 2.8(b) shows the view of Site 4 on SR89 in the foreground, Sugarloaf Peak to the left, Wilcox Peak to the right, and foothills in the foreground obscuring the view of the Verizon cellular towers to the southwest. The red plus marker represents the approximate LOS of the cellular tower from Site 4, which is clearly blocked by local terrain.

Figure 2.8 represents directional views towards the local Verizon cell towers and shows a clear rationale for the lack of cellular coverage along SR89 near Sugarloaf Peak.

2.5.3 Big Barr SR299W

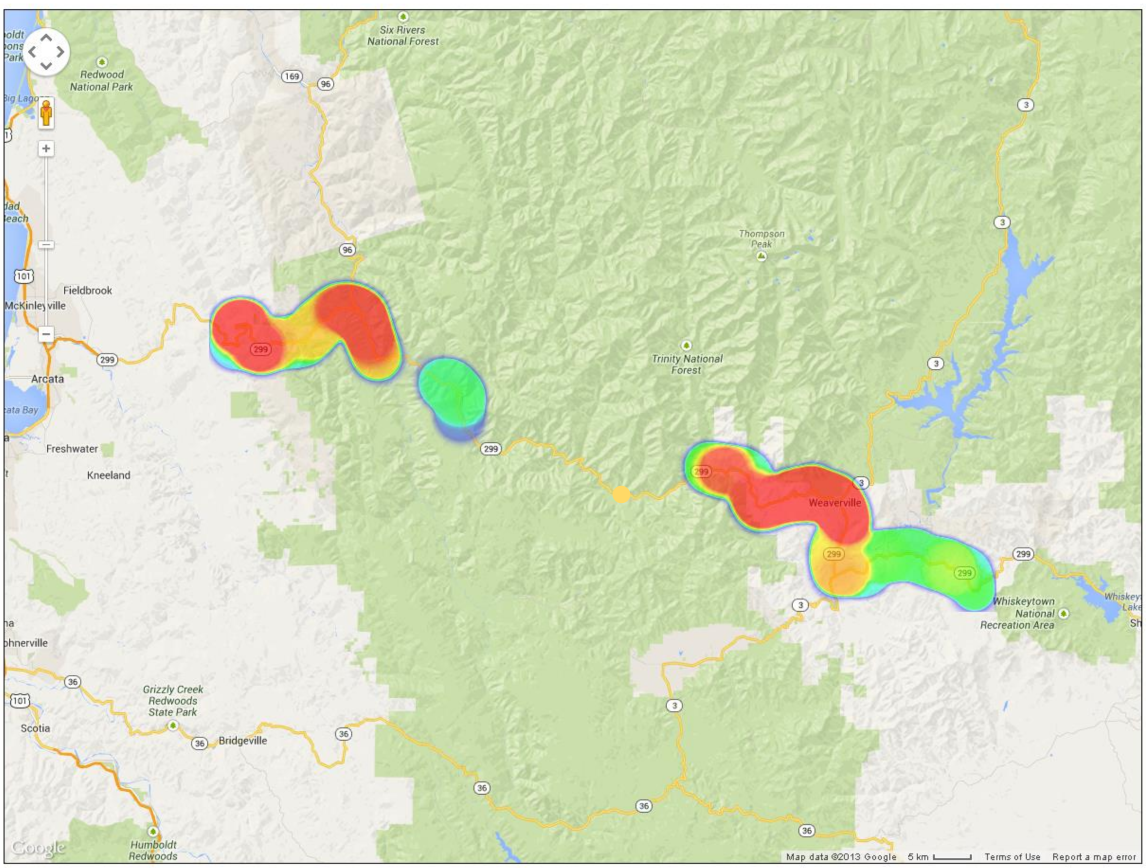

Figure 2.9: SR299W Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure 2.9 shows the Verizon cellular service availability measurements along SR299W west of Redding. The yellow marker represents an additional example analysis site. Notice that the cellular coverage is strong near Weaverville, but poor to non-existent through Sayler.

Figure 2.10(a) shows the approximate locations of a nearby Verizon cellular tower [3], represented by a blue marker, in addition to the example Site 5 location represented by a yellow marker. Looking at the tower locations with respect to the section of SR299W surrounding the example site location, there is also likely a significant chance of occluding geography between the two. Furthermore, looking at Figure 2.10(b) it can be seen that there is indeed local topography between the cellular towers and the example site.

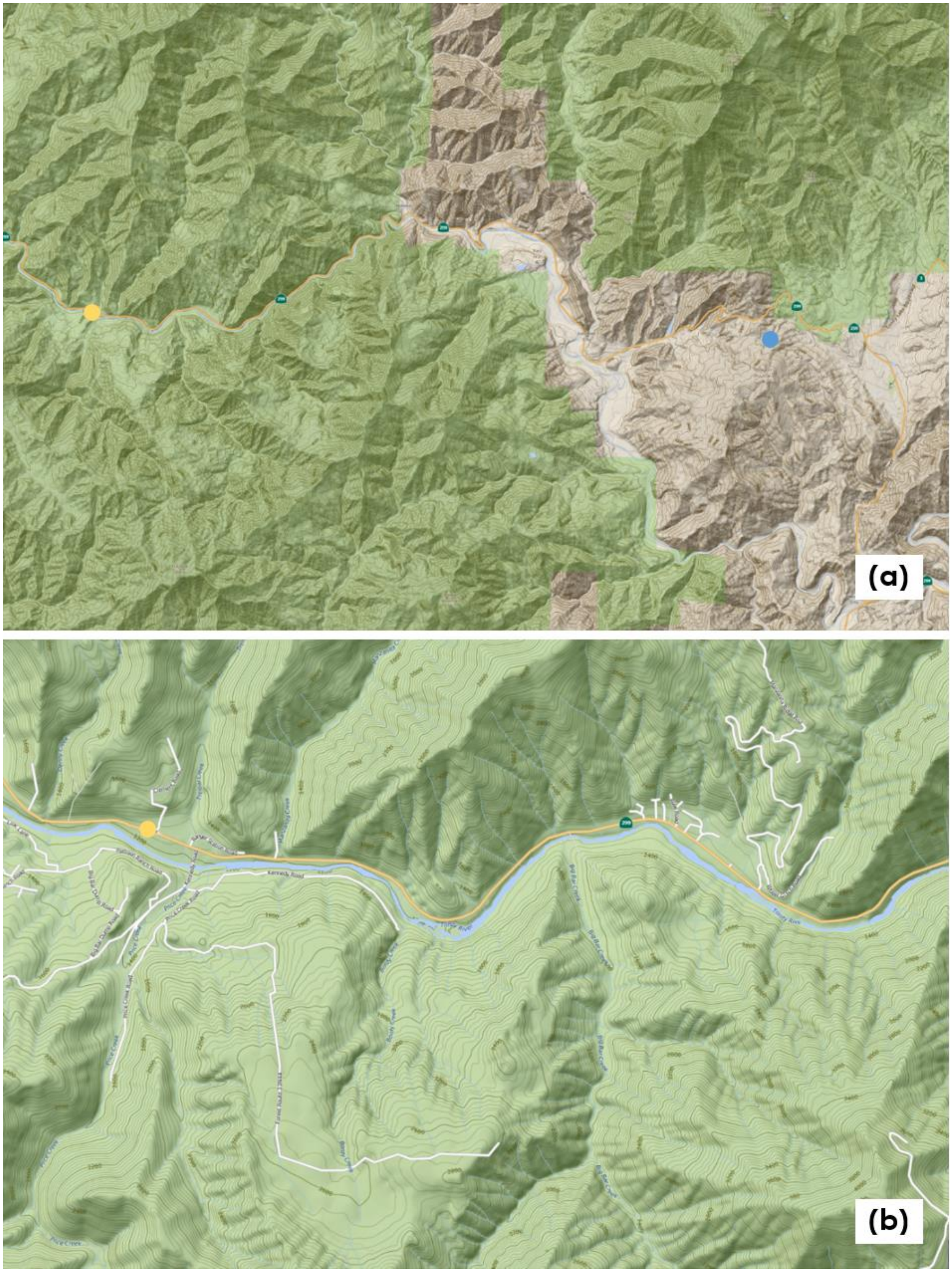

Figure 2.10: SR299W Topographic map with select cellular tower and example site approximate locations near Big Barr (a) Verizon cellular tower and site locations, (b) Site 5 (images courtesy of AHMCT Research Center)

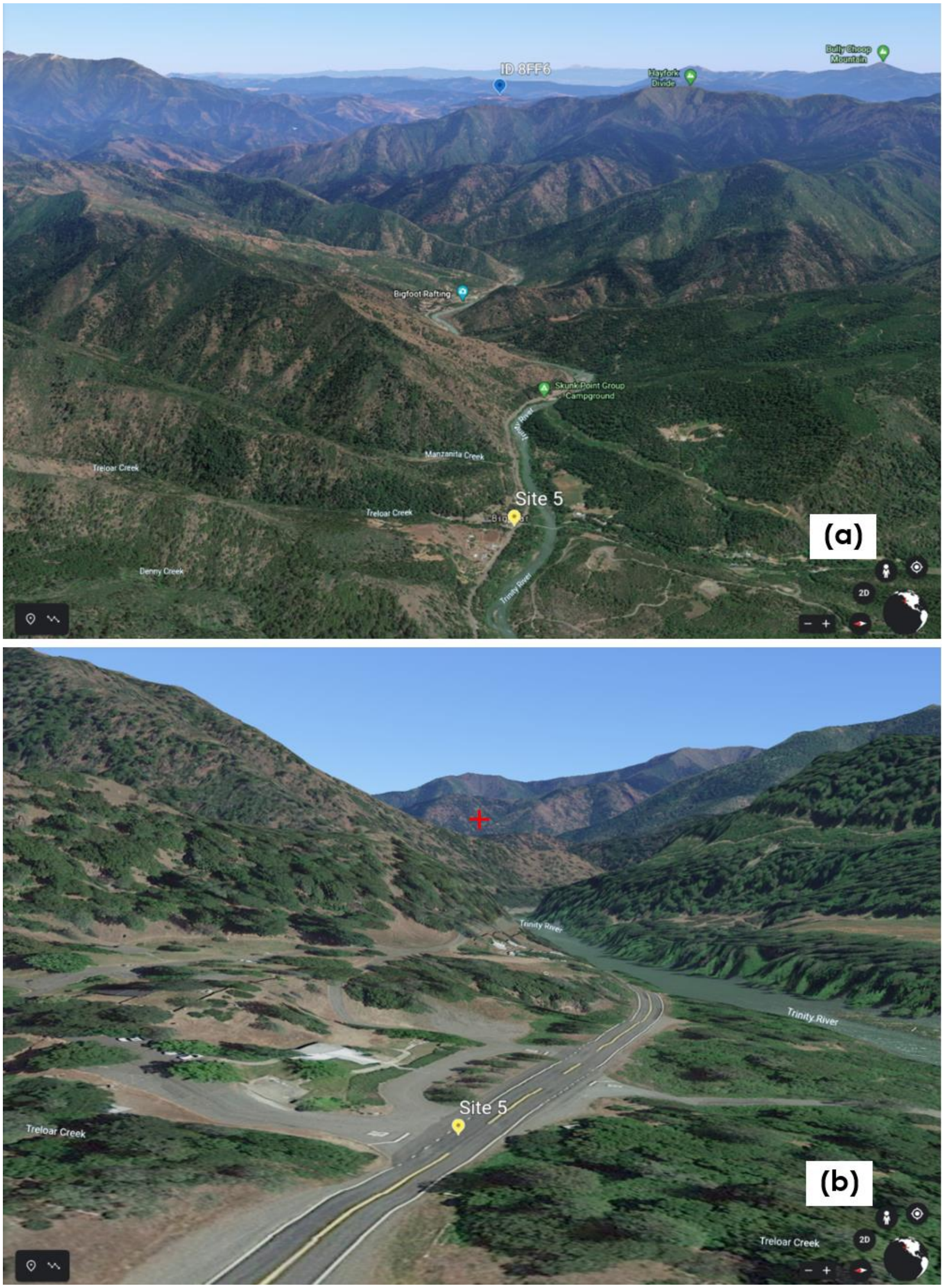

Figure 2.11: SR299W 3D map with select cellular tower and example site approximate locations near Big Barr (a) Verizon cellular tower and site locations, (b) Site 4 (images courtesy of Google Earth)

Figure 2.11 represents the cellular tower and example site approximate locations shown in the topographic maps of Figure 2.10 from the perspective of the example site location.

Figure 2.11(a) shows a high-altitude view of the Verizon cell tower location with ID 8FF6, represented by a blue marker, visible just to the south of Weaverville in the background. Site 5 along SR299W is represented by a yellow marker.

Figure 2.11(b) shows the view of Site 5 on SR299W in the foreground and steep canyons obscuring the view of the Verizon cellular tower to the east near Weaverville. The red plus marker represents the approximate LOS of the cellular tower from Site 5, which is clearly blocked by local terrain.

Figure 2.11 represents directional views towards the local Verizon cell tower and shows a clear rationale for the lack of cellular coverage along SR299W near Big Barr.

2.5.4 Summary

In each of the example Sites 1-5 within District 2, we have presented clear rationale for the lack of cellular signal coverage near the site location. The analysis of the local signal measurements and local terrain provide the motivation and justification for making changes to the typical use cases of existing cellular infrastructure.

3 Justification for and nature of changes

3.1 General

There is a need to expand the range and lower the costs of voice/data communications for existing rural systems. In general, successful voice/data communications are dependent on direct LOS and/or multipath signal propagation from radio-to-radio or radio-to-network, with acceptable signal degradation along the way. Typically, to improve communication coverage requires either additional or upgraded infrastructure. In rural environments enhancement or expansion of existing communications coverage is costly.

Caltrans employees in rural districts typically rely on mobile radio voice communications which suffer many of the drawbacks of cellular systems due to local terrain. For example, see Appendix A for mobile radio signal strength measurements in rural areas. Due to the constraints of the surrounding terrain, one logical solution is to change the direction of the signal propagation from surface-based point-to-point communications to surface-to-space and space-to-surface communications.

Satellite systems can be used for satellite voice communications, fixed position, and mobile satellite data/voice modems. At first glance, it would seem like satellite-based communications would solve all current needs. However, satellite systems have some drawbacks, including high equipment and ongoing data service costs. The availability of the satellite service is dependent on the type of satellite constellation, either low-earth orbit (LEO) or geostationary. LEO satellites move across the sky and are not always immediately available, but will eventually be within view. On the other hand, geostationary satellites are always available as long as there is not an obstruction between the satellite antenna and the satellite look-angle. For more information, see Appendix B for details on geostationary satellite systems and look angles. Portable satellite systems seem intuitive, but they are typically less sensitive, have less antenna gain, require manual antenna pointing, and suffer from low bandwidth. Higher bandwidth antenna systems are typically large and require expensive auto-positioning subsystems. In rural environments, numerous locations preclude use of geostationary satellite communication data solutions due to the surrounding geography and physical constraints.

In very remote rural locations, satellite phones can be utilized. However, some district users have reported that in portions of their operational environment, neither mobile radio nor satellite phones provide adequate service. For those users and situations that require data communications over large rural areas, satellite solutions become appealing for their capabilities and use anywhere not withstanding geographic constraints. However, the cost of deployment of satellite systems eventually limits large adoption.

Many end users with the desire to leverage data communications feel a gulf between the almost feasible use of inexpensive cellular data services that appear to always be just out of range and the expensive, hard-to-procure go-anywhere satellite systems. In many situations, a widely deployable cellular data service range extension solution would be very useful and desired.

3.2 Justification for changes

In each of the example locations in discussed in Chapter 2 we have clearly showed the rationale for limited to no cellular coverage due to local terrain occlusion of the local cell towers. We also showed that a LOS view of the cellular towers in each of the cases was possible if we could rise above ground level to establish a cellular network connection. In the following sections we discuss specific mitigations to each of the limitations to cellular reception illuminated in Chapter 2.

3.2.1 Bogard Buttes SR44

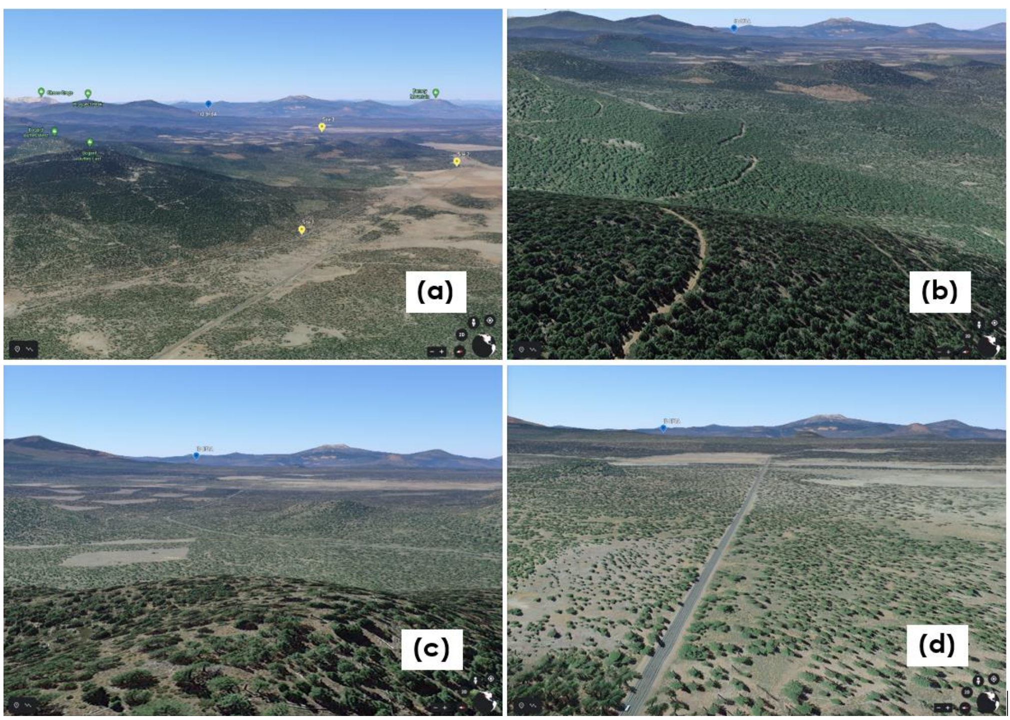

Figure 3.1: SR44 3D map with select cellular tower and example aerial view site approximate locations near Bogard Buttes (a) Verizon cellular tower and site locations, (b) aerial view of cellular tower from the north slope of Bogard Buttes East near Site 1, (c) aerial view of cellular tower above the top of a hill near Site 2, (d) aerial view of cellular tower above Site 3 (images courtesy of Google Earth)

Figure 3.1(a) shows a high-altitude view of the Verizon cell tower location with ID 8F8A, represented by a blue marker, visible to the north of Bogard Buttes East in the foreground, and Prospect Peak in the background. Sites 1, 2, and 3 along SR44 are represented by yellow markers.

Recall that Figure 2.4(b) shows the view of Site 1 on SR44 in the foreground, Bogard Buttes East to the left, and mountains in the background obscuring the view of Verizon cellular tower ID 8F8A. The red plus marker represents the approximate LOS of the cellular tower from Site 1, which is clearly blocked by local terrain. If one could move towards the direction of the cellular tower, up the north slope of Bogard Buttes East, one could establish a LOS view with the Verizon cellular tower as seen in Figure 3.1(b).

Recall that Figure 2.4(c) shows the view of Site 2 on SR44 north of Bogard Buttes East and a mountain in the background also obscuring the view of Verizon cellular tower ID 8F8A. The red plus marker represents the approximate LOS of the cellular tower from Site 2, which is also clearly blocked by local terrain. If one could move towards the direction of the cellular tower, above the top of the hill north of Bogard Buttes East, one would be able to establish a LOS view with the Verizon cellular tower as seen in Figure 3.1(c).

Figure 2.4(d) shows the view of Site 3 on SR44 west of Bogard Buttes and a mountain range in the background also obscuring the view of Verizon cellular tower ID 8F8A. The red plus marker represents the approximate LOS of the cellular tower from Site 3, which is blocked by terrain across the valley towards the cellular tower location. If one could rise above the roadway, one would be able to establish a LOS view with the Verizon cellular tower as seen in Figure 3.1(d).

3.2.2 Sugar Loaf SR89

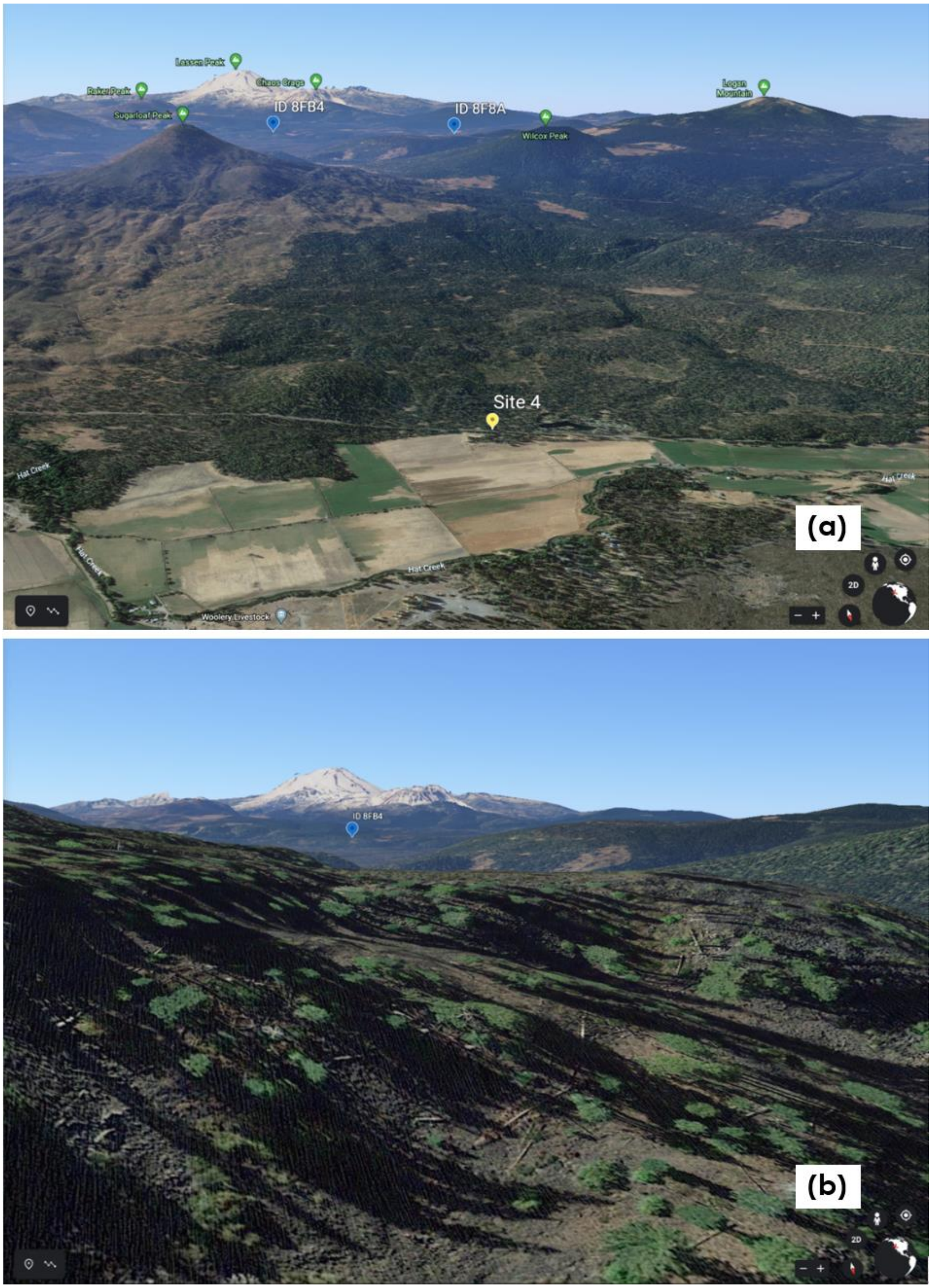

Figure 3.2: SR89 3D map with select cellular tower and site aerial view approximate locations near Sugarloaf Peak (a) Verizon cellular tower and site locations, (b) aerial view of cellular tower from the north slope of Sugarloaf Peak near Site 4 (images courtesy of Google Earth)

Figure 3.2 (a) shows a high-altitude view of the Verizon cell tower locations with ID 8FB4 and ID 8F8A, represented by blue markers, visible to the southwest of Sugarloaf Peak in the background. Site 4 along SR89 is represented by a yellow marker.

Figure 2.7(b) shows the view of Site 4 on SR89 in the foreground, Sugarloaf Peak to the left, Wilcox Peak to the right, and foothills in the foreground obscuring the view of the Verizon cellular towers to the southwest. The red plus marker represents the approximate LOS of the cellular tower from Site 4, which is clearly blocked by local terrain. If one were able to move towards the direction of the cellular tower up the north slope of Sugarloaf Peak, one would be able to establish a LOS view with the Verizon cellular tower as seen in Figure 3.2(b).

3.2.3 Big Barr SR299W

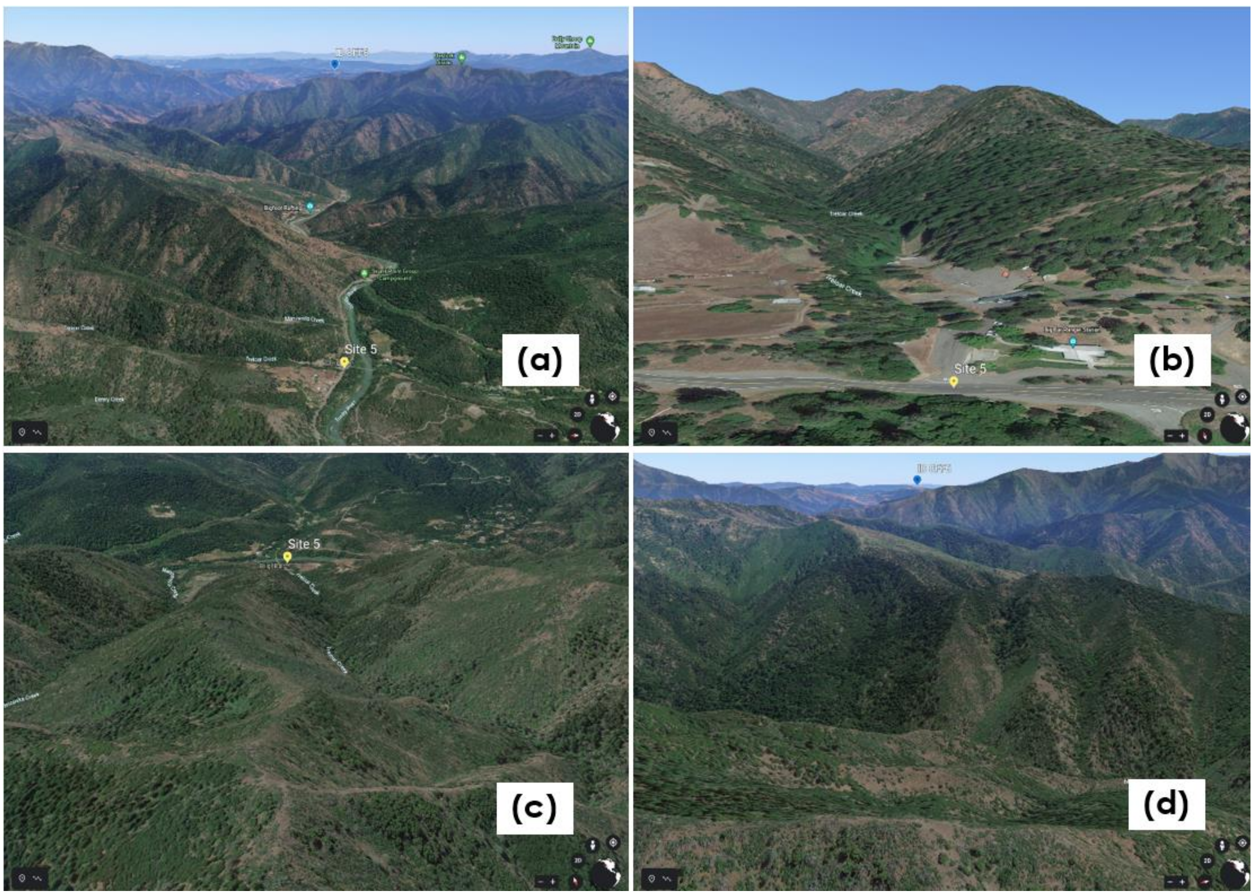

Figure 3.3: SR299W 3D map with cellular tower and example site aerial view approximate locations near Big Barr (a) Verizon cellular tower and site locations, (b) view from Site 5 up towards aerial site, (c) view from aerial site down towards Site 5, (d) view of cellular tower from aerial site (images courtesy of Google Earth)

Figure 3.3(a) shows a high-altitude view of the Verizon cell tower location with ID 8FF6, represented by a blue marker, visible just to the south of Weaverville in the background. Site 5 along SR299W is represented by a yellow marker.

Recall that Figure 2.10(b) shows the view of Site 5 on SR299W in the foreground and steep canyons obscuring the view of the Verizon cellular tower to the east near Weaverville. The red plus marker represents the approximate LOS of the cellular tower from Site 5, which is clearly blocked by local terrain. If one were able to move towards the direction of the cellular tower up the north slope of the canyon adjacent the roadway in Figure 3.3(b), one would be able to establish a LOS view with the Verizon cellular tower as seen in Figure 3.3(d).

3.2.4 Summary

In each of the example Sites 1-5 within District 2, we have presented specific mitigation to each of the limitations to cellular reception illuminated in Chapter 2. Specifically, we showed that a LOS view of the cellular towers in each of the cases was possible if we could rise above ground level to establish a cellular network connection.

3.3 Description of desired changes

The primary goal of the encompassing research project is to develop a prototype UAS containing a communications payload providing aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi clients. The UAS would allow for relatively easy deployment within the SHS right-of-way thus extending ubiquitous low-cost cellular network data services further into remote rural areas.

The proposed prototype system shall be

- Capable of carrying a communications payload with the ability to extend/enhance the usable range of existing cellular data services
- Capable of carrying a video camera payload with the ability to relay video in real-time to the ground users
- Capable of carrying modular payloads
- Comparatively easily deployable and operable within and near the SHS right of way
- Capable of flight within the full range of legally allowable air space
- Capable of self-flight (i.e. hold position). Self-flight beyond stationary positioning is dependent on existing regulations and current commentary.

Key components of the proposed prototype system, including the flight vehicle, shall be considered and selected such that they may be considered multi-use within Caltrans for the purposes of aiding in early adoption and hypothetical subsequent deployment.

Prototype systems under consideration shall be discussed, analyzed, and proposed such that hypothetical deployment of said system would follow all Federal, State, Local, and Caltrans regulations.

3.4 Priorities among changes

The description of desired changes are mapped and/or subdivided into prioritized sets of features. The essential features are considered top priority and an absolute requirement for furtherance of this research effort. The desirable features are considered secondary in priority, but are all likely to be pursued and implemented in the research prototype development. Finally, the optional features represent possibilities that are dependent on results of the research effort and could be pursued based on the various project decisions and constraints along the way.

- Essential features
    - UAS with near-vertical takeoff and hover capabilities
    - UAS with flight capability within the full range of legally allowable air space
    - Cellular-to-Wi-Fi communications payload
- Desirable features
    - Quick-change modular payload bay
    - Self-contained communications payload (i.e. payload does not rely on electrical connections to the UAS)
    - Streaming video from UAS
    - UAS multi-use capabilities within Caltrans
- Optional features
    - Miniaturization of communications payload
    - Long-range ground-to-air alternative wireless
    - Long-range alternative wireless to Wi-Fi router
    - Store and forward, which is application-dependent
    - Quick-change modular payload bay supporting electrical connection to the UAS main power

3.5 Changes considered but not included

The follow represent currently foreseen research application opportunities related to the use of UAS with the requisite onboard communications for the purposes of enhancing cellular data service availability throughout rural areas of the SHS. Certainly having a single, pilot operated, UAS with communications payload could provide substantial data communication coverage improvements. Furthermore, an intelligent UAS that could auto position/orient for optimal communications quality with little pilot interaction would be highly desirable. However, include below there are current barriers to pursuit of an automated solution at this point it time.

- UAS non-LOS operation. See Appendix F Policies and Constraints for current prohibition of this capability. Meeting certain requirements and receiving a waiver is possible, but outside the scope of this project.
- UAS autopilot, with preprogrammed terrain map, obstacle avoidance, and cellular tower locations. See Appendix F Policies and Constraints for current prohibition of these features. It is possible in certain circumstances and based on current commentary to investigate a partial implementation of self-guided flight. However, it is likely outside the scope of this project to conduct this effort.
- Multiple UAS working in concert. See Appendix F Policies and Constraints for current prohibition of these features. This would require clearing a series of high hurdles and waivers to achieve and is outside the scope of this project.

3.6 Assumptions and constraints

It is assumed that any developed prototype system will be considered research in nature and will be developed and operated outside of Caltrans and the SHS right-of-way. Actions proscribed by the UC Regents and the FAA related to UAS flight will be avoided.

Development and use of any prototype system will follow all applicable regulations and policies. See Appendix F Policies and Constraints.

4 Concepts for the proposed system

In general, workers in rural areas rely heavily on standard mobile radio voice communications. In many business use cases, it is desired/necessary to communicate data to management, the Transportation Management Center (TMC), or other outside parties, as well as from internal and external sources to the immediate field location. In rural locations, maintenance workers have limited data communications options.

Typically, they leverage cellular data services if local operations are within existing cellular coverage.

Another option is to utilize approved limited and bulky satellite communications solutions as seen in Appendix B.

An emerging option is the Responder System, as seen in Appendix C, which provides a seamless integration of both cellular and mobile satellite data services in a single package arbitrating between the two to provide optimal cost savings while ensuring maximum communications capabilities. Although the Responder system provides local Wi-Fi hotspot capabilities it is currently configured to only allow connections from the Responder App. It is important to note that while the integrated satellite capabilities are compact compared to existing Caltrans satellite system deployments, it can similarly suffer satellite look angle obstructions due to the inherent nature of geostationary satellite use, see Table B.2.

The existing options for rural data communications leave a sizeable opportunity for additional innovative and flexible data communication solutions.

Primary goals:

- **Enhance rural data communication options** – develop an aerial pop-up internet hotspot composed of a multi-rotor UAS containing a communications payload providing aerial network data transfer between a cellular data network backhaul and ground-based Wi-Fi clients
- **Ease of use** – allow for relatively easy and quick UAS deployment within the SHS right of way by appropriately trained operators. See Appendix F Policies and Constraints.
- **Keep data costs to a minimum** – leverage existing cellular network data services as the backhaul, thus extending ubiquitous low-cost network data services further into remote rural areas
- **Increase likelihood of early agency adoption** - develop a modular system solution that promotes flight system multi-use

4.1 Major system elements

The major system elements of the proposed system are the UAS, a Wi-Fi-to-cellular communications payload, a video camera payload, the cellular network infrastructure, and the client devices. The UAS multi-propeller rotorcraft will embody a rugged industrial grade platform suited for a variety of multi-use scenarios operable within enhanced environmental conditions. The UAS will be controlled by a remote control with integrated telemetry and First Person View (FPV) integrated screen for assistance and video streaming capabilities. The UAS may include vision-based collision avoidance. The communications payload will be compact, modular, and self-contained for quick attachment/detachment from the UAS. The UAS will also support the addition of a high-resolution pan-tilt video camera payload supporting real-time streaming video. The UAS will be available for future multi-use purposes within Caltrans and ideally will not be integrated with any payload or supply power to the communications payload.

The communications payload will be compact and self-contained for quick attachment and detachment from the UAS. The payload will be composed of a small-board computer, Long-Term Evolution (LTE) cellular network radio, Wi-Fi radio, and an internal power supply, as seen in Figure 4.1. The firmware will present the Wi-Fi interface as a typical access point, and handle all routing between the Wi-Fi and cellular network interfaces. The UAS will be available for multi-use purposes and will not be integrated with the supply power to the communications payload.

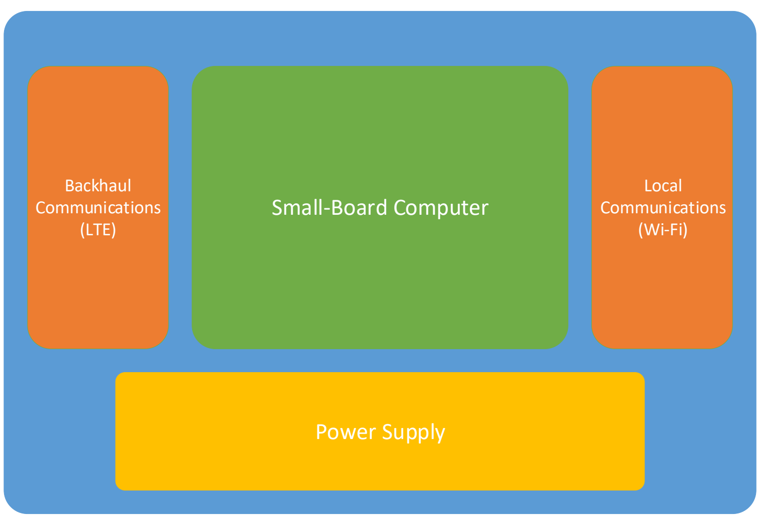

Figure 4.1: The hardware architecture of the UAS communications repeater

4.2 Capabilities

The primary capabilities of the proposed system are to provide local area network (LAN) Wi-Fi access point services supporting Dynamic Host Configuration Protocol (DHCP) to ground-based client devices while establishing a backhaul Wide Area Network (WAN) connection via the cellular network. This will be achieved through aerial positioning of the UAS by the local Remote Pilot in Command (RPIC) while following all flight regulations. See Appendix F for Policies and Constraint considerations. In addition, the system shall include a Closed-Circuit Television (CCTV) camera for streaming video.

4.3 Interface to external systems

The two primary interfaces to systems external to the UAS are the cellular backhaul and the Wi-Fi client devices.

1. **Backhaul** – this external system is accessed through the cellular interface, which interfaces wirelessly with the existing cellular network infrastructure
2. **Client devices** – these external systems are accessed through the Wi-Fi access point interface, which interfaces wirelessly with the various Wi-Fi-enabled devices (i.e. laptops, tablets, phones)

4.4 User classes

The following are the primary user classes that are envisioned in future use of the UAS by Caltrans along the SHS.

- **Pilot** – the RPIC is the person who has the final authority and responsibility for the operation and safety of the UAS operation and is primarily the person manipulating the controls
- **Observer** – the Visual Observer (VO) is the person designated by the RPIC to assist the person manipulating the flight controls of the UAS to see and avoid other air traffic or objects aloft or on the ground
- **Assistants** – additional personnel who aid in the general support of the UAS and operate Wi-Fi-enabled devices

It is important to note that Caltrans requires (see Appendix F Policies and Constraints) a pilot and an observer at all times when operating a UAS. Therefore, operation of any additional user equipment, such as a Wi-Fi enabled devise, while the UAS is airborne, necessarily requires additional assistant personnel.

4.5 General operational procedure

Any user will be able to easily remove the UAS from its carrying case, install the requisite number/size batteries, and power up the repeater. The pilot user must perform the pre-flight familiarization, inspection, and actions for aircraft operation according to §107.49 of [7]. Take-off and landing, conducted by the pilot user, will be vertical and the UAS will by default hover with no sustained input. Following all UAS regulations (see Appendix E Policies and Constraints), the pilot user will move the UAS into position above/beyond local obstructions in the direction of the chosen cellular tower assisted by the observer user. Provider cellular tower locations should be looked up on-line [3-4] as necessary. It is assumed that lookup and recording of all pertinent cellular locations, and any other related information, in the operational area will be performed ahead of time. When the repeater is able to detect and connect to a cell site, the repeater will begin routing data between the cellular and Wi-Fi interfaces. Assistant users can then establish Wi-Fi hotspot connections with the UAS and communicate as if they were directly connected to the cellular network.

Upon completion of data communications, the pilot user will guide the UAS back to the take-off location and successfully land the UAS. The UAS will then be easily placed back in its carrying case, and standard business operations will continue or conclude.

4.6 Operational Environment

While the system could operate in many locations, the primary operational environment of the proposed system focuses on operations along sections of the SHS within rural districts. Specifically, operational areas of rural environments include both those that fall outside the intended coverage of existing cellular infrastructure and those that fall inside the intended cellular coverage area but suffer from poor QOS. Many factors can affect both signal strength and signal quality between a cellular basestation and UE.

Some typical factors affecting general signal strength and quality:

- Distance between cell tower and mobile user locations
- Sector traffic load (i.e. interference from other users of same sector)
- Interference from nearby sectors
- Near-far problem (i.e. imbalance of power between the basestation, nearby mobile users, and faraway mobile users)
- Fading due to multi-path
- Sector antenna height, directivity, direction, and tilt with respect to mobile location

- Significant obstructions

Many times, in very rural areas of the SHS, significant LOS obstructions are one of the primary causes of little to no service, that is if the free space path loss between the basestation and the UE does not exceed system requirements. In this case, it is interesting to note that attempting to mitigate loss of service by moving the cellular UE from a ground based location to an aerial based location above a significantly tall obstruction at distance, while not suffering from excessive path loss due to the LOS distance from the basestation, may significantly degrade path loss due to sector antenna tilt.

While in remote rural areas of the SHS, it is definitely possible that a mobile user could run into the near-far problem when at a significant distance from the targeted basestation. This issue arises when an imbalance of Tx/Rx power between the basestation, nearby mobile users, and faraway mobile users results in significant interference to the weaker signal at the basestation. To combat the problem, basestation and mobile power control is employed. However, power control may not be able to sufficiently mitigate the various imbalances resulting in a significantly degraded QOS or altogether prohibit initiation of or an ongoing connection.

4.7 Performance Characteristics

Typical industrial grade UAS performance metrics:

- **Max Payload** 1.4 kg
- **Vertical Hovering Accuracy** (GPS) ±0.5 m
- **Horizontal Hovering Accuracy** (GPS) ±1.5 m
- **Max Ascent Speed** 5 m/s
- **Max Descent Speed** 3 m/s
- **Max Speed** 80 kph
- **Max Service Ceiling** 3000 m
- **Max Wind Resistance** 12 m/s
- **Max Flight Time** >30 min
- **Ingress Protection** rating IP43
- **Operating Temperature** -20° C to 50° C

The cellular network backhaul performance of the UAS will be similar to that of a cellular phone within LOS of a cellular tower at the same distance without local obstructions.

4.8 Cost of System Operations

The costs of the system operations are composed of the system maintenance including parts and labor, the cellular data service, and required refresher training. In general, this is a significant overall savings compared to the system operations costs of an average satellite-based system. Affordable compact geostationary Broadband Global Area Network (BGAN) satellite systems are typically between $5-10k/unit with data services on the order of $4-6/MB. While the primary cost of a UAS can vary widely in initial cost, typically between $5-10k/unit, the long-term up-front costs of UAS are trending downward. Clearly the hardware costs of the two systems are within the same order of magnitude but the daily data cost comparison between BGAN satellite-based solutions and the proposed system is two orders of magnitude difference. 1 GB/month of data service for BGAN satellite systems would cost approximately $5000/month, while cellular systems would be $40/month. It must be stated that non-BGAN satellite systems have a similar magnitude data cost compared to cellular, but either the hardware system is relatively quite large (see Appendix B Satellite) compared to BGAN systems, or a high-capability compact mobile system is an order of magnitude more expensive.

4.9 Operational Risk Factors

The obvious operational risk factors of the system can be considered low-risk if the operator is licensed and properly trained in the various operational scenarios within the SHS. Improper use of the system within the SHS can greatly increase the risk to the traveling public, cause human injury and/or death, property damage, and equipment damage, which could result in financial exposure to the operating agency.

5 Analysis of the proposed system

5.1 General

The long-term result of development, refinement, and deployment of this communication system concept would be an invaluable tool to Caltrans maintenance and emergency operations that fills a gap between hopeful future expansions of commercial cellular infrastructure into rural areas, and high-cost, moderate flexibility, low-deployment satellite solutions.

5.2 Benefits

New capabilities

- Expansion of cellular data services into rural areas
- Reduction of costs by reducing reliance on other alternatives
- Operation where other alternatives fail

Improved Performance

- Quality of service in existing edge of cellular service areas

5.3 Alternatives considered

The overall purpose of this effort was to investigate several possible flight platforms that might fit the operational needs of Caltrans. However, during the investigation, and subsequent development of this document, it quickly became apparent that two of the three initially envisioned concepts under investigation would not meet requirements due to one or more operational, organizational, and/or regulatory restrictions. As a result, this document does not include detailed discussion or scenarios of the rejected systems. These systems are discussed briefly here, including the rationale for exclusion.

5.3.1 Moored balloon

Initially, use of a non-powered platform such as a moored balloon seemed like a suitable option as the perceived risks to the SHS would be low. Interest in a moored balloon approach arose in part due to initial apprehension about operating a UAS within the right of way. In addition, at the time of this project's conception, no formal UAS policy existed within Caltrans.

5.3.1.1 Key regulations

The following are notable regulations when considering the efficacy and operational constraints of a moored balloon as a possible UAS solution.

- Moored balloon must have a device that will automatically and rapidly deflate the balloon if it escapes from its moorings according to §101.19 of [7]
- Moored balloon may not operate less than 500 ft from any cloud, more than 500 ft Above Ground Level (AGL), in an area where ground visibility is less than 3 mi, or within 5 mi of the boundary of any airport according to §101.13 of [7]
- Operation of a moored balloon above 150 ft requires 24-hr prior notification to the nearest FAA Air Traffic Control (ATC) according to §101.15 of [7]
- Moored balloons can only be operated during daylight unless the balloon and mooring lines are lighted appropriately. Mooring lines must be marked with colored pennants or streamers attached at not more than 50 ft intervals beginning at 150 ft AGL and visible for 1 mi according to §101.17 of [7]

5.3.1.2 Rationale for decision

Although a moored balloon is reasonably cheaper, and arguably safer than a UAS near the SHS, from a practical standpoint a moored balloon requires a significant amount of time to deploy, recover, and relocate. Additionally, the size of the balloon, winch, gas tank, and other accessories adds to the overall use case burden. Besides usability concerns, several regulations directly reduce the applicability of a balloon within the various use-case scenarios. Specifically, a moored balloon may not operate above 500 ft AGL. At face value, this operational requirement appears to be higher than that of a UAS with a 400 ft AGL requirement. However, a UAS is able to climb the face of a nearby mountain, while remaining under 400 ft AGL directly below its current position, and reach LOS to the nearest cellular tower. A moored balloon by its very nature is unable to navigate and therefore can only be used in cases where all obstructions between the mooring and the nearest cell tower are below 500 ft AGL with respect to the anchor location. These limitations prohibit the use of a moored balloon for most use cases.

5.3.2 Fixed-wing aircraft

Fixed-wing aircraft are beneficial to the overall use scenarios due to the long flight time compared to rotorcraft-type UAS. However due to the topography of likely operational use cases a fixed-wing aircraft may not have sufficient room to climb the face of a particular slope while remaining out of the roadway. Additionally, take-off and landing typically require some sort of runway, and the roadway may not be used unless a closure is in effect.

5.3.2.1 Key regulations and constraints

The following are notable regulations when considering the efficacy and operational constraints of a fixed-wing aircraft as a possible UAS solution.

- UAS must be multi-use within the Caltrans organization
- No operation over roadway, including takeoff and landing unless a closure is in effect according to §6.1 of [8]
- Fixed-wing UAS typically do not include native hover capability
- In general, no UAS autopilot, but it seems that autonomous UAS operation can be conducted and compliance with [7] can be maintained as long as the RPIC is able to provide direction to satisfactorily avoid a hazard or give right of way according to [9]

5.4.2.2 Rationale for decision

Although it is expected that a fixed-wing aircraft would typically have a longer average run-time compared to an equally equipped quadcopter aircraft, from a practical standpoint there are some key constraints when considering operation within the SHS and/or mountainous areas. In general, a fixed-wing aircraft requires a runway to take-off and/or land, and depending on the size of the aircraft, and the local topography, a suitable runway may not be available, especially when operating in tight quarters in very mountainous areas. Additionally, operation in tight quarters, such as steep slope canyons, become increasingly difficult to operate below AGL regulations at required air speeds. Finally, an equipment requirement that UAV must be multi-use within the Caltrans organization further limits fixed-wing aircraft as a viable option. For example, it is envisioned, within Caltrans that a deployed UAS would be used for other purposes (e.g. future CCTV site planning/exploration).

6 Operational scenarios

The operational scenarios of the proposed system are broken into two fundamental categories. Section 6.1 describes the system as an integration of the major elements and discusses the general operational scenario. The subsequent sections present the remaining specific use scenarios.

6.1 The system as a whole

The system as a whole, as seen in Figure 6.1, includes a UAS, the cellular-to-Wi-Fi communications payload, the cellular network infrastructure, the SHS, the operating environment, the RPIC, and a VO (optional, depending on agency). See Appendix F Policies and Constraints.

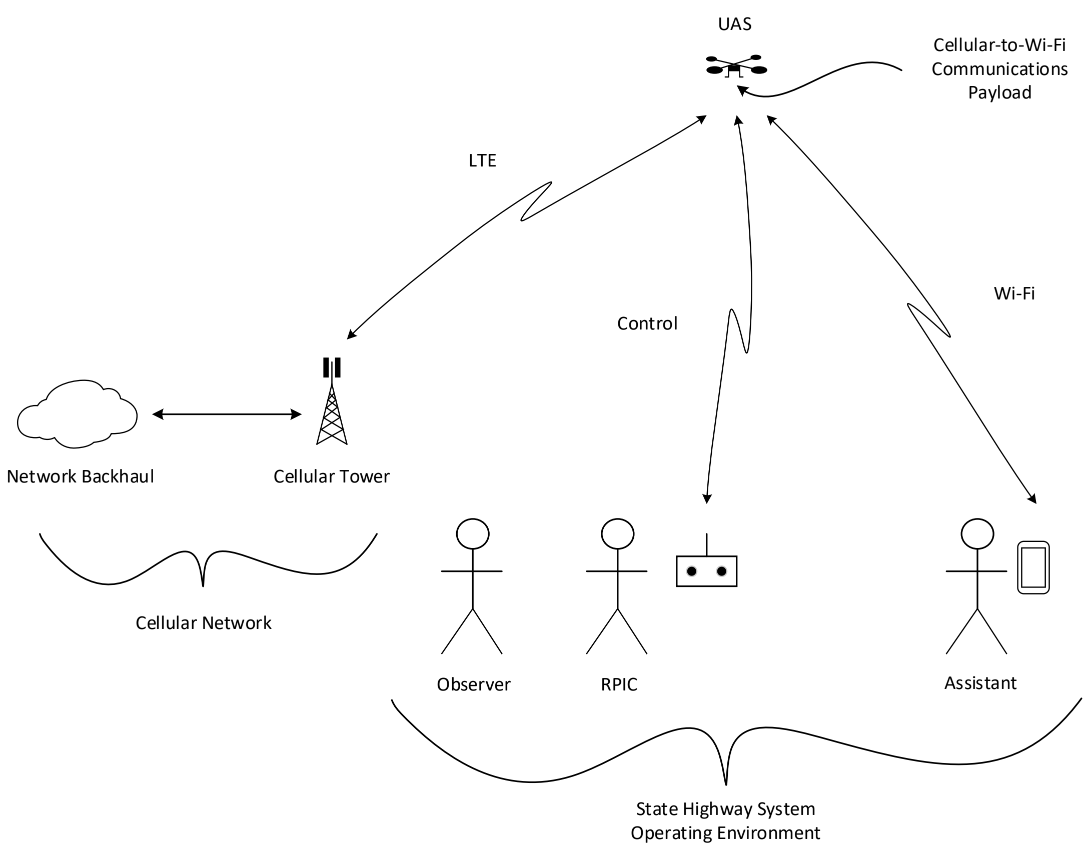

Figure 6.1: The high-level architecture of the proposed system

The core of the system is the UAS coupled with the Wi-Fi-to-cellular repeater, which provides hotspot services to ground-based devices. The RPIC is in charge of all flight operations and is responsible for following all operational policies and constraints as discussed in Appendix E Policies and Constraints. The required VO would aid in the location of the UAS, look for obstacles, watch for other aircraft in the vicinity, and communicate directly with the RPIC. Additional unassigned support personnel could actively operate a network-capable Wi-Fi device to send and receive data communications while the UAS is operational.

Key FAA Regulations Summary

These operational regulations are a summary of notable policies and regulations as described in Appendix E. These regulations are applicable to all operational scenarios discussed in the following sections.

- The UAS must weigh less than 55 lb
- The UAS must remain in unaided visual line-of-sight (VLOS) of the RPIC or VO at all times
- Small unmanned aircraft (UA) may not operate over any persons not directly participating in the operation
- Daylight-only operations
- Must yield right of way to other aircraft
- May use VO but not required
- Remote-Person View (RPV) camera cannot satisfy “see-and-avoid” requirement but can be used as long as this requirement is satisfied in other ways
- Maximum groundspeed of 100 mph
- Maximum altitude of 400 feet AGL or, if higher than 400 feet AGL, remain within 400 feet of a structure
- Minimum weather visibility of 3 miles from control station
- Operations in Class B, C, D, and E airspace are allowed with the required ATC permission according to [10]
- Operations in Class G airspace are allowed without ATC permission according to [10]
- No person may act as a RPIC or VO for more than one UA operation at one time
- Requires pre-flight inspection by the RPIC

In the general use scenario, the RPIC must first submit all pre-flight activity requests and receive appropriate permissions from their agency. The RPIC will conduct a pre-flight inspection, and will then take off and follow the local terrain while staying within 400 ft of the ground and other structures while maneuvering into an LOS view of the nearest cellular tower. The VO will assist in the situational awareness of the operational environment. When in position the RPIC will hover the UAS and support staff can connect to the Wi-Fi with a client device and perform the necessary data communications. Upon conclusion of communications or if the UAS power is running low, the RPIC will then return to the take-off location, observing all restrictions, and land. The RPIC will submit post-flight activity reports to their agency.

The entirety of this research project will be confined to Scenarios 1 and/or 2. Scenarios 3-12 are provided strictly to aid in the development of the proposed system, and subsequent research and development of the prototype UAS and associated payloads. It is instructive to look forward to hypothetical future deployment within Caltrans and consider the several classes of possible operational scenarios. The following scenarios are representative although not exhaustive of the set of challenging environments that exist within extreme rural sections of the SHS. The graphical sketches of the various scenarios are obviously not to scale, nor are the distances between key features. However, in each of the cases the 400 ft AGL ceiling noted on each drawing should give an idea of the relative size of key features under consideration. Additionally, it is our intention to clearly convey that the proposed UAS system would be designed to operate in any applicable scenario following all regulations without exception. See Appendix F Policies and Constraints.

6.2 Scenario 1: research development

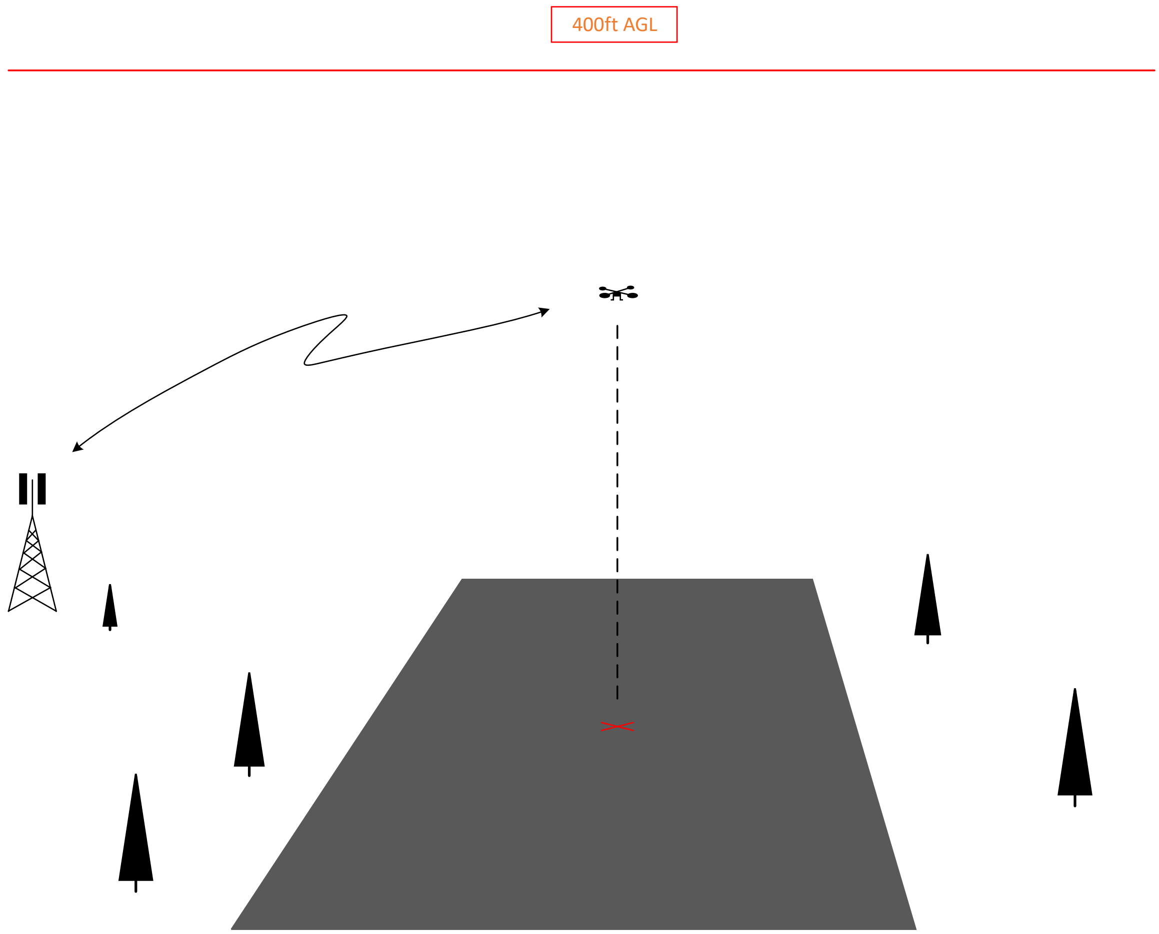

Figure 6.2: Use scenario with general research development

Figure 6.2 shows the use scenario while conducting general research and development of the system. While this scenario is not very challenging it will be the primary operational scenario for a significant portion of the research development phases of this project. To simulate LOS obstructions between local cellular towers and the research test location, appropriate signal conditioning will be inserted between the cellular communication antenna ports and the associated antenna.

6.3 Scenario 2: research verification

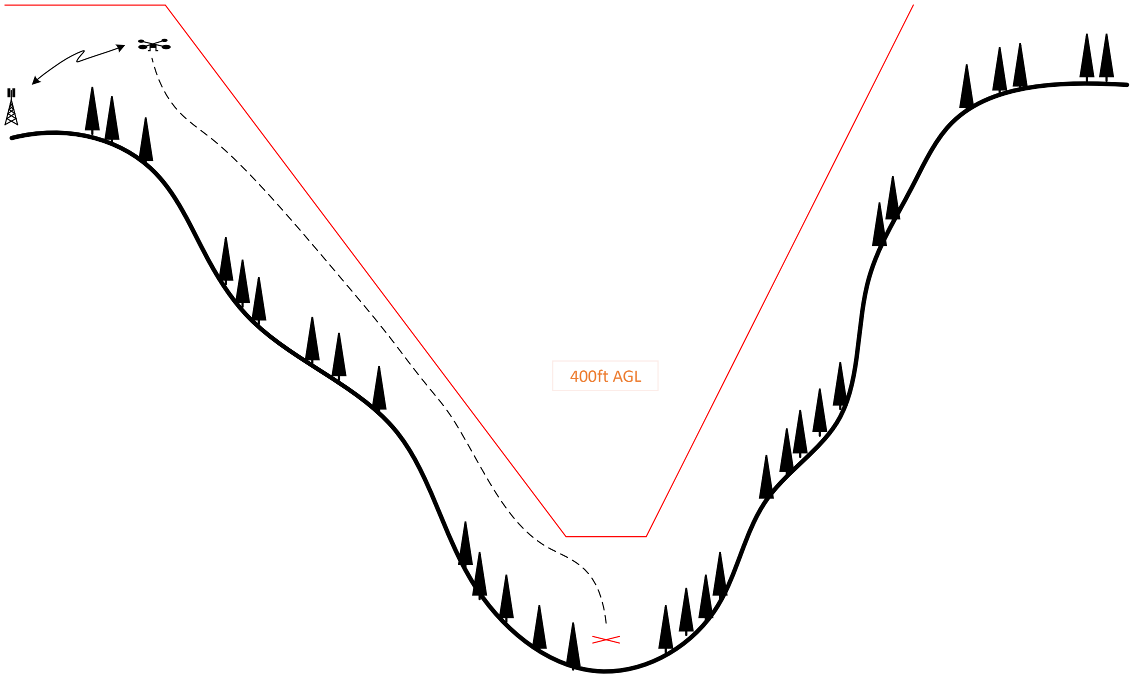

Figure 6.3: Use scenario with research verification

Figure 6.3 shows a possible use scenario while conducting verification research and development of the system. The topology shown in the figure is representative of a proposed verification site on private land. It is important to note that the depth of this canyon is greater than 1000 ft and the nearest cellular tower is at significant distance from the ridge. The area has almost no cellular reception except at a small number of sweet-spots near one location on the ridge. This site provides a good test analog for several of the difficult rural sections of the SHS while eliminating the risks associated with testing near the SHS.

6.4 Scenario 3: standard hill

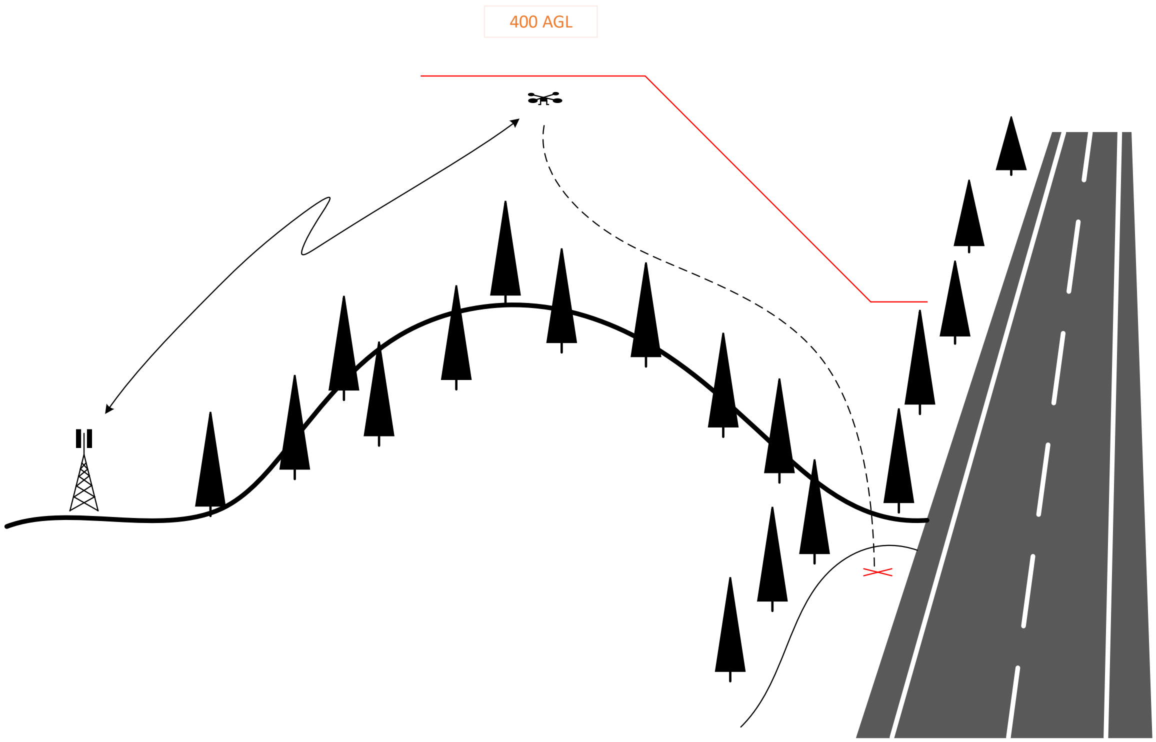

Figure 6.4: Use scenario with a hill close to the roadway

Figure 6.4 shows the use scenario when there is a typical hill between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. The VO will assist in the situational awareness of the operational environment. When the UAS is within site of the cellular tower, or at maximum height, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.5 Scenario 4: close hill

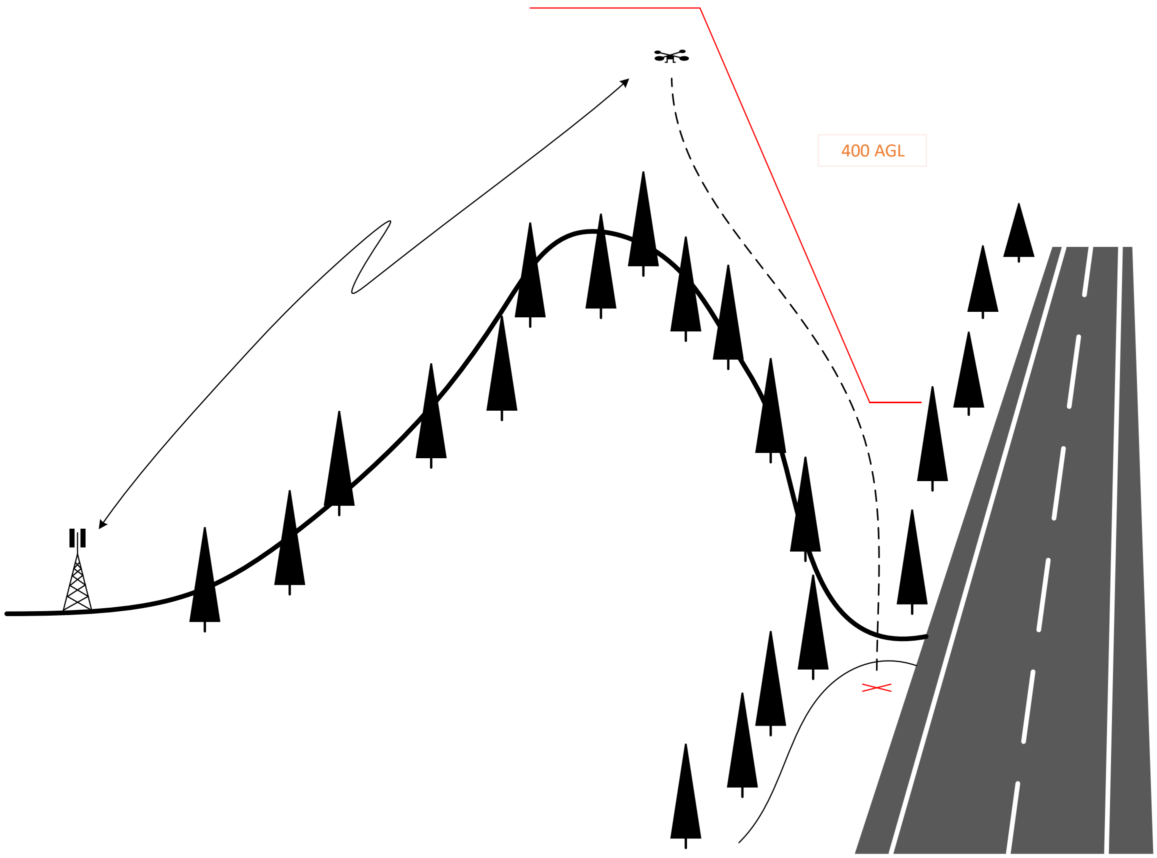

Figure 6.5: Use scenario with a hill close to the roadway

Figure 6.5 shows the use scenario when there is a very tall hill or rock wall between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off and move quickly up the steep face of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. The VO will assist in the situational awareness of the operational environment. In this scenario, it may be difficult to stay within the 400 ft AGL requirement while keeping LOS to the UAS due to the steep slope and immediately local trees and foliage. It may require the RPIC and/or VO to adjust positioning. When the UAS is within site of the cellular tower, or at maximum height, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.6 Scenario 5: far hill

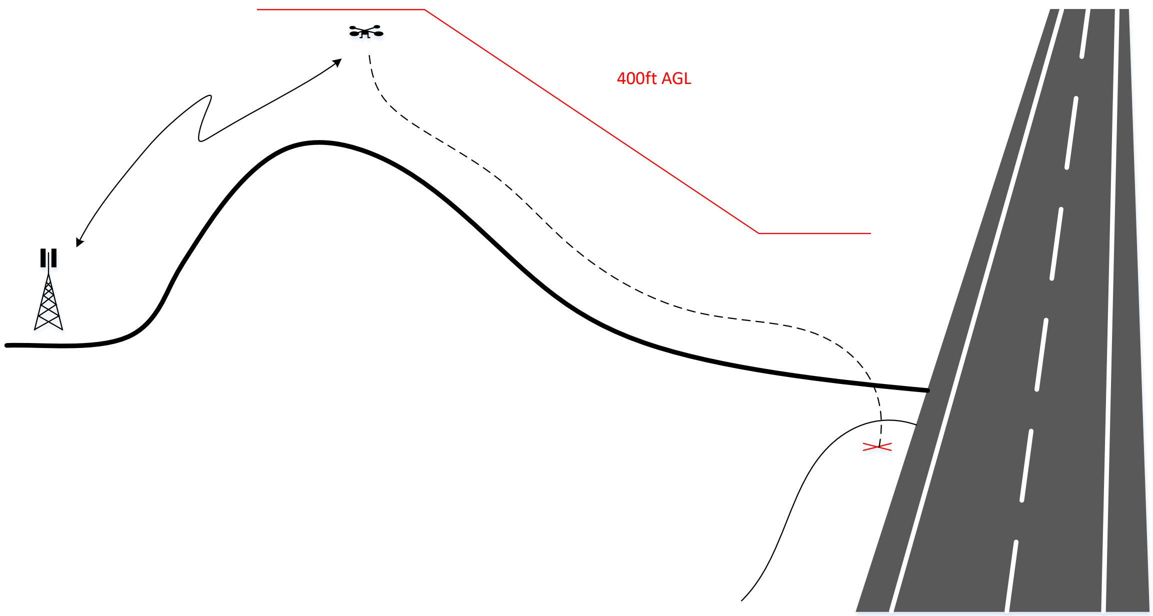

Figure 6.6: Use scenario with a hill far from the roadway

Figure 6.6 shows the use scenario when there is a far hill with a slowly rising smooth slope between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off and move smoothly along the shallow face of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. The VO will assist in the situational awareness of the operational environment. When the UAS is near the peak of the hill or side-slope depending on the topology, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.7 Scenario 6: maximum height

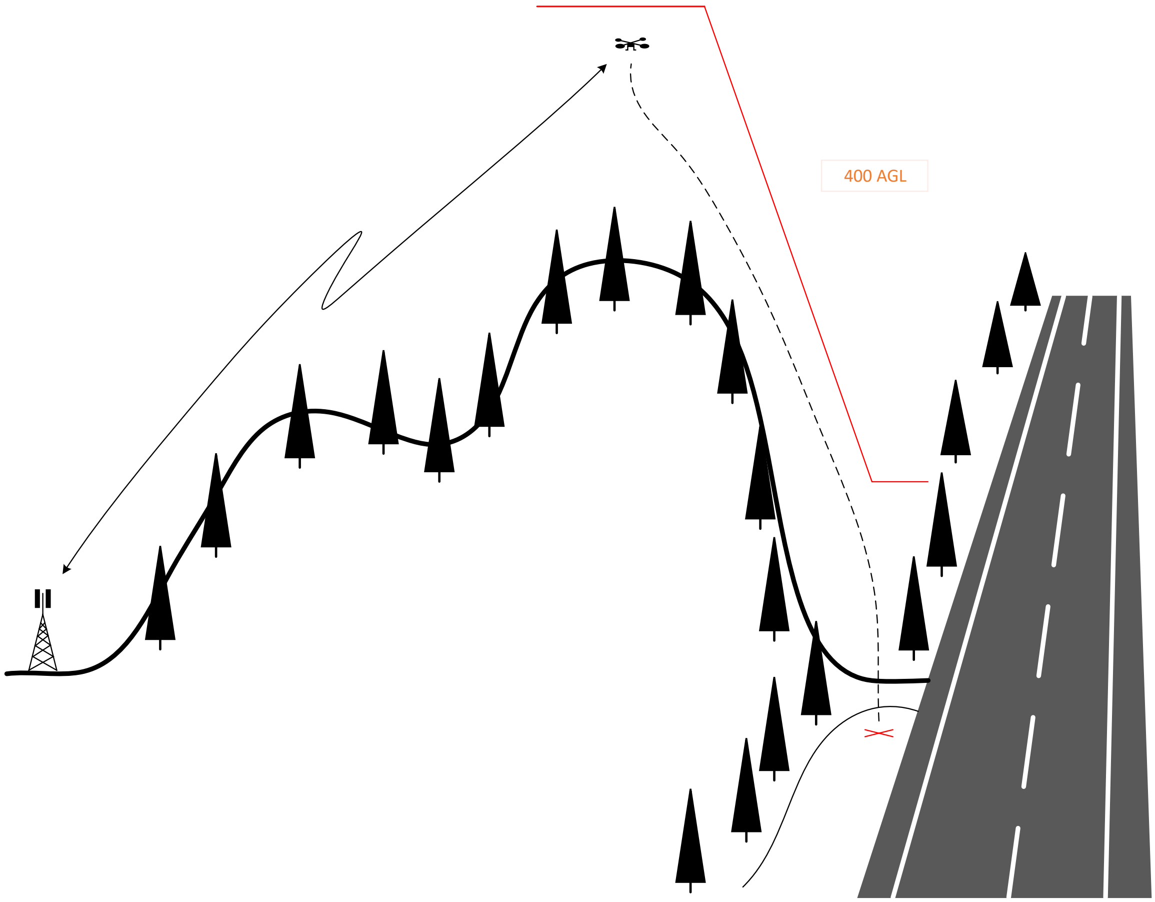

Figure 6.7: Use scenario requiring maximum height above ground

Figure 6.7 shows the use scenario when there is a very tall hill or rock wall between the roadway and the nearest cellular tower. Additionally, the initial hill has a smaller hill behind which may further obscure visibility of the cell tower location. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off and move quickly up the steep face of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. In this scenario, it is necessary to operate the UAS at maximum height AGL in order to achieve LOS to the cell tower location. The VO will assist in the situational awareness of the operational environment. When the UAS is at maximum height above the hill, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.8 Scenario 7: tower

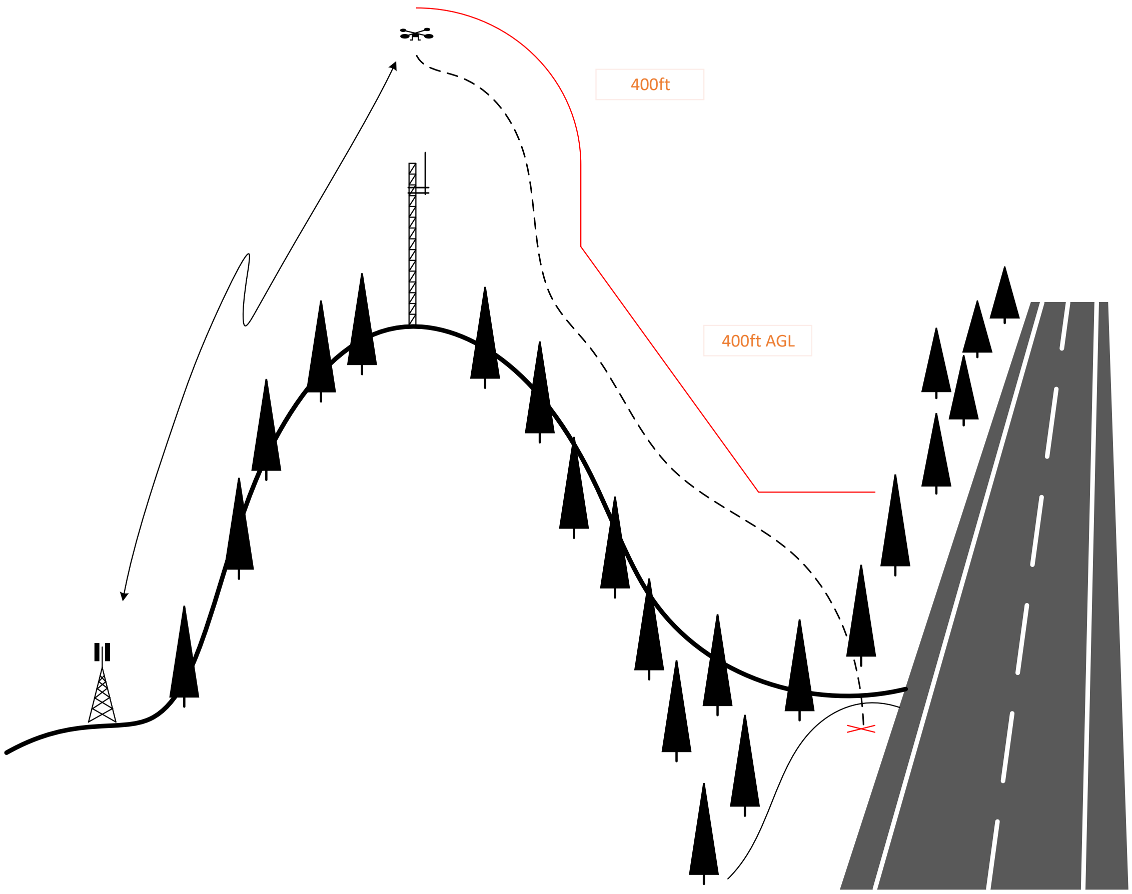

Figure 6.8: Use scenario with a structure

Figure 6.8 shows the use scenario when there is a moderately tall hill between the roadway and the nearest cellular tower with a structure, e.g. a tower, at the peak of the hill. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. Upon approaching the tower structure near the peak of the hill, the RPIC is allowed to pilot the UAS above the 400 ft AGL restrictions as long as the UAS stays within 400 ft of the structure. The VO will assist in the situational awareness of the operational environment. When the UAS is within site of the cellular tower, or at a maximum height of 400 ft above the tower structure, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.9 Scenario 8: valley

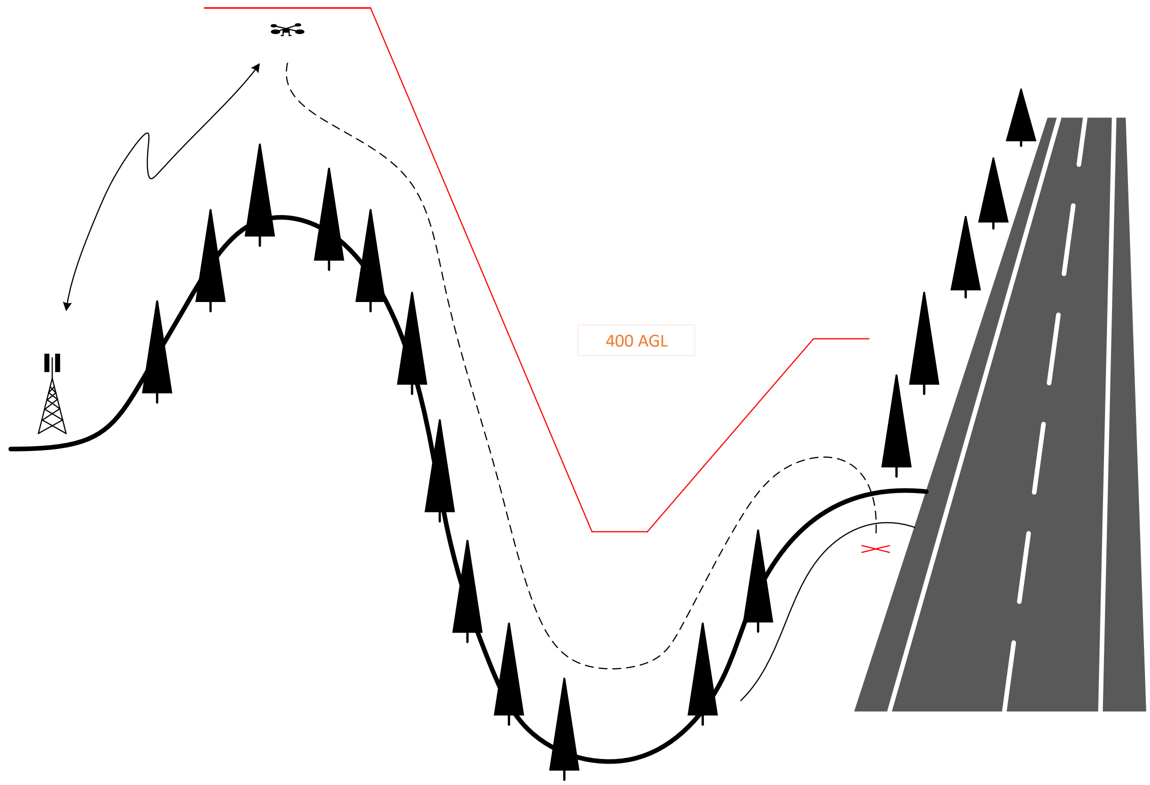

Figure 6.9: Use scenario with a valley near the roadway

Figure 6.9 shows the use scenario when there is an average hill and deep valley between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the valley and then the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. The VO will assist in the situational awareness of the operational environment. When the UAS is within site of the cellular tower, or at maximum height, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land. A key component of this sketch was the intention to convey that the 400 ft AGL ceiling is below the elevation of the roadway, and as such, requires the RPIC to navigate below roadway elevation before proceeding up the face of the occluding mountain.

6.10 Scenario 9: maximum valley

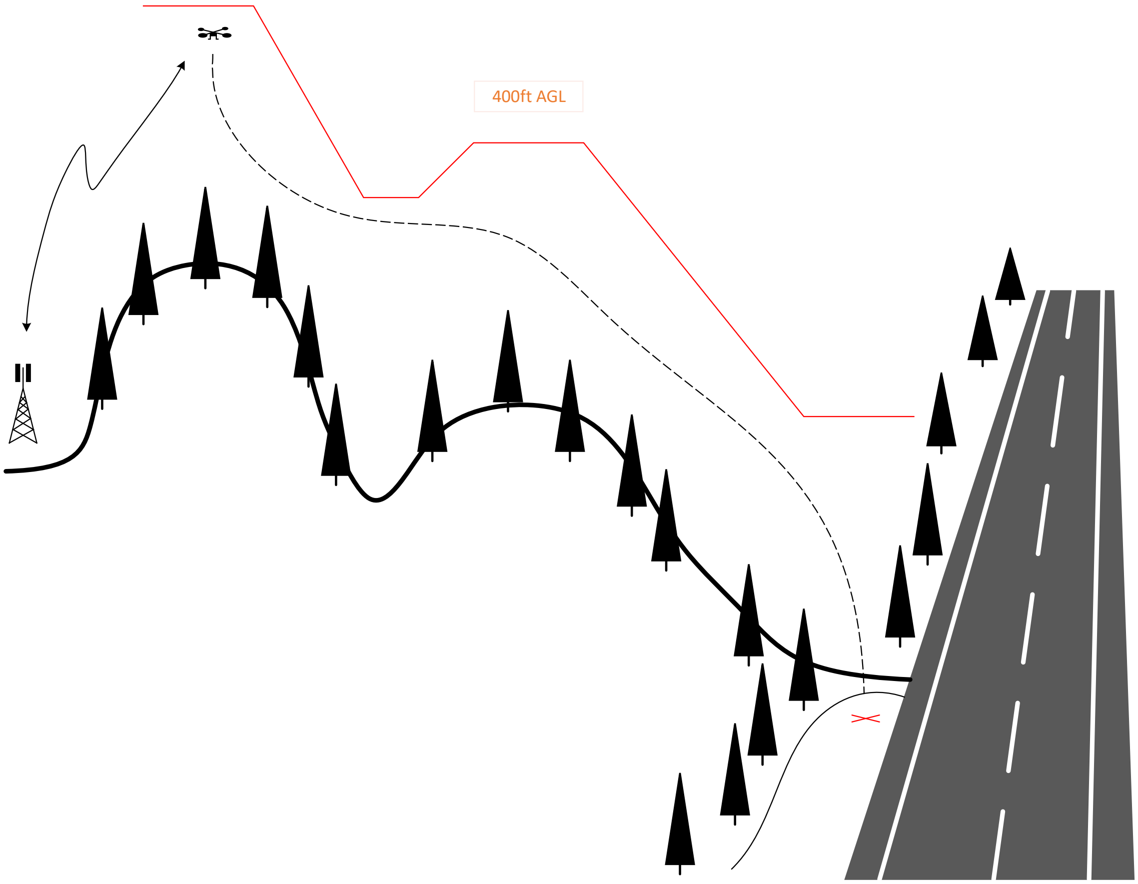

Figure 6.10: Use scenario with a maximum valley depth

Figure 6.10 shows the use scenario when there is tall hill with a hidden valley between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the left (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the hill, moving towards the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. In this scenario, it is important when traversing the hidden valley to observe the 400 ft AGL of the valley, before continuing up toward the peak of the hill. The VO will assist in the situational awareness of the operational environment. When the UAS is within site of the cellular tower, or at maximum height, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.11 Scenario 10: opposite hill

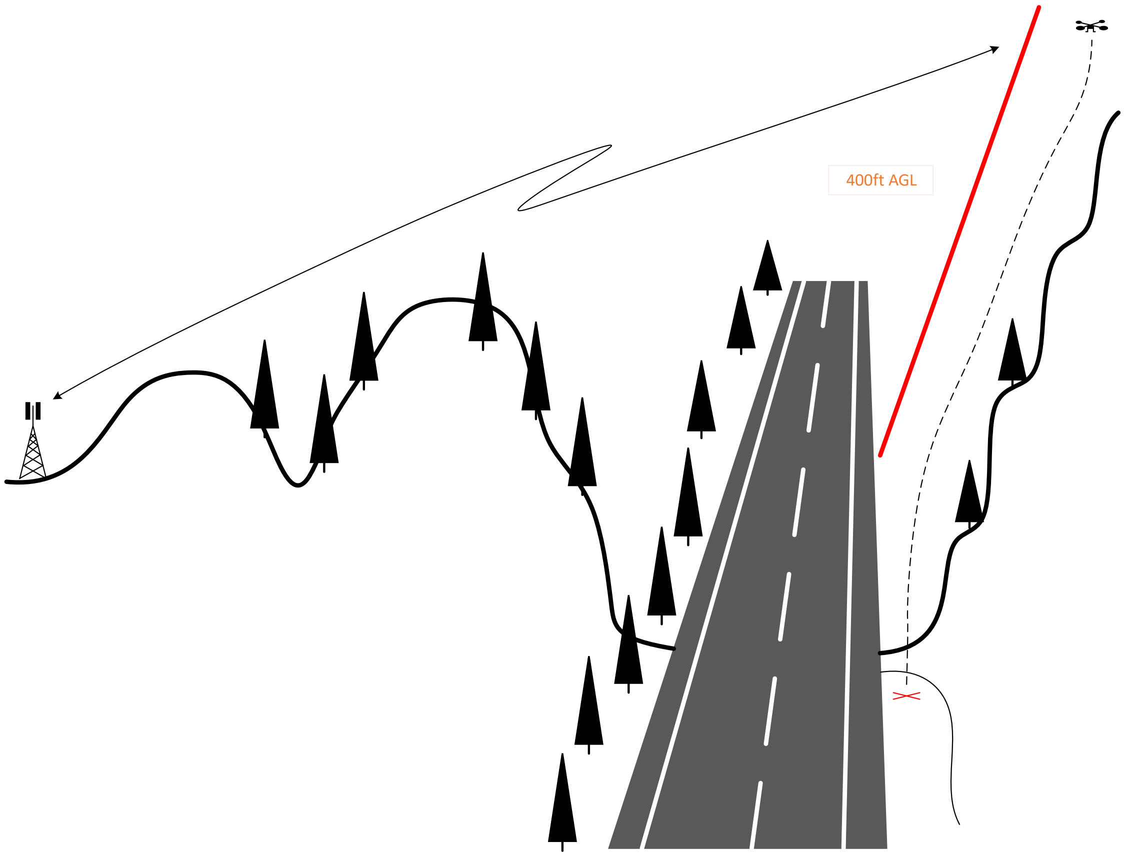

Figure 6.11: Use scenario requiring use of the opposing hill

Figure 6.11 shows the use scenario when there is tall close hill with a hidden valley between the roadway and the nearest cellular tower. The maintenance workers pull off the roadway into the turnout on the right (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the hill, moving away from the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. In this scenario, it is important to stay close to the face of the hill as 400 ft AGL can be easily exceeded when climbing very steep slopes at a distance from the face. The VO will assist in the situational awareness of the operational environment. When the UAS is within site of the cellular tower, or at maximum height of the adjacent hill, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

6.12 Scenario 11: curve

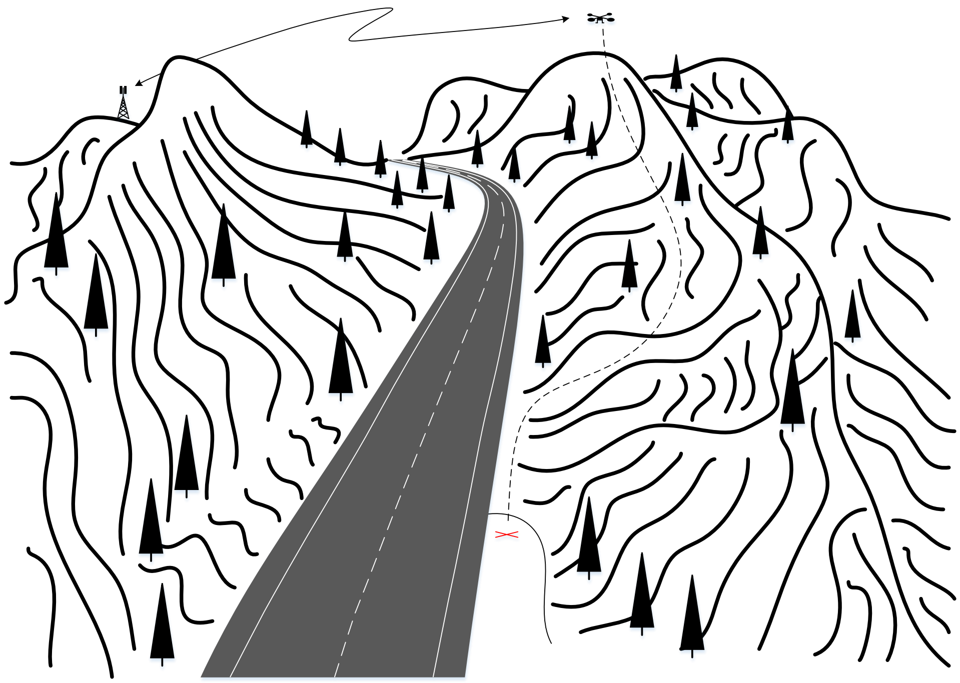

Figure 6.12: Use scenario with limited access and a curve

Figure 6.12 shows the use scenario when there are limited locations to turn out and the nearest cellular tower is behind a tall mountain around a curve. The maintenance workers pull off the roadway into the turnout on the right (figure view) side of the road. The RPIC and VO setup the UAS at the "X" marked location, and after a pre-flight check, take off following the slope of the hill to the right of the roadway, moving generally in the direction of the known cell tower location while staying below 400 ft AGL and keeping the UAS within sight at all times. The VO will assist in the situational awareness of the operational environment. When the UAS is at maximum height of the hill on the right-hand side of the road, the RPIC puts the UAS into hover mode and support staff can establish network connectivity. Once data communications have concluded, the RPIC returns the UAS to the take-off location to land.

7 Referenced documents

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Appendix A Mobile Radio

The voice-based mobile radios are composed of both low-band (47 MHz) and high-band (800 MHz) vehicle-mounted and handheld radio solutions. In the case of rural communications, the operating environment typically requires communication over long distances, near heavy foliage, and in mountainous terrain. It is common in difficult communications environments to rely on powered (100 W+) low-band systems, due to the inherently better propagation capabilities vs. lower-powered high-frequency high-band systems. However, the Office of Radio Communications (ORC) currently has an ongoing project to improve the radio coverage throughout the state. Districts 1, 2, 5, and 10 are currently being converted to 800 MHz from low-band frequencies. The following Figures show currently available 800 MHz coverage areas. Although the radio coverage is improving, it is still very common for vehicles operating in very rural areas to contain both high- and low-band radio systems.

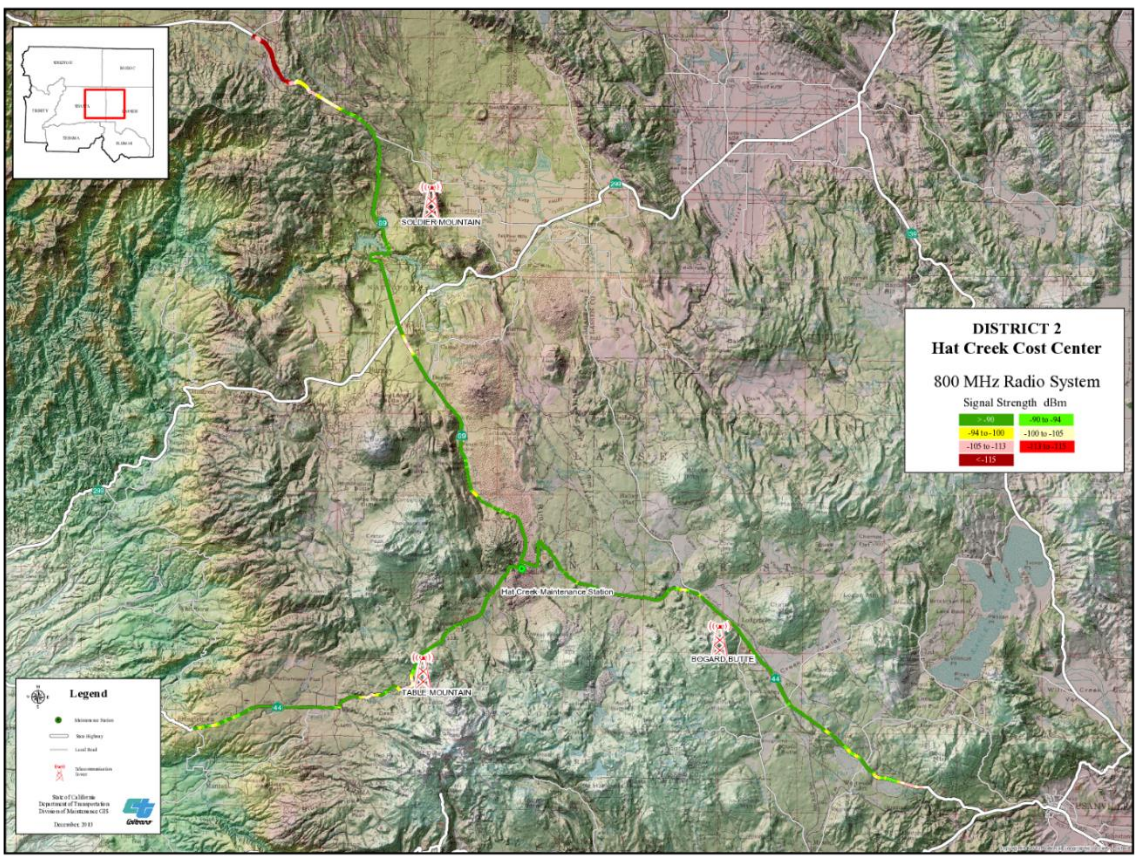


Figure A.1: SR44 Hat Creek 800 MHz radio system signal strength map

Figure A.1 shows the 800 MHz repeater system coverage in the area of the D2 Hat Creek Maintenance Station. From the signal strength measurements, the voice coverage is very good from Shingletown in the southwest to Roop Mountain in the southeast. However, the signal strength drops off quickly after rounding the mountains in the north past Soldier Mountain. The terrain in the area consists of slowly sloping hills with moderate foliage. The repeater system works well in the service area for LOS communications.

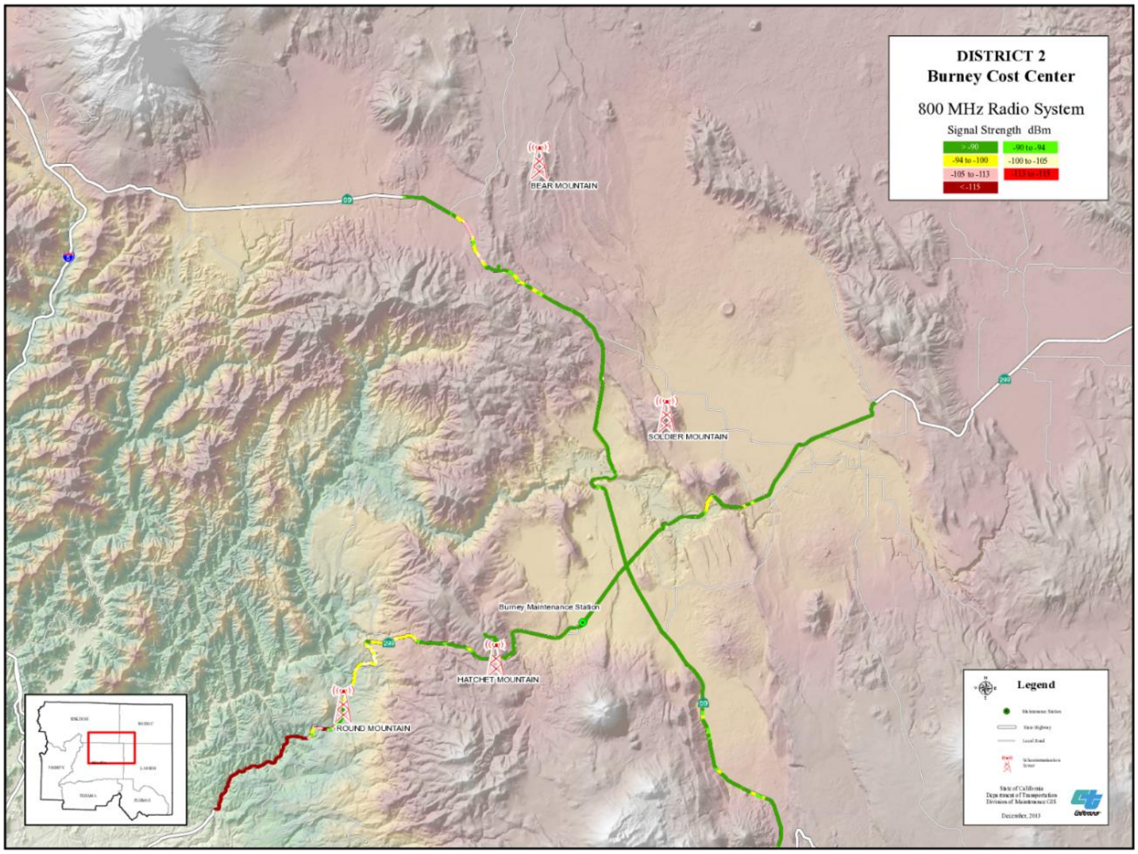


Figure A.2: SR299E Burney 800 MHz radio system signal strength map

Figure A.2 shows the 800 MHz repeater system coverage in the area of the D2 Burney Maintenance Station. The signal strength measurements show that the coverage is very good north of Bear Mountain. It appears that the Bear Mountain repeater was added since the signal strength measurements shown in Figure A.1. The Soldier Mountain repeater covers SR299 from the east of SR89 to the west of Hatchet Mountain. Between Hatchet Mountain and Round Maintain to the west the signal strength begins to fall off due to increasing terrain, and falls off quickly further west of Round Mountain. Signal strength is good in the LOS locations; however, the 800 MHz system performs poorly due to the high terrain slopes near the winding roadway.

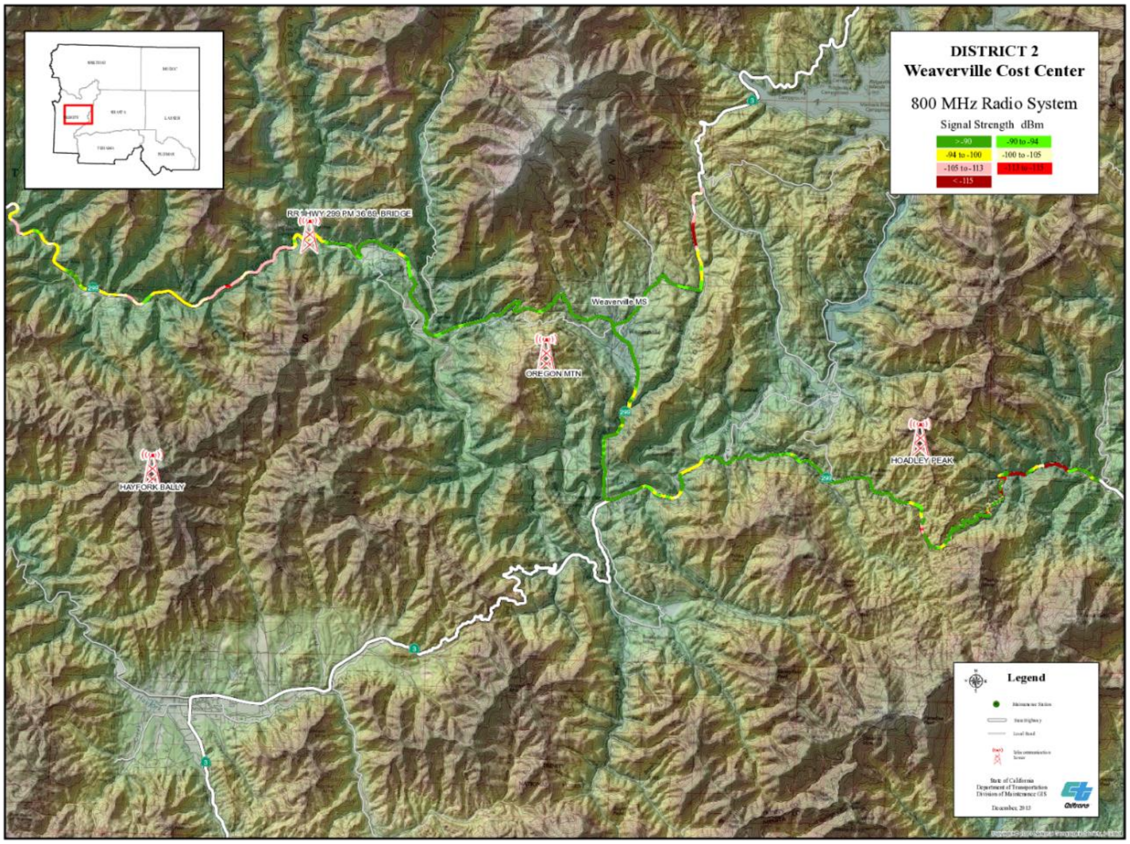


Figure A.3: SR299W Weaverville 800 MHz radio system signal strength map

Figure A.3 shows the 800 MHz repeater system coverage in the area of the D2 Weaverville Maintenance Station. From the map and the variable signal strength measurements, the terrain greatly affects the signal propagation in the area. On SR299, the signal strength is good between SR299 east of SR3 near Hoadley Peak and SR299 west of SR3 near Helena. However further east and west on SR299 the signal strength is intermittent due to the very high slope mountain terrain near the roadway. In these areas, LOS to the repeater towers is regularly occluded even with the mountain top or near roadway tower locations.

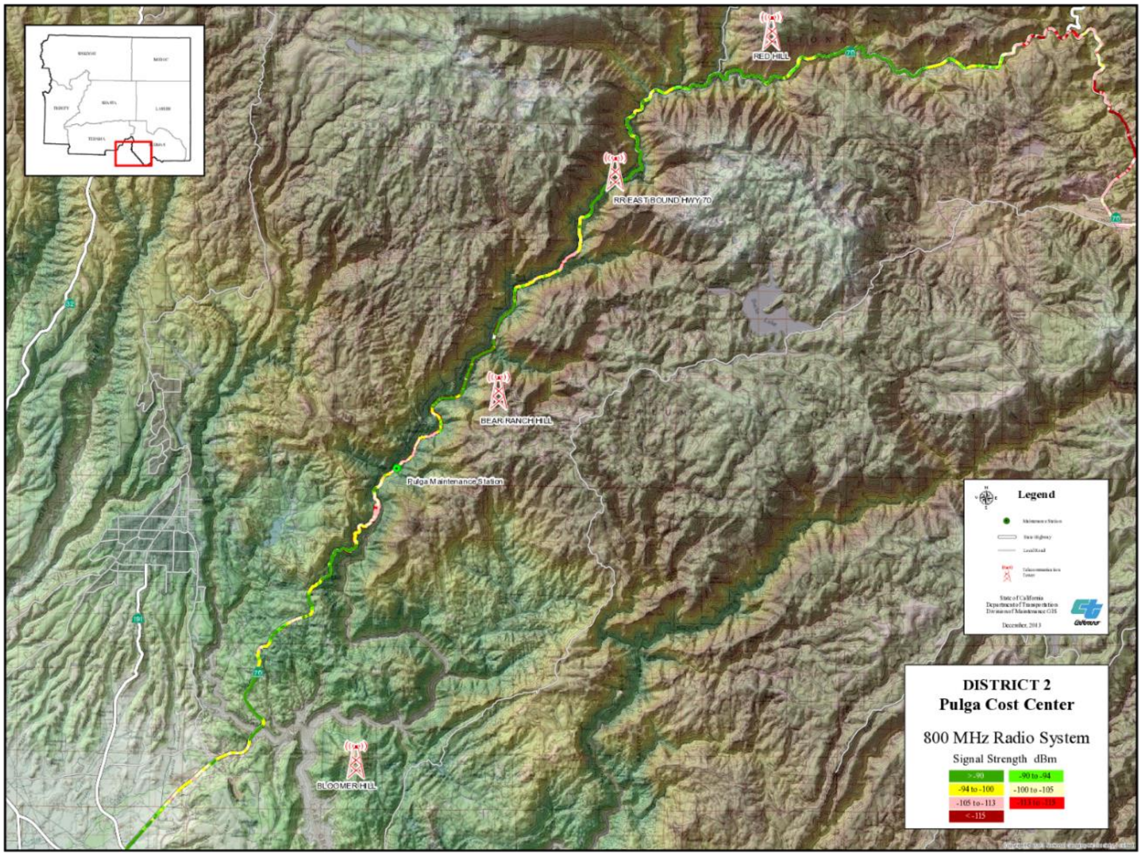


Figure A.4: SR70 Pulga 800 MHz radio system signal strength map

Figure A.4 shows the 800 MHz repeater system coverage in the area of the D2 Pulga Maintenance Station. The terrain just southwest of the station to the northeast on SR70 is very steep, with the majority of the roadway terraced into the side of the mountains to the east. The mountains in the area are quite steep and windy with many locations covered in considerable trees and shrubbery. The geographic conditions require repeaters to be located relatively close to the roadway to provide the necessary coverage. The signal strength measurements show that while the overall communication coverage from Pulga to Belden is reasonable, there are clearly low signal strength areas throughout and near dead spots to the northeast.

Appendix B Satellite Communications (SATCOM)

B.1 SATCOM Trailers

Figure B.1: A Caltrans SATCOM trailer

A Caltrans mobile SATCOM trailer used for a variety of emergency services is shown in Figure B.1. SATCOM systems are based in Districts 1, 3, 4, and 7. Each mobile trailer can run off external power, or continuously in remote locations with an on-board propane-operated generator. Each trailer can provide a multitude of communications services:

- 32 voice lines per trailer
- Caltrans WAN connection
- Video streaming, wireless and wired video camera system
- Mobile radio repeater system
- Email and web browsing
- Remote wireless telephone and network connections

Figure B.2: Caltrans SATCOM satellite hardware

Figure B.2 shows the Caltrans SATCOM hardware used in both portable units and SATCOM trailers.

- AVL Technologies / Cobham
- Ku-band
- Auto-acquire

Figure B.3: Caltrans SATCOM trailer emergency use at an I-10 bridge collapse

Figure B.3 shows a Caltrans SATCOM emergency trailer in use monitoring and managing a bridge collapse on I-10.

Key considerations for SATCOM include:

- (+) Capabilities: high bandwidth, camera, voice, data
- (-) Cost: very high
- (-) Size: very large
- (-) Units in service: 4-5

For various reasons, SATCOM systems are not very usable in rural areas, and thus not widely deployed.

B.2 Satellite Service

Figure B.4: Intelsat satellite coverage map (courtesy Intelsat)

Figure B.4 shows the Intelsat satellite coverage map [11] for Ku-band Very Small Aperture Terminal (VSAT)-based satellite systems. The family of Intelsat satellites are geostationary which means they are always available as opposed to LEO satellites that rapidly change position.

Although many satellites provide service coverage over the United States, look angles can vary significantly depending on the longitude of the satellite over the equator. Since look angles are a limiting factor in mountainous areas, it is important to select a service and satellite with the most capability in the given rural environment.

Table B.1: The Intelsat satellite antenna look angles from D2 headquarters

Satellite	Elevation	Azimuth
Galaxy 28 at 89W	32.0°	120.7°
Galaxy 12 at 91W	33.1°	122.9°
Galaxy 11 at 93W	34.2°	125.3°
Galaxy 25 at 93W	34.3°	125.3°
Galaxy 3C at 95W	35.3°	127.6°
Galaxy 19 at 97W	35.3°	127.6°
Galaxy 16 at 99W	37.3°	146.4°
Galaxy 18 at 123W	43.1°	167.0°
Horizons 1 at 127W	42.8°	173.2°

Table B.1 lists the calculated look angles [7] of various satellites providing service to Caltrans D2. The most important factor in very mountainous terrain is the elevation angle. Unfortunately, the further north the dish location, the lower the maximum elevation angle. However, if one judiciously selects satellites further to the west the look angles elevations increase. Thus, in the case of D2, Galaxy 16, 18 or Horizons 1 might be good candidates to maximize look angles.

Figures B.5-9 show satellite Equivalent Isotopically Radiated Power (EIRP) outputs with respect to geographic location. The EIRP of Galaxy 18 is 46.6 dBW, and Horizons 1 is 46.0 dBW; however, Galaxy 16 has an EIRP of 49.4 dBW. For maximum power, one would select Galaxy 16. For maximum elevation, one would select Galaxy 18.

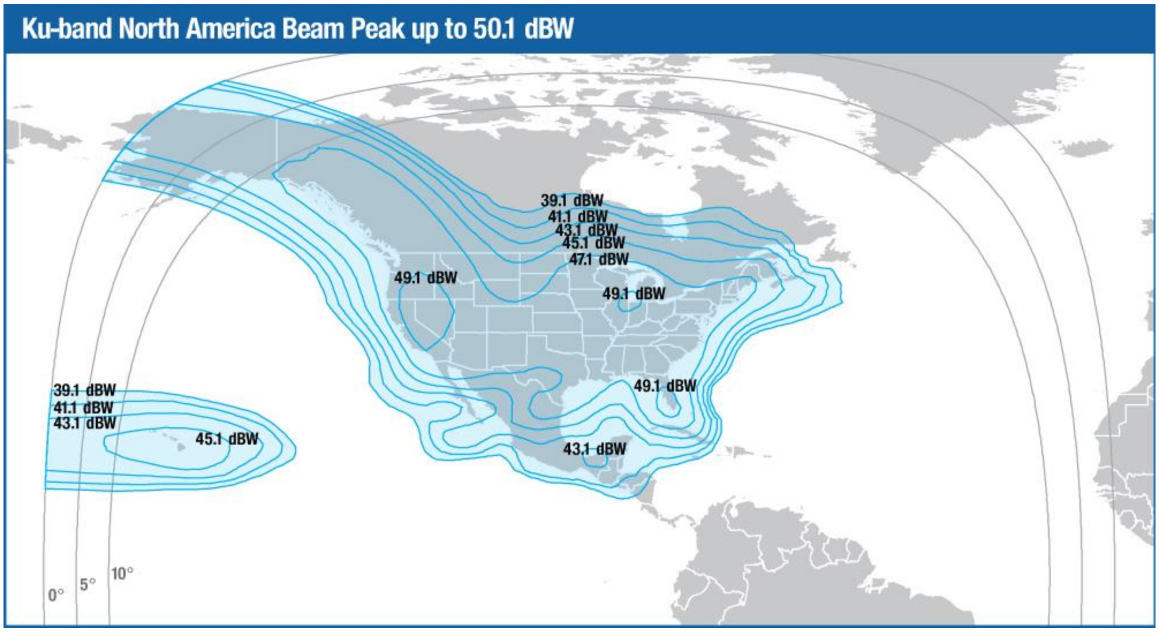


Figure B.5: Intelsat Galaxy 3C at 95°W (courtesy Intelsat)

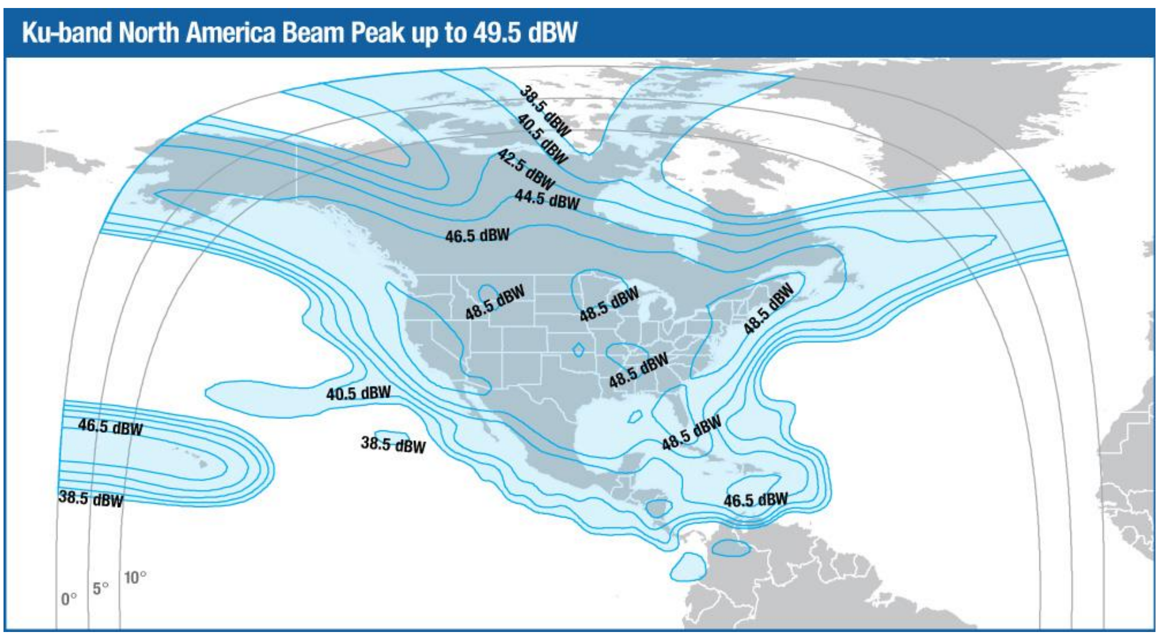


Figure B.6: Intelsat Galaxy 19 at 97°W (courtesy Intelsat)

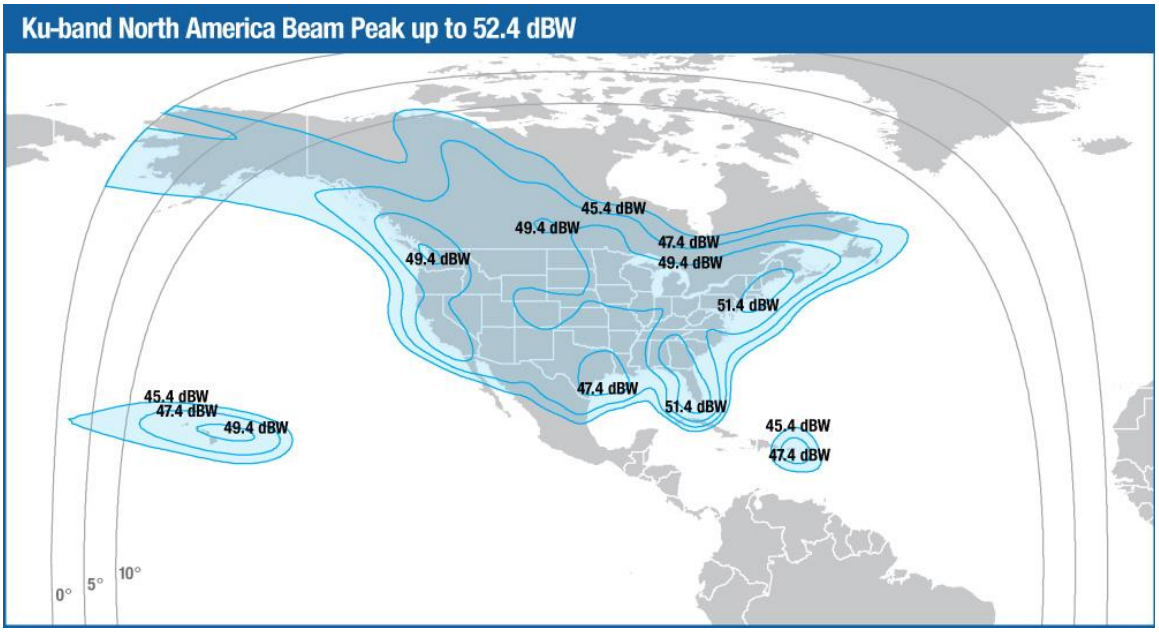


Figure B.7: Intelsat Galaxy 16 at 99°W (courtesy Intelsat)

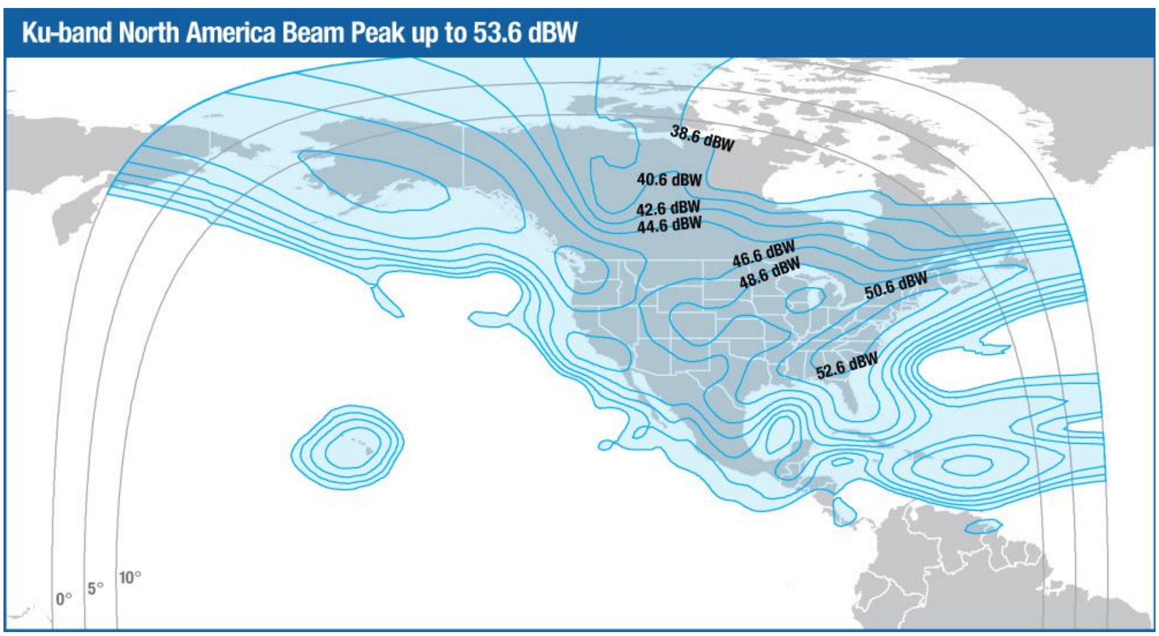


Figure B.8: Intelsat Galaxy 18 at 123°W (courtesy Intelsat)

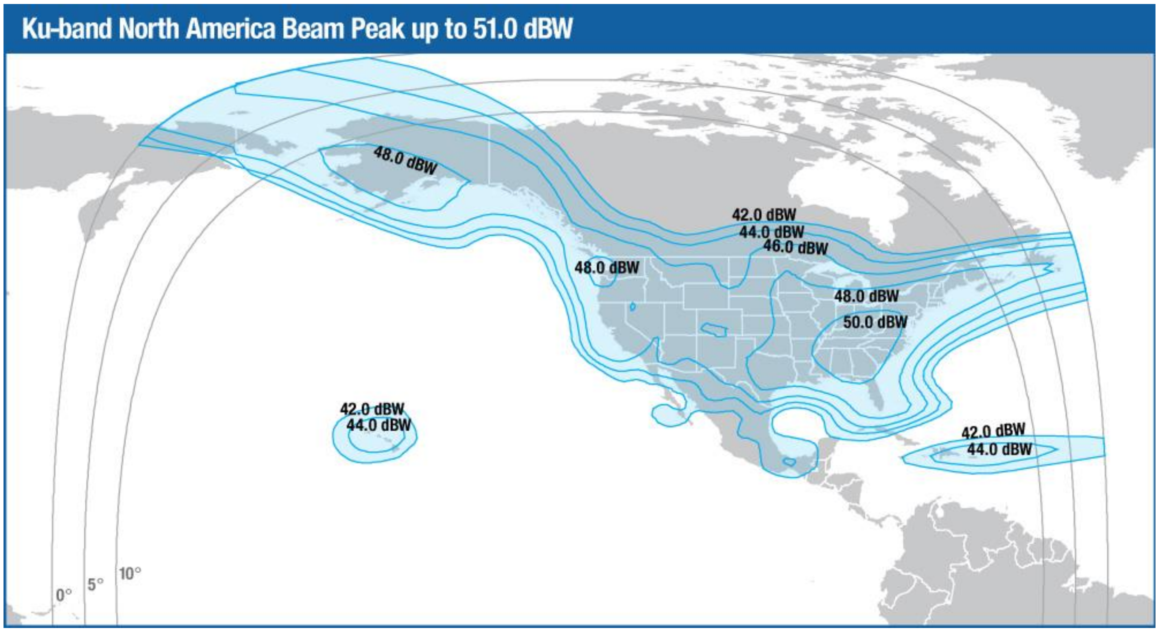


Figure B.9: Intelsat Horizon 1 at 127°W (courtesy Intelsat)

In addition to SATCOM vehicles, portable satellite telephones are available to employees within the Caltrans Division of Maintenance. The IsatPhone2 is available with support from the Inmarsat-4 geostationary satellites. Corresponding look angles are listed in Table B.2.

Table B.2: The Inmarsat satellite antenna look angles from District headquarters

District	Elevation	Azimuth
1	35.5°	128.0°
2	36.6°	130.3°
3	38.9°	130.9°
4	39.2°	129.5°
5	42.3°	130.7°
6	41.4°	132.8°
7	44.7°	133.9°
8	45.1°	135.5°
9	41.5°	135.1°
10	39.5°	131.0°
11	46.5°	135.0°
12	45.2°	134.5°

Table B.2 lists the calculated look angles [12] from various Caltrans district headquarters.

Appendix C Responder System

Responder System Allows Caltrans First Responders to Collect and Share At-Scene Information Quickly and Efficiently

Benefit — Allow first responders to provide information to get the right equipment and personnel dispatched to the site. This product will utilize resources effectively.

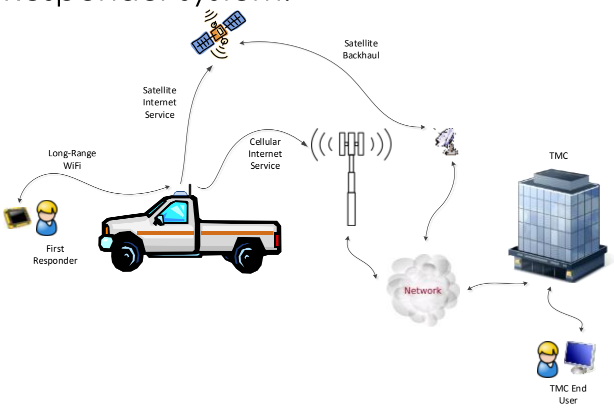
Advanced Highway Maintenance and Construction Technology (AHMCT) researchers have finalized the third generation of the Responder system, a communication tool that integrates hardware, software, and communications to provide incident responders, particularly those in rural areas with sparse communication coverage, with an easy to use means to accurately collect and communicate at-scene information with their managers and the TMC.

Motivation

Caltrans maintenance staff is a first responder to incidents on the state roadways. They must collect information, determine the appropriate response, and access and manage resources at-scene. Caltrans currently does not have an efficient means to collect at-scene incident information and share this information with their transportation management center (TMC) and other emergency responders. In most districts, emergency responders rely on voice communications to exchange information. However, Caltrans rural districts lack the ability to distribute incident support information to responders via data networks. Such information could better prepare responders for incident support, provide assistance for incident management, and guide responders in making safe and sound decisions. These rural districts have areas with no communication availability including no two-way radio communication and/or cellular coverage. Caltrans needs a communication tool for first responders to allow photos, drawings, weather information, and maps to be shared between responders and a TMC during an incident via cellular, satellite, or other forms of communications, that will work anywhere in the State.

Responder System Overview

The researchers at the UC Davis Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center have finalized the third generation of the Responder system. This prototype communication tool integrates hardware, software, and communications to provide incident responders, particularly those in rural areas, with sparse communication coverage, with an easy to use means to accurately collect and communicate at-scene information with their managers and the TMC. The incident responder uses a smart device such as a tablet or smartphone to operate the Responder system.

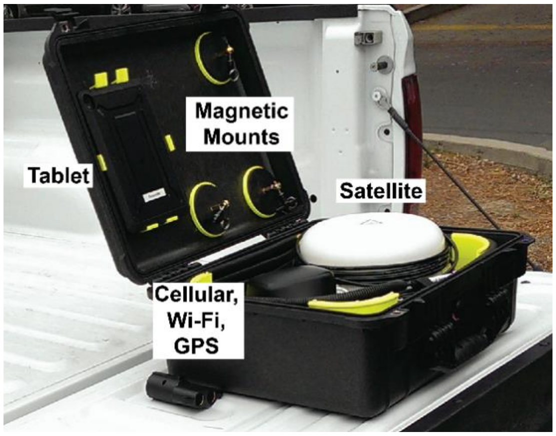


Unique features of Responder include ability for users to capture, annotate, and transmit images. Using Global Positioning System (GPS) readings, the system automatically downloads local weather, retrieves maps and aerial photos, and pinpoints the responder's location. By simply clicking on the "Send" button, an email message is automatically composed and sent to the TMC or other parties. The system connects to the most efficient and available service (cellular, satellite, or other). The system uses cellular where it can and satellite in areas with no other communications. The system allows responders to concentrate on work at the scene without burdening them with data input and reporting.

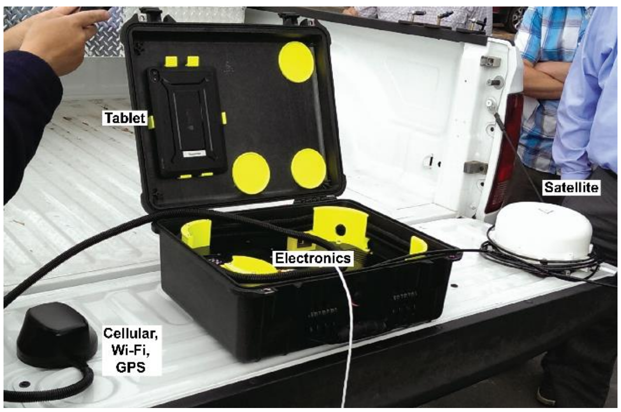
Approximate Cost

Hardware	$15,500
On-going communications	$40/month (cellular) $35/incident (satellite)

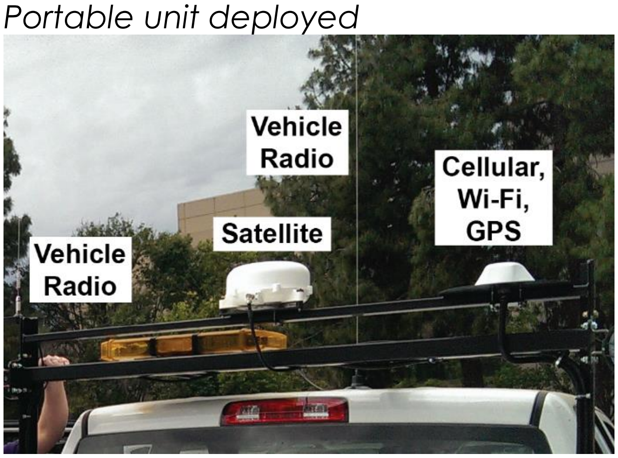
Hardware costs are subject to change due to vendor pricing. The cost is for equipment for either a truck-mounted system or a portable system. On-going costs are based on typical monthly cellular data plans and typical satellite data use cases. The remote-incident cost estimate is based on satellite-only data transmission of the incident report and revisions, CAL FIRE and InciWeb data feeds once per incident, Closed-Circuit Television (CCTV), Caltrans Chain Control, California Highway Patrol (CHP), Daily Forecast, Hourly Forecast, Road Information, Roadway Information System (RWIS), and Stream Flow data feeds once per hour, and Changeable Message Sign (CMS), Zone Alerts, and Zone Forecasts data feeds every 15 minutes, and assumed incident duration of 4 hours. Attachments such as pictures, map snapshots, and drawings are additional and cost estimates depend on quantity, resolution, and compression. Satellite rates are about $5.25/MB.



Portable unit in box



Portable unit deployed



Vehicle-based unit system antennas

Summary

The Responder system allows first responders to collect and share at-scene information quickly and efficiently. It is especially valuable in:

- Major incidents such as landslides, floods and earthquakes, where the damage could be extensive.
- Remote rural areas where communication is often limited to voice, and coverage is sparse.
- When the first responder is new or inexperienced in responding to certain situations.

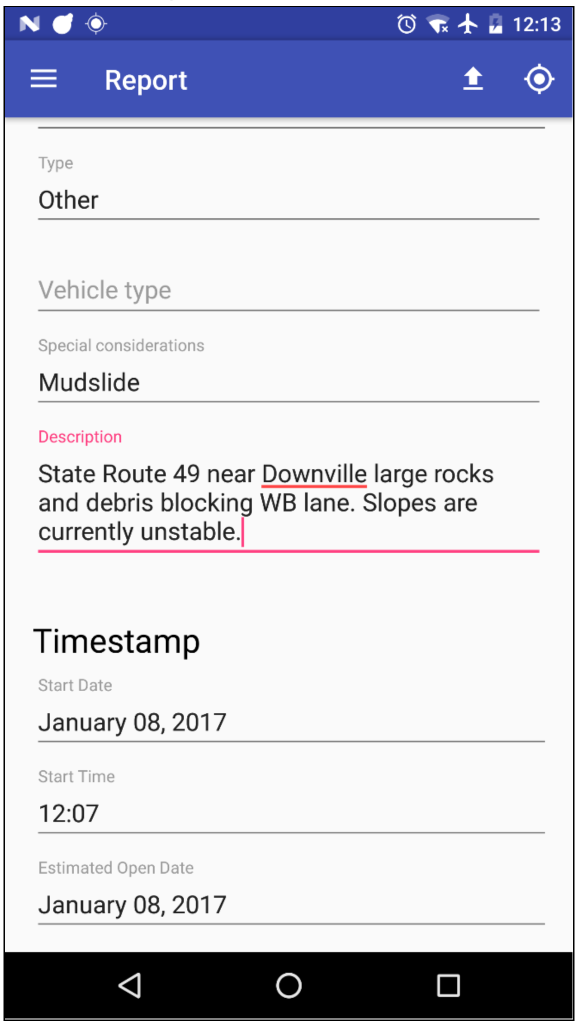
Responder utilizes resources effectively by:

- Supporting the ability to evaluate what is happening at the scene from a maintenance station or TMC without extended delay.
- Sending correct employees and equipment to the incident based on initial information that can be seen in the photo(s) and/or report(s) submitted by staff at the incident scene.
- Providing real-time information to other staff, such as Public Information Office, who may have to answer to outside agencies regarding what is happening at the incident.

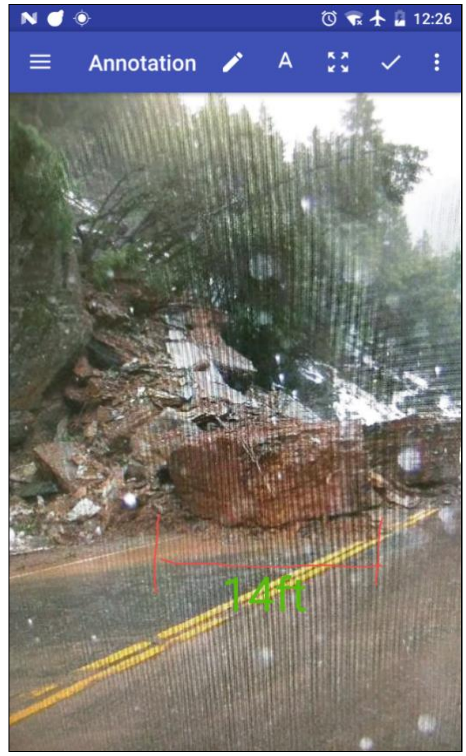
Status and Recommendation

The Responder system has been beta tested in Caltrans Districts 2, 3, 4, and 9, with additional pilot testing and actual field use in District 2. Caltrans staff provided positive feedback, which reiterated the purpose of the Responder system which is meant to be a useful tool for field maintenance first responders, potentially an improvement in health/life/safety during a serious incident.

Based on Caltrans' desire to deploy the system statewide, AHMCT is providing detailed documentation for knowledge transfer to a third-party vendor to reproduce more Responder system units and deploy them into Caltrans districts.



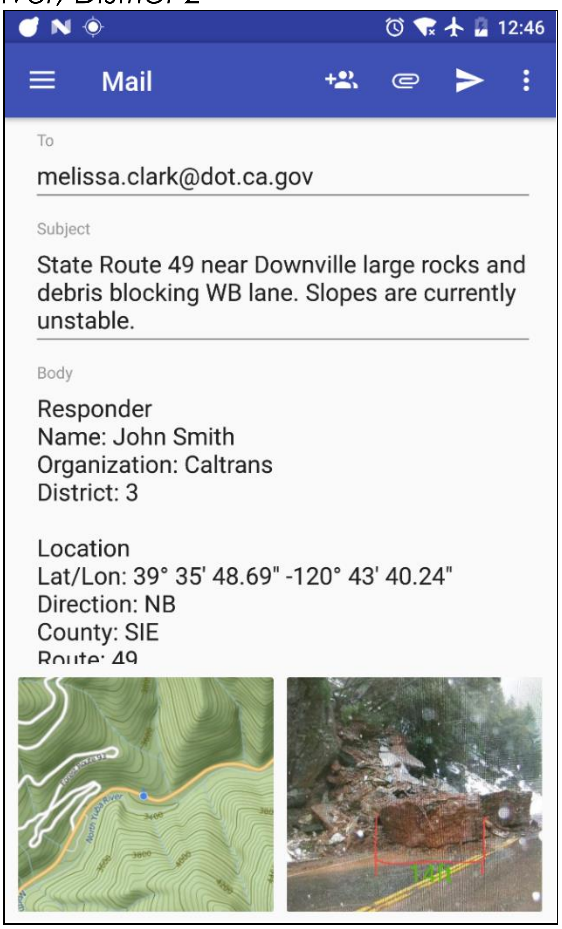
Sample Responder report screen



Responder photo including annotation

Rollover truck in District 2

Truck through guardrail and into river, District 2



Sample Responder email output including photos

For Additional Information

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Stephen Donecker	(530) 752-7946, smdonecker@ucdavis.edu, Lead Engineer

Appendix D Pulga Maintenance Station

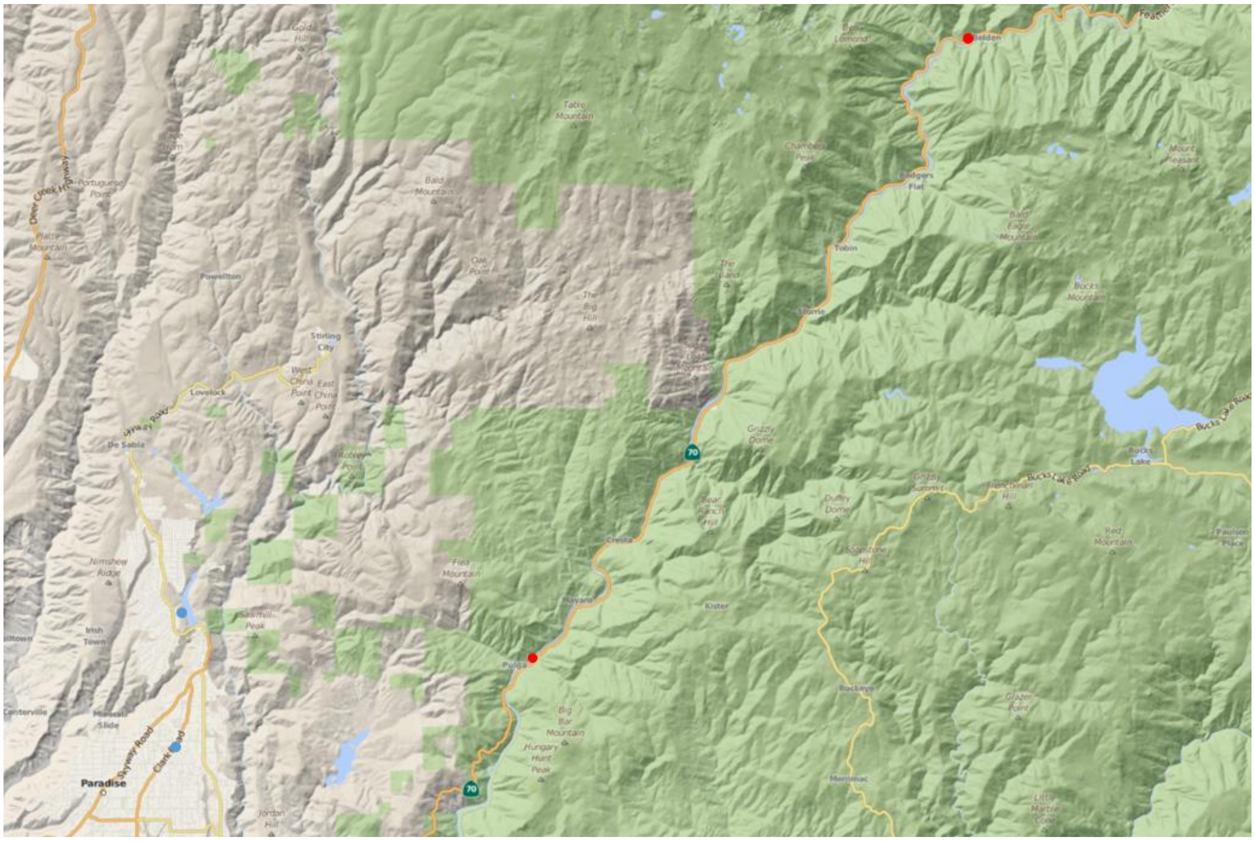

Figure D.1: SR70 Pulga maintenance station, Belden, and Verizon cellular tower approximate locations (courtesy of AHMCT Research Center)

Figure D.1 shows a topographic map of the Pulga Maintenance Station services area along SR70. A significant portion of the service area between Pulga (lower left red marker) and Belden (upper right red marker) is surrounded by significantly mountainous terrain. The nearest cellular towers serving the area are located in Magalia, and Paradise (leftmost blue markers). Based on clearly surrounding mountainous terrain, maintenance personnel reports, and verification testing, there is very little to no cellular service between Pulga and Belden.

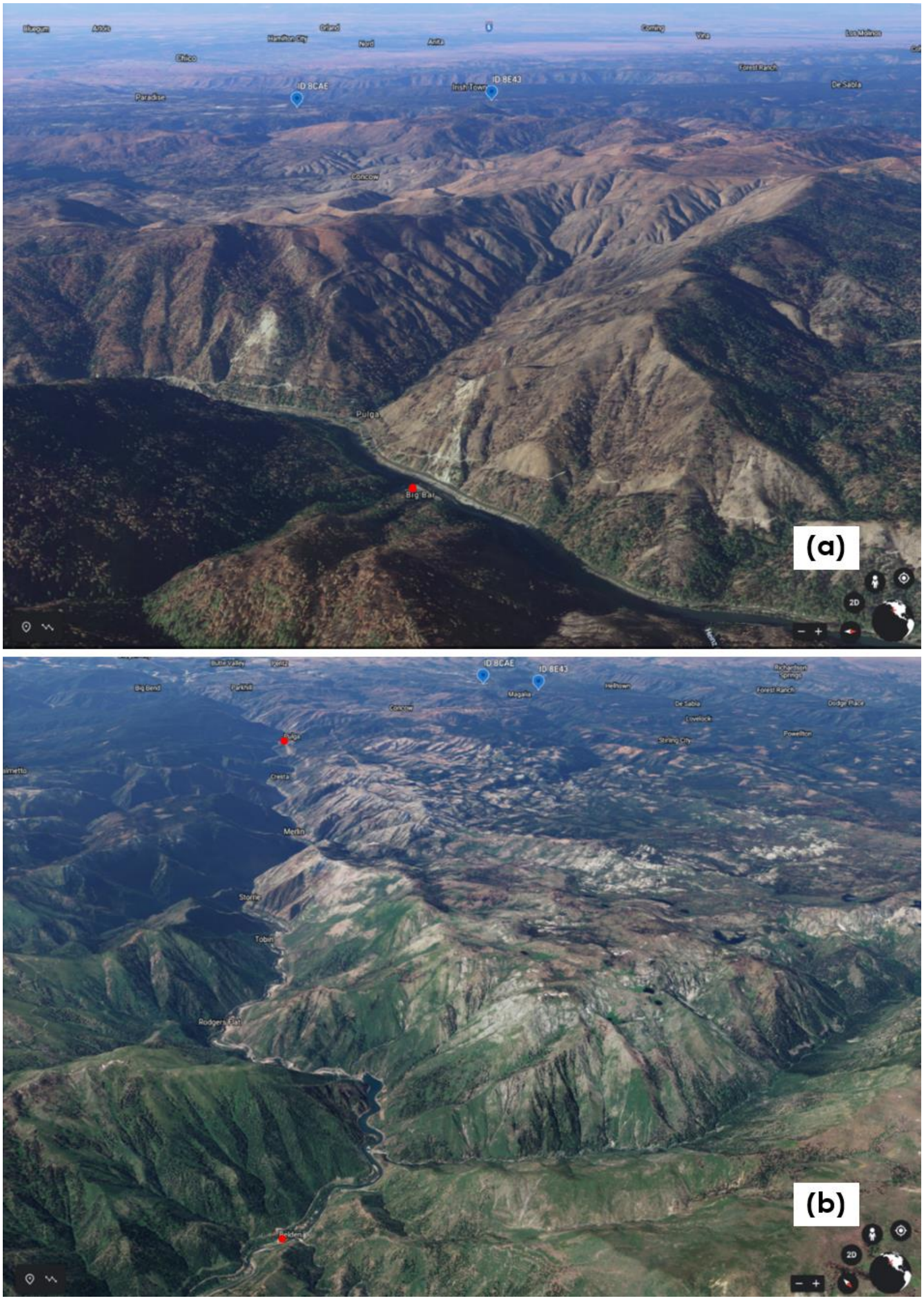

Figure D.2: SR70 viewing the Verizon cell towers in Paradise and Magalia (a) from Pulga, (b) from Belden (images courtesy of Google Earth)

Figure D.2(a) shows a high-altitude view of the Verizon cell tower locations with ID 8CAE and ID 8E43 visible in the background west of Concow in Paradise and Magalia with SR70 near Pulga Maintenance Station visible in the foreground. Also shown is the highly mountainous terrain surrounding the roadway.

Figure D.2(b) shows another high-altitude view of Verizon cell tower locations with ID 8CAE and ID 8E43 visible in the background with SR70 near Belden visible in the foreground. The entire length of SR70 is hidden in a canyon with no view of the Verizon cell towers.

Appendix E Caples Lake Maintenance Station

E.1 Verizon Measurements

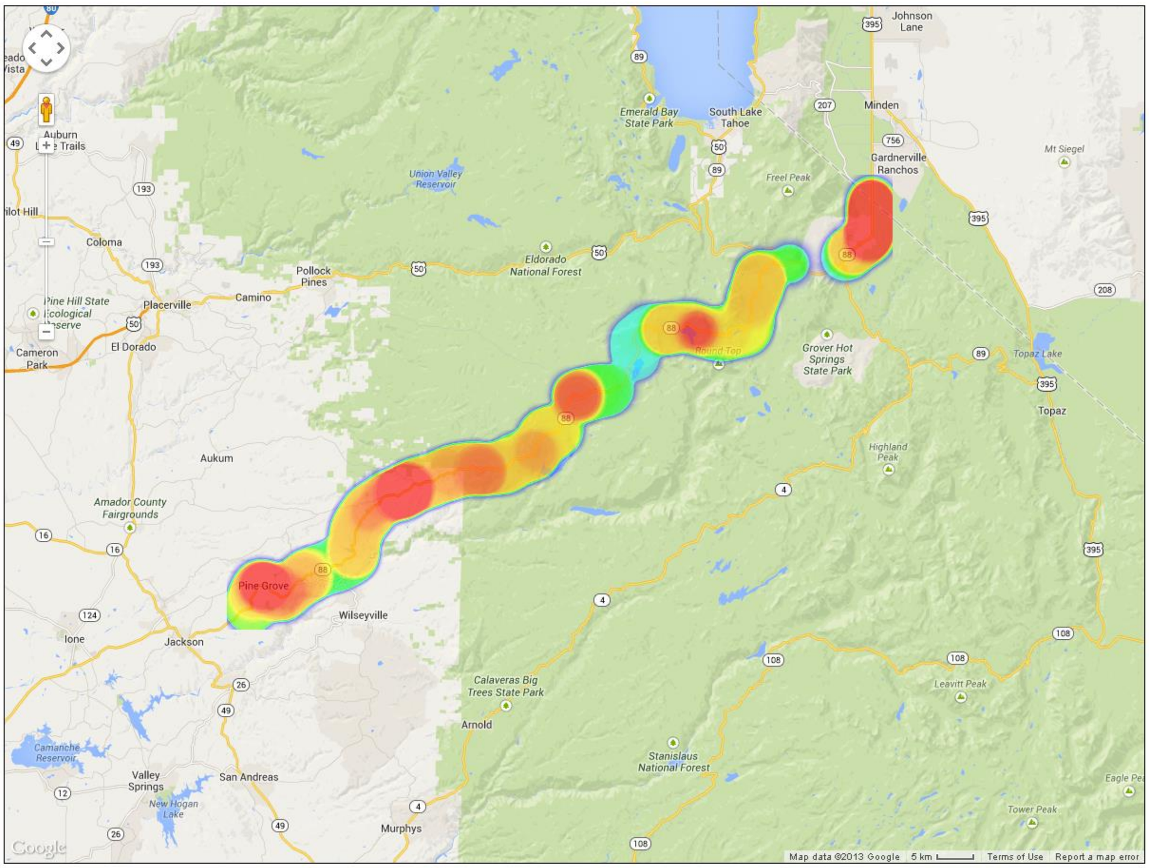

Figure E.1: SR88 Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure E.1 shows the Verizon cellular service availability measurements along SR88. The majority of the route appears to have sufficient signal coverage except for some weak spots near Caples Lake Maintenance Station, specifically the areas near the Carson Spur and the intersection of SR88 and SR89.

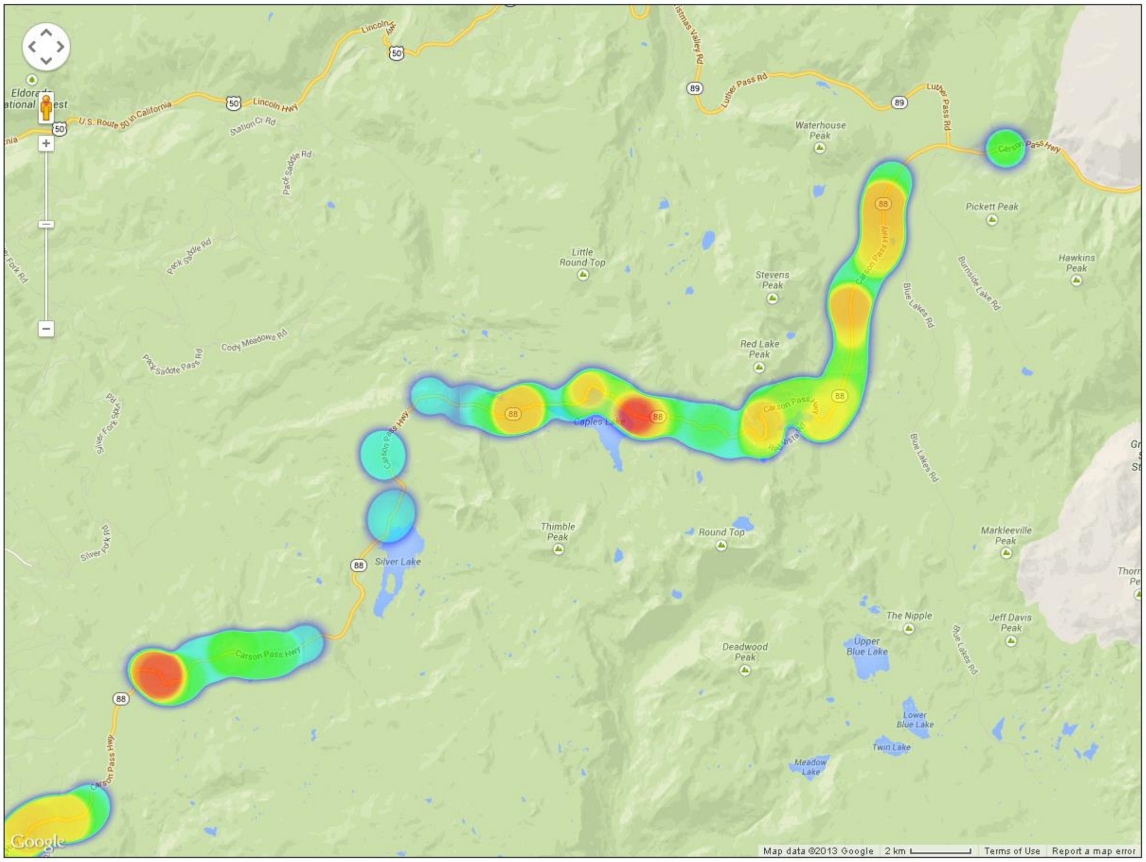

Figure E.2: SR88 Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure E.2 shows the zoomed-in view of the Verizon signal availability measurements on SR88 from before Silver Lake to past the Carson Spur and on past the Caples Lake Maintenance Station. This map clearly shows significant areas with no cellular coverage.

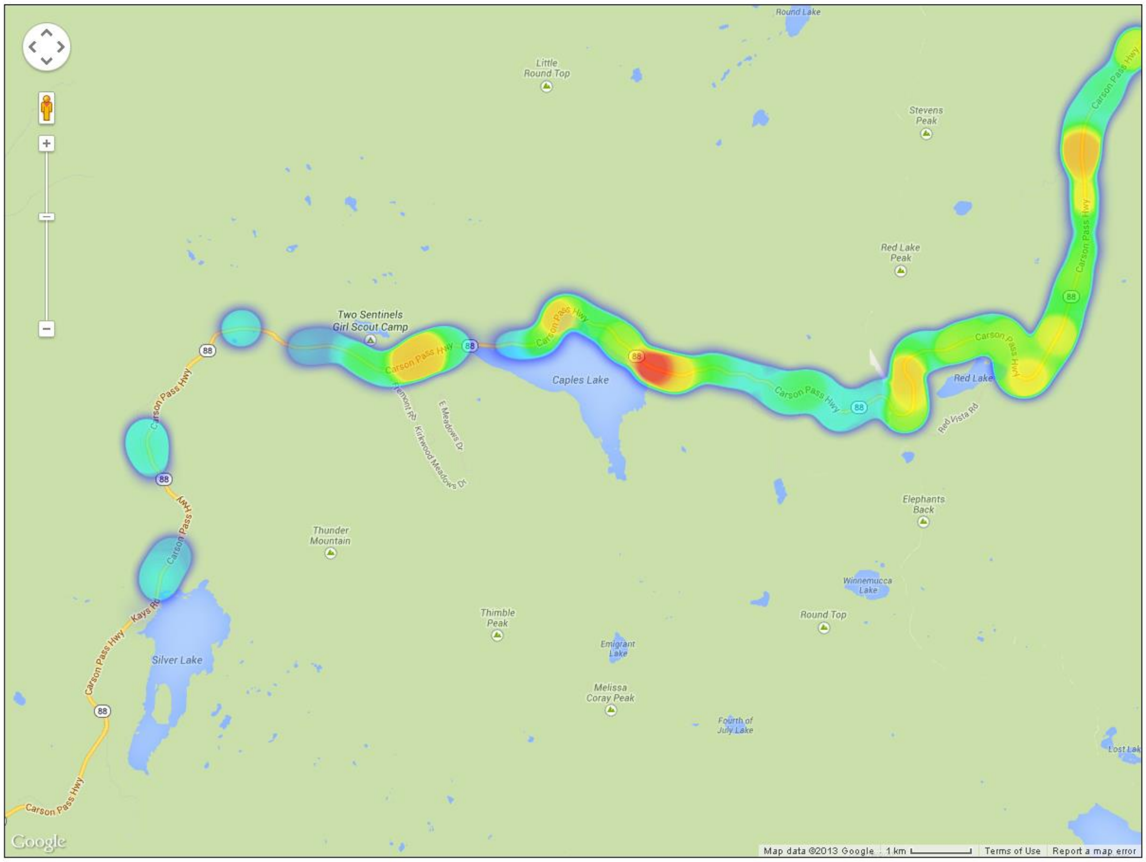

Figure E.3: SR88 Caples Lake Maintenance Station Verizon cellular service availability measurements (courtesy of AHMCT Research Center)

Figure E.3 shows a further zoomed-in view of the Verizon signal availability measurements on SR88 and shows significant areas with no cellular coverage between Silver Lake and the Caples Lake Maintenance Station. The Caples Lake Maintenance Station is in charge of winter maintenance avalanche operations along the Carson Spur and Carson Pass.

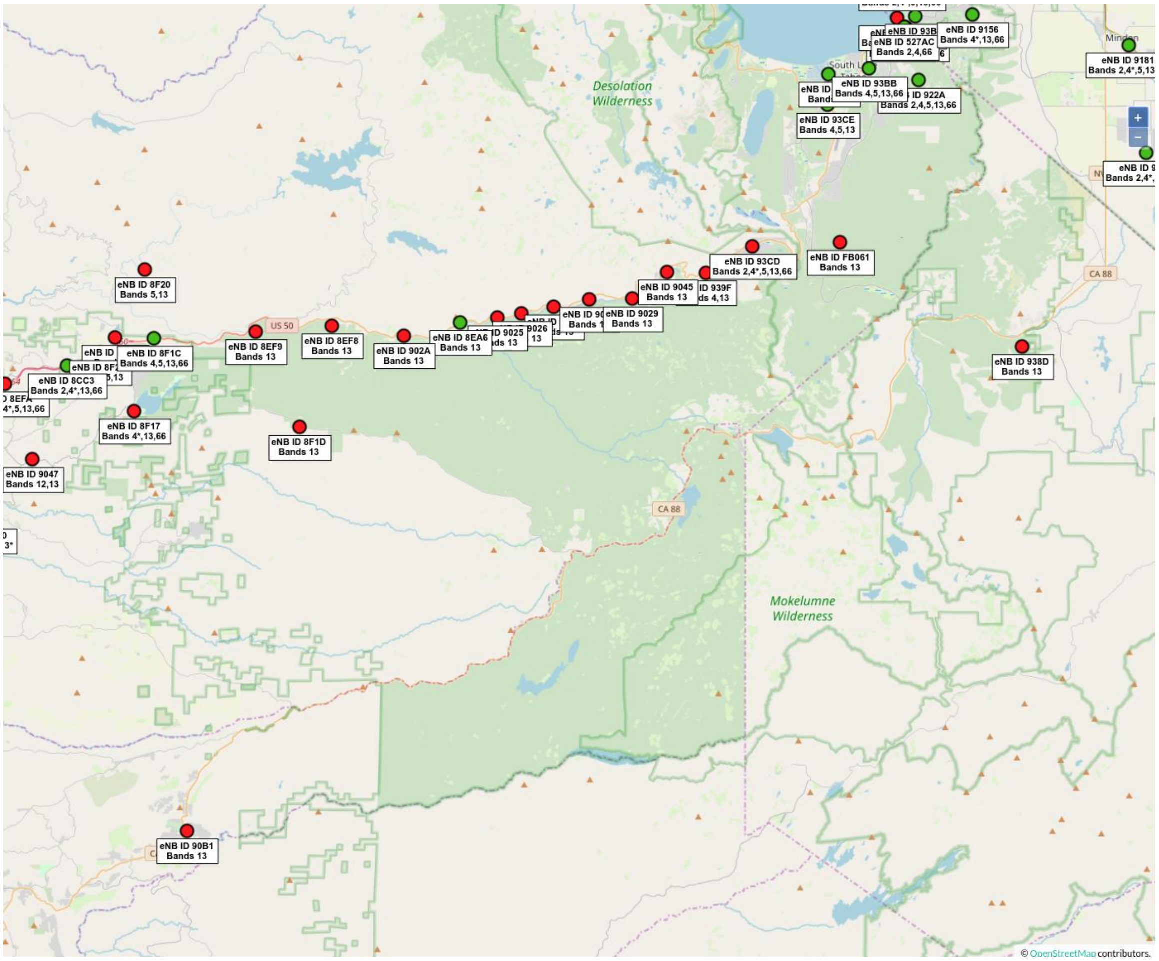

Figure E.4: SR88 Verizon cellular tower approximate locations (courtesy of Cell Mapper)

Figure E.4 shows the current Verizon cellular tower locations primarily located on US50 with respect to the Caples Lake area.

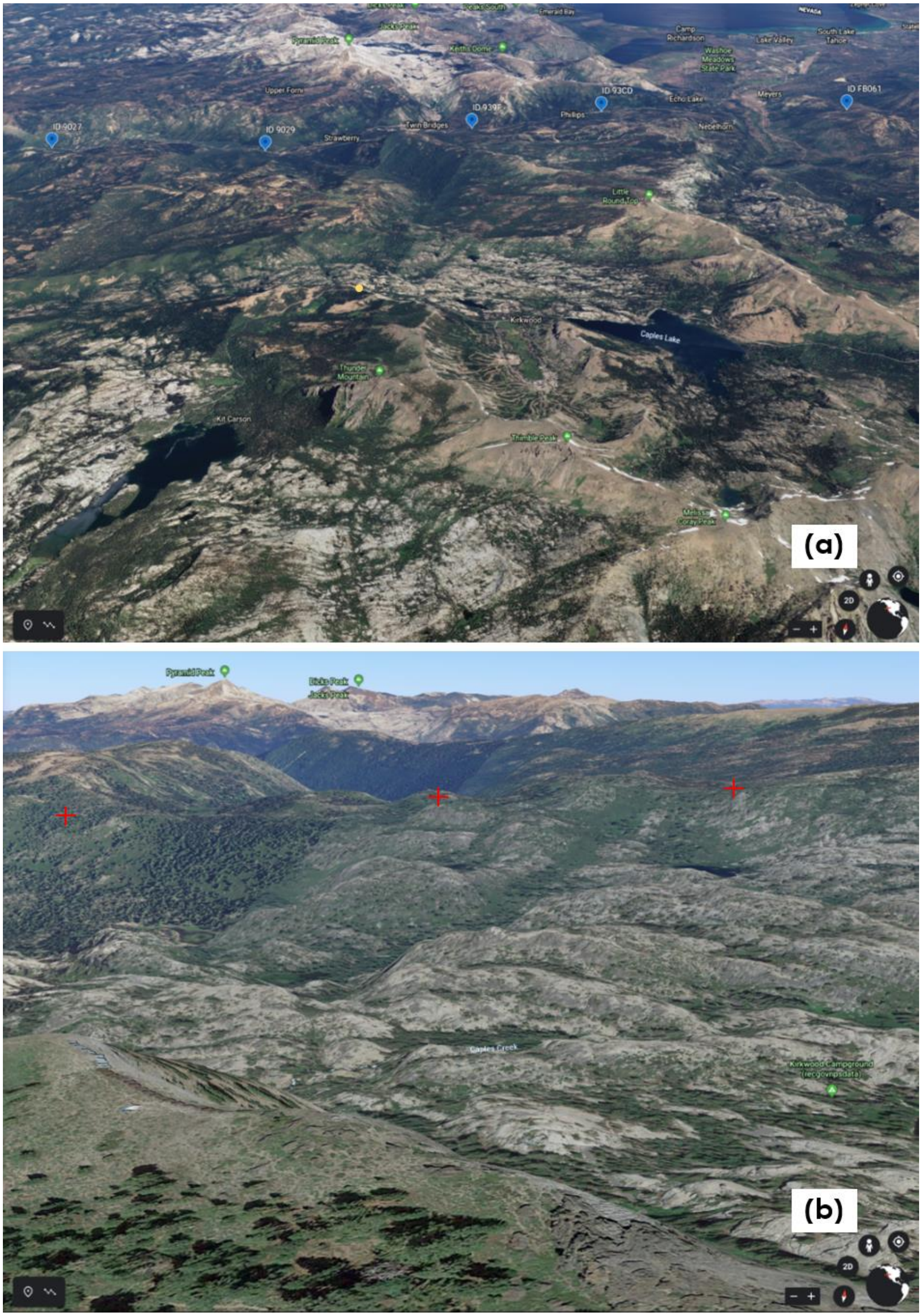

Figure E.5: SR88 3D map with select cellular tower and example site approximate locations near the Carson Spur (a) Verizon cellular tower and site locations, (b) view towards the cellular towers from the site (images courtesy Google Earth)

Figure E.5(a) shows several Verizon cell tower locations on US50 north of SR88 in the Caples Lake area. The Carson Spur site location is represented by a yellow marker. There are significant mountain ranges between the available cellular infrastructure and SR88.

Figure E.5(b) shows the northward view from the Carson Spur towards the Verizon cell tower locations on US50, which are completely obscured by the mountain ranges between SR88 and US50. The red plus markers represent the approximate LOS of the cellular towers from the Site, which are clearly blocked by local terrain. Recalling Figure E.3, with respect to this view, even though there are no LOS cellular towers, a small amount of the SR88 roadway near the Carson Spur is covered due to multipath signal between the various mountain faces.

E.2 ATT Measurements

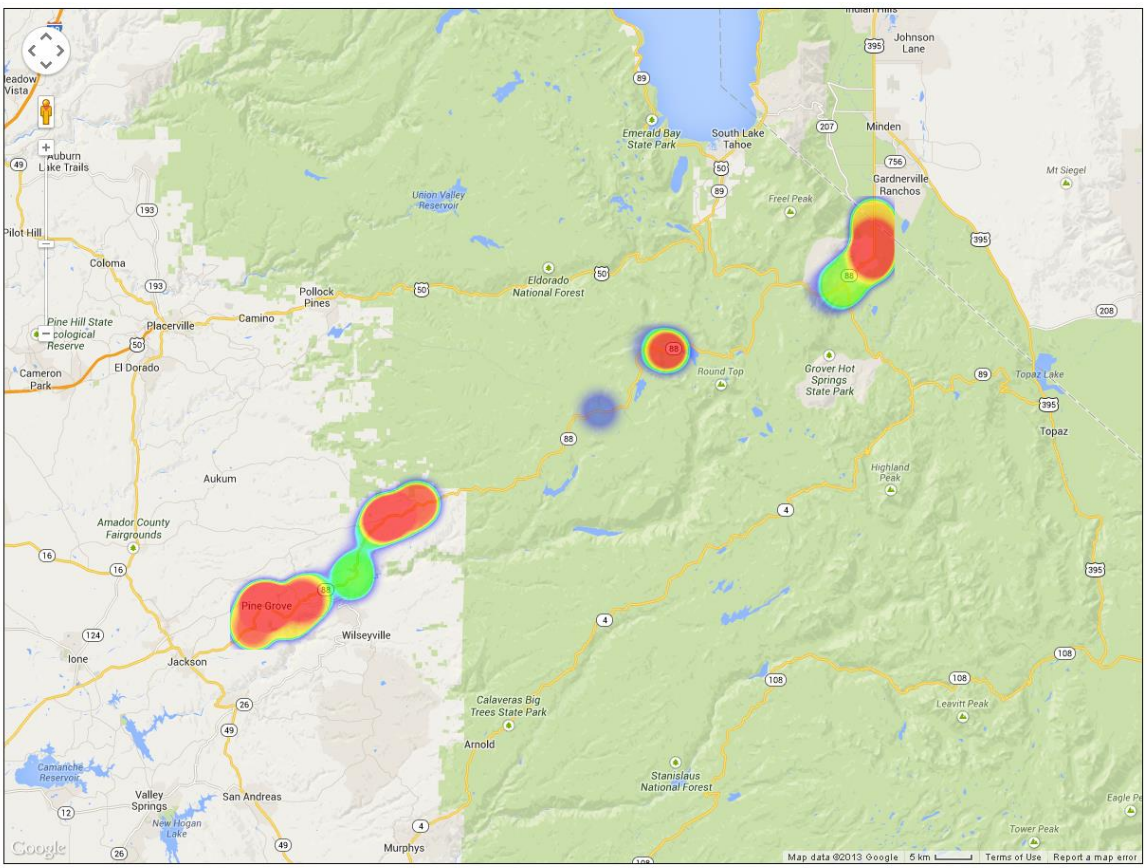

Figure E.6: SR88 ATT cellular service availability measurements (courtesy of AHMCT Research Center)

Figure E.6 shows the ATT cellular service availability measurements along SR88. Clearly there is significantly less cellular coverage than in Figure E.1, which illustrates the Verizon cellular service availability measurements.

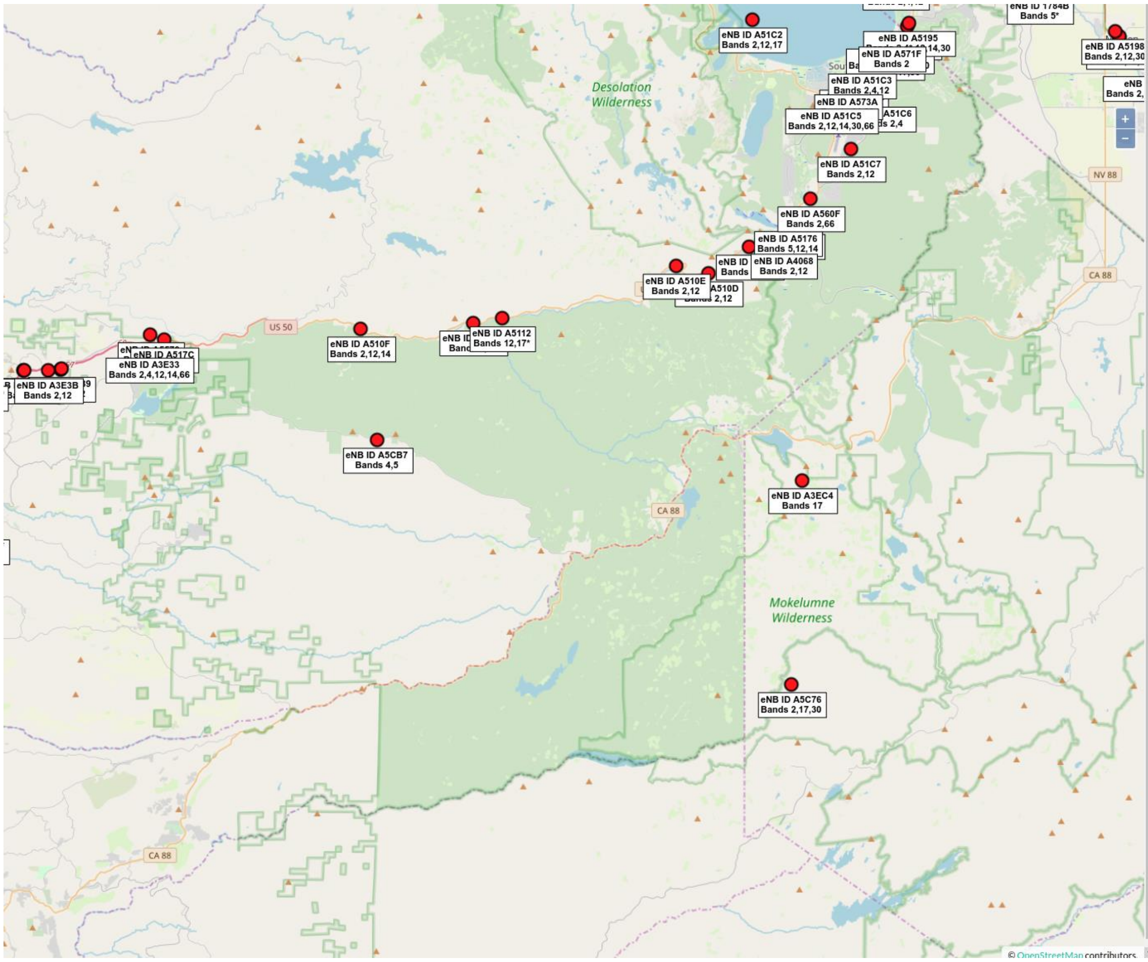

Figure E.7: SR88 ATT cellular tower approximate locations (courtesy of Cell Mapper)

Figure E.7 shows the current ATT cellular towers primarily located on US50 with respect to the Caples Lake area. Note the tower density and location differences with respect to those of Verizon in Figure E.4. The density and number of towers located on US50 north of Caples Lake is lower. Combined with the alternate multipath signal propagation, this results in significantly less coverage of the area.

E.3 T-Mobile Measurements

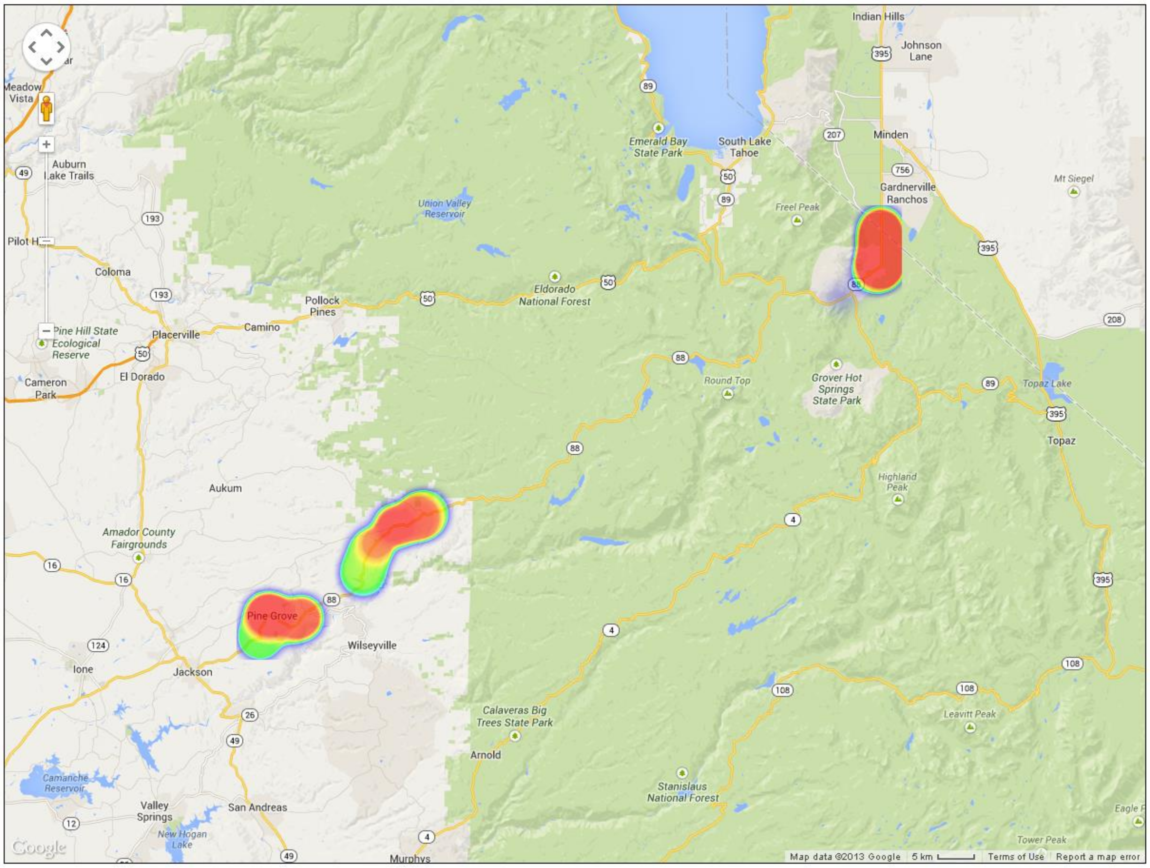

Figure E.8: SR88 T-Mobile cellular service availability measurements (courtesy of AHMCT Research Center)

Figure E.8 shows the T-Mobile cellular service availability measurements along SR88. Cellular coverage is significantly lower than that of Figure E.1 representing the Verizon cellular service availability measurements.

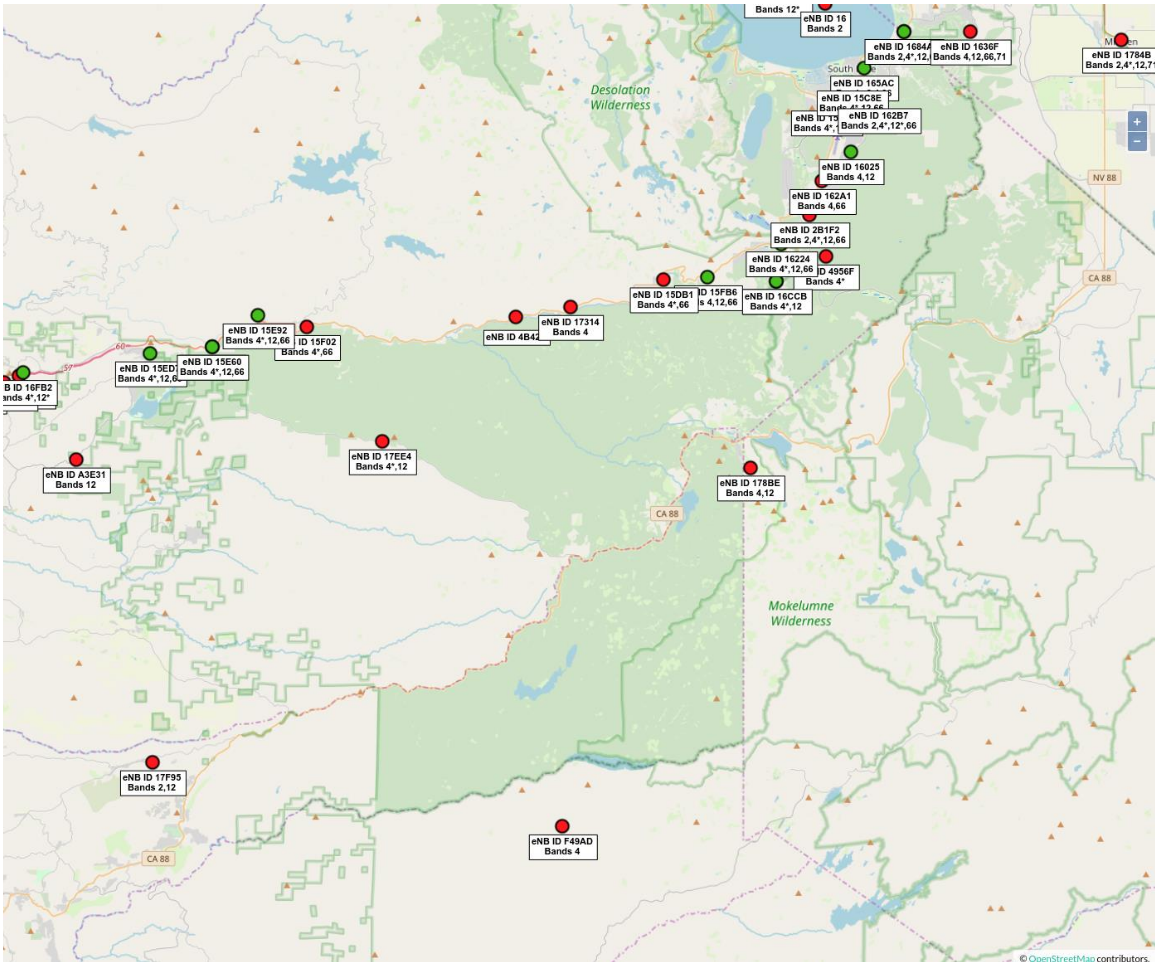

Figure E.9: T-Mobile cellular tower approximate locations (courtesy of Cell Mapper)

Figure E.9 shows the current T-Mobile cellular towers primarily located on US50, with the exception of one tower located at the Kirkwood ski resort, with respect to the Caples Lake area. Note the tower density and location differences with respect to Verizon in Figure D.4. The density and number of towers located on US50 north of Caples Lake is lower, and due to the alternate multipath signal propagation results in significantly less coverage of the area. Interestingly, the cell tower located at Kirkwood does not appreciably add to the cellular coverage along the Carson Spur. It is important to note that the Kirkwood ski resort is surrounded by mountains on three sides, and thus does not represent a direct LOS path to the Spur.

Appendix F Policies and Constraints

F.1 Operational policies and constraints

The research and development of the UAS will be conducted on UC property following all Federal, United States, State, Local, and University regulations and policies related to the operation of an UAS. Notable operational regulations and policies are summarized in the following subsections.

F.1.1 Federal

The major roles of federal UAS regulations are safety regulations, airspace and air traffic management, air navigation facilities, aircraft certification, and airman certification.

F.1.1.1 Operational

Federal UAS operational regulations include:

- Small UA must weigh less than 55 lb including payload according to §107.3 of [7]
- Accidents must be reported to the FAA no later than 10 calendar days in the event of serious injury or loss of consciousness to any person, or damage to any property, other than the small UA, exceeding $500 according to §107.9 of [7]
- Pilot must have a remote pilot certificate with a UAS rating according to §107.12, and §107.63 of [7]
- RPIC must be designated before flight, is the final authority on operation, and must ensure that the small UA will pose no undue hazard to other people, aircraft, or property in the event of loss of control according to §107.19 of [7]
- No hazardous operation of the small UA in a careless or reckless manner which would endanger life or property according to §107.23 of [7]
- No person may operate a small UA from a moving air/land/water vehicle unless flown over a sparsely populated area according to §107.25 of [7]
- No person may operate the small UA or act as a visual observer if they have an interfering medical condition or are under the influence of alcohol or drugs according to §107.17, §107.27, and §107.59 of [7]

- Small UA must be operated during daylight hours, or during civil twilight with anti-collision lighting according to §107.29 of [7]
- The small UA must remain within VLOS of the RPIC or VO at all times unaided by any device other than corrective lenses according to §107.31 of [7]
- A VO may be used to communicate and coordinate with the RPIC, scan the airspace for any potential collision hazard, and maintain awareness of the position of the small UA according to §107.33 of [7]
- A person may not operate or function as a VO for more than one UA at the same time according to §107.35 of [7]
- Small UA may not carry hazardous material according to §107.36 of [7]
- Small UA must yield right of way to other aircraft according to §107.37 of [7]
- Small UA may not operate over any persons not directly participating in the operation who are not under a covered structure or inside a stationary vehicle according to §107.39 of [7]
- The RPIC of the small UA may not operate in Class B, C, D or E airspace unless that person has prior authorization from the ATC according to §107.41 and §107.43 of [7]
- Small UA may not be operated in prohibited or restricted areas unless permission has been obtained from the controlling agency according to §107.45 of [7]
- The RPIC must conduct a pre-flight inspection of the small UA including control communications and payloads. Additionally, operating environment including weather conditions, airspace and flight restrictions, location of persons and property, and other ground hazards must be assessed according to §107.49 of [7].
- Small UA must be operated with a maximum ground speed of 100 mph, at a maximum of 400 ft AGL, or if above 400 ft AGL remain within 400 ft of a structure. The minimum weather visibility from the control station must be at least 3 mi according to §107.51 of [7].
- Waivers of §107.25, §107.29, §107.31, §107.33, §107.35, §107.37, §107.39, §107.41, and §107.51 of [7] may be issued if the applicant demonstrates that operation can safely be conducted under the terms of a certificate of waiver according to §107.200 and §107.205 of [7]

F.1.1.2 Registration

Federal UAS registration regulations include:

- The RPIC must ensure that the small UA complies with the existing registration requirements according to §107.13 of [7]
- The RPIC must have a Certificate of Aircraft Registration according to §91.203(a)(2) of [7]
- The FAA will issue a Certificate of Aircraft Registration for a small UA upon completion of the application requirements which must be submitted online according to §107.100 of [7]
- Registration of UAS may be done online at the FAADroneZone [13]
- The registered UAS must be properly marked with a unique identifier that is either the registration number or if authorized by the Administrator the small UA serial number according to §48.200 and §48.205 of [7]

F.1.2 California

California UAS regulations in addition to federal regulations include:

- California Penal Code §402(a)(2) may not fly a UAS over the scene of an emergency

F.1.3 University of California

F.1.3.1 Registration

UC UAS registration policies in addition to federal and state regulations include:

- UC-owned UAS must be registered to the Regents of the University of California. The Regents of the University of California are the legal owners of all UC property. Similar to BFB-BUS-19: Registration and Licensing of University-Owned Vehicles, all UC-owned UA must be registered to the Regents of the University of California to meet compliance obligations under §48 of [5].
- Register your University UAS with the FAA at the FAADroneZone and with the UC using the UC Drone Web App [14]

F.1.3.2 UAS activity

UC UAS activity policies in addition to federal and state regulations include:

- Approvals for UAS activity may be granted in many forms according to §5.1 of [15]
    - Single or set of UAS flights during a specific time-window
    - Set of UAS flights over a defined period of time

  - Scheduled recurrent UAS flights at a defined location
  - Unscheduled UAS usage at a series of predefined locations
  - Standing approvals
- All UAS activity is recorded in the UC Drone Web App according to §11.1 of [10]
- Submission of a UAS request form is conducted through the UC Drone Web App
- The System-wide Designated UAS Authority and/or a Designated Local Authority associated with the local campus will review the UAS activity request
- The criteria used to evaluate UAS activity, at a minimum, includes:
  - Review of compliance with applicable regulations according to §5.4.1 of [10]
  - Review of impacts to safety according to §5.4.3 of [10]
  - Review of impacts to privacy, civil rights, and liberties according to §5.4.4 of [10]
  - Review of insurance according to §5.4.5 of [10]
- The UAS Authority will either approve or disapprove the request
- When near airports, you must get permission from air traffic control to fly in controlled airspace. The FAA can grant permission either through Low Altitude Authorization and Notification Capability (LAANC) [15] or DroneZone [13].
- UAS activity reporting is conducted through the UC Drone Web App
- UAS activity accomplished by a 3rd party must be tracked and monitored according to §6.5 of [10]
- Accident reporting according to §7 of [10], and §107.9 of [7]

F.1.3.3 UAS insurance

UC UAS insurance policies include:

- The UC provides automatic coverage for UAS activity for UC-owned UAS according to §8.1 of [10], and [16]
- All 3rd-party UAS activity must submit appropriate insurance, including a written agreement which indemnifies and holds the University harmless from any resulting claims or harm to individuals and damage to University property according to §5.4.5 of [10], and [16]

- All 3rd-party UAS activity must have liability insurance with a preferred limit of $5 million according to §8.4 of [10], and [16]
- Any UAS activity that is not approved by a Designated Local Authority or System-wide Designated UAS Authority is not covered by this liability insurance coverage according to §8.1 of [10], and [16]

F.1.3.4 Waivers

UC UAS waivers of federal regulations include:

- The UC has a system-wide Certificate of Waiver for Title 14 of the Code of Federal Regulations §107.29 of [7] Daylight Operations Waiver Number: 107W-2018-11555. UC personnel are eligible to utilize the system-wide authorization for University Business, including research according to §10.7.1 of [10].
- The System-wide Designated UAS Authority is available to assist in the filing of FAA required authorizations according to §11.2 of [8]

F.1.4 California Department of Transportation

Caltrans requirements regarding UAS operations are summarized below for the purposes of Caltrans employees conducting operations within the state highway system.

- Shall follow all federal, state, local, and Caltrans regulations and policies related to the operation of a UAS
- Shall not operate UAS outside State right of way without securing permission to enter according to §6.1 of [14]
- Shall not operate UAS over a roadway, shoulder, bike lane, or sidewalk, unless a closure is in effect according to §6.1 of [14]
- Remote Pilot according to §3.2.1 of [14]
    - Obtain required approvals before operating a UAS
    - Caltrans employees must obtain approval from their Supervisor
    - Construction contractors must obtain approval from the Resident Engineer
    - Other Caltrans consultants or contractors must obtain approval from their task order or contract manager
    - Authorized encroachment permittee must obtain approval from the Caltrans encroachment permit representative

    - Operate UAS in compliance with Federal and State statutes and regulations, the Caltrans UAS Operations Handbook [8], Caltrans policies and procedures, and Deputy Directive DD-118
    - Ensure a UAS is properly registered with the FAA
    - Possess a valid Remote Pilot Certificate issued by the FAA to operate a UAS
    - Complete FAA appropriate recurrent training in a timely manner
    - Inspect UAS prior to flight, in accordance with UAS manufacturer recommendations and Caltrans UAS Operations Handbook [8]
    - Oversee scheduled maintenance of the UAS per manufacturer instructions
    - Complete a Caltrans UAS Operation Data (Form UAS-0052, Pre-flight and Post-flight)
    - Complete a Caltrans UAS Hazard Analysis (Form UAS-0054) when required, as specified in Caltrans UAS Operations Handbook [8]
    - Assign UAS Flight Crew duties
    - Operate the UAS in a safe and effective manner
    - Terminate UAS operations due to unsafe or changing conditions
    - Ensure that any accidents or incidents are reported as required by Caltrans UAS Operations Handbook [8] and the FAA
    - Participate and cooperate in investigations resulting from a UAS accident or incident or when a complaint or misuse of a UAS is reported
    - Maintain and improve UAS-related operational knowledge, skills, and abilities
- UAS hazard analysis according to §7.1.3 of [14]
    - Awareness of controlled airspace including the use of aeronautical charts such as AirMap [15]
    - Evaluation of all potential civil or military aviation activities nearby, including small landing strips, heliports, or potential crop dusting activities in agricultural areas
    - Checks of Notices to Airmen (NOTAM) [18] and Temporary Flight Restrictions (TFR) [17]
    - Checks of forecasted weather conditions including anticipated wind speed

- Verification of minimum flight visibility of three statute miles before the flight
- Awareness of State right of way boundaries
- Awareness of nearby facilities, residences, roads, and structures
- Verification of no encroachment outside of State right of way without permission
- Assurance that there is no overflight of people or moving vehicles
- Protection of the UAS Flight Crew from live traffic or other job site hazards
- Notification of traffic control (closures) in effect for any overflight of roadways, shoulders, bike lanes, or sidewalks
- Designation of emergency landing area
- Identification of overhead obstructions including power lines, trees, buildings, and communication towers
- Assurance that the UAS Flight Crew size is sufficient to effectively conduct the operation

Caltrans requirements regarding UAS operations are summarized below for the purposes of Caltrans contractors conducting operations within the state highway system.

- UAS insurance is required for all UAS operations by UAS Service Providers/Construction Contractors/Non-Caltrans Entities or Individuals within the State Highway System and/or for Caltrans business. The minimum insurance required for UAS operation is $2 million for each person/occurrence for bodily injury and $2 million for property damage for each occurrence specifically covering UAS use. Districts or divisions may request additional and higher UAS insurance limits, coverages, or bonding on a case-by-case basis according to §9.4 of [14].

F.1.5 Research and development

Currently it is not clear which UAS activity approval and reporting system (UC or Caltrans) will cover all likely operational and reporting use cases. The UC requires that all employees of the UC follow UC UAS policies and make UAS activity requests and reports through the UC system. The UC requires that all 3rd parties follow UC policies and carry their own insurance meeting UC requirements. Caltrans requires that all employees of Caltrans follow Caltrans UAS policies and make UAS activity requests and reports through the Caltrans system. Caltrans requires that all 3rd parties follow Caltrans policies and carry their own insurance meeting Caltrans requirements. Interestingly, there are components of UC insurance that do not meet the Caltrans insurance requirements, and components of Caltrans insurance that do not meet the UC insurance requirements. Finally, while the UC regularly conducts research for Caltrans, it does not fall under Caltrans UAS policies.

Until more information is ascertained for research use cases, it is recommended that all operations on UC property are conducted by UC personnel, and all operations inside the SHS right of way are conducted by Caltrans personnel. Operations outside of either domain will be investigated further, and a resolution will be determined at the time.

The scope of this research project does not include any operation inside the SHS right of way.

Appendix G Glossary

Air Traffic Control - a service operated by appropriate authority to promote the safe, orderly, and expeditious flow of air traffic.

Beyond Visual Line of Sight (BVLOS) - a person is operating a UAS beyond the definition of Visual Line of Sight (VLOS).

Control Station - an interface used by the remote pilot to control the flight path of a small unmanned aircraft.

Corrective Lenses - spectacles or contact lenses.

Federal Aviation Administration - a division of the US Department of Transportation that inspects and rates civilian aircraft and pilots, enforces the rules of air safety, and installs and maintains air navigation and traffic-control facilities.

National Airspace System (NAS) - the common network of U.S. airspace, including all navigable airspace from the ground up, excluding regions under military jurisdiction. The NAS additionally does not include inside buildings or enclosed structures.

Regents of the University of California - as defined by Section 9, Title IX of the Constitution of the State of California, the Regents of the University of California is the governing board of the UC system.

Remote Pilot Certificate - a certificate issued by the FAA that certifies that the owner of the certificate has sufficient aerospace knowledge to operate a UA within the NAS.

Remote Pilot in Command - the person who has the final authority and responsibility for the operation and safety of an UAS operation. This may or may not be the person operating the UA. A person may manipulate the controls of a UA under the direct and immediate supervision of an RPIC.

Right of Way - easement granted or reserved over the land for transportation purposes, such as a highway or freeway

Small Unmanned Aircraft - an unmanned aircraft weighing less than 55 lb on takeoff, including everything that is on board or otherwise attached to the aircraft.

Small Unmanned Aircraft System - a small unmanned aircraft and the associated elements (including communication links and the components that control the small unmanned aircraft) required for the safe and efficient operation of the small unmanned aircraft in the NAS.

System-wide Designated UAS Authority - provides expertise, support, and training for regulatory compliance, risk management, and the safe operation of UAS across the University of California system. It also grants certain forms of approval for UAS operations in the US.

UAS Activity - the act of flying, may represent a single flight or a set of flights.

University Business - the official activities of the University that contribute to any one of the University's major functions of teaching, research, patient care, or public service, or to any other non-recreational University purpose.

University Location - any property or building that is owned or leased by the University where University business or University activities take place.

Unmanned Aircraft - an aircraft operated without the possibility of direct human intervention from within or on the aircraft.

Visual Line of Sight - a person is able to 1) know the UA's location, 2) determine the UA's attitude, altitude and direction of flight, 3) observe the airspace for other air traffic or hazards, and 4) determine that the UA does not endanger the life or property of another.

Visual Observer - a person designated by the remote pilot in command to assist the remote pilot in command and the person manipulating the flight controls of the small UAS to see and avoid other air traffic or objects aloft or on the ground.

Appendix B: Interim Report Summarizing Literature and Product Search

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document provides the Literature and Product Search.

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Unmanned Aerial Systems Communications Repeater (UASC-R) Literature and Product Search

Stephen M. Donecker &
Ty A. Lasky: Principal Investigator

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February 2, 2022

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
3D	Three-dimensional
ADS-B	Automatic Dependent Surveillance Broadcast
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
Caltrans	California Department of Transportation
DAA	Detect and Avoid
DOT	Department of Transportation
FAA	Federal Aviation Administration
GPR	Ground-Penetrating Radar
IP	Ingress Protection
IPP	Integration Pilot Program
LiDAR	Light Detection and Ranging
Mini-PCIe	Mini Peripheral Component Interconnect Express
Radar	Radio Detection and Ranging
UAS	Unmanned Aircraft System
UTM	UAS Traffic Management
VTOL	Vertical Takeoff and Landing
WWAN	Wireless Wide Area Network

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1 Introduction

Communication options in rural districts within the California Department of Transportation (Caltrans) are intermittent and in some cases unavailable. The aim of this project is to extend the edge of existing cellular infrastructure service boundaries further into rural districts. We seek to accomplish this by employing an Unmanned Aerial System (UAS) with a communications payload developed to provide a cellular data service range extension via routing between a cellular modem Wireless Wide Area Network (WWAN) and a Wi-Fi base access point interface.

The purpose of this document is to provide a literature and product search related to the project scope. We began with a literature search of the various state Departments of Transportation (DOTs) to ascertain the level of adoption of UASs within department operations. Specifically, we sought to identify DOTs who have not only created a UAS policy/program, but who have begun to regularly use UAS for structure inspection, construction monitoring, traffic management, and/or incident management. We sought to find DOTs that employed UAS with advanced sensors and use cases, ideally ones related to wireless communications.

Following our investigation into existing DOT operations, we surveyed existing research related to ubiquitous cellular and Wi-Fi communications when used for aerial communications.

Finally, we surveyed product offerings over a wide range of capability and applicability to our project scope and offer a recommended category of products that will allow for development of a UAS communications repeater.

2 Literature Search

2.1 States and Departments of Transportation

In general, most states and DOTs use UAS for damage assessment, aerial reconnaissance, situational awareness, and live streaming during incidents. Some DOTs are participating in Federal Aviation Administration (FAA) programs, allowing advanced use cases (see Section 2.2).

2.1.1 Georgia

The Georgia DOT has used UAS to perform project documentation, emergency condition assessment, incident management, bridge inspection, traffic operation, and project documentation.[1] The DOT currently uses the DJI Phantom 4 Pro UAS for various operations across various districts and offices.

2.1.2 Kansas

The Kansas DOT has used UAS to perform bridge inspection, tower inspection, and perform disaster response. Kansas is part of the FAA UAS Integration Pilot Program (IPP) and the BEYOND program (see Section 2.2). They started with a focus on Beyond Visual Line of Sight (BVLOS) operations in rural communities.[2] They are seeking to leverage a statewide Unmanned Traffic Management (UTM) system to facilitate precision agriculture operations. The operations will focus on Detect and Avoid (DAA), Automatic Dependent Surveillance Broadcast (ADS-B) for national airspace surveillance, satellite communications, and geo-fencing. ADS-B is a surveillance technology that relies on broadcast, telemetry, and satellite navigation coordinates to ground stations and other aircraft for situational awareness. This is the new, preferred technology over existing Radio Detection and Ranging (radar)-based technologies. The areas of research focus are in precision agriculture and long-line linear infrastructure inspection.

The DOT performed the first FAA approved BVLOS flight without a requirement for visual observers or ground-based radar. The team flew a nine-mile strip to inspect power lines in rural areas. They partnered with Iris Automation to develop the necessary collision avoidance system for BVLOS (see Section 2.4.1).

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[1] GDOT Unmanned Aerial System Program Update (http://www.dot.ga.gov/AboutGeorgia/Board/Board%20Meeting%20Documents/UnmannedAerialSystemPolicyandUsage.pdf), State Transportation Board Intermodal Committee, Presented by Joanna Campbell, Asst. Div. Director, Division of Intermodal, June 19, 2019

[2] Operations | Kansas UAS IPP (https://www.ippkansas.org/operations)

2.1.3 Minnesota

The Minnesota DOT has used UAS to perform bridge inspections.[3] The DOT has continued, across multiple phases, to inspect 50 bridges of varying sizes and types using still, video, and infrared images. Inspection images were processed into three-dimensional (3D) models using Pix4D software. The current phase of the project is investigating collision-tolerant UAS during inspections.[4] These UAS will allow inspection of confined spaces.[5]

2.1.4 Montana

The Montana DOT has used UAS to conduct mapping, infrastructure inspection, construction monitoring, stockpile and earthwork volume measurements, rock fall site investigation, and vegetative health assessment.[6] Stockpile and earthwork volume measurements have been conducted using a DJI Phantom 4 Pro to fly over the area of interest at 60 m (200 ft) using the 12 MP camera allowing one pixel/in to collect the necessary images.[7] The images were post-processed with Pix4D and created a 2D orthomosaic map, a color-coded digital elevation map, and a 3D model. From the 3D model, a program can calculate the volume of a stockpile.

2.1.5 Nebraska

The Nevada DOT has used UAS to inspect bridge roadway surfaces for delamination on bridge decks, inspect bridge roadway surfaces for overlay failure, and developing an unmanned aircraft program.

In the research "Detecting, Quantifying and Mapping of Delamination of Bridge Decks using Aerial Thermography," a UAV-based aerial thermographic method to detect and map the delamination on concrete bridge decks was

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[3] Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS) (https://www.dot.state.mn.us/research/reports/2018/201826.pdf), Barritt Lovelace, Principal Investigator, Final Report 2018-26, July 2018

[4] Phase 3 of Drone Bridge Inspection Research Focuses on Confined Spaces (https://mntransportationresearch.org/2017/08/24/new-project-phase-3-of-drone-bridge-inspection-research-focuses-on-confined-spaces/), Crossroads, Minnesota's transportation research blog

[5] Elios-Inspect & Explore Indoor and Confined Spaces-Flyability (https://www.flyability.com/elios/)

[6] Montana DOT UAS applications (https://www.mdt.mt.gov/other/webdata/external/Research/DOCS/RESEARCH_PROJ/UAV/REF_MAT/uav.pdf)

[7] Unmanned Aerial Vehicle (UAV) Mapping Demonstration (https://www.mdt.mt.gov/other/webdata/external/Research/DOCS/RESEARCH_PROJ/UAV/REF_MAT/MAP_DEMO.pdf), Montana DOT

developed.[8] In this effort, a DJI Matrice 210 RTK Drone outfitted with a FLIR A8300sc camera system was mounted to the drone for data collection. The defect detection method is based on infrared thermographic technology for subsurface anomaly detection based on the temperature difference between solid and debonded areas. In general, the heat transfer rates between the delaminated areas and properly bound areas are different with the surface temperature of the debonded area being higher. Using computer vision image processing methods, various algorithms to predict delamination areas were developed and used to process the bridge deck survey data. Subsequently, core samples were made on the validation bridge decks to compare to the predicted delamination areas. During this process, some of the field test data results were fed back into the image processing algorithms to improve detection accuracy. This research resulted in an approximately 80% correct prediction rate using level-set and deep learning methods.

The "Field Demonstration of GPR and UAV Technologies for Evaluation of Two US 75/77 Bridges" research focused on two bridges with asphalt overlay.[9] A ground-penetrating radar (GPR) was used to perform non-destructive testing to the bridge deck sub-surface. A UAV was used to collect aerial images of the deck surface. The two sets of sensor data were fused together, analyzed using deep learning, and used to determine if UAV data alone is a suitable predictor of future roadway defects.

In general, the Nebraska DOT has developed an unmanned aircraft program.[10] Of specific note is the type of UAS that the department has relied on for current operations. They appear to be relying heavily on the DJI suite of equipment, specifically the DJI Matrice 210, Phantom 4, and Mavic 2.

2.1.6 New Jersey

The New Jersey DOT has used UAS for structural inspections, construction project monitoring, traffic incident management, aerial 3D corridor mapping, emergency response assessments, and traffic congestion assessments.

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[8] To Automate Detecting, Quantifying and Mapping of Delamination via Aerial Thermography (https://dot.nebraska.gov/media/114485/m109-aerial-thermographic-nde-final-report-1-12-21.pdf), Zhigang Shen, Chongsheng Cheng, Ri Na, Zhexiong Shang, December 31, 2020

[9] Field Demonstration of GPR and UAV Technologies for Evaluation of Two US 75/77 Bridges (https://dot.nebraska.gov/media/115469/fy21-012-final-report-0714-1.pdf), Sepehr Pashoutani, Jinying Zhu, Chungwook Sim, Brendan Barnes, Department of Civil Engineering, University of Nebraska-Lincoln, July 2021

[10] Research and Education for Optimizing the Development and Implementation of an Unmanned Aircraft Program at the Nebraska Department of Transportation (https://dot.nebraska.gov/media/115060/m117-final-report-v3.pdf), Wayne Woldt, Jon Starr and Christopher Neale, NU-AIRE Laboratory, University of Nebraska-Lincoln, May 2021

2.1.7 North Carolina

The North Carolina DOT has used UAS to perform wetlands mapping, submerged aquatic vegetation monitoring, bridge inspections, endangered and threatened species monitoring, erosion control, monitoring, landslide modeling, traffic accident scene capture/modeling, earthworks modelling and measuring, wildflower site planning, construction site monitoring, hurricane damage assessments, and sign inspections.[11] The two primary uses of UAS in the DOT are focusing on bridge structures management and earthworks locations and surveys.

North Carolina is part of the FAA UAS IPP (see Section 2.2). They have participated in local UAS package delivery within rural, suburban, and urban areas throughout the state. They focused on medical package delivery, food delivery, and transportation infrastructure inspection. Under the IPP, the team conducted a total of 12,792 flights, working with industry partners Matternet, UPS, Flight Forward, Zipline, Volansi, and Flytrex at healthcare facilities and neighborhoods throughout the state. The delivery of medical packages accounted for 94% of all flights.

The state has continued to participate in the BEYOND program as well (see Section 2.2). Of primary interest in the DOT is operations over people, and BVLOS related to conducting infrastructure inspection (i.e., bridge structures), and mapping (i.e., earthworks).

The DOT also uses UAS for collision investigations and reconstructions.[12] The obvious benefit is that large incidents can be documented in less than 30 minutes, allowing roadways to be cleared and opened more quickly over existing procedures. In this research effort, the DOT aviation team mapped the scene using three different UAS, the DJI Phantom 4 Pro, Mavic Pro, and Inspire 2. The collected imagery was processed using photogrammetry software, Agisoft PhotoScan, to complete a 3D map. Following aerial mapping of the crash scene, a FARO Focus3D X330 laser scanner was used to collect detailed data and then compared to the image mapping. The research showed that using UAS for collision scene reconstruction provides comparable accuracy with a 344% reduction in on-site data collection time.

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11 Innovative Work in the UAS Space (https://www.ncdot.gov/about-us/board-offices/boards/board-transportation/Documents/MM_Innovative_Work_In_the_UAS_Space.pdf#search=uas), Ben Spain, UAS Program Manager, Division of Aviation, North Carolina DOT, January 6, 2021

12 Collision Scene Reconstruction & Investigation using Unmanned Aircraft Systems (https://www.ncdot.gov/divisions/aviation/Documents/ncshp-uas-mapping-study.pdf#search=uas), Division of Aviation, UAS Program Office, North Carolina DOT, August 2017

2.1.8 North Dakota

The North Dakota DOT has used UAS to conduct surveys for the design and construction of highways and bridges, asset management, and natural disasters. They have recently selected GeoCue technology for their UAS program. Specifically they are using a GeoCue True View 640 3D Imaging System.[13] The sensor is a survey-grade Light Detection and Ranging (LiDAR) image sensor that creates 3D colorized LiDAR point clouds.

North Dakota is a partner of the FAA UAS IPP (see Section 2.2). During this program, they focused on package delivery, law enforcement support, infrastructure inspections, disaster damage assessments, and agricultural applications. The state has continued to participate in the BEYOND program as well (see Section 2.2). They focused on expanding UAS operations at night and BVLOS in multiple types of airspace, such as linear infrastructure inspection, cargo delivery and public safety.

2.1.9 Ohio

The Ohio DOT has used UAS for aerial photography, exterior/interior inspections, construction monitoring, traffic monitoring, natural disasters, emergency management, and structure inspections. In 2020, the Ohio DOT logged 2,009 flights over 552 projects.[14] It is interesting to note that the DOT is using UAS traffic monitoring of multiple intersections at once to optimize traffic signals. They also monitor special event traffic and adjust traffic controls accordingly.

The Ohio UAS Center aircraft fleet currently includes:

- Eight – DJI Phantom 4 RTK
- Four – Skydio 2
- Three – DJI Matrice 210 v1 and v2
- Two – DJI Inspire 2
- One – DJI Phantom 4 Multispectral
- One – DJI Matrice 600

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[13] GeoCue True View 640 3D Imaging System (https://geocue.com/products/true-view-survey-grade-riegl-sensor/)

[14] UAS Center Briefing (https://www.dot.state.oh.us/Divisions/Planning/LocalPrograms/LTAP/Documents/UASC_LTAP_20210301_David.pdf), David Gallagher, Flight Operations Manager, Ohio UAS Center

2.1.10 Oregon

The Oregon DOT has used UAS for bridge and tower inspection, construction inspection, and emergency response. The DOT has conducted research into using UAS for structural inspection. A significant number of bridges and communication towers were inspected and documented using both visible and thermal imagery, and the efficacy and cost benefit was evaluated.[15]

Oregon DOT is currently exploring additional structural inspection opportunities, including delamination of bridge decks using thermal imaging, mapping, and improved documentation. For construction inspection, they are exploring opportunities to use UAS for estimates and bidding, progress documentation, stockpiles and quantities, and surveying and site analysis. During incident management, they are looking to enhance efficient and detailed site investigations, replace manual sketching, and expedite evidence recording.

An investigation was conducted into using a UAS with Structure from Motion sensing as a cost-effective, suitable alternative to an expensive survey grade LiDAR-based UAS.[16] The difference in price between the two systems is substantial. Both systems performed similarly over bare earth, but the LiDAR-based system excelled over asphalt.

2.1.11 Utah

The Utah DOT has used UAS for aerial photography, photogrammetry, bridge inspections, geotechnical field investigations, LiDAR applications, public outreach, mapping construction sites and conditions, asset management, asset inspections, traffic monitoring, incident management, disaster response, and training exercises.

In a recent roadway project, the DOT used a UAS to create a 3D model as a contractual document.[17] During the project, the UAS was used to supplement the LiDAR work, creating a hybrid model used to check construction work.

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[15] Eyes in The Sky: Bridge Inspections with Unmanned Aerial Vehicles (https://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR787_Eyes_in_the_Sky.pdf) , Daniel T. Gillins, Christopher Parrish, Matthew N. Gillins, Chase Simpson, Final Report, SPR 787, Oregon State University, February 2018

[16] A Comparison of Drone-Based SfM and Drone-Based Lidar for Dense Topographic Mapping Applications (https://www.oregon.gov/odot/ETA/Documents_Geometronics/UAS2-3-Comparison-of-Drone-Based-SfM-Lidar-Simpson.pdf), Chase Simpson, Instructor of Geomatics, Oregon State University

[17] Innovation of the Month: Unmanned Aerial Systems (https://www.fhwa.dot.gov/innovation/everydaycounts/edcnews/20200423.cfm), EDC Weekly News, FHWA Center for Accelerating Innovation, April 23, 2020

Throughout the project, the UAS were used for topographical mapping, determining the earthwork quantities, and monitoring construction progress. Following completion of the project, they used the hybrid models as the final 3D as-built. The DOT is currently seeking approval for a high-end survey-grade LiDAR-based UAS.

2.1.12 Washington

The Washington DOT has used UAS for construction documentation, structure inspection, litigation, and emergency operations. They have evaluated UAS applications in aerial roadway surveillance and avalanche control.

2.2 Federal

The UAS IPP sought to bring state and local governments together with private sector participants to evaluate the integration of civil and public drone operations into our national airspace system.[18] Of key importance was identifying ways to balance local and national interests related to drone integration, improving communications with various jurisdictions, addressing security and privacy risks, and acceleration the approval of operations that require special authorizations. Lead participants include the Kansas DOT, the North Carolina DOT, and the North Dakota DOT.

The program began in 2017 and concluded October 25, 2020. To continue work on the remaining challenges of UAS integration, the FAA is now focusing on the remaining challenges of UAS integration into our national airspace through a new program called BEYOND.[19] A primary goal of this continued effort is BVLOS operations that are repeatable, scalable, and economically viable with emphasis on infrastructure inspection, public operations, and small package delivery. This program started October 26, 2020 and includes IPP participants.

The FAA has also developed a UAS test site program.[20] The participants of the program include airports and universities within Alaska, Nevada, New Mexico, New York, North Dakota, Texas, and Virginia. The purpose of the program is to verify the safety of public and civil UAS operations and related navigation procedures before their integration into the national air space. The UAS test sites are focusing their research and demonstration operations on the following areas:

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[18] FAA UAS Integration Pilot Program (https://www.faa.gov/uas/programs_partnerships/completed/integration_pilot_program/)

[19] FAA BEYOND Program (https://www.faa.gov/uas/programs_partnerships/beyond/)

[20] UAS Test Site Program (https://www.faa.gov/uas/programs_partnerships/test_sites/)

- DAA
- Command and Control (C2)
- Airworthiness
- BVLOS operations
- Standards for the safe operation of UAS in various airspace classes
- Air traffic control operational and communications procedures
- Multiple UAS operations
- Counter UAS
- UTM
- Test and evaluation of proposed UAS standards, processes and procedures
- Environmental impacts
- Urban Air Mobility

This program began in 2014 and is scheduled to continue until September 30, 2023.

2.3 Publications

The purpose of these references is to bring to attention some of the constraints that may arise when developing and deploying UAV-based communication systems and operating procedures. These references are more technical in nature, and not all sections of each are directly related to our specific initial use case. However, key pieces are germane to the development and operational use cases applicable for this effort. Key highlights are summarized for each.

Uplink Cooperative NOMA for Cellular-Connected UAV (https://www.researchgate.net/publication/331080929_Uplink_Cooperative_NOMA_for_Cellular-Connected_UAV)

Operation of cellular-connected UAV can cause significant interference to nearby cellular base stations. The interference mitigation is a challenging issue due to the strong line-of-sight air-to-ground communication channels due to the UAV antenna directivity. The UAV may impose severe uplink/downlink interference to/from the cellular base stations as compared to ground mobile users. This article discusses a network-coordinated non-orthogonal multiple access solution.

Flying UAVs without Affecting Terrestrial UEs (https://ece.northeastern.edu/wineslab/papers/BertizzoloHotmobile20.pdf)

This article discusses an alternative interference mitigation to nearby base stations and user equipment due to the strong line-of-sight air-to-ground communications between cellular-connected UAV and cellular base stations. Existing approaches to address UAV interference mainly focus on cooperative interference cancellation through base station coordination or cooperative non-orthogonal multiple access solutions. An interference mitigation solution using path planning and directional antenna is discussed.

An extensive survey on the Internet of Drones (https://www.sciencedirect.com/science/article/abs/pii/S1570870521001335?dgcid=rss_sd_all)

This article is a survey of several facets of the Internet of Drones including, but not limited to, communication channel modeling and characterization, non-line-of-sight communications using UAV, networks of UAV, relaying and routing, cooperative networks, path planning and position optimization, and Wi-Fi communications.

A Survey of Channel Modeling for UAV Communications (https://ieeexplore.ieee.org/document/8411465)

This article is an extensive survey of measurements and modeling of various communication channels typical in UAV communications. Of specific interest are the summaries and references to 802.11 wireless-based UAV measurements and cellular-connected UAV measurements. Relevant important issues included are airframe shadowing and diversity gain.

A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems (https://hal-centralesupelec.archives-ouvertes.fr/hal-02873979/document)

UAV wireless networks are discussed along with important challenges and tradeoffs. Key challenges include deployment, performance analysis, air-to-ground and air-to-air channel modeling, energy efficiency, and cellular-connected UAV.

2.4 Companies

The following companies have interesting options related to advanced capabilities that may apply to our targeted use cases. It is important to note that as the FAA has been loosening control, UAS development and deployment in an automated BVLOS fashion are moving at an accelerated rate, and as such, there is a myriad of large commercial operations and suppliers providing advanced technology that has been omitted due to the scope of this project.

2.4.1 Iris Automation

Iris Automation's primary product offering is the Casia Detect-and-Avoid, which allows for a UAS to achieve BVLOS.[21] They support nearly all industrial multirotor, fixed-wing, and vertical takeoff and landing (VTOL) UAS.

Their software solution is based on advanced machine learning and computer vision technology. They created the first commercial in-flight collision avoidance safety avionics for UAS. They provide two systems, the CASIA and the CASIA X. The CASSIA includes a single 8.9 MP sensor and associated hardware/software and provides a >1,200 m (3,900 ft) detection range. The CASSIA X includes 5 8.9 MP cameras for a full 360-degree view. Both systems include ADS-B. The machine vision classification can detect all known aircraft and estimate the distance by the real-world known size. If the system detects a potential conflict, it will automatically perform an evasive maneuver. The systems currently have a 95% detection capability from 1.2 km (3,900 ft) away.

Iris Automation Casia-equipped systems have received BVLOS approvals in five countries. They aid in the BVLOS approval process. The basic Casia single camera system is about $9,000.

Their primary supported use cases are utility and power line, pipeline inspection, railway inspection, precision agriculture, and package delivery.

[21] Onboard Detect-and-Avoid for Beyond Visual Line of Sight Drone Flight (https://www.irisonboard.com/), Iris Automation

3 Products

The product discussion in the following sections is not exhaustive but is representative of widely used UAS within state DOTs. It is the authors' opinion that the listed products will provide a good development platform for the scope of this project and will provide a platform for both future research needs as well as allow for robust UAS demonstration and use within Caltrans.

3.1 Aerial vehicles

The majority of existing DOT UAS fleets are based on the DJI Phantom series and the DJI Matrice 200 series. It is challenging to compare systems from different manufacturers, or even for a single manufacturer, as each system includes specifications not found in other data sheets. Here, we provide the common specifications for the three DJI systems considered, in a single table for each of aircraft (Table 3.1.1), vision system (Table 3.1.2), infrared sensing system (Table 3.1.3), remote controller (Table 3.1.4), charger (Table 3.1.5), and intelligent flight battery (Table 3.1.6). For completeness, we also provide the full specifications for the three systems, the DJI Phantom 4 Pro v2.0, the DJI Matrice 200 V2, and the DJI Matrice 300 RTK, in the appendix.

Table 3.1.1: Common aircraft specifications, with key specifications highlighted in orange

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Weight	1375 g	Approx. 4.69 kg (with two TB55 batteries)	Approx. 3.6 kg (without batteries) Approx. 6.3 kg (with two TB60 batteries)
Dimensions	N/A	Unfolded, propellers and landing gears included, 883×886×398 mm Folded, propellers and landing gears excluded, 722×247×242 mm	Unfolded, propellers excluded, 810×670×430 mm (L×W×H) Folded, propellers included, 430×420×430 mm (L×W×H)
Diagonal Wheelbase	350 mm	643 mm	895 mm

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Max Takeoff Weight	N/A	Approx. 4.69 kg (with two TB55 batteries)	9 kg
Max Payload	N/A	1.45 kg	0.93 kg
Operating Frequency	N/A	2.4000-2.4835 GHz; 5.725-5.850 GHz	2.4000-2.4835 GHz 5.725-5.850 GHz
EIRP	N/A	2.4 GHz: ≤ 26 dBm (NCC/FCC); ≤ 20 dBm (CE/MIC); ≤ 20 dBm (SRRC) 5.8 GHz: ≤ 26 dBm (NCC/FCC); ≤ 14 dBm (CE); ≤ 26 dBm (SRRC)	2.4000-2.4835 GHz: 29.5 dBm (FCC); 18.5dBm (CE) 18.5 dBm (SRRC); 18.5dBm (MIC) 5.725-5.850 GHz: 28.5 dBm (FCC); 12.5dBm (CE) 28.5 dBm (SRRC)
Hovering Accuracy	N/A	Vertical:±1.64 feet (±0.5 m) or ±0.33 feet (±0.1 m, Downward Vision System enabled) Horizontal:±4.92 feet (±1.5 m) or ±0.98 feet (±0.3 m, Downward Vision System enabled)	Vertical: ±0.1 m (Vision System enabled) ±0.5 m (GPS enabled) ±0.1 m (RTK enabled) Horizontal: ±0.3 m (Vision System enabled) ±1.5 m (GPS enabled) ±0.1 m (RTK enabled)
Max Angular Velocity	N/A	Pitch: 300°/s, Yaw: 120°/s	Pitch: 300°/s, Yaw: 100°/s
Max Pitch Angle	N/A	S-mode: 35°; P-mode: 30° (Forward Vision System enabled: 25°); A-mode: 30°	30° (P-mode, Forward Vision System enabled: 25°)

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Max Ascent Speed	S-mode: 6 m/s P-mode: 5 m/s	16.4 ft/s (5 m/s)	S mode: 6 m/s P mode : 5 m/s
Max Descent Speed	S-mode: 4 m/s P-mode: 3 m/s	9.8 ft/s (3 m/s)	S mode: 5 m/s P mode : 4 m/s
Max Speed	S-mode: 45 mph (72 kph) A-mode: 36 mph (58 kph) P-mode: 31 mph (50 kph)	S-mode/A-mode 81 kph (50.3 mph); P-mode: 61.2 kph (38 mph)	S mode: 23 m/s P mode : 17 m/s
Max Service Ceiling Above Sea Level	19685 ft (6000 m)	9842 feet (3000 m, with 1760S propellers)	5000 m (with 2110 propellers, takeoff weight ≤ 7 kg) / 7000 m (with 2195 propellers, takeoff weight ≤ 7 kg)
Max Wind Resistance	10 m/s	39.4 ft/s (12 m/s)	15 m/s (12 m/s when taking off or landing)
Max Flight Time	Approx. 30 minutes	38 min (no payload), 24 min (takeoff weight: 6.14 kg)	55 min
Supported DJI Gimbals	N/A	Zenmuse X4S/X5S/X7/XT/XT2/Z30	Zenmuse XT2/XT S/Z30/H20/H20T/DJI P1/DJI L1
Supported Gimbal Mount/Config	N/A	Single Gimbal, Downward	Single Downward Gimbal, Dual Downward Gimbals, Single Upward Gimbal, Upward and Downward

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
			Gimbals, Triple Gimbals
Ingress Protection Rating	N/A	IP43	IP45
Satellite Positioning Systems	GPS/GLONASS	GPS/GLONASS	GPS/GLONASS/ BeiDou/Galileo
Operating Temperatur e	32° to 104°F (0° to 40°C)	-4° to 122° F (-20° to 50° C)	-20°C to 50°C (-4°F to 122° F)

Table 3.1.2: Common vision system specifications

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Velocity Range	≤31 mph (50 kph) at 6.6 ft (2 m) above ground	<32.8 ft/s (10 m/s) at the height of 6.56 feet (2 m)	N/A
Altitude Range	0-33 ft (0-10 m)	<32.8 feet (10 m)	N/A
Operating Range	0-33 ft (0-10 m)	<32.8 feet (10 m)	N/A
Obstacle Sensing Range	2-98 ft (0.7-30 m)	N/A	Forward/Backward /Left/Right: 0.7-40m Upward/Downwar d: 0.6-30m
FOV	Forward: 60° (Horizontal), ±27° (Vertical) Backward: 60° (Horizontal), ±27° (Vertical) Downward: 70° (Front and Rear), 50° (Left and Right)	N/A	Forward/Backward /Downward: 65° (H), 50° (V) Left/Right/Upward: 75°(H), 60°(V)

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Operating Environment	Surface with clear pattern and adequate lighting (lux>15)	Surfaces with clear patterns and adequate lighting (> 15 lux)	Surfaces with clear patterns and adequate lighting (> 15 lux)

Table 3.1.3: Common infrared sensing system specifications

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Obstacle Sensory Range	0.6-23 feet (0.2-7 m)	0-16.4 feet (0-5 m)	0.1-8m
FOV	70° (Horizontal), ±10° (Vertical)	±5°	30° (±15°)
Operating Environment	Surface with diffuse reflection material, and reflectivity > 8% (such as wall, trees, humans, etc.)	Large, diffuse and reflective obstacles (reflectivity >10%)	Large, diffuse and reflective obstacles (reflectivity >10%)

Table 3.1.4: Common remote controller specifications

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Operating Frequency	2.400-2.483 GHz and 5.725-5.850 GHz	2.4000-2.4835 GHz; 5.725-5.850 GHz	2.4000-2.4835 GHz 5.725-5.850 GHz
Max Transmitting Distance	2.400-2.483 GHz, 5.725-5.850 GHz (Unobstructed, free of interference) FCC: 10000 m CE: 6000 m SRRC: 6000 m MIC: 6000 m	NCC/FCC: 5 mi (8 km); CE/MIC: 3.1 mi (5 km); SRRC: 3.1 mi (5 km)	NCC/FCC: 15 km CE/MIC: 8 km SRRC: 8 km
EIRP	2.400-2.483 GHz FCC: 26 dBm CE: 20 dBm SRRC: 20 dBm MIC: 17 dBm 5.725-	2.4 GHz: ≤ 26 dBm (NCC/FCC); ≤ 20 dBm (CE/MIC); ≤ 20 dBm (SRRC) 5.8	2.4000-2.4835 GHz: 29.5 dBm (FCC) 18.5dBm (CE) 18.5 dBm (SRRC);

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
	5.850 GHz FCC: 26 dBm CE: 14 dBm SRRC: 20 dBm	GHz: ≤ 26 dBm (NCC/FCC); ≤ 14 dBm (CE); ≤ 26 dBm (SRRC)	18.5dBm (MIC) 5.725-5.850 GHz: 28.5 dBm (FCC); 12.5dBm (CE) 20.5 dBm (SRRC)
Battery	6000 mAh LiPo 2S	N/A	Name: WB37 Intelligent Battery Capacity: 4920 mAh Voltage: 7.6V Type: LiPo Energy: 37.39Wh Charging time (using BS60 Intelligent Battery Station): 70 minutes (15°C to 45°C); 130 minutes (0°C to 15°C)
USB Power Supply	N/A	1 A⎓ 5.2 V (max)	5 V / 1.5 A
Operating Temperature	32° to 104°F (0° to 40°C)	-4° to 122° F (-20° to 50° C)	-20°C to 40°C (-4 °F to 104 °F)

Table 3.1.5: Common charger specifications

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Voltage	17.4 V	26.1 V	N/A
Rated Power	100 W	180 W	N/A

Table 3.1.6: Common intelligent flight battery specifications

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Capacity	5870 mAh	7660 mAh	5935 mAh
Voltage	15.2 V	22.8 V	52.8 V
Battery Type	LiPo 4S	LiPo 6S	LiPo 12S

	DJI Phantom Pro 4	DJI Matrice 200	DJI Matrice 300 RTK
Energy	89.2 Wh	174.6 Wh	274 Wh
Net Weight	468 g	Approx. 885 g	Approx. 1.35 kg
Operating Temperature	N/A	-4° to 122° F (-20° to 50° C)	-4°F to 122°F (-20°C to 50°C)
Charging Temperature	41° to 104°F (5° to 40°C)	41° to 104° F (5° to 40° C)	-4°F to 104°F (-20°C to 40°C) (When temperature is lower than 5°C, self-heating function will be automatically enabled. Charging in low temperature may shorten lifetime of battery)
Max Charging Power	160 W	180 W	N/A

The DJI Phantom 4 Pro v2.0, shown below in Figure 3.1.1, is primarily used for image and video collection without the ability to support additional payloads. The DJI Phantom 4 Pro V2.0 is priced at $1,600.

Figure 3.1.1: DJI Phantom 4 Pro (courtesy of DJI)

The DJI Matrice 200 V2, shown below in Figure 3.1.2, is a robust wide-temperature-range UAS used by many government agencies. The UAS supports multiple simultaneous payloads and adapter brackets for dual downward facing payloads or a single downward and a single upward payload. In our case, it might be advantageous to mount the camera above the UAS and the communications equipment below depending on hardware dimensions and antenna locations.

Figure 3.1.2: DJI Matrice 200 V2 (courtesy of DJI)

Note that the flight time is dependent on the payload weight. The payload capacity of the UAS is about 2 kg (4.4 lb). The DJI Matrice 210 V2 is priced at roughly $15,000 depending on camera choice and other options.

Another alternative UAS is the DJI Matrice 300 RTK shown below in Figure 3.1.3.

Figure 3.1.3: DJI Matrice 300 RTK (courtesy of DJI)

This UAS appears preferable over the Matrice 200 series, especially based on the flight time and improved environmental capabilities. However there are significantly more detailed specifications than listed in this section for each of the UAS as well as subsequent payload design considerations. The DJI Matrice 300 RTK is base priced at roughly $13,000 depending on selected camera and the cost of other additional features.

3.2 Payload

3.2.1 Communications

The primary backhaul communications link (WWAN) will be based on a 5g/4g cellular modem. Sierra Wireless provides many reliable options in the embedded m.2 form factor as seen in Figures 3.2.1.1 and 3.2.1.2. Depending on the embedded CPU board selection, the following cards are available in the Mini-Peripheral Component Interconnect Express (Mini-PCIe) form factor.

Figure 3.2.1.1: Sierra Wireless 4g EM Series m.2 module (courtesy of Sierra Wireless)

The EM7511 Cat-20 LTE-Advanced Pro Module provides up to 2 Gbps downlink and 211 Mbps uplink high speed connectivity with automatic 3G fallback. The module contains an integrated GNSS receiver as well.

- 4G LTE bands: B1, B2, B3, B4, B5, B7, B8, B9, B12, B13, B14, B18, B19, B20, B26, B29, B30, B32, B41, B42, B43, B46, B48, B66
- 3G bands: B1, B2, B3, B4, B5, B8, B9
- Data speed peak: download 2 Gbps, peak upload 211 Mbps
- Satellite: Galileo, GLONASS, GPS, Beidou
- System drivers: Linux
- Interfaces: USB 3.1, PCIe generation 3 (or 2), 1 lane
- Temperature range -30 C – 70 C (-22 F to 158 F)
- Carriers: ATT, Verizon, T-Mobile
- Embedded sim

Figure 3.2.1.2: Sierra Wireless 5g EM Series m.2 module (courtesy of Sierra Wireless)

The EM9191 5G Module provides up to 4.5 Gbps downlink and 660 Mbps uplink high-speed connectivity with automatic 4G and 3G fallback. The module contains an integrated GNSS receiver as well.

- 5G: n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n38, n40, n41, n48, n66, n71, n77, n78, n79
- 4G LTE: B1, B2, B3, B4, B5, B7, B8, B12, B13, B14, B18, B19, B20, B21, B25, B26, B28, B29, B30, B32, B34, B38, B39, B40, B41, B42, B43, B46, B48, B66, B71
- Peak download 4.5 Gbps
- Peak upload 660 Mbps
- Satellite: Galileo, GLONASS, GPS, Beidou
- System drivers: Linux
- Interfaces: USB 3.1, PCIe generation 3 (or 2), 1 lane
- Temperature range -30 C – 70 C (-22 F to 158 F)
- Carriers: ATT, Verizon, T-Mobile
- Embedded sim

The primary service communications link will likely be based on Wi-Fi 802.11ac(ax) technology. Several options exist in both the m.2 and Mini-PCIe form factors. Selection criteria will be based on the availability of a suitable single board computer based upon availability in small quantities, Linux support, network card driver support, and power output. Currently, several options exist based on form factor, features, and power output.

Single board computers from Gateworks are offered with card slots in mini-PCIe. An interesting option is shown below in Figures 3.2.1.3 and 3.2.1.4.

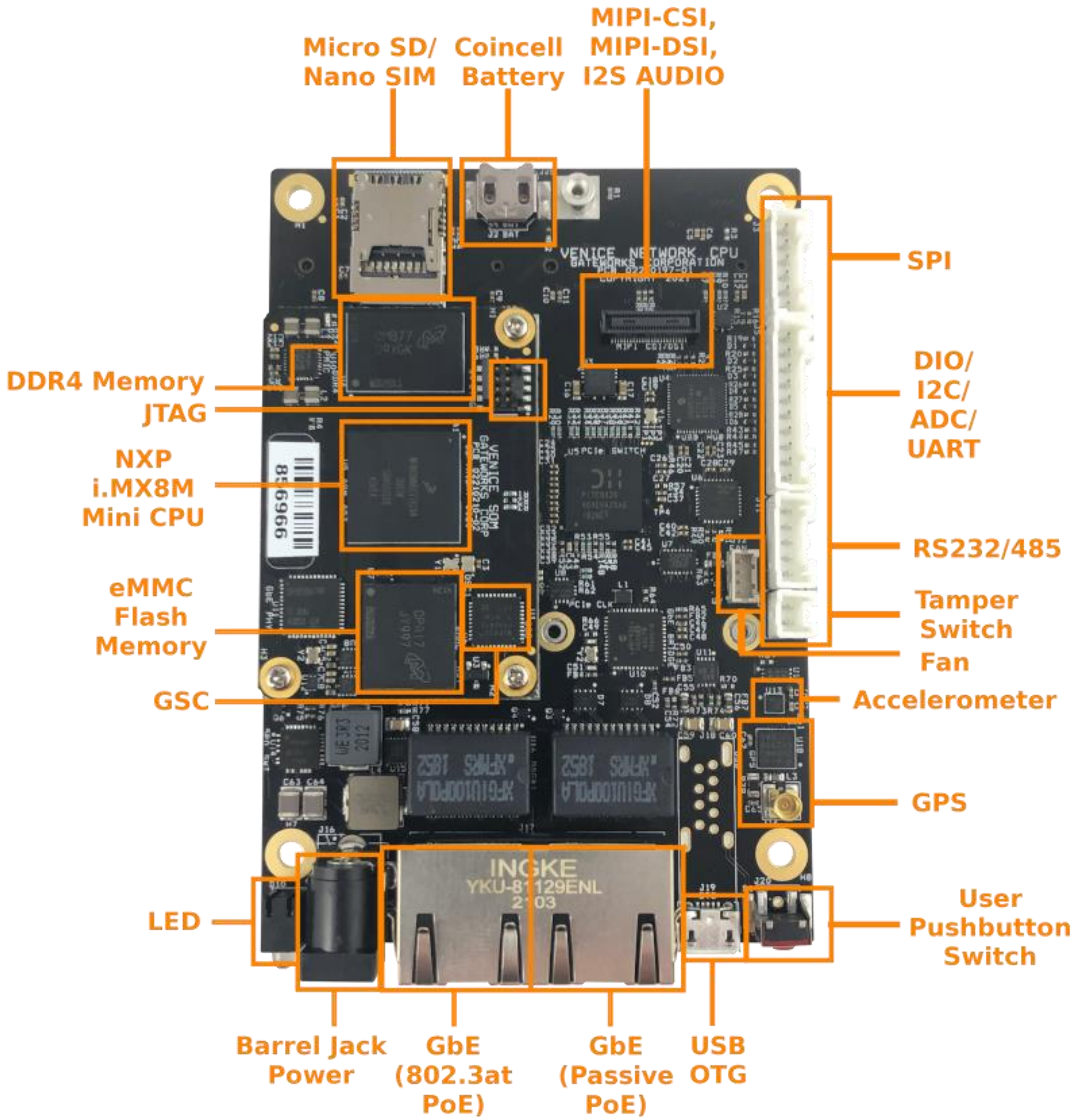

Figure 3.2.1.3: Gateworks Newport GW7200 Industrial Single Board Computer (courtesy Gateworks)

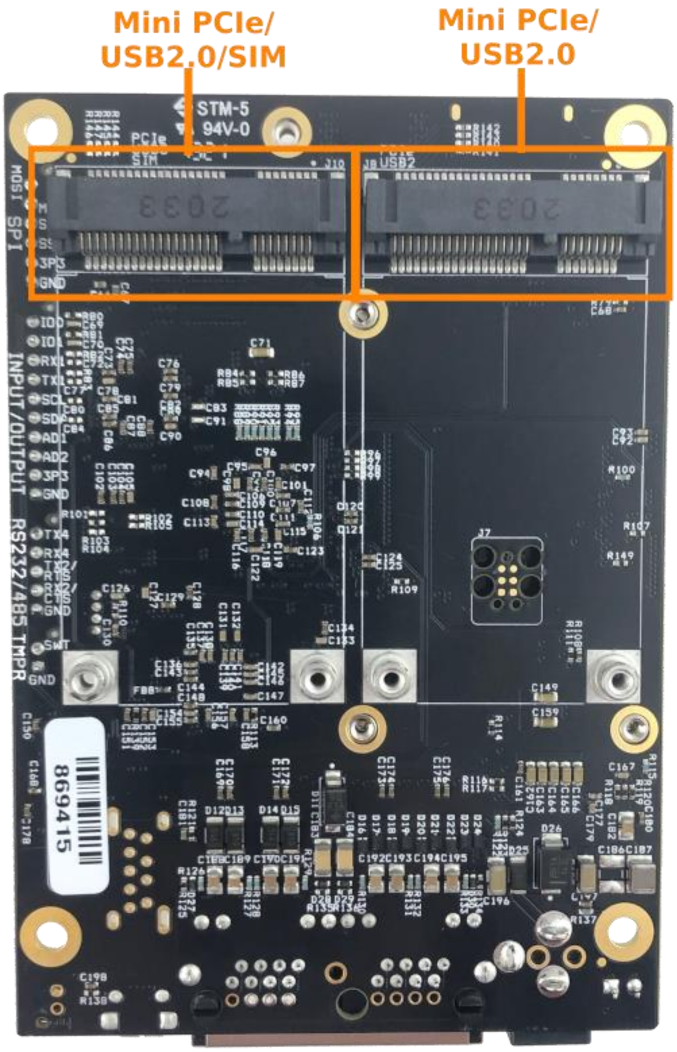

Figure 3.2.1.4: Gateworks Newport GW6903 Industrial Single Board Computer (courtesy Gateworks)

- Board size 70 x 100 mm (2.75 in to 4 in)
- Mini-PCIe slots 2
- i.MX8M Mini Quad Core CPU @ 1.6GHz
- Memory 4GB DDR4-2133

The selected single board computer will be configured to run Linux with the appropriate drivers for both the cellular modem and Wi-Fi cards. In the most simplistic case, the system will be configured so that the Wi-Fi will be configured as a hotspot for client connections and all data will be routed between the Wi-Fi and cellular modem interfaces.

The selected single board computer should be capable of handling routing and access point services as well as support a lightweight backhaul communications telemetry API for ground station status updates. Specifically, the ground user would want to know the currently available cellular base stations within range of the UAS and their associated telemetry.

3.2.2 Video

The DJI Zenmuse Z30, shown in Figure 3.2.2.1, is a lower-end camera that is compatible with both the Matrice 200 and 300 series UAS.

Figure 3.2.2.1: DJI Zenmuse Z30 camera (courtesy DJI)

- Weight 556 g (1.23 lb)
- 30X optical zoom
- 6X digital zoom
- Total magnification of 180X
- Powerful Integrated Aerial Zoom Camera
- Stabilization within 0.01°
- CMOS 1/2.8" sensor

- 2.13 effective megapixels
- MOV and MP4 video

This camera is priced at $2,500.

Appendix A: Vendor Product Sheets

Relevant vendor product sheets are included in this appendix. The product sheets are copyright the individual companies. They are included here for easier future reference and archival purposes.

Aerial Vehicles

DJI Phantom 4 Pro v2.0

DJI Matrice 200 V2

DJI Matrice 300 RTK

Communications Systems

Video Systems

Appendix C:
Interim Report Summarizing System Requirements

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION
TECHNICAL REPORT DOCUMENTATION PAGE
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16. ABSTRACT
This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document provides the system requirements.

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Unmanned Aerial Systems Communications Repeater (UASC-R) System Requirements

Stephen M. Donecker &
Ty A. Lasky: Principal Investigator

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Table of Contents

List of Acronyms and Abbreviations

Acronym	Definition
4G	Fourth Generation
ATG	Air-to-Ground
Caltrans	California Department of Transportation
DOT	Department of Transportation
DRAM	Dynamic Random Access Memory
EIRP	Equivalent Isotropic Radiated Power
FAA	Federal Aviation Administration
IP	Ingress Protection
LTE	Long Term Evolution
Mini-PCIe	Mini Peripheral Component Interconnect Express
OEM	Original Equipment Manufacturer
p-mode	positioning mode
SBC	Small Board Computer
SHS	State Highway System
SIM	Subscriber Identity Module
UAS	Unmanned Aircraft System
UASC-R	Unmanned Aircraft System Communication Repeater
UCD	University of California - Davis
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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1 Introduction

Communication options in rural districts within the California Department of Transportation (Caltrans) are intermittent and in some cases unavailable. The aim of this project is to extend existing cellular infrastructure service boundaries further into rural districts. We seek to accomplish this by employing an Unmanned Aerial System (UAS) with a communications payload developed to provide cellular data service range extension via routing between a cellular interface Wireless Wide Area Network (WWAN) and a wireless interface Wireless Local Area Network (WLAN).

The purpose of this document is to provide the system requirements for system design and sub-system procurement for this research effort.

2 UASC-R System Requirements

The following are the system requirements for the UAS Communication Repeater (UASC-R). The requirements established here and by agreement with the project panel and the PM will guide subsequent tasks, including Task 5 "Develop detailed system design for selected research concept" and Task 6 "Procure hardware for aerial repeater research." The requirements will directly drive the Task 5 system design, and will dictate acceptable systems and subsystems to be procured in Task 6. Any UAS procured in Task 6 must clearly meet the requirements listed below that seek to address the overall Concept of Operations developed in the prior Task 2 document "Unmanned Aerial Systems Communications Repeater Prototype System Operational Concepts."

2.1 General Operational Requirements

The general operational requirements address regulatory issues as well as the fundamental operational requirements as described in detail in the concept of operations document.[1] The Task 2 Concept of Operations document discussed current cellular data service availability within rural sections of the State Highway System (SHS), presented coverage shortcomings within these areas, provided mitigating and system concepts, outlined key operational and/or business constraints, and proposed a prototype system that would significantly extend the usable range of existing cellular infrastructure data services. This Task 4 interim report defines the formal engineering system requirements to achieve these results.

2.1.1 The UAS shall be operated according to all applicable Federal Aviation Administration (FAA) regulations

2.1.2 The UAS shall be operated according to all applicable state regulations

2.1.3 The UAS shall be operated according to all local regulations

2.1.4 The UAS shall be operated according to all applicable University of California - Davis (UCD) policies when on UCD property

2.1.5 The UAS shall be operated according to all applicable Caltrans policies when on Caltrans property

[1] Stephen M. Donecker and Ty A. Lasky, "Unmanned Aerial Systems Communications Repeater Prototype System Operational Concepts," AHMCT Research Report UCD-ARR-20-06-25-01, June 2020.

2.1.6 The UASC-R shall provide Air-to-Ground (ATG) communication between ground-based Wi-Fi users and a cellular base station

2.1.7 The UASC-R shall be designed to operate within rural locations

2.1.8 The UASC-R shall be operated in such a manner that interference to other nearby cellular base stations is minimized

2.2 UAS Requirements

This section presents the UAS-specific requirements. Here, the focus is on functional capability and performance, rather than regulatory issues. The requirements are broken into subsections for hardware, software, and operational requirements.

2.2.1 UAS Hardware Requirements

2.2.1.1 The UAS shall have a minimum payload capability of 3 lb

2.2.1.2 The UAS may have a maximum Equivalent Isotropic Radiated Power (EIRP) at 2.4 GHz of 26 dBm

2.2.1.3 The UAS may have a maximum EIRP at 5.8 GHz of 26 dBm

2.2.1.4 The UAS shall have a minimum vertical hovering accuracy in positioning mode (p-mode) of ±1.75 ft

2.2.1.5 The UAS shall have a minimum horizontal hovering accuracy in p-mode of ±5 ft

2.2.1.6 The UAS shall have a minimum ascent speed capability of 15 ft/s

2.2.1.7 The UAS shall have a minimum decent speed capability of 9 ft/s

2.2.1.8 The UAS shall have a minimum p-mode speed capability of 35 mph

2.2.1.9 The UAS shall have a minimum flying wind resistance capability of 39 ft/s

2.2.1.10 The UAS shall have a minimum flight time capability of 38 min

2.2.1.11 The UAS shall have a minimum Ingress Protection (IP) rating of 43

2.2.1.12 The UAS shall have a minimum operational temperature range of -4 to 122 °F (-20 to 50 °C)

2.2.1.13 The UAS shall have a downward vision system

2.2.1.14 The UAS shall have a forward vision system

2.2.1.15 The UAS may have on-board lighting

2.2.1.16 The UAS may support hot-swappable, rechargeable batteries

2.2.1.17 The UAS should support high-capacity rechargeable batteries to maximize flight time

2.2.1.18 The UAS shall have a charging hub capable of charging multiple batteries at once

2.2.1.19 The UAS shall have a remote control

2.2.1.20 The UAS remote control may support video capabilities

2.2.1.21 The UAS shall support an Original Equipment Manufacturer (OEM) dual-payload mounting adapter

2.2.2 UAS Software Requirements

N/A

2.2.3 UAS Operational Requirements

2.2.3.1 The UAS may be selected to maximize payload capacity

2.2.3.2 The UAS EIRP should be selected to reduce potential interference with payload communications

2.2.3.3 The UAS should be selected with the capability to reduce overlap of operational frequencies with the payload

2.2.3.4 The UAS should be selected to maximize flight time

2.2.3.5 The UAS may be selected to maximize IP rating

2.2.3.6 The UAS charging hub should support use in a vehicle

2.2.3.7 The UAS shall be capable of operation during the night with the appropriate lighting modifications and associated waiver

2.2.3.8 The UAS may be similar (make/model) to UAS's used by other Department of Transportation (DOT) or state agencies

2.3 Payload Requirements

This section presents payload requirements as they relate to the performance and specification of the UAS. The requirements are broken into subsections for hardware, software, and operational requirements.

2.3.1 Payload Hardware Requirements

2.3.1.1 The UAS payloads shall be selected or designed to minimize weight

2.3.1.2 The UAS payloads shall be selected or designed to maximize flight time

2.3.1.3 The UAS payloads shall be selected or designed to minimize dimensions

2.3.1.4 The UAS payloads should use existing OEM mounting interfaces and/or adapter plates

2.3.1.5 The UAS payloads should use existing OEM mounting interface electrical interfaces

2.3.2 Payload Software Requirements

N/A

2.3.3 Payload Operational Requirements

2.3.3.1 The UAS payloads shall be mounted below the airframe

2.3.3.2 The UAS may support mounting a payload above the airframe

2.4 Communication Payload Requirements

This section presents the payload requirements as they relate to the UASC-R communications performance. Communications extension is the fundamental goal of this research. The requirements are broken into subsections for hardware, software, and operational requirements.

2.4.1 Communication Hardware Requirements

2.4.1.1 The UASC-R shall be self-contained with the exception of power

2.4.1.2 The UASC-R may be powered by the UAS using OEM electrical interfaces

2.4.1.3 The UASC-R may be entirely self-contained and require no power from the UAS

2.4.1.4 The UASC-R shall include a low-power Small Board Computer (SBC)

2.4.1.5 The UASC-R shall include a cellular modem card as the WWAN interface

2.4.1.6 The UASC-R may include a Wi-Fi adapter card as the WLAN interface

2.4.1.7 The UASC-R may support optional wireless adapter cards as the WLAN interface

2.4.1.8 The UASC-R SBC shall include a multi-core processor

2.4.1.9 The UASC-R SBC shall include a process clock of at least 1 GHz

2.4.1.10 The UASC-R SBC shall include at least 1 GB of dynamic random access memory (DRAM)

2.4.1.11 The UASC-R SBC shall include at least 8 GB of flash memory

2.4.1.12 The UASC-R SBC shall have at least two expansion slots

2.4.1.13 The UASC-R SBC expansion slots may be Mini Peripheral Component Interface Express (Mini-PCIe)

2.4.1.14 The UASC-R SBC expansion slots may be m.2-based

2.4.1.15 The UASC-R SBC shall have a Nano Subscriber Identity Module (SIM) in at least one slot for a cellular modem card

2.4.1.16 The UASC-R SBC may use an expansion slot adapter

2.4.1.17 The UASC-R SBC shall have a wide temperature operating range

2.4.1.18 The UASC-R WWAN card connecter may be m.2-based

2.4.1.19 The UASC-R WWAN card connector may be Mini-PCIe based

2.4.1.20 The UASC-R WWAN card shall support Fourth Generation (4G) Long Term Evolution (LTE)

2.4.1.21 The UASC-R WWAN card shall be Verizon network-compatible

2.4.1.22 The UASC-R WWAN card shall be AT&T network-compatible

2.4.1.23 The UASC-R WWAN card upload bandwidth may be 150 Mbps

2.4.1.24 The UASC-R WWAN card download bandwidth may be 300 Mbps

2.4.1.25 The UASC-R WWAN card shall provide a minimum of 22 dBm transmit power

2.4.1.26 The UASC-R WWAN card may use Hirose U.FL antenna connectors

2.4.1.27 The UASC-R WWAN card shall support diversity antenna

2.4.1.28 The UASC-R WWAN antenna may be directional

2.4.1.29 The UASC-R WWAN antenna may be omnidirectional

2.4.1.30 The UASC-R WWAN antenna gain should be a minimum of 3 dBi

2.4.1.31 The UASC-R WLAN card may support IEEE 802.11ac

2.4.1.32 The UASC-R WLAN card may support IEEE 802.11ax

2.4.1.33 The UASC-R WLAN card shall provide a minimum of 21 dBm transmit power

2.4.1.34 The UASC-R WLAN card may use Hirose U.FL antenna connectors

2.4.1.35 The UASC-R WLAN card may support multiple antennas

2.4.1.36 The UASC-R WLAN antenna may be omnidirectional

2.4.1.37 The UASC-R WLAN antenna may be directional

2.4.1.38 The UASC-R WLAN antenna may be a downward-facing patch antenna

2.4.1.39 The UASC-R WLAN antenna gain should be a minimum of 3 dBi

2.4.1.40 The UASC-R shall be mounted to the UAS using OEM mounting interfaces

2.4.2 Communication Software Requirements

2.4.2.1 The UASC-R SBC shall support a Linux-based operating system

2.4.2.2 The UASC-R SBC vendor may provide a Linux board support package

2.4.2.3 The UASC-R WWAN card shall provide or be compatible with an existing Linux driver

2.4.2.4 The UASC-R WLAN card shall provide or be compatible with an existing Linux driver

2.4.2.5 The UASC-R shall contain software to route between the WWAN and WLAN interfaces

2.4.2.6 The UASC-R may contain software to present the WLAN as a wireless hotspot for multiple users

2.4.2.7 The UASC-R may contain software to configure the WLAN as a network link to a ground-based Wi-Fi hot spot

2.4.2.8 The UASC-R may contain software to provide real-time telemetry

2.4.3 Communication Operational Requirements

2.4.3.1 The UASC-R shall include backhaul communications capability

2.4.3.2 The UASC-R shall include local communications capability

2.4.3.3 The UASC-R shall properly shut down when powered down

2.4.3.4 The UASC-R shall properly shut down if powered by the UAS when main power is off

2.4.3.5 The UASC-R shall properly start up if powered by the UAS when main power is on

2.4.3.6 The UASC-R shall properly shutdown if powered by the UAS when main power is off

2.4.3.7 The UASC-R shall properly start up if powered by a self-contained battery and the power is switched on

2.4.3.8 The UASC-R shall properly shutdown if powered by a self-contained battery and the power is switched off

2.4.3.9 The UASC-R shall properly shutdown if powered by a self-contained battery which reaches low power

2.5 Camera Payload Requirements

This section presents the payload requirements as they relate to visual identification of nearby cellular towers. The requirements are broken into subsections for hardware, software, and operational requirements.

2.5.1 Camera Hardware Requirements

2.5.1.1 The UAS camera payload shall use OEM hardware mounting interfaces

2.5.1.2 The UAS camera payload shall use OEM electrical interfaces

2.5.2 Camera Software Requirements

N/A

2.5.3 Camera Operational Requirements

2.5.3.1 The UAS may necessitate a camera payload depending on the selected UAS

2.5.3.2 The UAS camera payload must be of sufficient capability to visually identify the location of nearby cellular towers

Appendix D:
Interim Report Summarizing Detailed System Design

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TECHNICAL REPORT DOCUMENTATION PAGE

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16. ABSTRACT

This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document provides the system design.

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Unmanned Aerial Systems Communications Repeater (UASC-R) System Design

Kin S. Yen

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November 23, 2022

California Department of Transportation

Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DHCP	Dynamic Host Configuration Protocol
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FAKRA	Fachkreis Automobil
GPS	Global Positioning System
GNSS	Global Navigation Satellite Systems
IP	Internet Protocol
LiPo	Lithium Polymer
LTE	Long-Term Evolution
MIMO	Multiple input, multiple output
RP-SMA	Reverse Polarity SubMiniature version A
SIM	Subscriber Identity Module
SMA	SubMiniature version A
SNMP	Simple Network Management Protocol
SR	State Route
UAS	Unmanned Aerial System

Acronym	Definition
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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Chapter 1: Introduction

Communication options in rural districts within the California Department of Transportation (Caltrans) are intermittent and in some cases unavailable. The aim of this project is to extend existing cellular infrastructure service boundaries further into rural districts. We seek to accomplish this by employing an Unmanned Aerial System (UAS) with a communications payload developed to provide cellular data service range extension via routing between a cellular interface Wireless Wide Area Network (WWAN) and a wireless interface Wireless Local Area Network (WLAN). The purpose of this document is to provide the system design for this research effort.

Based on the concept (Task 2) and requirements (Task 4), AHMCT developed a system design for the UAS repeater prototype for experimentation and evaluation. This design document will include the following elements:

- Hardware necessary for system take-off, flight, use, and landing
- Major software configuration
- System design ready for subsequent development, integration, and investigation

System Requirements

The system requirements for the UASC-R were developed in Task 4, and documented in an interim report.[1] The requirements included high-level functional requirements (support payload, fly to height to achieve cellular data connection, and provide a Wi-Fi downlink to the local users), as well as detailed requirements for the anticipated implementation approach. The final system achieves the functional requirements, as demonstrated in fall 2022. However, the commercial landscape evolved between the time of detailed requirements generation and final design and system implementation. In particular, Commercial Off-the-Shelf (COTS) components have emerged or have been identified which provide the capability of the UASC-R payload. As such, AHMCT did not design and build its own custom payload. This is precisely in line with the overall design philosophy of maximizing COTS use, and is in the long-term interests of Caltrans and the system maintainability. Because of this change,

[1] Stephen M. Donecker and Ty A. Lasky, "Unmanned Aerial Systems Communications Repeater (UASC-R) System Requirement," UCD-ARR-21-09-30-01, February 24, 2022

some of the detailed design requirements for the payload have not been met, or may not be met. Here, "may not" is due to proprietary information of the COTS systems, such that we cannot determine whether some detailed requirements have been met. The most important point is that the final design and implementation of the UASC-R (flight platform and communications package) clearly meet the functional requirements of the original proposal and requirements document. A detailed assessment of final design vs. original requirements will be provided separately in the project final report.

Design Considerations

- Utilize COTS components with high-reliability and environmental robustness as much as possible
- Lightweight (Requirements 2.3.1.1 & 2.3.1.3)
- Simple integration
- Support for 5G is lower priority since the system will be primarily used in rural area where 5G deployment is lagging behind. In addition, 5G range is shorter than 4G range.
- Support for MIMO (multiple input, multiple output) Wireless Fidelity (Wi-Fi) (Requirement 2.4.1.35)
- Support for Simple Network Management Protocol (SNMP) for evaluation and testing.
- Integration with directional antenna. High-gain directional antennas will improve signal strength. However, they increase weight and operational complexity orientating the UAS toward the users or the cell site.
- Product availability and supply chain constraints.

Chapter 2:
Final Design

Design Concept Evaluation and Experimentations

The original concept was to develop a custom WWAN to Wi-Fi hotspot using COTS motherboard, WWAN and WLAN card with embedded Linux operating system for data traffic routing. The commercial landscape has changed since the initial design concept development. Several COTS WWAN modems with MIMO Wi-Fi and advanced routing features are available. Using a completely integrated and factory-tested COTS solution would speed up the reproduction for future deployment. Thus, a COTS integrated solution was chosen over custom development solution.

Several Long-Term Evolution (LTE) routers with and without integrated Wi-Fi were considered. Some WWAN routers, such as the Mikrotik SXT LTE 6, have an integrated high-gain antenna that may provide better signal reception when the directional high-gain antenna is pointed toward the LTE cell tower. Other WWAN modem, such as the Sierra Wireless MP70, have external antennas connections that enables users to use various antennas and configurations.

The Sierra Wireless MP70 router with Wi-Fi 5 was chosen based on its specifications and researchers' previous experience with Sierra Wireless products including interfacing for data collection and logging. Data collection and logging is not required for the final system. However, WWAN signal and location data would provide feedback to system performance and support exploration and optimization of different antenna configurations for both LTE and Wi-Fi. Omnidirectional antennas for both Wi-Fi and WWAN are utilized first. High-gain directional antennas may result in stronger signal provided that the antenna is pointed in the proper direction. If omnidirectional antennas provide adequate performance, the UAS operational constrains would reduce since the UAS operator would not be required control the UAS to point the antenna(s) in the proper direction.

Several experiments on the ground and in the air with the DJI M300 were conducted to evaluate different design and antenna configurations (Wi-Fi) antenna gain and spacing. The MP70 Wi-Fi range with different antenna configuration was compared with a consumer grade Wi-Fi 6 router for baseline comparison. Under current FAA rules, the UAS must be operated within the operator's line of sight. For DJI M300, the maximum line of sight distance is about 3000 feet in good visibility condition. The goal is to have a Wi-Fi range equal to or above the UAS maximum line of sight distance. Ground testing shows that the MP70 maximum Wi-Fi range to an Android phone and tablet ranges from 1500 to 2200 feet depending on antenna gain and spacing. Figure 2.1 shows an example ground based Wi-Fi test setup. During ground based testing, researchers found that Android devices would constantly disconnect from the MP70 Wi-Fi or baseline Wi-Fi router when the Wi-Fi signal is weak even through Wi-Fi data communication is viable.

Aerial testing showed that a high-gain omnidirectional antenna might not be suitable for UAS aerial operation. Omnidirectional antennas have a doughnut shaped radiation pattern and are ideal for connecting devices that are on the same plane. Higher gain omnidirectional antennas have a narrower vertical beam. When the UAS is high above ground, the Wi-Fi client can be standing directly underneath a transmitting antenna, and be in a dead zone. The omnidirectional antennas may be tilted to the ground to provide stronger Wi-Fi signal. High-gain antenna on the UASC-R would result in large fluctuation in the Wi-Fi signal resulting in unreliable connection when the UAS is flying. Connection reliability is crucial in real world application. Thus, lower-gain omnidirectional Wi-Fi antennas are used instead.

In addition, experiments show that ground-based Wi-Fi repeater or Wi-Fi bridge with high-gain antenna can improve data connection speed and connection reliability. Our Android devices used for testing tend to disconnect from the UASC-R Wi-Fi in search of other better Wi-Fi connection instead of staying connected to UASC-R Wi-Fi. Reconnecting UASC-R Wi-Fi using Android may take from 10 to over 60 seconds (time includes searching for Wi-Fi available, establish connection, and the operating system need to validate the Wi-Fi connection using the internet connection) depending on the signal strength and connection speed. This circumstance was not anticipated in the requirement and design phase.

The addition of Wi-Fi repeater eliminated this problem. Wi-Fi repeater provides the Wi-Fi clients with strong signal at the ground level resulting in less auto-disconnecting by the operating system. Thus, a Wi-Fi repeater and a Wi-Fi bridge were added. The Wi-Fi bridge was added to measure Wi-Fi signal strength for analysis.

Figure 2.1: Experimental setup to investigate Wi-Fi range with different Wi-Fi antenna and antenna spacing. Sierra Wireless MP70 with LTE, Global Navigation Satellite Systems (GNSS), and 9 dB gain Wi-Fi antennas with 9-inch spacing.

UAS Wi-Fi Hot Spot

The Sierra Wireless MP70 LTE modem with integrated Wi-Fi was selected for the final design. Figure 2.2 shows a system block diagram of the final design configuration. The MP70 has a Sierra Wireless EM5711 PCIe m.2 card for WWAN data connection, an activated Verizon SIM card, a GNSS location module for location data, and a Compex VLE900VX Wi-Fi adapter. It is powered by a LiPo 3S 11.1 V 1500 mAh battery.

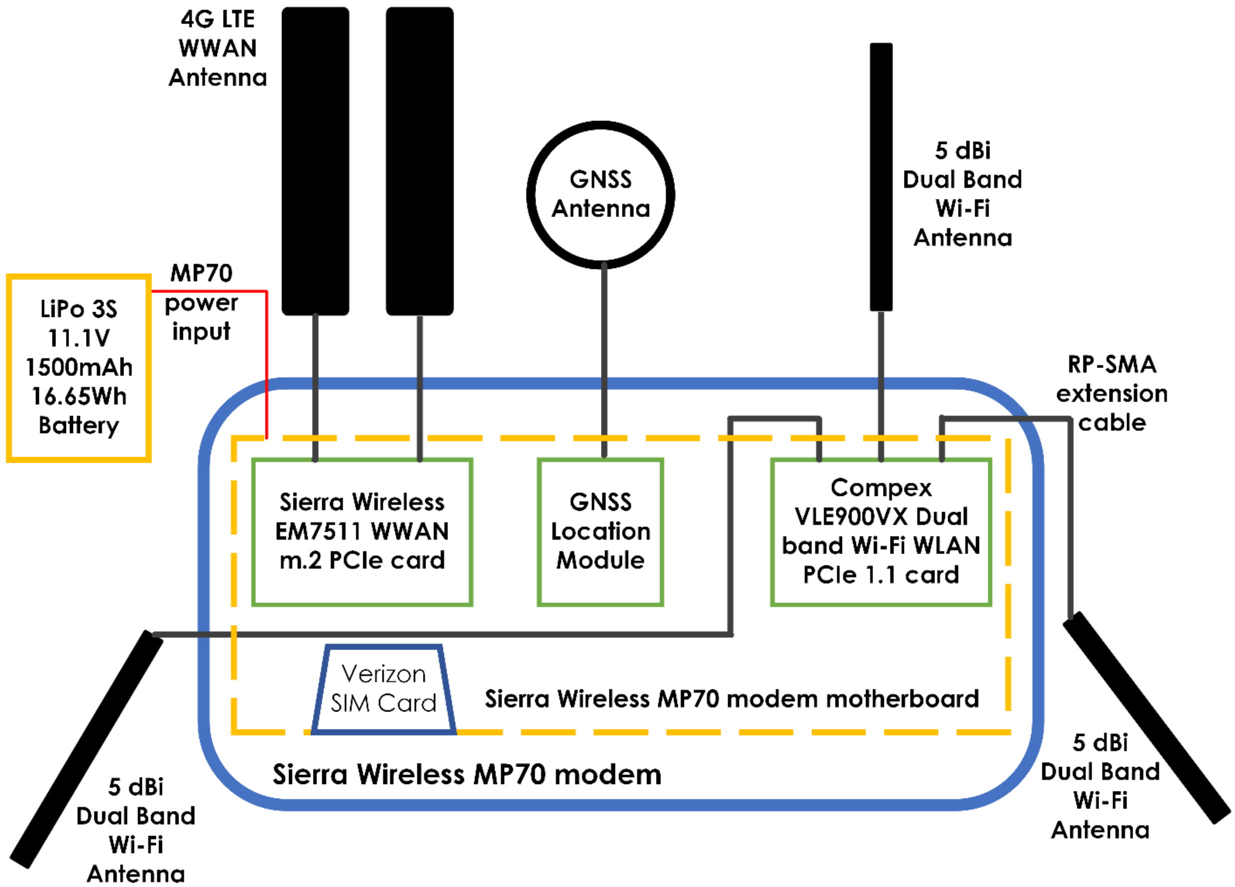

Figure 2.2: UASC-R system block diagram

Figure 2.3 shows the inside of the MP70 WWAN router. The thermal conductive material was removed to reveal the internal part information. The MP70 aluminum case was designed as an integrated heat sink for the WWAN card, Wi-Fi card, and motherboard. The majority of the system weight is the aluminum case.

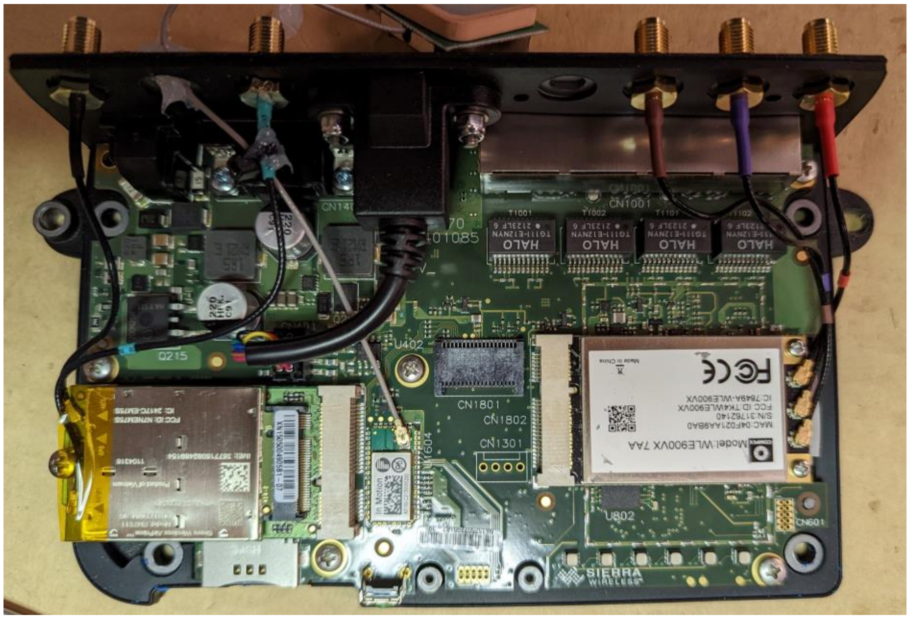

Figure 2.3: UAS aerial repeater design block diagram

Figures 2.4 and 2.5 show the setup of the UAS Wi-Fi hot spot. Different LTE WWAN antennas were tested and evaluated.

Figure 2.4: Sierra Wireless MP70 with LTE, GNSS, and 5 dB gain Wi-Fi antennas mounted on the UAS mounting plate

Figure 2.5: Sierra Wireless MP70 with LTE, GNSS, and 5 dB gain Wi-Fi antennas mounted on the UAS. The LTE antennas were changed to the final version - compare to the LTE antennas shown in Figure 2.4.

Table 2.1: List of UASC-R COTS components (not including ground station components)

Make/Model/Part	Descriptions
Sierra Wireless MP70	LTE modem/router with built-in Wi-Fi
5 dB Wi-Fi Antenna	5 dB Wi-Fi antenna with Reverse Polarity SubMiniature version A (RP-SMA) connector
Bingfu 4G LTE Antenna	Bingfu 4G LTE antenna 9 dBi SMA male cellular antenna (2-Pack), compatible with 4G LTE
GNSS antenna	28 dB high-gain Global Positioning System (GPS) active antenna ceramic patch GPS marine navigation antenna with UFL Interface
Bingfu Wi-Fi Antenna Extension Cable	RP-SMA male to RP-SMA female bulkhead mount RG316 cable 12-inch length
HOOVO 3S battery	11.1 V 1500 mAh lithium polymer (LiPo) battery with XT60 plug
Verizon SIM card	Activated Verizon Subscriber Identity Module (SIM) card

Key MP70 Firmware Setup

- Set Internet Protocol (IP) address to 192.168.31.254
- Change password
- Enable Dynamic Host Configuration Protocol (DHCP)
- Enable Simple Network Management Protocol (SNMP)
- Configure MP70 to use 5 GHz Wi-Fi channel 149. The DJI Matrice 300 UAS remote control frequency is set to 2.4 GHz by default. The 5 GHz Wi-Fi channel is chosen to avoid any potential interference with the UAS remote control.
- Enable 3x3 MIMO
- Enable GNSS

Wi-Fi Bridge/Repeater Ground Station

Ground experiments demonstrated that the use of a Wi-Fi bridge or Wi-Fi repeater can improve the Wi-Fi connection (data transfer rate, connection reliability, and connection range). Both the Wi-Fi bridge and Wi-Fi repeater have higher gain antenna compared to a laptop, tablet, or smartphone. The TP-Link AC1200 Wi-Fi repeater has 4x4 MIMO which should provide better reception than laptop, tablet, or smartphone Wi-Fi which usually have only 2x2 MIMO. During the initial experiments without any ground stations, the users has to constantly reconnect the UASC-R Wi-Fi manually resulting in loss of data and increased data collection time. As a result, ground station components were added to improve connection reliability by reducing triggering of Wi-Fi disconnect by the operating system. The exact reason and criteria that trigger the automatic/intermittent Wi-Fi disconnection is beyond researcher control. This negative factor degraded the Wi-Fi data connection without ground station was not anticipated in the requirements development and design phase. However, data connection reliability is very vital in practice for any real world applications. Both Wi-Fi bridge and Wi-Fi repeater was used during the final experiments and evaluation to see if there is any performance difference.

The TP-Link AC1200, as shown in Figure 2.9, was configured as a Wi-Fi Repeater, and the MikroTik SXTsq 5, as shown in Figure 2.7, was used as Wi-Fi Bridge and is connected to a laptop. Figure 2.6 illustrates how data are transferred between the laptop and the WWAN internet. The MikroTik SXTsq 5 has integrated directional 5 GHz 16 dBi gain antenna. The MikroTik router firmware provides the Wi-Fi signal strength reading via its propriety software. However, the MikroTik router firmware also supports SNMP, so Wi-Fi signal strength reading and other data can be obtained via a future custom application, thus avoiding the proprietary software. The major drawback of the high-gain directional antenna is the requirement for users to point the antenna toward the UAS.

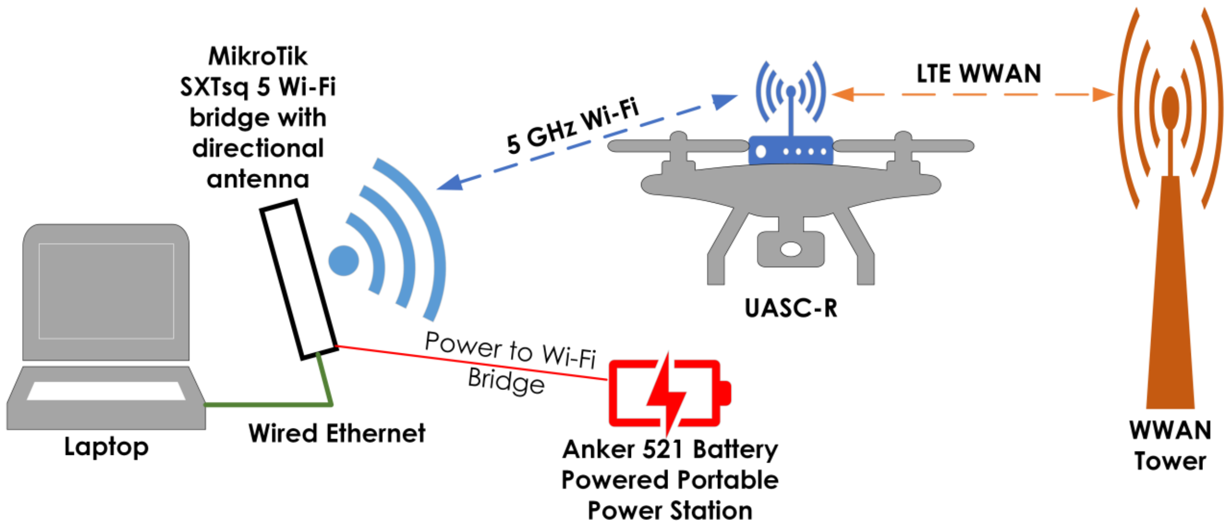

Figure 2.6: Block diagram of MikroTik SXTsq 5 Wi-Fi bridge with laptop client

Figure 2.7: MikroTik SXTsq 5 High Power with integrated 5 GHz 16 dBi antenna mounted on a tripod

A Pixel 6 Pro smartphone was connected to the Wi-Fi repeater, as illustrated in Figure 2.8, since it does not have a build-in wired Ethernet connection. There was no major difference in data transfer rate between clients using the Wi-Fi bridge or the Wi-Fi repeater in the final demonstration.

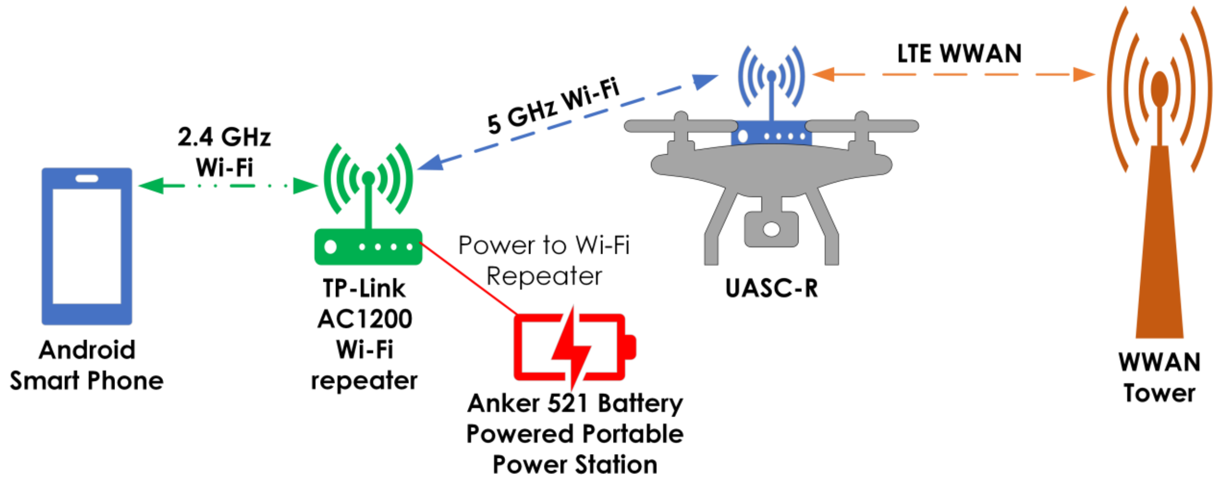

Figure 2.8: Block diagram of TP-Link AC1200 Wi-Fi repeater with smartphone as Wi-Fi client connection

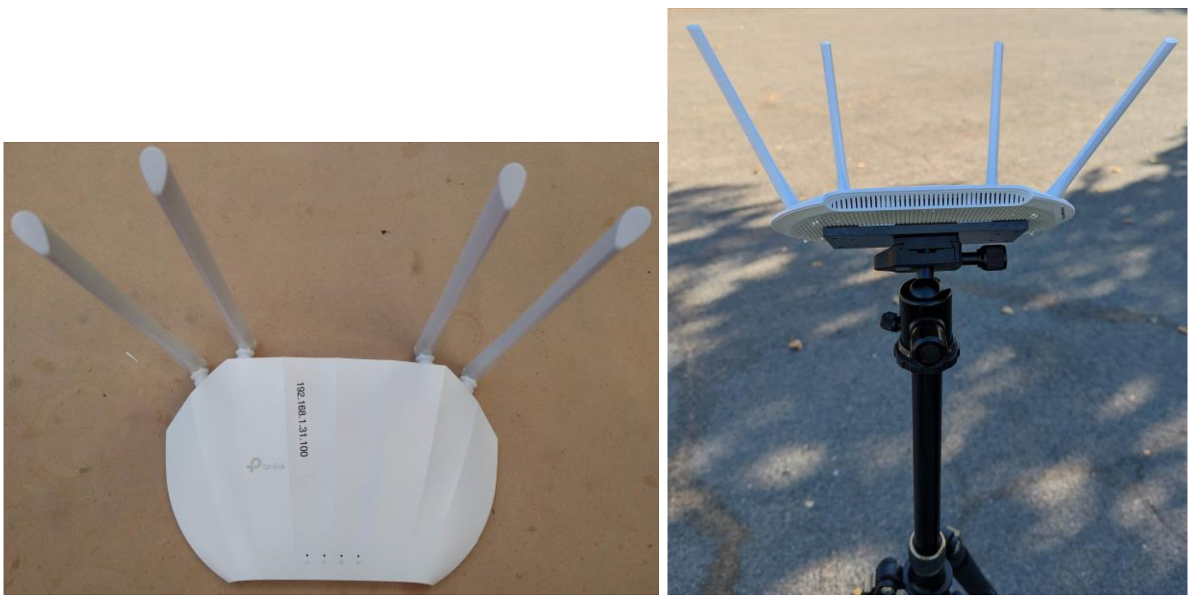

Figure 2.9: TP-Link AC1200 Wi-Fi repeater mounted on a tripod

Based on the final experimental results, the Wi-Fi repeater without directional antenna should be sufficient in simple use case where the UAS is fairly close to the ground station. However, some use cases may require the use of high-gain directional antenna. The major Wi-Fi repeater requirements are:

- 4x4 MIMO or better
- Support dual-band Wi-Fi and dual radio (2.4 and 5 GHz)
- Support Wi-Fi 5 or better
- Support crossband Wi-Fi repeating (bridging 2.4 to 5 GHz channels)

A portable COTS battery power station (Figure 2.10) was used to power the Wi-Fi Bridge and Wi-Fi Repeater.

Figure 2.10: COTS battery power station (Anker 521) used to power the Wi-Fi Bridge and Wi-Fi Repeater

Table 2.2: List of Wi-Fi ground station COTS components

Make/Model/Part	**Description**
TP-Link AC1200	Configured as a Wi-Fi repeater for Wi-Fi client without wired Ethernet port (Android phone or tablet).
MikroTik SXTsq 5	Configured as a Wi-Fi bridge with high-gain antenna for computer client with wired Ethernet port.
Anker 521	Portable power station with AC and 12-Volt DC output is used to power the Wi-Fi repeater and Wi-Fi bridge. It may also be used for charging various client devices.

Lessons Learned

The final demonstration results show that the UASC-R concept works in practice. Modifications can be made to improve system performance. Some of the future work details are provided in the Task 13 final report.

Key Issue Encountered

The issue of Wi-Fi automatic disconnection by the operating system (OS) was not expected. Recent versions of Android and Microsoft Windows 11 OS would check and validate the Wi-Fi internet connection on every reconnect, consuming time, and the OS would automatically disconnect whenever Wi-Fi signal strength was below a threshold, with the goal of forcing the user to connect to a better Wi-Fi. There may be ways to force Android and Microsoft Windows 11 to stay connected to a particular Wi-Fi even with low Wi-Fi signal strength. More research is need in this area in order to eliminate the need for the ground station.

Areas for Potential Improvement

Weight Reduction

The UAS payload weight can be reduced from the current design:

- Design and 3D print custom MP70 plastic enclosure with integrated heat sinks.
- Use lightweight fasteners (e.g. plastic, aluminum, or titanium).
- Reduce number of coax connectors and connections.

Design Improvements

- Design and build custom antennas inside plastic DJI UAS legs to replace existing DJI carbon fiber UAS legs.
- Replacing the SMA and RP-SMA coax connectors with FAKRA connectors would reduce assembly time in the field. FAKRA connectors meet the mechanical and environmental requirements of the UASC-R. FAKRA connectors are used in the automotive industry for applications such as cellular, GPS navigation, and Wi-Fi. FAKRA connection can be made by simply pushing the connectors together.

Antenna placement

The current Wi-Fi antennas and their placement are not optimal. Combined experiments and computer simulations would result in a better Wi-Fi performance.

Appendix E:
Interim Report Summarizing Hardware Integration

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16. ABSTRACT
This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This report documents the hardware integration.

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Unmanned Aerial Systems Communications Repeater (UASC-R) Hardware Integration

Kin S. Yen

Report Number: CA23-3280
AHMCT Research Report: UCD-ARR-22-11-27-01
Interim Report of Contract: 65A0726 Task 3280

November 27, 2022

California Department of Transportation

Division of Research, Innovation and System Information

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List of Figures

List of Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
GNSS	Global Navigation Satellite System
LiPo	Lithium Polymer
LTE	Long-Term Evolution
PVC	Polyvinyl chloride
RF	Radio Frequency
UAS	Unmanned Aerial System
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Jeremiah Pearce with the Office of ITS Engineering and Support, and Sean Campbell with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1: Introduction

Communication options in rural districts within the California Department of Transportation (Caltrans) are intermittent and in some cases unavailable. The aim of this project is to extend existing cellular infrastructure service boundaries further into rural districts. We seek to accomplish this by employing an Unmanned Aerial System (UAS) with a communications payload developed to provide cellular data service range extension via routing between a cellular interface Wireless Wide Area Network (WWAN) and a wireless interface Wireless Local Area Network (WLAN). The purpose of this document is to document the hardware integration for this research effort.

Integrated aerial repeater concept

Based upon the detailed design of Task 5, AHMCT integrated all hardware components and developed the prototype powered aerial repeater systems and repeater payloads. Hardware integration included the following:

- Any modification to the aerial platform (DJI Matrice 300)
- Modification to the Sierra Wireless MP70
- Long-Term Evolution (LTE), Global Navigation Satellite System (GNSS), and Wireless Fidelity (Wi-Fi) antennas mounting and placement
- UAS repeater power system
- Mounting brackets

System Requirements

The system requirements for the UASC-R were developed in Task 4, and documented in an interim report.[1] The requirements included high-level functional requirements (support payload, fly to height to achieve cellular data connection, and provide a Wi-Fi downlink to the local users), as well as detailed requirements for the anticipated implementation approach. The final system achieves the functional requirements, as demonstrated in fall 2022. However, the commercial landscape evolved between the time of detailed requirements

[1] Stephen M. Donecker and Ty A. Lasky, "Unmanned Aerial Systems Communications Repeater (UASC-R) System Requirement," UCD-ARR-21-09-30-01, February 24, 2022

generation and final design and system implementation. In particular, Commercial Off-the-Shelf (COTS) components have emerged or have been identified which provide the capability of the UASC-R payload. As such, AHMCT did not design and build its own custom payload. This is precisely in line with the overall design philosophy of maximizing COTS use, and is in the long-term interests of Caltrans and the system maintainability. Because of this change, some of the detailed design requirements for the payload have not been met, or may not be met. Here, "may not" is due to proprietary information of the COTS systems, such that we cannot determine whether some detailed requirements have been met. The most important point is that the final design and implementation of the UASC-R (flight platform and communications package) clearly meet the functional requirements of the original proposal and requirements document. The resulting UASC-R system design is documented in another interim report.[2] A detailed assessment of final design and implementation vs. original requirements will be provided separately in the project final report.

Integration Considerations

- Avoid blocking existing UAS collision detection sensors onboard the UAS
- Lightweight mount (Requirement 2.3.1.1)
- Minimize radio frequency (RF) interference (carbon fiber legs)
- Maximize UAS expected flight time. Minimize the UAS repeater battery power supply to reduce weight (Requirement 2.3.1.1). The user is expected to replace the UAS repeater battery after each flight.
- Balance center of gravity
- Minimize modification to the commercial off–the-shelf (COTS) UAS transport case

[2] Kin S. Yen, "Unmanned Aerial Systems Communications Repeater (UASC-R) System Design," UCD-ARR-22-11-23-02, November 23, 2022

Chapter 2: Hardware Integration

UAS Repeater Mounting on DJI Matrice 300

The UAS repeater is mounted on top of the DJI Matrice 300 using the Matrice 300's existing sensor mount (four M3x0.5 mm threaded holes) as shown in Figure 2.1. The Sierra Wireless MP70 and Wi-Fi antennas are secured to the mounting plate with four M5x0.8 mm 16-mm long screws as shown in Figure 2.2. The detail drawing and rendering of the mount plate is available in Appendix A.

Figure 2.1: UAS repeater to DJI Matrice 300 mounting plate secured with four M3x0.5 mm screws

Figure 2.2: Sierra Wireless MP70, Wi-Fi antennas, and battery secured to DJI Matrice 300 mounting plate

Figure 2.2 shows the MP70 power supply 3S 1500 mAh Lithium polymer (LiPo) battery secured to the top of the MP70 using Velcro hook and loop. The GNSS antenna is located next to the battery. The Wi-Fi antenna tilt angle can be adjusted to best suit the expected location and direction of the Wi-Fi client.

Lesson Learned

The current assembly time to mount the MP70 on top of the UAS can be improved. However, the current UAS carrying case created very tight constraints on what can be added to the UAS without getting a bigger case.

The authors speculate that placing Wi-Fi antennas below the UAS body and carbon fiber legs may improve Wi-Fi performance for client devices on the ground. Further testing is required to substantiate this.

Based on the experimental data, the MP70 power supply battery capacity could be reduced by as much as 50% to save weight.

Appendix A:
Computer-Aided Design Drawing and Rendering

All dimensions are in millimeters. The material is ¼"-thick polyvinyl chloride (PVC) plastic with M5x0.8mm helicoil inserts for the MP70 mount.

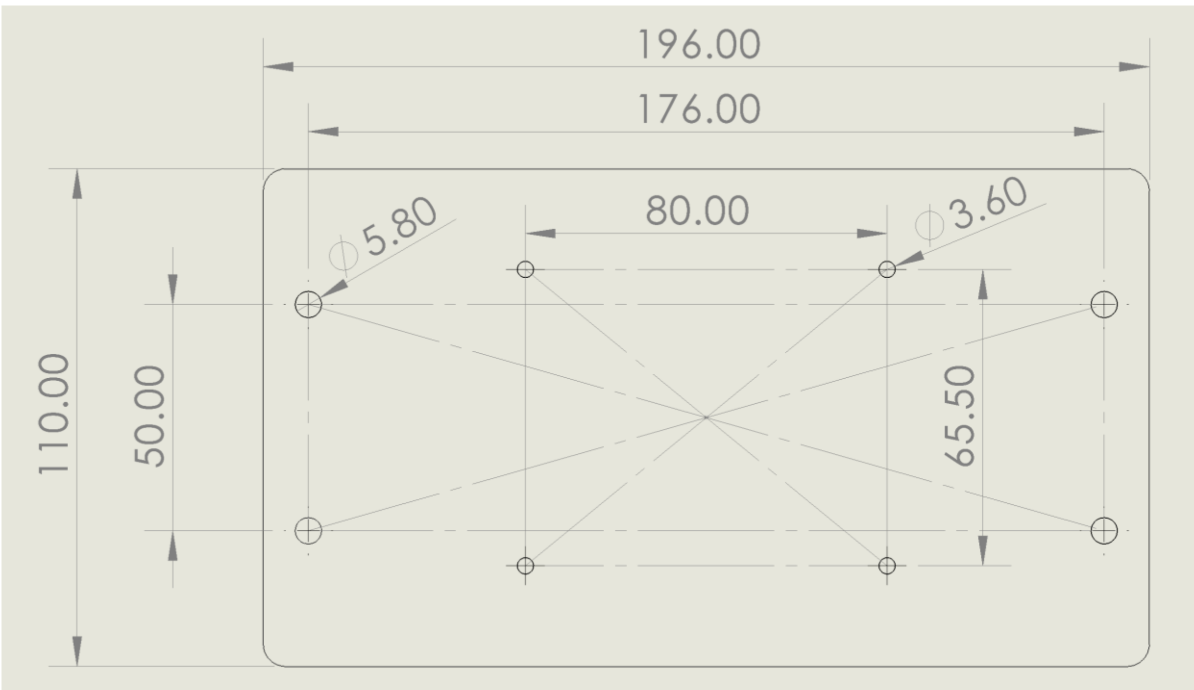

Figure A.1: UAS Repeater mounting adapter plate for DJI Matrice 300

Figure A.2: UAS Repeater Computer-Aided Design 3D model rendering

Appendix F:
Interim Report Summarizing Software Development

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Unmanned Aerial Systems Communications Repeater (UASC-R) Software Development

Travis Swanston &
Ty A. Lasky: Principal Investigator

Report Number: CA23-3280
AHMCT Research Report: UCD-ARR-22-09-09-01
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DRISI	Caltrans Division of Research, Innovation and System Information
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LTE	Long Term Evolution
MIB	Management Information Base
OID	Object Identifier
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indication
SINR	Signal-to-Interference-plus-Noise Ratio
SNIR	Signal-to- Noise-plus-Interference Ratio
SNMP	Simple Network Management Protocol
SR	State Route
UAS	Unmanned Aerial System

Acronym	Definition
UASC-R	Unmanned Aerial Systems Communications Repeater
UTC	Coordinated Universal Time
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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The purpose of this report is to document the software development for this research effort.

Chapter 2: Software Development

Based on the maturity of the Commercial Off–The-Shelf (COTS) modem and router market, AHMCT did not need to develop custom communications routing software between the cellular (WWAN) and WiFi (WLAN) networks. We also did not need to develop custom software for the UAS control. Software development within this research was limited to data logging and similar research support activities. The data logging for the wireless modem/router is documented in this interim report.

In this chapter, the key code segments are presented and discussed, along with the key definitions. We also present the output log format. For the complete code listing, refer to Appendix A. As noted therein, the code is subject to any necessary revision beyond finalization of this report.

Key Code Segments

The code heading and global definitions section is provided in Figure 1. This section dictates the code dependencies. The most obvious dependency is on python3, the programming language, and components of the Python Standard Library. The code is intended to run on the Linux operating system. The following command line will install *python3*, and the preferred package manager, *pip*:

sudo apt-get install python3

sudo apt-get install python3-pip

The remaining dependency is the SNMP library for Python, i.e. PySNMP (https://pysnmp.readthedocs.io/en/latest/). To install PySNMP, after installing *python* and *pip*, use the following:

pip install pysnmp

With *python*, *pip*, and *pysnmp*, all dependencies for the modem/router logging code are installed.

```
#!/usr/bin/env python3
#
# sierralogger, version 20220908.0

# Copyright © 2022 The Regents of the University of California
# All Rights Reserved

"""Reads, displays, and logs data fields from Sierra Wireless modem/router."""

import csv
from datetime import datetime
import os
import sys
from time import sleep
from pysnmp.hlapi import getCmd
from pysnmp.proto import rfc1902
from pysnmp.hlapi import CommunityData
from pysnmp.hlapi import ContextData
from pysnmp.hlapi import ObjectIdentity
from pysnmp.hlapi import ObjectType
from pysnmp.error import PySnmpError
from pysnmp.hlapi import SnmpEngine
from pysnmp.hlapi import UdpTransportTarget

MPMODEL_SNMPV1  = 0
MPMODEL_SNMPV2C = 1

logFileBase = 'sierra'
logFileExtn = '.csv'

sleeptime = 1

# to translate modem readings to actual lat/lon:
gnssScale = 100000
```

Figure 2.1: Imports and global definitions for modem/router logging code

The usage and main routines are provided in Figure 2.2. The essential query routines are provided in Figure 2.3. Here, there is the base query routine, which is used for both *query_integer* and *query_displaystring*. These two query routines enable all needed data queries from the modem, and the subsequent logging. The primary program functionality, specifically grabbing data at regular update rate and displaying this data to screen and/or logging this data to a file is provided by the *log_data* routine shown in Figure 2.4. The logging routine

always generates a unique log file name based on the date and time at the start of logging, in the form of
"sierra[year][month][day]_[hour][minute][second].log",
for example sierra20220812_085238.log.

```
def usage_exit(exitcode):
   print ("USAGE:")
   print ("  " + appname + " IP_ADDR PORT_NUM COMMUNITY_STRING")
   sys.exit(exitcode)

def main(argv):
   if len(argv) != 3:
      usage_exit(1)
   ip = argv[0]
   port = str_to_int(argv[1])
   if not port:
      usage_exit(1)
   community = argv[2]
   # initialize objects
   snmpeng = SnmpEngine()
   commdata = CommunityData(community, mpModel=MPMODEL_SNMPV2C)
   transtarg = UdpTransportTarget((ip, port))
   # log data until user issues break signal, ctrl-c:
   log_data(snmpeng, commdata, transtarg)
```

Figure 2.2: Usage and main routines of modem/router logging code

```
def query_integer(snmpeng, commdata, transtarg, oid):
   val = query(snmpeng, commdata, transtarg, oid + '.0', rfc1902.Integer)
   # return int(val)
   return int(val)

def query_displaystring(snmpeng, commdata, transtarg, oid):
   val = query(snmpeng, commdata, transtarg, oid + '.0', rfc1902.OctetString)
   return str(val)

def query(snmpeng, commdata, transtarg, oid, expected_type):
   try:
      it = getCmd(
         snmpeng,
         commdata,
         transtarg,
         ContextData(),
         ObjectType(ObjectIdentity(oid)),
         lookupMib=False
      )
      (err_indic, err_stat, err_idx, var_binds) = next(it)
   except PySnmpError:
      return None
   if err_indic or err_stat or (len(var_binds) != 1):
      return None
   val = var_binds[0][1]
   if (type(val) != expected_type):
      return None
   return val
```

Figure 2.3: Query routines of modem/router logging code

```
def log_data(snmpeng, commdata, transtarg):
   global logFileBase, logFileExtn, gnssScale
   now = datetime.now()
   fileDateTime = now.strftime('%Y%m%d_%H%m%S')
   logfile = logFileBase + fileDateTime + logFileExtn
   with open(logfile, 'w', newline='') as csvfile:
      logwriter = csv.writer(csvfile, delimiter=',',
                     quotechar='"', quoting=csv.QUOTE_MINIMAL)
      header = ['date',
         'time',
         'voltage',
         'boardTemperature',
         'rssi',
         'rsrq',
         'rsrp',
         'sinr',
         'wifiChannel',
         'satelliteCount',
         'latitude',
         'longitude',
         'heading']
      logwriter.writerow(header)
      print(header)
      while True:
         try:
            # voltage
            pwrin_string = query_displaystring(snmpeng, commdata, transtarg,
OID_powerIn)
            # board temperature (note the misspelling of the object name)
            brdtemp_int = query_integer(snmpeng, commdata, transtarg,
OID_boardTemprature)
            # RSSI
            rssi_int = query_integer(snmpeng, commdata, transtarg, OID_rssi)
            # RSRQ
            rsrq_int = query_integer(snmpeng, commdata, transtarg, OID_rsrq)
            # RSRP
            rsrp_int = query_integer(snmpeng, commdata, transtarg, OID_rsrp)
            # SINR
            sinr_string = query_displaystring(snmpeng, commdata, transtarg,
OID_sinr)
            # GPS number sat, lat, lon, heading
            gpsSatCount_int = query_integer(snmpeng, commdata, transtarg,
OID_satelliteCount)
```

```
            gpsLatitude_string = query_displaystring(snmpeng, commdata,
transtarg, OID_latitude)
            gpsLongitude_string = query_displaystring(snmpeng, commdata,
transtarg, OID_longitude)
            gpsHeading_string = query_displaystring(snmpeng, commdata,
transtarg, OID_heading)
            # Convert to real latitude/longitude:
            gpsLatitude_string = str(int(gpsLatitude_string)/gnssScale)
            gpsLongitude_string = str(int(gpsLongitude_string)/gnssScale)
            # WiFi channel
            channel_int = query_integer(snmpeng, commdata, transtarg,
OID_wifiChannel)
            # time
            dt = datetime.now()
            date = str(dt.date())
            time = str(dt.time())
            # Print each time, log at specified frequency:
            dataRow = [date, time, pwrin_string, str(brdtemp_int), \
                  str(rssi_int), str(rsrq_int), str(rsrp_int), sinr_string, \
                  str(channel_int), str(gpsSatCount_int), \
                  gpsLatitude_string, gpsLongitude_string, gpsHeading_string]
            print(dataRow)
            logwriter.writerow(dataRow)
            sleep(sleeptime)
         except KeyboardInterrupt:
            print('Closing CSV file')
            sys.exit()
```

Figure 2.4: Logging routine of modem/router logging code

The core of the logging routine is the query section. Example queries for GPS information are shown in Figure 2.5. Here, integer satellite count is obtained using *query_integer*, while strings for latitude, longitude, and heading are obtained with *query_displaystring*. The query routines leverage the Management Information Base (MIB) Object Identifiers (OIDs), pointers into the modem data locations. There are approximately 874 OIDs (either base or derivative) defined for the Sierra Wireless modem. The relevant OIDs for the current program are provided in Figure 2.6. Remaining OIDs can be found in the dull python code provided separately.

```
# GPS number sat, lat, lon, heading
gpsSatCount_int = query_integer(snmpeng, commdata, transtarg,
OID_satelliteCount)
gpsLatitude_string = query_displaystring(snmpeng, commdata, transtarg,
OID_latitude)
gpsLongitude_string = query_displaystring(snmpeng, commdata, transtarg,
OID_longitude)
gpsHeading_string = query_displaystring(snmpeng, commdata, transtarg,
OID_heading)
# Convert to real latitude/longitude:
gpsLatitude_string = str(int(gpsLatitude_string)/gnssScale)
gpsLongitude_string = str(int(gpsLongitude_string)/gnssScale)
```

Figure 2.5: Example queries for Global Positioning System (GPS) data, illustrating use of *query_integer* and *query_displaystring and conversion to actual latitude and longitude*

```
# Sierra MIB OIDs
#
OIDBASE_sierrawireless        = '1.3.6.1.4.1.20542'
OIDBASE_sharks                = OIDBASE_sierrawireless + '.9'
OIDBASE_mibversion1           = OIDBASE_sharks      + '.1'
OIDBASE_statustab             = OIDBASE_mibversion1   + '.1'

OIDBASE_home                  = OIDBASE_statustab     + '.1'
OID_powerIn                   = OIDBASE_home        + '.266'   # DisplayString (ro)
OID_boardTemprature           = OIDBASE_home        + '.267'   # INTEGER
(ro)
OID_rssi                      = OIDBASE_home        + '.261'   # INTEGER      (ro)

OIDBASE_cellular              = OIDBASE_statustab     + '.2'
OID_rsrq                      = OIDBASE_cellular     + '.10209' # INTEGER      (ro)
OID_rsrp                      = OIDBASE_cellular     + '.10210' # INTEGER      (ro)
OID_sinr                      = OIDBASE_cellular     + '.10211' # DisplayString (ro)

OIDBASE_gps                   = OIDBASE_statustab     + '.7'
OID_satelliteCount            = OIDBASE_gps         + '.901'   # INTEGER      (ro)
OID_latitude                  = OIDBASE_gps         + '.902'   # DisplayString (ro)
OID_longitude                 = OIDBASE_gps         + '.903'   # DisplayString (ro)
OID_heading                   = OIDBASE_gps         + '.904'   # DisplayString (ro)

OIDBASE_lan                   = OIDBASE_statustab     + '.3'
OID_wifiChannel               = OIDBASE_lan         + '.4508'  # INTEGER      (ro)
```

Figure 2.6: Explicit MIB OIDs used in the of modem/router logging code

Running the Logging Program

To run the logging program from the Linux command line, change to the directory containing the logging code. Upon initial installation, enable execution via:

chmod u+x sierralogger.py

For subsequent execution, use the following:

./sierralogger.py 192.168.31.254 161 public@ahmct

To stop logging, simply hit ctrl-c

Output Log File

The program generates a log in the form of a comma-separated value (CSV) file. The header for this file, based upon the collected data elements, is shown in Figure 2.7.

```
date, time, voltage, boardTemperature, rssi, rsrq, rsrp, sinr, wifiChannel,
satelliteCount, latitude, longitude, heading
```

Figure 2.7: CSV log file header

The fields can be briefly described as follows:

date, *time*: Date and time for the log entry. Time is UTC (Coordinated Universal Time).

voltage: Modem board voltage measurement (volts).

boardTemperature: Modem board temperature measurement (degree Celsius).

rssi: Received Signal Strength Indication, a measurement of the power present in the received cellular radio signal (dB).

rsrq: Reference Signal Received Quality, applies to 4G LTE (Long Term Evolution) networks, and is a measure of the signal quality of a cellular connection (dB).

rsrp: Reference Signal Received Power, a measurement of the received power level in an LTE cell network (dB).

sinr: Signal-to-Interference-plus-Noise Ratio (also known as the signal-to-noise-plus-interference ratio [SNIR]) gives theoretical upper bounds on the cell channel capacity (or the rate of information transfer) in wireless communication systems.

wifiChannel: The current channel (frequency range) in use by the modem. The channels are numbered. The 2.4 GHz band has 11 channels, while the 5 GHz band has 45 channels.

satelliteCount: The number of navigation satellites (Global Navigation Satellite System [GNSS]) included in the current navigation solution for the modem location.

latitude: The latitude of the current GNSS navigation position solution for the modem location (degrees).

longitude: The longitude of the current GNSS navigation position solution for the modem location (degrees).

heading: The heading (orientation) of the current GNSS navigation solution for the modem location (degrees).

A small sample of a log CSV output is provided in Figure 2.8, along with the corresponding conversion to Excel in Figure 2.9. Logging of GPS epoch (time) was requested. While this reading would be useful, this data is unfortunately not available from the Sierra Wireless SNMP interface.

```
date,time,voltage,boardTemperature,rssi,rsrq,rsrp,sinr,wifiChannel,satelliteCount,latitude,longitude,heading
9/8/2022, 09:18:10.861846,12.39,38,-35,-20,-83,-8.8,149,17,38.58341,-121.7043,182
9/8/2022, 09:18:12.430448,12.39,38,-35,-20,-83,-9.5,149,17,38.58341,-121.7043,182
9/8/2022, 09:18:14.011200,12.39,38,-41,-20,-83,-10.1,149,17,38.58341,-121.7043,182
9/8/2022, 09:18:15.605760,12.39,38,-41,-20,-83,-10,149,17,38.58341,-121.7043,182
9/8/2022, 09:18:17.158870,12.39,38,-41,-20,-83,-10,149,17,38.5834,-121.7043,182
9/8/2022, 09:18:18.749036,12.39,38,-41,-20,-83,-9.8,149,17,38.5834,-121.7043,182
9/8/2022, 09:18:20.312969,12.39,38,-41,-20,-83,-9.7,149,16,38.5834,-121.7043,182
9/8/2022, 09:18:21.891410,12.39,38,-41,-20,-83,-9.5,149,16,38.5834,-121.7043,182
9/8/2022, 09:18:23.517831,12.39,38,-41,-20,-83,-9.3,149,16,38.5834,-121.7043,182
9/8/2022, 09:18:25.133473,12.39,38,-41,-20,-83,-9.3,149,17,38.5834,-121.7043,182
….
```

Figure 2.8: Sample log CSV output for modem/router logging code

date	time	voltage	boardTemperature	rssi	rsrq	rsrp	sinr	wifiChannel	satelliteCount	latitude	longitude	heading
9/8/2022	09:18:10.861846	12.39	38	-35	-20	-83	-8.8	149	17	38.58341	-121.704	182
9/8/2022	09:18:12.430448	12.39	38	-35	-20	-83	-9.5	149	17	38.58341	-121.704	182
9/8/2022	09:18:14.011200	12.39	38	-41	-20	-83	-10.1	149	17	38.58341	-121.704	182
9/8/2022	09:18:15.605760	12.39	38	-41	-20	-83	-10	149	17	38.58341	-121.704	182
9/8/2022	09:18:17.158870	12.39	38	-41	-20	-83	-10	149	17	38.5834	-121.704	182
9/8/2022	09:18:18.749036	12.39	38	-41	-20	-83	-9.8	149	17	38.5834	-121.704	182
9/8/2022	09:18:20.312969	12.39	38	-41	-20	-83	-9.7	149	16	38.5834	-121.704	182
9/8/2022	09:18:21.891410	12.39	38	-41	-20	-83	-9.5	149	16	38.5834	-121.704	182
9/8/2022	09:18:23.517831	12.39	38	-41	-20	-83	-9.3	149	16	38.5834	-121.704	182
9/8/2022	09:18:25.133473	12.39	38	-41	-20	-83	-9.3	149	17	38.5834	-121.704	182

Figure 2.9: Corresponding sample log output converted into Excel

Appendix A:
Full Modem/Router Logger Code

This appendix provides the listing for the Python code for the Sierra Wireless modem/router logging program. The code is subject to modification as needed following the finalization of this report. This listing omits the 874 OID definitions. The key OID definitions are provided in Chapter 2.

```
#!/usr/bin/env python3
#
# sierralogger, version 20220908.0

# Copyright © 2022 The Regents of the University of California
# All Rights Reserved

"""Reads, displays, and logs data fields from Sierra Wireless modem/router."""

import csv
from datetime import datetime
import os
import sys
from time import sleep
from pysnmp.hlapi import getCmd
from pysnmp.proto import rfc1902
from pysnmp.hlapi import CommunityData
from pysnmp.hlapi import ContextData
from pysnmp.hlapi import ObjectIdentity
from pysnmp.hlapi import ObjectType
from pysnmp.error import PySnmpError
from pysnmp.hlapi import SnmpEngine
from pysnmp.hlapi import UdpTransportTarget

MPMODEL_SNMPV1  = 0
MPMODEL_SNMPV2C = 1

logFileBase = 'sierra'
logFileExtn = '.csv'

sleeptime = 1
```

```
# to translate modem readings to actual lat/lon:
gnssScale = 100000

def usage_exit(exitcode):
    print ("USAGE:")
    print ("  " + appname + " IP_ADDR PORT_NUM COMMUNITY_STRING")
    sys.exit(exitcode)

def main(argv):
    if len(argv) != 3:
        usage_exit(1)
    ip = argv[0]
    port = str_to_int(argv[1])
    if not port:
        usage_exit(1)
    community = argv[2]
    # initialize objects
    snmpeng = SnmpEngine()
    commdata = CommunityData(community,
mpModel=MPMODEL_SNMPV2C)
    transtarg = UdpTransportTarget((ip, port))
    # log data until user issues break signal, ctrl-c:
    log_data(snmpeng, commdata, transtarg)

def log_data(snmpeng, commdata, transtarg):
    global logFileBase, logFileExtn, gnssScale
    now = datetime.now()
    fileDateTime = now.strftime('%Y%m%d_%H%m%S')
    logfile = logFileBase + fileDateTime + logFileExtn
    with open(logfile, 'w', newline='') as csvfile:
```

```
        logwriter = csv.writer(csvfile, delimiter=',',
                    quotechar='"', quoting=csv.QUOTE_MINIMAL)
        header = ['date',
          'time',
          'voltage',
          'boardTemperature',
          'rssi',
          'rsrq',
          'rsrp',
          'sinr',
          'wifiChannel',
          'satelliteCount',
          'latitude',
          'longitude',
          'heading']
        logwriter.writerow(header)
        print(header)
        while True:
          try:
            # voltage
            pwrin_string = query_displaystring(snmpeng, commdata, transtarg,
OID_powerIn)
            # board temperature (note the misspelling of the object name)
            brdtemp_int = query_integer(snmpeng, commdata, transtarg,
OID_boardTemprature)
            # RSSI
            rssi_int = query_integer(snmpeng, commdata, transtarg, OID_rssi)
            # RSRQ
            rsrq_int = query_integer(snmpeng, commdata, transtarg, OID_rsrq)
            # RSRP
            rsrp_int = query_integer(snmpeng, commdata, transtarg, OID_rsrp)
            # SINR
```

```
            sinr_string = query_displaystring(snmpeng, commdata, transtarg,
OID_sinr)
            # GPS number sat, lat, lon, heading
            gpsSatCount_int = query_integer(snmpeng, commdata, transtarg,
OID_satelliteCount)
            gpsLatitude_string = query_displaystring(snmpeng, commdata,
transtarg, OID_latitude)
            gpsLongitude_string = query_displaystring(snmpeng, commdata,
transtarg, OID_longitude)
            gpsHeading_string = query_displaystring(snmpeng, commdata,
transtarg, OID_heading)
            # Convert to real latitude/longitude:
            gpsLatitude_string = str(int(gpsLatitude_string)/gnssScale)
            gpsLongitude_string = str(int(gpsLongitude_string)/gnssScale)
            # WiFi channel
            channel_int = query_integer(snmpeng, commdata, transtarg,
OID_wifiChannel)
            # time
            dt = datetime.now()
            date = str(dt.date())
            time = str(dt.time())
            # Print each time, log at specified frequency:
            dataRow = [date, time, pwrin_string, str(brdtemp_int), \
                str(rssi_int), str(rsrq_int), str(rsrp_int), sinr_string, \
                str(channel_int), str(gpsSatCount_int), \
                gpsLatitude_string, gpsLongitude_string, gpsHeading_string]
            print(dataRow)
            logwriter.writerow(dataRow)
            sleep(sleeptime)
        except KeyboardInterrupt:
            print('Closing CSV file')
            sys.exit()
```

```
def run_demo(snmpeng, commdata, transtarg):
    # voltage
    pwrin_string = query_displaystring(snmpeng, commdata, transtarg,
OID_powerIn)
    print('voltage:    ' + pwrin_string + ' V')
    # board temperature (note the misspelling of the object name)
    brdtemp_int = query_integer(snmpeng, commdata, transtarg,
OID_boardTemprature)
    print('board temp: ' + str(brdtemp_int) + ' \u00B0C')
    # RSSI
    rssi_int = query_integer(snmpeng, commdata, transtarg, OID_rssi)
    print('RSSI:       ' + str(rssi_int) + ' dBm')

def query_integer(snmpeng, commdata, transtarg, oid):
    val = query(snmpeng, commdata, transtarg, oid + '.0', rfc1902.Integer)
    # return int(val)
    return int(val)

def query_displaystring(snmpeng, commdata, transtarg, oid):
    val = query(snmpeng, commdata, transtarg, oid + '.0', rfc1902.OctetString)
    return str(val)

def query(snmpeng, commdata, transtarg, oid, expected_type):
    try:
        it = getCmd(
            snmpeng,
            commdata,
            transtarg,
            ContextData(),
            ObjectType(ObjectIdentity(oid)),
            lookupMib=False
        )
```

```
        (err_indic, err_stat, err_idx, var_binds) = next(it)
    except PySnmpError:
        return None
    if err_indic or err_stat or (len(var_binds) != 1):
        return None
    val = var_binds[0][1]
    if (type(val) != expected_type):
        return None
    return val

def str_to_int(s):
    try:
        return int(s)
    except ValueError:
        return None

#####################################################
# ………………… Sierra MIB OID definitions omitted here…………………
#####################################################

if __name__ == '__main__':
    global appname
    appname = sys.argv[0]
    main(sys.argv[1:])
```

Appendix G: Interim Report Summarizing Aerial Repeater Research Investigations and Analysis of Investigation Results

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16. ABSTRACT
This report is part of AHMCT's research project "Development and Testing of an Unmanned Aerial System (UAS) Cellular & Wi-Fi Repeater: Phase 1." The purpose of the research is to investigate the possibility of extending the range of existing wireless communications infrastructure for a variety of remote communications use cases in existing rural projects (Responder, Handheld Terminal, etc.). The ultimate goal of the research is to evaluate the benefits and drawbacks of the aerial repeater concept via investigative flights. This document provides the analysis for the research investigations.

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Unmanned Aerial Systems Communications Repeater (UASC-R) Research Investigation Analysis

Dave Torick, Kin Yen, &
Ty A. Lasky: Principal Investigator

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Division of Research, Innovation and System Information

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List of Acronyms and Abbreviations

Acronym	Definition
AGL	Above Ground Level
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ATC	Air Traffic Control
Caltrans	California Department of Transportation
COM	Center of Mass
CSV	Comma-separated value
Deg	Degrees
DRISI	Caltrans Division of Research, Innovation and System Information
Elev	Elevation
FAA	Federal Aviation Administration
IMU	Inertial Measurement Unit
LAANC	Low Altitude Authorization and Notification Capability
NOTAMs	Notice to Airmen or Notice to Air Missions
RPIC	Remote Pilot in Command
RTH	Return to home
SOP	Standard Operating Procedure
TFRs	Temporary Flight Restrictions
UAS	Unmanned Aerial System
UASC-R	Unmanned Aerial Systems Communications Repeater

Acronym	Definition
VLOS	Visual Line of Sight
VO	Visual Observer
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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Chapter 1: Introduction

Communication options in rural districts within the California Department of Transportation (Caltrans) are intermittent and in some cases unavailable. The aim of this project is to extend existing cellular infrastructure service boundaries further into rural districts. We seek to accomplish this by employing an Unmanned Aerial System (UAS) with a communications payload developed to provide cellular data service range extension via routing between a cellular interface Wireless Wide Area Network (WWAN) and a wireless interface Wireless Local Area Network (WLAN).

The reader should be aware that the final UASR-C that was developed and utilized in this task is summarized and compared to the systems requirements in an appendix in the final report for this research task.

The purpose of this document is to provide the analysis for the research investigations.

Chapter 2: Research Investigation Analysis

The aerial repeater system successfully created a communication network while the UAS was at its maximum safe distance of 2000 ft and maximum altitude of 400 ft above ground level (AGL).

Through the research investigations, the Advanced Highway Maintenance and Construction Technology (AHMCT) researchers established a Standard Operating Procedure (SOP) for UAS operations that is discussed in Section 2.1. The RPIC is legally responsible for the maintenance and operations of the UAS, our SOP's below are based on current Federal Aviation Administration (FAA) Part 107 requirements, our investigations, and research. Since the UAS field is relatively new, it is recommended that the SOP's be revisited and re-evaluated on a regular basis to insure the safe legal operations of the UAS.

The UAS performance on task elements with and without the aerial repeater payload are discussed in Section 2.2. Section 2.3 contains the system performance of the final design. Appendix A contains the Research Investigation Summaries.

2.1 SOP

2.1.1 Pre-Flight

The safe operation of a UAS occurs with planning and checklists. In this section we describe the SOPs that we used for our research investigations.

The University of California has created an extensive [Drone Map of California (https://ucdrones.github.io/map/)](https://ucdrones.github.io/map/) for use by a Remote Pilot in Command (RPIC) for mission planning. This online map provides further details regarding airspace restrictions beyond what is typically found using online resources.

2.1.1.1 Day Before Flight

Proper mission planning relative to the flight location is also critical the day before a flight. It is recommended to print a satellite image of the flight location and mark hazards. Below is a list of items that should be checked and noted on the image to act as a reference when the flight occurs:

- Take-off area
- Landing area
- Potential obstacles and mitigation to:
  - Visual Line of Sight (VLOS)
  - Flight path, such as vertical structure heights and locations

    - Control communications
- Impact of sun or shadows on best visual angles for flight and locations of Visual Observer (VO) and RPIC
- Anticipated people or vehicles in flight path
- Emergency landing plan / locations
- Wind forecast
- Weather forecast
- Flight geographic objective

After the above site planning has occurred it is important to verify the UAS and the airspace you will be flying in. The researchers found it useful to follow the checklist below to insure that proper preparation has occurred:

- Check and charge all batteries
- Update all software, battery controller, tablets, drone
- Inspect propellers
- Scout your location using the FAA's B4UFLY app (https://www.faa.gov/uas/getting_started/b4ufly)
- Use VFRMap to check on additional flight hazards and airport information (https://vfrmap.com)
- If needed, get Low Altitude Authorization and Notification Capability (LAANC) approval (https://www.faa.gov/uas/programs_partnerships/data_exchange)
- Check for Notices to Airmen (NOTAMs) (https://notams.aim.faa.gov/notamSearch/nsapp.html#/)
- Check for Temporary Flight Restrictions (TFRs) (https://tfr.faa.gov/tfr2/list.html)
- Packing
    - UAS
    - UAS payload(s)
    - Spare propellers, and tools to change propellers
    - Batteries
    - Controller
    - Landing Mat
    - First aid
    - Fire extinguisher

Given the manner that UAS systems receive firmware updates, it is essential to carefully monitor such updates, and test the UAS operation rigorously after any firmware updates. From the experience of the current research, as well as indications from the user community, the vendors do not always sufficiently test functionality as they update system firmware, and do not tend to notify users when there are issues. Untested firmware can lead to inability to fly in a culture of safety. Caltrans operators must place safety first for UAS operation. If an operator identifies an issue that would keep the UAS from flying safely, whether due to software, hardware, or some external factor, the operator must ground the UAS until safety can be reestablished.

2.1.1.2 Day of Flight

Following a checklist and documenting your process is a key responsibility of an RPIC. The use of online systems that can easily integrate into the controller is recommended. Below is a minimum list of items that should be checked:

- Confirm airspace and permissions for Air Traffic Control (ATC) if required
- Review local NOTAMs and TFRs
- Identify air traffic routes for collision avoidance
- Confirm current and forecast weather conditions are safe for UAS operations
    - Visibility greater than 3 miles
    - Cloud ceiling is above 500 feet AGL
    - Wind speed is within UAS operating limits
    - Participating personnel only allowed under UAS flight path
    - Non-participating personnel must be under protective covering
    - Safety briefing conducted
    - Risk to property and personnel assessed and mitigated
    - Location of ground hazards assessed
    - Level of risk assessed
    - Flight boundary area identified
    - Primary and alternative take-off and landing location determined
    - Batteries are sufficient for planned flight time
    - UAS in safe condition for flight

2.1.2 In-Flight

After performing the pre-flight checklist, the UAS can take-off. Before take-off the RPIC should:

- Position the drone so it is facing into the wind
- Stand behind the drone so the RPIC forward perspective matches forward on the controller and the drone
- Verify that there are no overhead obstructions, again
- Verify controller, drone, and battery systems are functioning properly

    - Insure all firmware updates are current
    - Verify Inertial Measurement Unit (IMU) and compass calibration
    - Verify values for RTH, collision avoidance, maximum height, and maximum range are correct
- Announce that they are energizing the UAS (turning on the rotors)
- Announce that they are launching

Once the drone is airborne a final in-flight inspection should occur before the mission. This procedure should include the following at a minimum:

- Hover at eye level to perform several checks:
    - Verify home location was properly set by the drone on the map
    - Listen for abnormal sounds
    - Yaw 90 degrees left, and verify all latches are closed and payload is secure
    - Yaw 180 degrees right, and verify all latches are closed and payload is secure
- Increase drone elevation to several feet above RPIC's head
    - Verify the drone pitches forward and backward
    - Verify the drone rolls left and right
- Conduct mission
- At the conclusion of the mission, announce that they are landing

After the above checks have been conducted it is now safe to carry out the mission.

It is essential to monitor for frequency/signal interference between UAS control, video telemetry, and the communications payload modem/Wi-Fi. For initial operations with a new system, first test on the ground. If all is well, i.e. there appears to be no interference, test the system with low-level flight at less than 10~feet. If again there is no interference, monitor for signs during the initial full-scale flight. If there is interference, one option would be to restrict the UAS control to one frequency. This is not ideal, as the UAS will perform better if the controller can automatically switch frequencies for the best signal; however, this may be essential if there is interference with the other subsystems.

2.1.3 Post-flight/Maintenance

For safe and proper use of a UAS-based system, it is essential to maintain a culture of safety, including initial and consistent follow-up training and regular practice and skills refresh. Logging is essential for all aspects of safe and efficient UAS use.

It is also necessary to verify the condition of the UAS after flight. The blades should be inspected to insure they are not damaged, and proper safety precautions should occur for the battery storage. It is recommended to charge the batteries post-flight in the battery charging case. The batteries will self-discharge after a set amount of time to insure the longest battery life possible.

The RPIC should also insure that the UAS manufacturer's maintenance and inspection plan is followed. Online systems also offer an efficient method for tracking this information and providing reminders to the RPIC.

2.2 Aerial Repeater Performance based on Task Elements

The aerial repeater UAS system worked as expected during the research investigations. The complete set of research summaries is located in Appendix A.

2.2.1 Take-off and Landing Task

The UAS was able to safely and consistently take off and land. The UAS should take off and land from a weighted drone landing pad to avoid flying debris and to keep air quality high by reducing dust. The steps and checklists discussed in Section 2.1 must be conducted before all flight operations to insure safe operations.

Landing can be performed using the Return-To-Home (RTH) button on the controller. This is not recommended, as the UAS will go to the pre-programmed RTH height and then take a straight line back to the home point, without regard to lower-level obstacles. Once it is above the home point it will automatically land. Should the RTH be used, if the RPIC needs to override the RTH feature, they can take control again by moving the joysticks; this will stop the RTH feature.

It is recommended that the UAS lands under manual control and the RPIC and UAS are in the same forward orientation as take-off. A VO will be beneficial in helping land if the landing location is relatively far from the RPIC. The RPIC can orient the drone horizontally with respect to the landing area, while the VO can help insure the UAS is at the proper depth to land on the landing zone. If a VO is not available, the RPIC should first locate the drone horizontally above the landing zone and then walk to the left or right to allow the drone to be at the proper depth. An angle of about 15° should be sufficient for depth perception, however, the greater the angle the better the depth perception.

2.2.2 Flight Time Task

The Matrice M300 has an advertised flight time of up to 55 minutes in ideal conditions. However, through our investigations we did not approach this duration. To insure better battery life, it is recommended to begin your landing procedure at around 30% battery charge remaining. This may be one reason our results differed so dramatically from the company's website information. With a full battery, normal operating conditions and flight, and landing at 30% battery charge the UAS has about 33 minutes of useful flight time.

The aerial repeater payload decreases the above mentioned useful flight time due to the additional mass that the UAV must lift and support. With the full aerial repeater payload (mounting hardware, mounting plate, antennas, repeater, and battery) of 1.3 kg, the UAV's flight time decreased to 27 minutes.

2.2.3 Payload Task

The payload task verification required the most research investigations to complete in order to insure that negative impacts to the UAS airworthiness would be minimalized during each validation. Upon completion of the investigation, it was found that the UAS can fly normally and can use both its 2.4 GHz and 5 GHz frequencies for communication without impacting Wi-Fi communication network created by the aerial repeater payload.

Investigation #5 was a short indoor flight to calibrate the new center of mass (COM) with the aerial repeater payload installed on the drone. COM recalibration is necessary when a non-DJI payload is added to the UAS. DJI products that connect through the DJI Skyport automatically adjust the UAS COM. These products, such as the DJI cameras, allow quick connections and minimal effort to insure safe flight operations. The COM recalibration is done through the Pilot 2 application on the controller and remains until the COM is recalibrated. Note that if the payload is removed the COM should be recalibrated before flight operations of the UAS.

Investigation #6 was an outdoor flight to validate the safe operation of the UAS in an outdoor environment and to determine the impact on flight time of the added mass of the payload. There were no issues with flight performance, so the research progressed to the next investigation.

Investigation #7 was an indoor flight with the aerial repeater payload on and transmitting/receiving. There was no impact on the flight performance or control of the UAS, therefore the research continued.

Investigation #8 was an outdoor flight to verify that safe operations of the UAS can occur with the payload transmitting/receiving. The maximum height of this flight was 50 feet AGL to minimize any potential negative outcomes. There were no issues with flight performance or control of the UAS, therefore the research continued.

2.2.4 Flight Data Task

The UAV records inflight data such as location, altitude, wind speed, battery charge. This data can be viewed using DJI Pilot, a tool from the UAS manufacturer However, third-party companies can provide deeper interaction with the data. These applications typically allow the RPIC to download a comma-separated value (CSV) file of the entire flight and store the data in the cloud. Through our research investigations we utilized Airdata Drone Data Management and Flight Analysis app (https://airdata.com) to record and view our flight data.

The CSV file has over 50 columns of data from the UAS and it provides the data at a 10 Hz sampling rate. Summary information can also be viewed through Airdata's web interface. Figures 2.1 thru 2.3 are samples from an investigative flight.

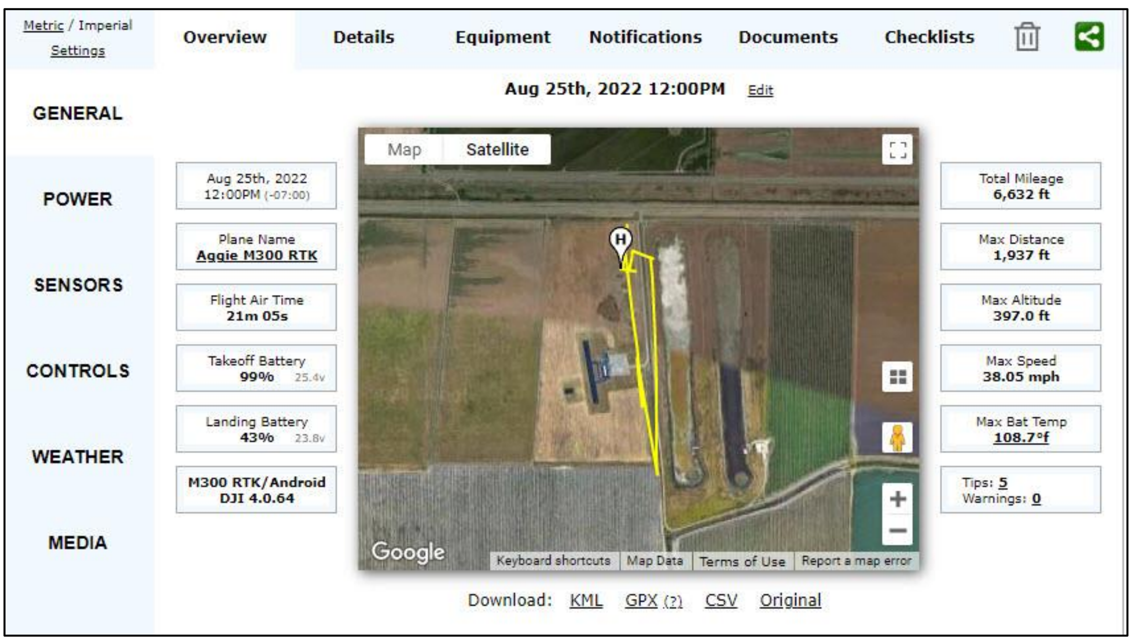


Figure 2.1: Overview of UAS flight data from Airdata

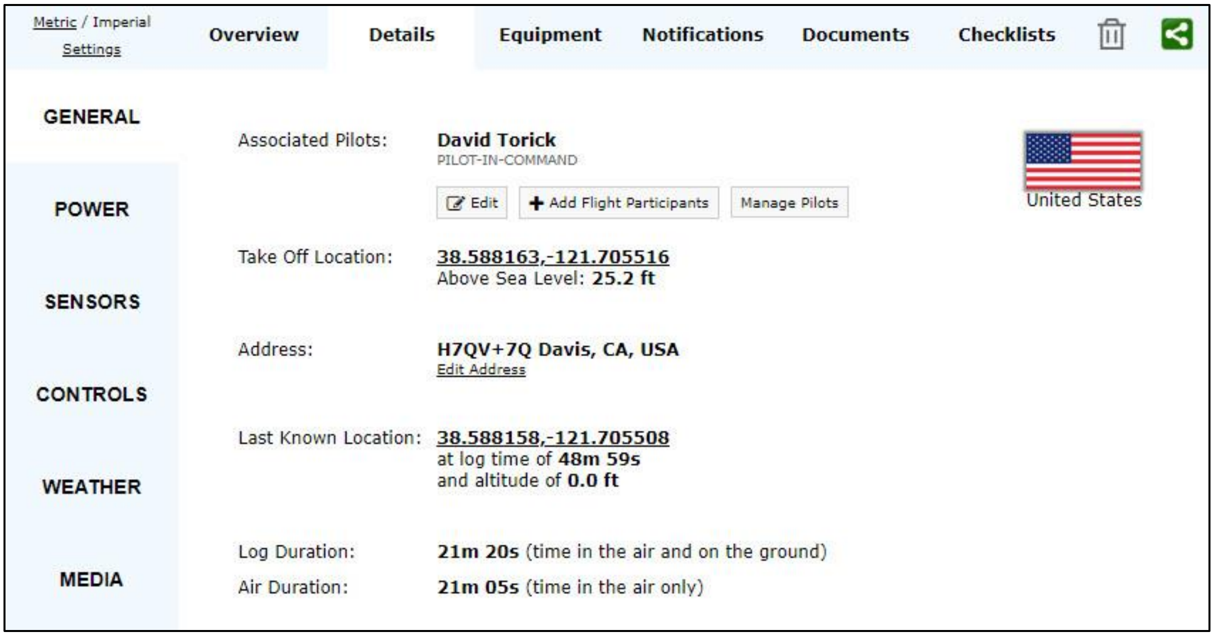


Figure 2.2: Details of a UAS flight from Airdata

Figure 2.3: Equipment utilized for a UAS flight documented on Airdata

2.2.5 Communication Test Task

Investigations #9 and #10 were conducted to determine Wi-Fi network quality. These investigations were carried out in normal operating parameters of up to 400 ft AGL, and up to 2000 ft from the take-off location. Through these investigations, we determined the optimal aerial antenna combination and hardware on the ground. These details are summarized in the next section.

2.3 Aerial Repeater System Performance

Through the research investigation and subsequent design modifications we can categorize the final system performance into flight, payload, and communication. The aerial repeater system was able to upload and download data using its communication link to a cell tower at the extents of safe flight based on the UAS's size and FAA Part 107 requirements.

The University of California's [Visual Line of Distance Estimator (https://ucdrones.github.io/library/vlos/)](https://ucdrones.github.io/library/vlos/) provides a recommendation for the safe maximum distance of a UAS. Figure 2.4 is a screen shot of the values for an M300, the maximum AGL is 400 ft per FAA Part 107, and the maximum distance at that height is approximately 2000 ft.

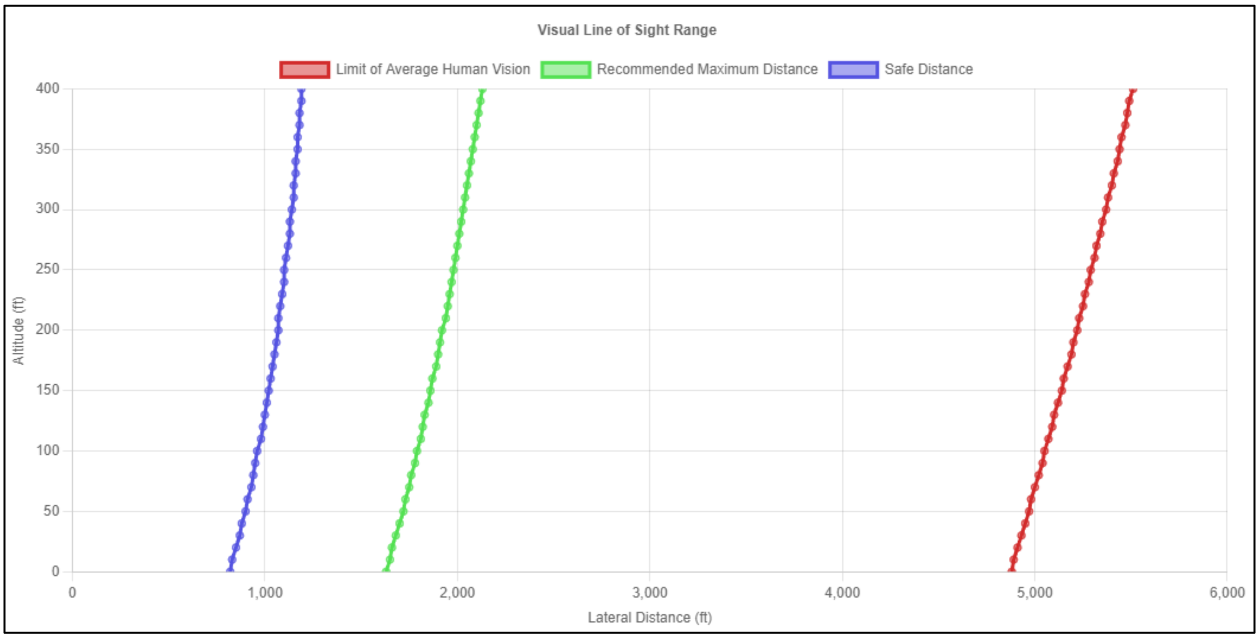


Figure 2.4: Visual Line of Sight Range for the Matrice M300, downloaded from [Visual Line of Distance Estimator (https://ucdrones.github.io/library/vlos/)](https://ucdrones.github.io/library/vlos/)

The devices used for the system performance test on the ground were either a PC connected to the SXTsq5 Wi-Fi bridge or a Pixel 6 smartphone connected to a TP-Link TL-WA1201wireless access point. The aerial repeater was a Sierra Wireless MP70. Table 2.1 summarizes the results of research Investigation #10, while Table 2.2 provides an overall aerial repeater system summary.

Table 2.1: Research Investigation #10 Wi-Fi Network Parameters

UAS Location (distance@ height [orientation])	Device	Signal Strength (dBm)	Signal to Noise Ratio (dB)	Internet connection download speed (4G) (Mb/s)	Internet connection upload speed (4G)(Mb/s)	Latency (ms)
1500' @ 400' Elev	PC via SXTsq5	-64	56	4.56	2.5	96
1500' @ 400' Elev	Pixel 6 via TL-WA1201	N/A	N/A	0.25	3.98	65
1500' @ 400' Elev Turned 180 deg	PC via SXTsq5	-67	50	2.72	1.58	26
1500' @ 400' Elev Turned 180 deg	Pixel 6 via TL-WA1201	N/A	N/A	2.85	3.96	34
2000' @ 400' Elev	PC via SXTsq5	-65	54	2.72	8.22	32
2000' @ 400' Elev	Pixel 6 via TL-WA1201	N/A	N/A	1.75	7.24	39
2000' @ 400' Elev Turned 180 deg	PC via SXTsq5	-68	49	3.2	2.2	28
2000' @ 400' Elev Turned 180 deg	Pixel 6 via TL-WA1201	N/A	N/A	1.17	1.06	31
2000' @ 400' Elev	PC via SXTsq5	-64	50	5.8	7.9	25
2000' @ 400' Elev	Pixel 6 via TL-WA1201	N/A	N/A	3.7	5.8	34

Table 2.2: Aerial Repeater System Performance

Category	Metric	Value
Flight	Maximum flight time, no payload, land at 30% battery	33 minutes
	Maximum flight time, with repeater payload, land at 30% battery	27 minutes
	Maximum safe distance at 400' AGL	Less than 2200 ft
Payload	Weight of complete aerial repeater payload	1.3 kg
Communication Link @ 2000'@400'Elev	Signal Strength	-65 dBm
	Signal to Noise	54 dB
	Download Speed	2.7 Mb/s
	Upload Speed	8.2 Mb/s
	Latency	32

Appendix A: Collection of Investigation Summaries

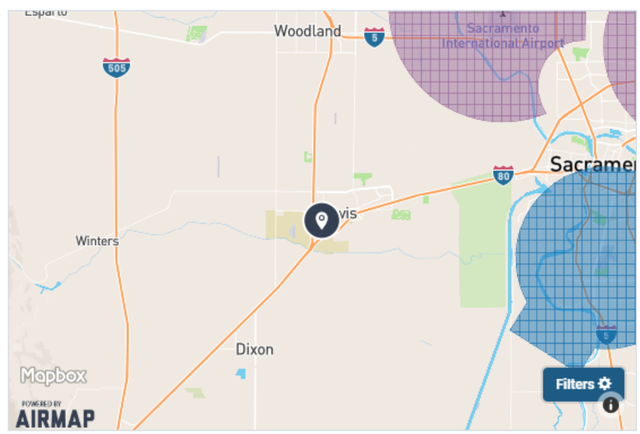
Investigative Summary- Aerial Repeater

Investigation #	1
Investigation date	04/20/2022
Investigation name	Initial Supplier Drone Training
Purpose	Classroom and flight time to learn the proper preparations for UAS flight and basic flight control training provided by UAS supplier.
Post-investigation summary	Full detailed notes of the training event are in Appendix B of this task Key takeaways: • Battery maintenance, charge before storage • Update firmware frequently • Follow pre-flight checklist • Enterprise drones have strong anti-collision and route planning abilities

Flight Request

Project: Initial Supplier Drone Training
From: Apr 20, 2022 - **To:** Apr 21, 2022

Flight Nickname	Initial Supplier Drone Training - 1
Flight Purpose	Testing or Flight Instruction
UAS Regulation	107
Date Time	Apr 20, 2022 12:00 PM
Field Time	240
Number of flights	6
Location	38.53993200270014, -121.75973539821132
Max Distance	400 ft.
Flight Altitude	400 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	Initial 1 day training with Drone Supplier
Operation Restriction	Weather issue – High winds,Weather issue – Rain/Thunderstorm
Comments	Our trainer and Sean Campbell will also fly the drone during the training. Sean is a Caltrans employee who has Trust token certificate ERAU10000021473
RiskAssessment	High winds or rain will decrease our planned max distance and altitude
Observers	Ty Lasky, Sean Campbell

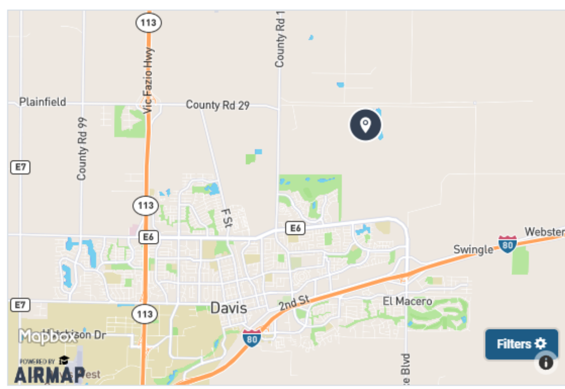


Investigative Summary- Aerial Repeater

Investigation #	2
Investigation date	07/07/2022
Investigation name	Basic Flight Investigation #1
Purpose	Take-off and landing
Post-investigation summary	The drone was able to successfully take-off and land. While taking off it is important to do an initial inspection while in the air to verify controls and also allow the home point to update. Both of these steps worked well repeatedly. While landing, it is challenging to insure that you are over top of the landing zone, and it is recommend to descend slowly and make adjustments based off of the disturbances on the ground from the properly wash. It is also recommended that an observer is located off to one side of the landing zone to help determine the depth of the drone relative to the landing zone. The pilot can easily determine the drone's horizontal location to the landing zone, but can benefit from an observer for the depth to the landing zone.

Flight Request

Flight Nickname	Aerial Repeater- Data flgiht
Flight Purpose	Other – Research
UAS Regulation	Other
Date Time	Jul 7, 2022 01:00 pm
Field Time	120
Number of flights	5
Location	38.585597663117426,-121.70582377290542
Max Distance	200 ft.
Flight Altitude	100 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	1. Insure clear skies and clear launch area 2. Take off and verify controls at 10 feet AGL 3. Ascend to 100 feet 4. Maneuver at 100 feet within 200 feet of launch zone. 5. Return to takeoff zone
Operation Restriction	
Comments	Gather information and practice pilot abilities for research project related to flight data that is recorded and accessible after downloading from drone/controller.
RiskAssessment	Flying out of Woodland Davis Aeromodelers Airfield Adverse weather conditions will cause postponement on flight to another date. Flight day is not critical.
Observers	Sean Campbell

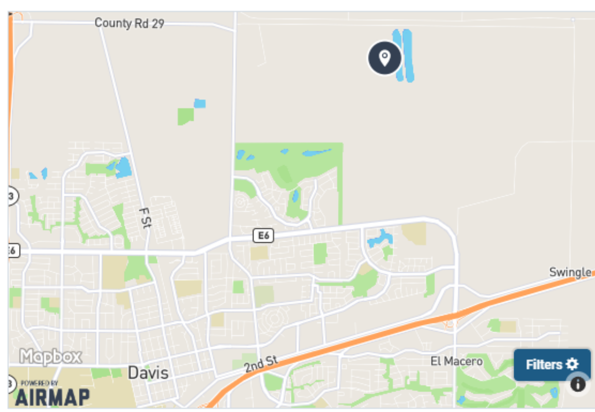


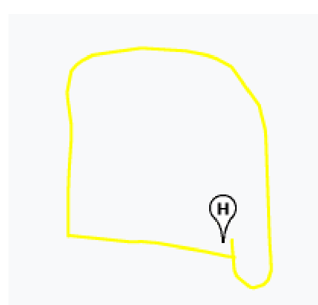
Investigative Summary- Aerial Repeater

Investigation #	3
Investigation date	07/18/2022
Investigation name	Basic Flight Investigation #2
Purpose	Landing without a VO
Post-investigation summary	Individual practice on landing without a VO. Multiple short flights were conducted to determine an approach utilizing the camera and map on the controller to land on the landing zone. While at a distance from the landing zone, the camera can be utilized to determine the depth to the landing zone if the drone faces 90 degrees away from the POC. Once the depth is confirmed, the pilot can then use visual observations to align horizontally. The POC also practiced moving about 30 degrees off axis, to help establish the depth of the drone, however, this approach has limitations due to potential take-off and landing zone limitations for safety and topography.

Flight Request

Flight Nickname	Aerial Repeater- Data flgiht
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Jul 18, 2022 01:30 PM
Field Time	90
Number of flights	2
Location	38.585597663117426, -121.70582377290542
Max Distance	200 ft.
Flight Altitude	100 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	1. Insure clear skies and clear launch area 2. Take off and verify controls at 10 feet AGL 3. Ascend to 100 feet 4. Maneuver at 100 feet within 200 feet of launch zone. 5. Return to takeoff zone
Operation Restriction	
Comments	Repeat from operation on 07/15/2022, 01:00 pm, flight did not occur due to scheduling - Gather information and practice pilot abilities for research project related to flight data that is recorded and accessible after downloading from drone/controller.
RiskAssessment	Flying out of Woodland Davis Aeromodelers Airfield Adverse weather conditions will cause postponement on flight to another date. Flight day is not critical.
Observers	Sean Campbell



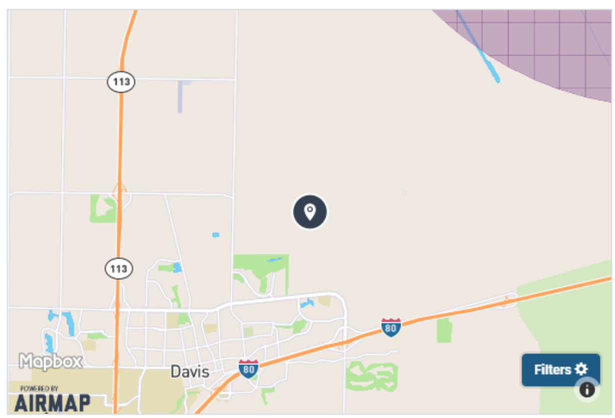


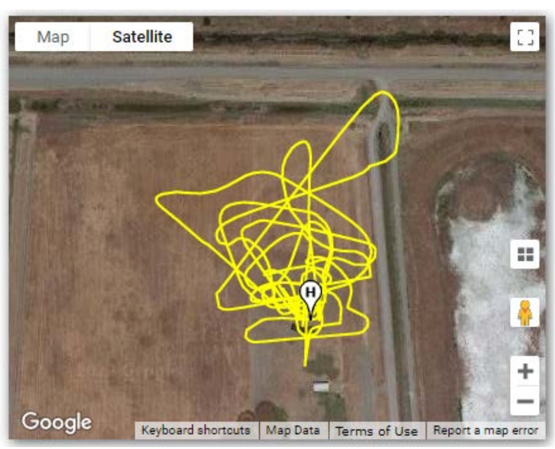
Investigative Summary- Aerial Repeater

Investigation #	4
Investigation date	07/18/2022
Investigation name	Basic Flight Investigation #3
Purpose	PIC training and flight data gathering and post-flight review
Post-investigation summary	Multiple flights were conducted to gather multiple data sets for review using Airdata.com. This subscription service was able to translate the data into a user-friendly summary, as can be seen from the map below with the yellow flight lines of the UAS. The summary screen also shows key elements such as: flight time, battery levels at takeoff and landing, max distance, max altitude, max speed, and max battery temperature. We were also able to download the flight data as a*.csv file for further analysis.

Flight Request

Flight Nickname	Aerial Repeater- Data flgiht
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Jul 18, 2022 01:30 PM
Field Time	90
Number of flights	2
Location	38.585597663117426, -121.70582377290542
Max Distance	200 ft.
Flight Altitude	100 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	1. Insure clear skies and clear launch area 2. Take off and verify controls at 10 feet AGL 3. Ascend to 100 feet 4. Maneuver at 100 feet within 200 feet of launch zone. 5. Return to takeoff zone
Operation Restriction	
Comments	Repeat from operation on 07/15/2022, 01:00 pm, flight did not occur due to scheduling - Gather information and practice pilot abilities for research project related to flight data that is recorded and accessible after downloading from drone/controller.
RiskAssessment	Flying out of Woodland Davis Aeromodelers Airfield Adverse weather conditions will cause postponement on flight to another date. Flight day is not critical.
Observers	Sean Campbell



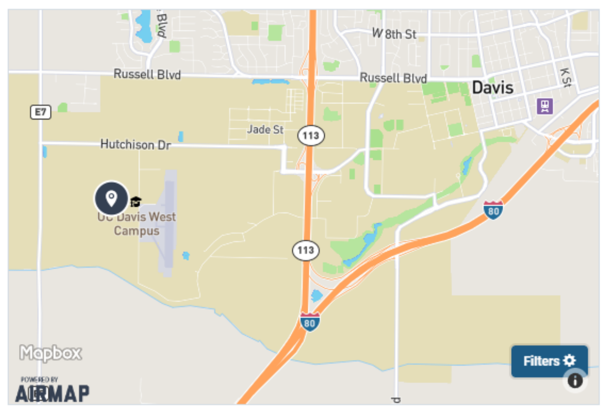


Investigative Summary- Aerial Repeater

Investigation #	5
Investigation date	08/03/2022
Investigation name	Payload Investigation #1
Purpose	Verification of airworthiness of repeater payload
Post-investigation summary	A short indoor flight was conducted to ensure that the UAS could successfully carry the cargo and recalibrate the COM. There were no issues with the UAS. The UAS performed as expected both before and after recalibration of the center of mass. The UAS is now currently set with a new COM, if flights are to be conducted without the payload, then the COM should be recalibrated in an indoor environment.

Flight Request

Flight Nickname	Aerial Repeater- Payload trials
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Aug 3, 2022 08:30 AM
Field Time	15
Number of flights	1
Location	38.534088414234844, -121.79405822815454
Max Distance	1 ft.
Flight Altitude	5 ft.
Flying over people	No
Flying near building	Yes
Flying indoors	Yes
Flight Procedure	We have designed a payload for the drone and will recalibrate Center of Gravity per user manual. Verify no other employees are in vehicle bay, insure 10 feet of clearance to drone. Fly only to recalibrate and then land.
Operation Restriction	
Comments	Next phase of research project, prove payload is airworthy.
RiskAssessment	PIC will be located close to a cabinet that they can move behind if catastrophic issues arise
Observers	None

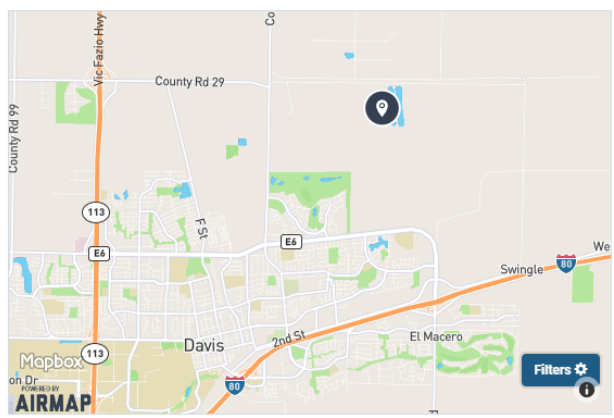


Investigative Summary- Aerial Repeater

Investigation #	6
Investigation date	08/03/2022
Investigation name	Payload Investigation #2
Purpose	Determine the flight time of UAS with repeater payload
Post-investigation summary	2 flights were conducted with fully charged battery sets to determine the flight time of the UAS with the aerial payload. The first flight was 27 minutes and with the initial battery percentage of 99% and the landing battery percentage of 26%. The second flight was also 27 minutes with an initial battery percentage of 100% and a landing battery percentage of 35%. The difference in battery level can be attributed to variations in the battery pairs or variations in the aerial maneuvers of the UAS, the UAS was flown around the airfield as can be seen by the flight path in yellow below.

Flight Request

Flight Nickname	Aerial Repeater- Data flgiht
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Aug 3, 2022 10:00 AM
Field Time	120
Number of flights	4
Location	38.585597663117426, -121.70582377290542
Max Distance	1000 ft.
Flight Altitude	400 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	1. Insure clear skies and clear launch area 2. Take off and verify controls at 10 feet AGL 3. Ascend to 100 feet 4. Maneuver at 100 feet within 200 feet of launch zone. 5. Return to takeoff zone
Operation Restriction	
Comments	Short range air trials of new payload. Dependent on successful Center of Gravity test earlier in the day.
RiskAssessment	Flying out of Woodland Davis Aeromodelers Airfield Adverse weather conditions will cause postponement on flight to another date. Flight day is not critical.

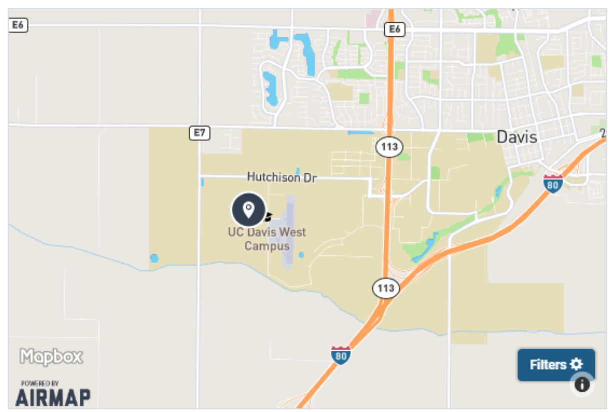


Investigative Summary- Aerial Repeater

Investigation #	7
Investigation date	08/12/2022
Investigation name	Communication test #1
Purpose	Initial test of repeater payload to determine if there is any interference of UAS control due to the Wi-Fi network the repeater payload will produce.
Post-investigation summary	The UAS performed as expected with no interference from the Wi-Fi network that was created from the repeater payload. It is okay to proceed to an outdoor flight test based on these results.

Flight Request

Flight Nickname	Aerial Repeater- Payload trial #2
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Aug 12, 2022 10:30 AM
Field Time	30
Number of flights	2
Location	38.53488307480251, -121.79419380578894
Max Distance	500 ft.
Flight Altitude	100 ft.
Flying over people	No
Flying near building	Yes
Flying indoors	Yes
Flight Procedure	1. follow checklist 2. fly indoors with payload transmitting 3. If 2 is okay, then fly outdoors with payload transmitting
Operation Restriction	
Comments	Next phase of testing for cellular repeater drone project, verified payload does not impact flight performance. Now we will, in a controlled fashion determine if payload being on will impact the SUAS system.
RiskAssessment	If any communications issues arise flight will terminate and troubleshooting occurs
Observers	Kin Yen

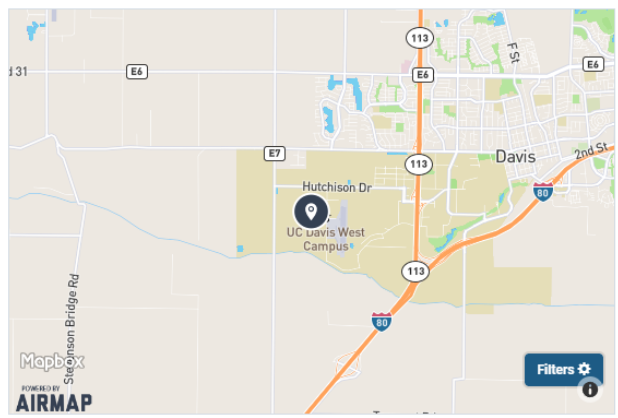


Investigative Summary- Aerial Repeater

Investigation #	8
Investigation date	08/12/2022
Investigation name	Communication test #2
Purpose	Next test of repeater payload to determine Wi-Fi signal strength and data transfer rates using the Wi-Fi generated from the payload.
Post-investigation summary	The wi-fi network created by the repeater payload created a network that we were able to connect with at close range. However, we were not able to connect with it at a greater distance, antenna revisions are planned before the next flight.

Flight Request

Flight Nickname	Aerial Repeater- Payload trial #2
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Aug 12, 2022 10:30 AM
Field Time	30
Number of flights	2
Location	38.53488307480251, -121.79419380578894
Max Distance	500 ft.
Flight Altitude	50 ft.
Flying over people	No
Flying near building	Yes
Flying indoors	Yes
Flight Procedure	1. follow checklist 2. fly indoors with payload transmitting 3. If 2 is okay, then fly outdoors with payload transmitting
Operation Restriction	
Comments	Repeat from operation on 08/12/2022, 10:30 AM - Next phase of testing for cellular repeater drone project, verified payload does not impact flight performance. Now we will, in a controlled fashion determine if payload being on will impact the SUAS system. Max altitude of 50 feet AGL.
RiskAssessment	If any communications issues arise flight will terminate and troubleshooting occurs
Observers	Kin Yen

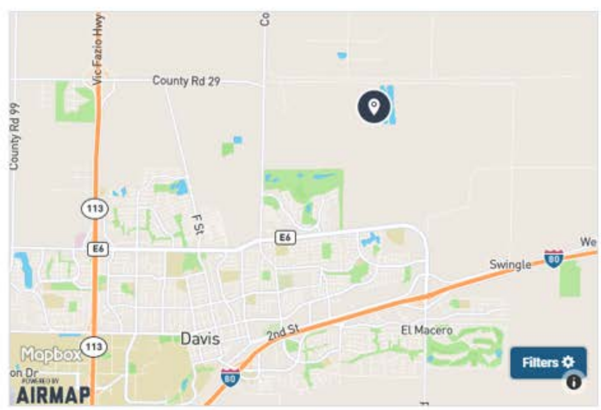


Investigative Summary- Aerial Repeater

Investigation #	9
Investigation date	08/25/2022
Investigation name	Communication test #3
Purpose	Evaluate new antenna package and verify connection to Wi-Fi network created from repeater payload.
Post-investigation summary	The new antenna improved the Wi-Fi network through measurements of an increased signal strength and higher data transfer rates. The system performed best when the drone was at low altitudes of around 100 feet AGL. When the UAS was at 400 feet the directional characteristics of the antenna became evident with an inability to connect to the Wi-Fi network. In future flights, the antenna will be adjusted downward to a calculate angle that will direct the Wi-Fi network towards the researchers.

Flight Request

Flight Nickname	Aerial Repeater- Payload trial #3
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Aug 25, 2022 08:30 AM
Field Time	120
Number of flights	8
Location	38.585597663117426, -121.70582377290542
Max Distance	2500 ft.
Flight Altitude	50 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	Follow pre-flight checklist Verify payload is secured Conduct research flights to verify wireless network. we will head directly west from the starting location and travel up to 2500 feet away. The Matrice M300 is visible at this distance.
Operation Restriction	
Comments	Continued research, final phase of project. We have verified that the drone can fly with the payload, and the payload can transmit without interference to drone controls. We are now verifying the range of the network the drone can create.
RiskAssessment	Any adverse conditions will cause a cancellation, research is not urgent.
Observers	Kin Yen

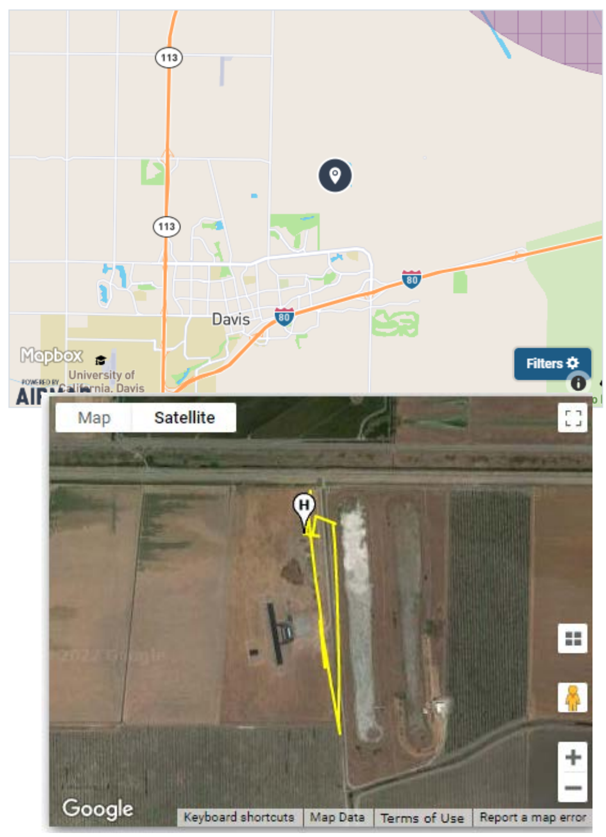


Investigative Summary- Aerial Repeater

Investigation #	10
Investigation date	09/08/2022
Investigation name	Communication test #4
Purpose	Evaluate impact of a Wi-Fi bridge and verify improvements made with tilting the antennas downward a set angle on connection quality to the repeater payload.
Post-investigation summary	The use of the SXTsq5 High Power was critical in creating a useable network with a significant horizontal distance to the drone. It was also important to adjust the antenna of the drone to insure that the signal from the UAS aerial repeater was directed towards the Wi-FI Bridge.

Flight Request

Flight Nickname	Aerial Repeater- Payload trial #4
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Sep 8, 2022 08:30 AM
Field Time	120
Number of flights	8
Location	38.585603626729664, -121.70720628972353
Max Distance	2000 ft.
Flight Altitude	400 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	Follow pre-flight checklist Verify payload is secured Conduct research flights to verify wireless network. Will fly at 400 feet,, and test at a range of 500, 1000, 1500, and 2000 feet Will utilize AMA airfield and stat away from normal AMA flight paths for model plains.
Operation Restriction	
Comments	Continued research, final phase of project. We have verified that the drone can fly with the payload, and the payload can transmit without interference to drone controls. We are now verifying the impact on antenna angle to increase the range of the network the drone can create.
RiskAssessment	Any adverse conditions will cause a cancellation, research is not urgent.
Observers	Kin Yen

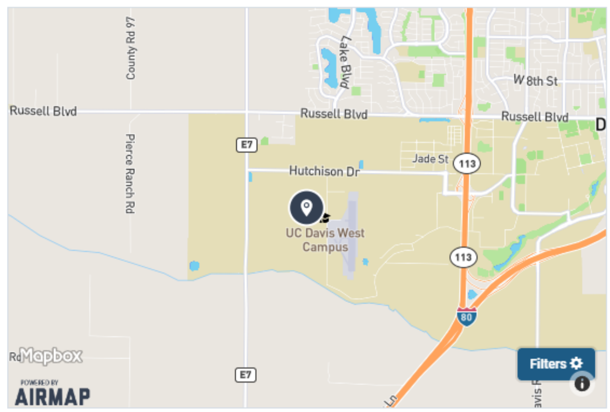


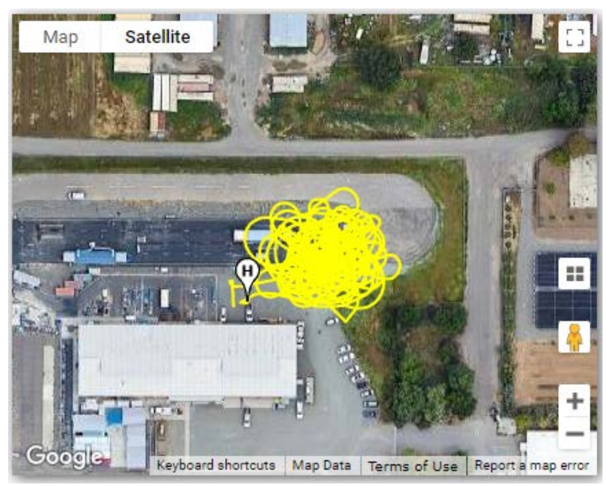
Investigative Summary- Aerial Repeater

Investigation #	11
Investigation date	10/20/2022
Investigation name	Max Flight Time
Purpose	Evaluate the maximum flight time of the UAS without a payload
Post-investigation summary	The flight time of the drone was 33 minutes, well below the advertised time of 55 minutes

Flight Request

Flight Nickname	Aerial Repeater
Flight Purpose	Other – Research
UAS Regulation	107
Date Time	Oct 20, 2022 03:00 PM
Field Time	60
Number of flights	1
Location	38.535038973601814, -121.79366921533531
Max Distance	500 ft.
Flight Altitude	49 ft.
Flying over people	No
Flying near building	No
Flying indoors	No
Flight Procedure	Follow pre-flight checklist Determine max flight time without a payload
Operation Restriction	
Comments	Basic Flight to verify max flight time
RiskAssessment	Any adverse conditions will cause a cancellation, research is not urgent.
Observers	Kin Yen





Matrice-specific training

April 20, 2022, 8 am to 2 pm

Trainer: Don Solleder, contractor for DSLR Pros

Attendees: Sean Campbell, Keith Koeppen, Ty Lasky, Dave Torick, Kin Yen

Unmanned aerial vehicle (UAV): DJI Matrice 300 RTK (M300)

Miscellaneous:

- The M300 comes with a calibration panel for the camera. It is in a pouch in the M300 case. The calibration panel is for the obstacle avoidance cameras and must be used in conjunction with the DJI Assistant program, a free download on their website. The other camera payloads, including FPV, do not require calibration.
- The system includes a dual gimbal mount for attaching cameras and other payloads
- If only using one gimbal mount, load the right gimbal when facing gimbal from M300 front. If working on M300 upside down, it would be on the left.
- Recommend 128 GB high-speed micro SD cards for controller, M300, and camera (camera came with 32 GB). Do not use cheaper low-speed cards.
- If using a non-DJI payload we must recalibrate the Center of Gravity (CG) - hover at 10 ft indoors to do. Must be done for that payload, and if payload removed, must again recalibrate.

- *The M300 USB port is located on top, near the beacon. The port cover must be securely closed to maintain water resistance.*

- The two tall thin antennas are for radio control.

- The round antennas are specifically for RTK. The regular GNSS receivers are inside the main body, and support GPS (USA), GLONASS (Russia), Galileo (Europe), and Beidou (China). The dual antennas support GNSS-based heading. The RTK improves *x,y,z* accuracy in high-noise environments or for photogrammetry accuracy

- RTK can use NTRIP protocol, which Caltrans has. Can do post-processing.
- RTK is good for photogrammetry, getting absolute positioning. Also, if operating near high-power lines, microwave, which throw off GPS and other sensors.
- RTK can provide cm-level accuracy
- You can get all manuals etc. from http://dji.com/download including specs
- Connectors for mounting on both bottom and top.
- If do not need dual gimbal, can probably switch to single.
- ***Where leg attaches, can remove screws, insert a mounting plate, and screw leg back on, just use longer screws***

- The controller records the onboard FPV camera unless H20 is installed and selected

- H20 has both zoom and fixed cameras. It also has a laser range finder, which supposedly is good to 1800 feet.

Firmware updates:

- Set up Wi-Fi on controller
- It will communicate with DJI and will grab all relevant latest firmware (controller(s), UAV, camera, and batteries).
- Everything has firmware
- Power up every 2 weeks to keep firmware relatively current. Alternatively, power up the system a day before use to check for firmware updates.
    - We should use a different pair of batteries in each two-week cycle to get firmware updated on batteries.
- If a set of batteries is not on the M300, they will not update. But, if swap them in when out in the field, the controller will know, advise firmware is out of synch, and offer to do the update then.

Batteries:

- Lithium-polymer battery (48 V, 5935 mA / 274.2 Wh)
- *Batteries can be unstable if damaged, can catch fire or explode. Damage is commonly caused by dropping the battery.*
- They self-discharge after 5-6 days. Duration is programmable when batteries are in M300, via the controller.
- They self-heat. Good for D2 in winter.
- 48 volt, 12 cell, about $700 per battery, and you need a pair to fly the M300.
- *Should keep batteries paired, so label them as such. This way, common number of cycles, will keep lifecycle similar.*
- If battery cells in a given battery have more than about 0.5 V variation, then the battery has a damaged cell
- They are hot-swappable.

- *When removing batteries, you have to apply a fair amount of pressure to disengage. Use other hand at back of battery to keep them from shooting away from M300 and being damaged.*

- If you are letting things sit idle, leave the batteries alone, but not for more than about a year.
- *Do not leave batteries charging for extended period. Put batteries in the charging box, charge up, then unplug the box, and leave batteries in the box for storage and transport. Batteries will slowly discharge, but this is OK.*
- You can check approximate charge by pushing button, see how many of 12 LEDs light up
- *The M300 batteries cannot be transported on a commercial flight, not even in hold. They would have to be shipped.*
- The controller has internal battery as well as external. It uses the external first, and this is hot-swappable
- Do a full charge about every month. Takes about 1.5 hours.
- Supposedly battery has life of about 200 cycles. Don has seen considerably more, so do not count on this, just monitor health.
- *Every 50 cycles, do a full discharge/charge.*

Controller:

- Controller supports a cellular dongle at bottom of controller (T-Mobile, Verizon, etc.). Main use would be getting current updates for flights and safety info.
- *Controller charger is USB-C. Can use any charger, but strongly recommend only the one shipped by DJI. It is 24 W, probably double the power of a cell charger.*
- Internal controller battery is not user swappable or replaceable
- *Make sure external battery is firmly connected to the controller. Double check.*
- The two buttons on the back (C1 and C2) and the five buttons on the front are all programmable via controller settings. For example, could use C1 to switch between FPV camera and H20 zoom camera, and C2 to bring gimbal back to center.
- Controller OS is Android
- Controller has a Return to Home (RTH) button. Press and hold for three seconds, and the M300 executes RTH maneuver.
- Pause button, e.g. on auto mission, will pause motion
- Power, push and hold, turns controller off
- The controller top includes an HDMI port useful for training or sharing screen during an incident, and an SD card slot, for recording what shows on screen.
- There are buttons on top back for recording screen, or taking a screenshot
- The controller can record a lower resolution copy of what the main payload cameras see for later review, but the record screen function only records the video as it is on the screen, including telemetry data. The aircraft has approximately 20 GB internal storage that can store FPV camera footage accessible by connecting a USB cable and downloading to a computer.

Unpacking 300 RTK:

- *Put the legs on first, while the M300 is still in the case, and lock the rings (not too tight)*

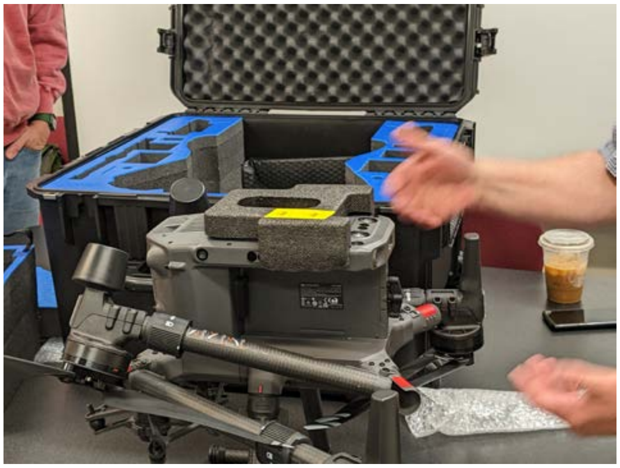
- The controller reads the left side (while M300 upside down) connector first, so connect camera there
- If only using one gimbal mount, load the right gimbal when facing gimbal from M300 front. If working on M300 upside down, it would be on the left.

- *Do not extend the blades until ready to take off. Then extend most way, but they will spin out.*
- *Check for any blade damage when extending the blades.*

- The M300 comes with arm pad/holders. Can get rid of these, or keep only if shipping.

- Lock the arms in their extended position using the twist locks

- There is a leveling pad in the case. It is somewhat in the way. Keep it, but not in the case, just with the storage or tooling location. This allows putting the M300 upside down, its top is not level, and the pad levels and steadies the M300.



Operations:

- *Having a landing/take-off pad is recommended. Keeps debris away from the M300, particularly the motors. Available from Amazon.*
- *The only "safety" to prevent the M300 coming on is the rotating battery catch. If it is horizontal, the batteries are locked in, and operation is possible. If it is vertical, the batteries are not locked, and the M300 will not power up.*

- There is a visible white light beacon (flashing) on top and bottom, which is visible to 3 statute miles as required by FAA for night operations

- *The side, top, and bottom all have visual and DOF (depth of field) sensors, for obstacle detection / avoidance. These work for large obstacles, but not for smaller branches or power lines, for example. There are blind spots, maybe +/- 20 degrees near each motor.*

- There is also an optional CSM radar module that can be mounted on top of the M300. The CSM radar sees everything. We did not get this.
- The system has a built-in FPV camera at the front of the M300

- App for requesting LAANC (Low Altitude Authorization and Notification Capability) authorizations is called 'ALOFT'. It can be used to request authorization in restricted airspace. There is another process that needs to be completed to unlock DJI UAVs for use in restricted airspace. Some can be done fairly quickly and others may take a little time depending on where you want to fly so plan accordingly.
- Don (trainer) will be providing info for filing a NOTAM (Notice to Airmen or Notice to Air Missions (US wording), a notice filed with an aviation authority to alert aircraft pilots of potential hazards along a flight route or at a location that could affect the flight. NOTAMs are unclassified notices or advisories distributed by means of telecommunication that contain information concerning the establishment, conditions, or change in any aeronautical facility, service, procedure, or hazard, the timely knowledge of which is essential to personnel and systems concerned with flight operations. Don has a short document describing how to file a NOTAM.
- Don provided the maintenance manual for the M300
- If we had communications, e.g. via cellular dongle, we could get up to date “Fly Safe” info in the field. This seems less than critical for our modes of operation.

- Need SD Cards, recommend 128 GB. One for controller, one for M300, one for H20 camera.
- Clean camera lenses regularly or before each flight
- *Remove camera covers only when just ready to fly, keep lenses protected and cleaner*
- *Do not take off from a vehicle or other large metal object, this will throw off calibration, e.g. compass*
- Controller screen and setting info:
  - SRE: Sunlight readability enhancement (Don says he never used)
  - Linking: For 2nd controller
  - Capture: Screenshot
  - Record: Video recording of all showing up on screen
  - *Sound: Turn it all the way up so can hear in field environment*
  - Screen brightness will impact battery life
  - USB: Can import/record, for example KML of flight polygon for planned flight
  - Can sideload Android apps, e.g. for LAANC authorization in real time
  - *HMS: Health management system, check this every time take off. If something is yellow, check it, use caution. If something is red, can't take off.*
  - Need to enter M300 serial number into controller to pair controller with M300
- Label each controller so it is paired with an M300. Two controllers can be paired to an M300 allowing one operator to control the H20 camera independently.
- Manual flight:
  - *For all RTH: If more than 30 meters, will rise to RTH height, return above home, then descend. If closer, it flies directly to home. Need to watch for intervening obstacles.*
  - *Set RTH height 50 feet above highest obstacle*
    - Smart RTH: Hold button, M300 comes back.
    - Fail-safe RTH: Controller dies, or loss of communication, M300 does RTH
    - Battery RTH: Battery drops below preset level, M300 does RTH
  - Max flight distance may be set to 1575 feet. May need to increase this.
  - *Max altitude, good setting is usually 394 (due to 400 foot limitation). However, 400 foot is AGL, so if you are working up a hill, the M300 could be 400 feet AGL (the hill), but much further above the controller.*
  - *To climb a hill, one option is as follows: set downward distance (obstacle range) somewhat higher (Don suggested 50 ft), increase max height, fly toward hill, then the UAV should automatically climb up the hill with this combination. You still need to watch for small obstacles, e.g. branches or power lines. This may be good for some of our scenarios.*
  - Caltrans standard procedure is to do a compass calibration for every flight
  - After takeoff, hover the UAS at "eye level," then check all flight control (up, down, yaw, roll, and pitch).
  - Battery, set critical 15%, and low 24% (or about).These will determine Battery RTH. Caltrans standard is 40% battery for warning and return to home.
  - Omni sensing, for collision avoidance: 10 feet brake, 30 feet warn. Can set different values for different directions (down, up, sides). So, up 3.3 ft brake, 10.2 ft warn
  - *Do not take off until hear that a home point has been set. This is essential for RTH.*

- Normally, home point is set to take-off location. Can force it to controller location. This is useful when operating from a moving platform, e.g. a boat.
- *There is a control stick mode. Check this before each flight. Only use "2", standard quadcopter mode. Left stick up/down, left right turning.*
- When showing FPV camera on controller screen, also have flight info, e.g. forward speed, wind speed, altitude above sea level, compass.
- *For new pilots, suggest maximum wind speed for flying is 15 mph. The main issue is takeoff. Small gusts can flip the M300 even at lower wind speeds. The best practice is to have the front of the M300 facing the wind, hammer the throttle on takeoff to get quickly 5 – 10 ft above ground, level out, then do flight. The advanced technique is to pitch forward into the wind on takeoff.*
- *Controller has three modes, designated TPS. T is for tripod, stick is dumbed down, slow. P is normal operating mode. S is sport, up to 60 mph, very responsive, only for racing, obstacle detection is disabled in S mode, do not use. Only use P mode.*
- Controller has HDMI port to support training, or screen viewing/sharing during operations, e.g. by police
- Screen shows obstacle detection / ranging over 360 degrees. Also can see the blind spots.
- Shows heading. Yellow house shows heading to home.
- Map mode will show UAV location, controller, and home
- *H20 camera can laser a target, and add a pin for its location. We could do this if we see a cell tower, for example.*
- *Can pre-download map for working area. Probably a good idea.*
- Flight controller settings:
    - Sensor status: check when init, and if move locations
    - Recalibrate if needed, e.g. compass
    - CG auto-calibration, e.g. when change or add payload
    - Obstacle sensing
    - Controller: may want to do remote controller calibration after about a year. Particularly if notice M300 is drifting while stick is centered.
    - Button actions: maybe toggle live video / map (C1), and gimbal re-center (C2)
    - ***Image transmission, leave in dual band. For our use, we may want to set to only one band, to avoid communications interference.***
    - Aircraft battery: provides details, all 12 cells for each battery. Here, do not want more than 0.5 volt variation between cells. If see more, may be damage. Also shows cycle counts.
    - Gimbal: can pitch 90 degrees down. Can modify settings to allow 30 degrees up.
    - Gimbal calibration about once a month or 10 flights. Or at longest each quarter.
    - Can also choose controller units (SI, imperial), view/set M300 serial number, etc.

- Mission flights:
    - We will likely not need these, but very useful for future research or for Caltrans use, e.g. site monitoring, photogrammetry, etc.
    - Can manually draw operating polygon on the controller

- Can import the polygon as KML from Google Earth.
- By default, the system adds 40 to 80 feet outside the boundary. Can override this.
- *You can also create a future mission using a manual flight and gathering waypoints. Every time you take a camera image, it sets a waypoint. This could be very helpful if we want to try one of our scenarios several times, and want to ensure essentially the same flight path and actions.*
- Also supports linear flight, which would be useful for flying along a road. Again, may be of particular interest to Caltrans, as long as comply with FAA Part 107 regulations.

Appendix H: Checklists as of End of Project

Mission Checklist

Flight Date: ______________________________ Prepared by: ______________________________

sUAS: _________________________________ Mission Name: ____________________________

Complete Prior to Mission Operations

Mission Pre-planning (at least 7 days prior)

	1. Evaluate Mission Requirements
	2. Check Airspace Access
	3. Check land access
	4. Obtain necessary permits
	5. File LAANC Manual Authorization (if necessary)
	6. Develop Mission Plan and Risk Analysis
	7. Prepare Field Safety Plan and Checklist
	8. Print Satellite image of area and mark flight details, obstructions, and preferred takeoff/landing sites

Mission Preparation (at 24 hours prior)

Review Mission Plan	New	Revised	No Change
Perform Risk Analysis			
Review Weather Report			
Verify no impact from NOTAM's or TFR's			
Inspect UAS			
Verify Payload			
Simulated/expected Flight Time			
Batteries Charged			
Update firmware and verify safe operations if updated			
Pack UAS, batteries, and other required items			

On-Site Setup

	1. *Brief Flight Plan with Crew
	1a. Flight Plan
	1b. Crew Responsibilities
	1c. Communication Plan
	1d. Contingency Plans
	1e. Air Traffic Conditions
	1f. Abort Conditions
	2. Area is clear and secure
	2a. Validate takeoff/landing sites and ensure they are free of obstacles and marked for safety
	2b. Identify emergency landing sites, and ensure they are free of obstacles and marked for safety
	2c. Ensure Area is clear of nonparticipating persons
	3. SUAS/Payload Set-up Checklist

Complete During Mission Operations

*Pre-Flight Checklist (utilize Airdata app)

	1. Weather
	1a. Visibility greater than 3 miles
	1b. Cloud ceiling above 500 feet AGL
	1c. Wind speed within UAS operating limits
	2. Personnel, participating personnel only allowed under flight path, non-participating under protective covering
	3. Safety briefing conducted
	3a. Risk to personnel and property assessed and mitigated
	3b. Location of ground hazards assessed
	3c. Level of risk assessed
	4. Site verification
	4a. Flight boundary area identified
	4b. Primary and alternative takeoff and landing locations verified
	5. Drone is safe for flight and batteries are sufficient for planned flight time

Clear for Launch

In-Flight

	1. Face into wind prior to take off, Pilot is behind drone a safe distance
	2. Verify no overhead obstacles
	3. Announce UAS is energizing (rotors on)
	4. Announce launching
	5. Take-off to eye-level and hover
	5a. Verify home position on map and IMU
	5b. Listen for abnormal sounds
	5c. Yaw 90 degrees left and verify latches and payload are secure
	5d. Yaw 180 degrees right and verify latches and payload are secure
	5e. Increase elevation to overhead and verify 4 pitch axis
	9. Perform mission

*Landing Checklist

	SUAS in position
	Announce SUAS is landing
	Landing Location is free of obstacles
	All crew in position and ready

Initiate Landing Sequence

Post-Flight Checklist

	Document Flight Results
	Remove battery/fuel
	UAS Post-Flight Inspection
	Payload Data Checklist

Mission Checklist

Flight Date: ______________________________ Prepared by: ______________________________

sUAS: _________________________________ Mission Name: ____________________________

NOTES:

Appendix I: U.S. National Airspace System (NAS) as Relevant to UAS Pilots

Appendix I:
U.S. National Airspace System (NAS) as Relevant to UAS Pilots

Table I.1 summarizes key aspects of the U.S. National Air Space (NAS) as relevant for sUAS flight and pilots. All of Class B, C, D, and E are controlled. Class B, C, D, and E as surface area for an airport all require FAA authorization to fly in that space. Most of Class E and all of Class G do not require permission to fly. There are eight Class E spaces, but only three are relevant here: surface area for an airport, extending from 700 ft AGL, and extending from 1,200 ft AGL. The remaining Class E spaces are:

- At and above 14,500 ft MSL
- Areas Designated as an Extension To a Class C Surface Area
- Areas Designated as an Extension to a Class D or Class E Surface Area
- En route Domestic Airspace Areas
- Offshore Airspace Areas
- Areas Designated As Federal Airways

If a section of the chart has none of the colored airspace circles, it is Class G airspace from the surface up to 1,200 ft AGL, and then it becomes Class E controlled airspace.

Table I.1: Summary of National Airspace System classes relevant to UAS pilots, showing only key Class E cases

Class	Chart color	Limits graphic	Start (MSL)	End (MSL)	Config	Reg?
B	Blue	Solid line	See chart, e.g. SFC=Surface, 20 = 2,000	See chart, e.g. 110 = 11,000	Inner area surrounded by two or more outer. Like upside- down wedding	Y
C	Magenta	Solid line	SFC	~4,000, see fraction	Usually consists of a surface area with a five nautical mile (NM) radius and an outer circle with a ten NM radius. Towered	Y
D	Blue	Dotted line	SFC	~2,500, see number in brackets. If negative, means up to but not including.	Single cylinder. Towered. ***If not operating hours, reverts to Class E or E/G***	Y
E	Magenta	Dotted line	SFC	To surrounding class, or 18,000		Y
E	Magenta	Thick fuzzy line	700 AGL	To surrounding class, or 18,000	Class E airspace that starts at 700 ft AGL	N Up to 700 ft it is G
E	Magenta	Dotted line		To surrounding	Extension that is not part of	N

Appendix J:
UASR-C System Requirements Comparison Table

2.1 General Operational Requirements

Req #	Requirement Description	Final Design Specifications
2.1.1	The UAS shall be operated according to all applicable Federal Aviation Administration (FAA) regulations	All UAS pilots obtained FAA Part 107, and operations UAS accordant to all FAA regulations. UASs are registered with FAA.
2.1.2	The UAS shall be operated according to all applicable state regulations	All state regulations were followed with operating UAS during the project.
2.1.3	The UAS shall be operated according to all local regulations	All local regulations were followed with operating UAS during the project.
2.1.4	The UAS shall be operated according to all applicable University of California - Davis (UCD) policies when on UCD property	All UCD regulations and policies was followed with operating UAS during the project.
2.1.5	The UAS shall be operated according to all applicable Caltrans policies when on Caltrans property	All Caltrans regulations and policies was followed with operating UAS during the project.
2.1.6	The UASC-R shall provide Air-to-Ground (ATG) communication between ground-based Wi-Fi users and a cellular base station	Final UASC-R communicate with ground based client via Wi-Fi and pass data to cellular base station
2.1.7	The UASC-R shall be designed to operate within rural locations	The UASC-R was designed to operate within rural locations
2.1.8	The UASC-R shall be operated in such a manner that interference to other nearby cellular base stations is minimized	The UASC-R does not interference with other nearby cellular base stations.

2.2.1 UAS Hardware Requirements[KY1]

Req #	Requirement Description	DJI M300 UAS Specifications
2.2.1.1	The UAS shall have a minimum payload capability of 3 lbs.	The UAS has a payload capability of 5.9 lbs
2.2.1.2	The UAS may have a maximum Equivalent Isotropic Radiated Power (EIRP) at 2.4 GHz of 26 dBm	The UAS has a maximum EIRP of 29.5 dBm, research investigations were performed to determine this did not have a negative impact on UASC-R
2.2.1.3	The UAS may have a maximum EIRP at 5.8 GHz of 26 dBm	The UAS has a maximum EIRP of 28.5 dBm, research investigations were performed to determine this did not have a negative impact on UASC-R
2.2.1.4	The UAS shall have a minimum vertical hovering accuracy in positioning mode (p-mode) of ±1.75 ft	The UAS has a minimum vertical hovering accuracy of 1.6 feet
2.2.1.5	The UAS shall have a minimum horizontal hovering accuracy in p-mode of ±5 ft	The UAS has a minimum horizontal hovering accuracy of 4.9 feet
2.2.1.6	The UAS shall have a minimum ascent speed capability of 15 ft/s	The UAS has a maximum ascent speed of 16.4 ft/s
2.2.1.7	The UAS shall have a minimum decent speed capability of 9 ft/s	The UAS has a maximum descent speed of 13.1 ft/s
2.2.1.8	The UAS shall have a minimum p-mode speed capability of 35 mph	The UAS has a maximum horizontal speed capability of 38 mph
2.2.1.9	The UAS shall have a minimum flying wind resistance capability of 39 ft/s	The UAS has a maximum wind resistance of 49 ft/s

Req #	Requirement Description	DJI M300 UAS Specifications
2.2.1.10	The UAS shall have a minimum flight time capability of 38 min	The UAS has a maximum flight time of 55 minutes per manufacturer, and 33 minutes of flight time if landing at 30% battery life
2.2.1.11	The UAS shall have a minimum Ingress Protection (IP) rating of 43	The UAS has an IP rating of 45
2.2.1.12	The UAS shall have a minimum operational temperature range of -4 to 122 °F (-20 to 50 °C)	The UAS has a minimum operational temperature range of -4 to 122 °F (-20 to 50 °C)
2.2.1.13	The UAS shall have a downward vision system	The UAS has a downward obstacle sensing range of 2 – 98 feet
2.2.1.14	The UAS shall have a forward vision system	The UAS has a forward obstacle sensing range of 2 – 131 feet
2.2.1.15	The UAS may have on-board lighting	The UAS has top and bottom lighting with an effective distance of 16 feet
2.2.1.16	The UAS may support hot-swappable, rechargeable batteries	The UAS requires 2 batteries that are hot-swappable and rechargeable
2.2.1.17	The UAS should support high-capacity rechargeable batteries to maximize flight time	The UAS requires 2, 5.9 Ah 52.8 V (311Wh) rechargeable batteries
2.2.1.18	The UAS shall have a charging hub capable of charging multiple batteries at once	The UAS has a charging hub capably of holding 8 UAS batteries, and charging 2 UAS batteries at once
2.2.1.19	The UAS shall have a remote control	The UAS has a dual band remote control, 2.4 GHz and 5.8 GHz

Req #	Requirement Description	DJI M300 UAS Specifications
2.2.1.20	The UAS remote control may support video capabilities	The UAS remote control has a built in 5.5-inch, 1000cd/m^2, 1920x1080 pixel screen, it also has HDMI out capabilities, it can receive up to 2 1080 P video transmissions
2.2.1.21	The UAS shall support an Original Equipment Manufacturer (OEM) dual-payload mounting adapter	The UAS supports an OEM dual downward gimbal mounting adapter as well as a single upward/downward gimbal mounting adapter

2.2.3 UAS Operational Requirements[KY2]

Req #	Requirement Description	DJI M300 UAS Operation
2.2.3.1	The UAS may be selected to maximize payload capacity	The UAS has a payload capability of 5.9 lbs
2.2.3.2	The UAS EIRP should be selected to reduce potential interference with payload communications	The UAS has a maximum EIRP of 28.5 dBm, slightly above Req # 2.2.1.2/3, research investigations were performed to determine this did not have a negative impact on UASC-R communications
2.2.3.3	The UAS should be selected with the capability to reduce overlap of operational frequencies with the payload	The UAS can be set to operate at either 2.4GHz or 5.8 GHz to avoid the payload operating frequency, however payload interference was not realized during research investigations
2.2.3.4	The UAS should be selected to maximize flight time	The UAS has a maximum flight time of 55 minutes per manufacturer, 33 minutes of flight time if landing at 30% battery life and no payload, and 27 minutes of flight time with the UASC-R payload
2.2.3.5	The UAS may be selected to maximize IP rating	The UAS has an IP rating of 45
2.2.3.6	The UAS charging hub should support use in a vehicle	The UAS charging hub supports use in a vehicle equipped with a 110V, 1070 W peak power circuit
2.2.3.7	The UAS shall be capable of operation during the night with the appropriate lighting modifications and associated waive	The UAS is capable of nighttime operations and has a flashing anti-collision light that is visible for at least 3 statute miles
2.2.3.8	The UAS may be similar (make/model) to UAS's used by other Department of Transportation (DOT) or state agencies	The UAS manufacturer is used by Caltrans and UC Davis, the M300 model is used by other researchers at UC Davis

2.3 Payload Requirements

Req #	Requirement Description	Final Payload Specifications
2.3.1.1	The UAS payloads shall be selected or designed to minimize weight	Weight is one of the major consideration when selecting COTS UASC-R.
2.3.1.2	The UAS payloads shall be selected or designed to maximize flight time	Minimizing weight is one major design criteria in order to maximize flight time.
2.3.1.3	The UAS payloads shall be selected or designed to minimize dimensions	Size is another key design and components selection criteria
2.3.1.4	The UAS payloads should use existing OEM mounting interfaces and/or adapter plates	Current UASC-R uses the DJI M300 top mounting screw holes (4 total) to secure itself to the UAS.
2.3.1.5	The UAS payloads should use existing OEM electrical interfaces	Payload does not use existing UAS OEM electrical interfaces. This requirement was not met.
2.3.3.1	The UAS payloads shall be mounted below the airframe	Payload is mounted on top of the UAS in order to allow the OEM camera be mounted in original designed location. This requirement was not met.
2.3.3.2	The UAS may support mounting a payload above the airframe	Payload is mounted above the airframe.

2.4 Communication Payload Requirements

2.4.1 Communication Hardware Requirements

Req #	Requirement Description	Final Payload Specifications
2.4.1.1	The UASC-R shall be self-contained with the exception of power	The Sierra Wireless MP70 is self-contained with external antennas and LiPO power supply battery. The UASC-R assembly is self-contained.
2.4.1.2	The UASC-R may be powered by the UAS using OEM electrical interfaces	UASC-R is power by 3S. 11.1 V, 1500 mAhr, 16.65 Wh LiPo Battery pack using the MP70 OEM power cable.
2.4.1.3	The UASC-R may be entirely self-contained and require no power from the UAS	This requirement was not met.
2.4.1.4	The UASC-R shall include a low-power Small Board Computer (SBC)	The MP70 has an embedded low power (3 to 12 watts total power consumption) SBC running embedded Linux.
2.4.1.5	The UASC-R shall include a cellular modem card as the WWAN interface	The UASC-R (MP70) include a cellular modem card (Sierra Wireless EM7511 with PCIe M.2 interface).
2.4.1.6	The UASC-R may include a Wi-Fi adapter card as the WLAN interface	The UASC-R (MP70) include a Wi-Fi 5 card (Compex WLE900VX WiFi 5 with PCIe 1.1 interface).
2.4.1.7	The UASC-R may support optional wireless adapter cards as the WLAN interface	This requirement was not met.
2.4.1.8	The UASC-R SBC shall include a multi-core processor	Detail MP70 CPU data is not available. This requirement may or may not be met.

Req #	Requirement Description	Final Payload Specifications
2.4.1.9	The UASC-R SBC shall include a process clock of at least 1 GHz	Detail MP70 CPU data is not available. This requirement may or may not be met.
2.4.1.10	The UASC-R SBC shall include at least 1 GB of dynamic random access memory (DRAM)	Detail MP70 DRAM specifications data is not available. This requirement may or may not be met.
2.4.1.11	The UASC-R SBC shall include at least 8 GB of flash memory	Detail MP70 flash memory specifications data is not available. This requirement may or may not be met.
2.4.1.12	The UASC-R SBC shall have at least two expansion slots	The MP70 have two internal expansion slots being used by the EM7511 and WLE900VX cards.
2.4.1.13	The UASC-R SBC expansion slots may be Mini Peripheral Component Interface Express (Mini-PCIe)	The MP70 has one Mini-PCIe and one m.2 card slot.
2.4.1.14	The UASC-R SBC expansion slots may be m.2-based	The MP70 has one Mini-PCIe and one m.2 card slot.
2.4.1.15	The UASC-R SBC shall have a Nano Subscriber Identity Module (SIM) in at least one slot for a cellular modem card	The MP70 has one standard SIM card slot. Nano SIM card may be used via a SIM card adapter.
2.4.1.16	The UASC-R SBC may use an expansion slot adapter	This requirement was not met.
2.4.1.17	The UASC-R SBC shall have a wide temperature operating range	The MP70 operating temperature range is from -30°C to +70°C / -22°F to +158°F.
2.4.1.18	The UASC-R WWAN card connecter may be m.2-based	The MP70 EM7511 WWAN card connected to the SBC using a m.2 connector.

Req #	Requirement Description	Final Payload Specifications
2.4.1.19	The UASC-R WWAN card connector may be Mini-PCIe based	This requirement was not met.
2.4.1.20	The UASC-R WWAN card shall support Fourth Generation (4G) Long Term Evolution (LTE)	MP70 support 4G LTE with Cat 12 top speed.
2.4.1.21	The UASC-R WWAN card shall be Verizon network-compatible	MP70 is compatible with Verizon network
2.4.1.22	The UASC-R WWAN card shall be AT&T network-compatible	MP70 is compatible with AT&T FirstNet network
2.4.1.23	The UASC-R WWAN card upload bandwidth may be 150 Mbps	MP70 top uplink speed is 150Mbps.
2.4.1.24	The UASC-R WWAN card download bandwidth may be 300 Mbps	MP70 top downlink speed is 600Mbps (Cat 12).
2.4.1.25	The UASC-R WWAN card shall provide a minimum of 22 dBm transmit power	EM7511 WWAN card transmit power is 22 dBm or higher depending on the channel frequency.
2.4.1.26	The UASC-R WWAN card may use Hirose U.FL antenna connectors	EM7511 WWAN card has two Hirose U.FL antenna connectors
2.4.1.27	The UASC-R WWAN card shall support diversity antenna	EM7511 WWAN card supports diversity antenna
2.4.1.28	The UASC-R WWAN antenna may be directional	WWAN direction antenna may be used on the UASC-R. However, directional antenna was not used in the tested configuration.
2.4.1.29	The UASC-R WWAN antenna may be omnidirectional	The UASC-R uses 5 dBi omni-directional antenna.
2.4.1.30	The UASC-R WWAN antenna gain should be a minimum of 3 dBi	The UASC-R uses 5 dBi omni-directional antenna.

Req #	Requirement Description	Final Payload Specifications
2.4.1.31	The UASC-R WLAN card may support IEEE 802.11ac	The Compex WLE900VX WiFi card support 2.4 GHz 802.11b/g/n, max 21dBm per channel and 5 GHz 802.11a/n/ac, max 20dBm per channel
2.4.1.32	The UASC-R WLAN card may support IEEE 802.11ax	IEEE 802.11ax is not supported by the WLE900VX. This requirement was not met.
2.4.1.33	The UASC-R WLAN card shall provide a minimum of 21 dBm transmit power	The WLE900VX WiFi card support 2.4 GHz, max 21dBm and 5 GHz max 20dBm
2.4.1.34	The UASC-R WLAN card may use Hirose U.FL antenna connectors	The WLE900VX WiFi card has three Hirose U.FL antenna connectors
2.4.1.35	The UASC-R WLAN card may support multiple antennas	The WLE900VX WiFi card support up to 3 antenna
2.4.1.36	The UASC-R WLAN antenna may be omnidirectional	The WLE900VX WiFi card support omnidirectional antennas
2.4.1.37	The UASC-R WLAN antenna may be directional	The WLE900VX WiFi card support directional antennas
2.4.1.38	The UASC-R WLAN antenna may be a downward-facing patch antenna	The UASC-R does not use downward-facing patch antenna. This requirement was not met.
2.4.1.39	The UASC-R WLAN antenna gain should be a minimum of 3 dBi	The UASC-R WLAN uses 5dBi omnidirectional antenna.
2.4.1.40	The UASC-R shall be mounted to the UAS using OEM mounting interfaces	The UASC-R is mounted on top of the DJI M300 UAS using its OEM mounting interface.

2.4.2 Communication Software Requirements

Req #	Requirement Description	Final Payload Specifications
2.4.2.1	The UASC-R SBC shall support a Linux-based operating system	The MP70 is running a custom embedded Linux operating system.
2.4.2.2	The UASC-R SBC vendor may provide a Linux board support package	Sierra Wireless does provide their Linux source code in accordance to the open source license.
2.4.2.3	The UASC-R WWAN card shall provide or be compatible with an existing Linux driver	EM7511 WWAN card SDK is available for Linux.
2.4.2.4	The UASC-R WLAN card shall provide or be compatible with an existing Linux driver	The Compex WLE900VX uses Qualcomm Atheros QCA9880 chipset which has extended community support under Linux ATH10K.
2.4.2.5	The UASC-R shall contain software to route between the WWAN and WLAN interfaces	The MP70 has custom routing software and may be configured using its web interface.
2.4.2.6	The UASC-R may contain software to present the WLAN as a wireless hotspot for multiple users	The MP70 may be used as a wireless hotspot for up to 128 clients.
2.4.2.7	The UASC-R may contain software to configure the WLAN as a network link to a ground-based Wi-Fi hot spot	The MP70 may be configured using its web interface to use ground-based Wi-Fi hotspot.
2.4.2.8	The UASC-R may contain software to provide real-time telemetry	The MP70 provide real-time telemetry via SNMP interface.

2.4.3 Communication Operational Requirements

Req #	Requirement Description	Final Payload Specifications
2.4.3.1	The UASC-R shall include backhaul communications capability	The UASC-R has Wireless WAN and wired WAN interface.
2.4.3.2	The UASC-R shall include local communications capability	MP70 has up to 4 local Ethernet ports for local communications.
2.4.3.3	The UASC-R shall properly shut down when powered down	MP70 support a switch for proper shut down
2.4.3.4	The UASC-R shall properly shut down if powered by the UAS when main power is off	UASC-R is not powered by the UAS. Not Applicable.
2.4.3.5	The UASC-R shall properly start up if powered by the UAS when main power is on	UASC-R is not powered by the UAS. Not Applicable.
2.4.3.6	The UASC-R shall properly shutdown if powered by the UAS when main power is off	UASC-R is not powered by the UAS. Not Applicable.
2.4.3.7	The UASC-R shall properly start up if powered by a self-contained battery and the power is switched on	UASC-R automatically powered up with power is supplied by the battery pack.
2.4.3.8	The UASC-R shall properly shutdown if powered by a self-contained battery and the power is switched off	MP70 support a switch for proper shut down
2.4.3.9	The UASC-R shall properly shutdown if powered by a self-contained battery which reaches low power	MP70 support low voltage cut off. MP70 is configured to power itself off below 11 Volt.

2.5 Camera Payload Requirements[KY3]

Req #	Requirement Description	DJI H20 Camera Specifications
2.5.1.1	The UAS camera payload shall use OEM hardware mounting interfaces	THE DJI H20 is mounted onto a single or dual OEM mounting system that connects to the UAS with 4 screws
2.5.1.1	The UAS camera payload shall use OEM electrical interfaces	The DJI H20 uses the OEM mounting system to connect to the PSDK ports providing 17/13.6 V at up to 4 A
2.5.3.1	The UAS may necessitate a camera payload depending on the selected UAS	The UAS does not require a camera payload for operations
2.5.3.1	The UAS camera payload must be of sufficient capability to visually identify the location of nearby cellular towers	The DJI H20 has a 20 MP zoom camera capable of 23X optical/ 200X digital zoom and a 12 MP wide angle camera capable of identifying cellular towers

Appendix K: Procured Hardware and Mapping to Requirements

Vendor	Manufacturer	Part Number	Item	Qty	Requirement #	Category
Amazon	Hoodman		HDLP Drone Landing Pad (5-foot diameter)	1	2.1	UAS System
Amazon	Uniden	BC125AT	Uniden Bearcat BC125AT Handheld Scanner (VHF)	1	2.1	Support
Lenovo	Lenovo	4640854047	ThinkPad X1 Carbon Gen 10 Intel	1	2.1.6	UASC-R client
Amazon	Google		Pixel 6 Pro smartphone	1	2.1.6	UASC-R client
DSLR Pros	DJI	B-DJI-M300	Matrice 300 RTK (UAS)	2	2.2.1	UAS System
DSLR Pros	GPC	GPC-DJI-M300-V2	Matrice 300 Hard Case	2	2.2.1	UAS System
DSLR Pros	DJI	CP.EN.00000224.01	BS60 Intelligent Battery Station for Matrice 300 RTK	2	2.2.1	UAS System
DSLR Pros	DJI	CP.EN.00000262.01	TB60 Intelligent Flight Battery for Matrice 300 RTK	8	2.2.1	UAS System
DSLR Pros	DJI	WB37	Intelligent Battery for CrystalSky/Cendence controller	4	2.2.1	UAS System
DSLR Pros	DJI		Smart Controller Enterprise	1	2.2.1	UAS System
DSLR Pros	DJI		Dual Gimbal Connector	2	2.2.1	UAS System
DSLR Pros	DJI	14	1x (Pair) Matrice 300 Propellers	6	2.2.1	UAS System
DSLR Pros	DJI		Silver Star Matrice 300 Maintenance	2	2.2.1	UAS System
DSLR Pros	DJI	V-NB-FIRM-UPG	Firmware Upgrade Service	2	2.2.1	UAS System
DSLR Pros	DJI	S-ECA-EUAS	Enterprise Concierge Assist	2	2.2.1	UAS System
DSLR Pros	DJI		Enterprise care	2	2.2.1	UAS System
DSLR Pros	DJI	T-NB-1DF	1 Day Free Hardware	2	2.2.1	UAS System
DJI	DJI	CP.EN.00000262.01	TB60 battery	4	2.2.1	UAS System
Amazon	Kestrel	5000	Kestrel 5000 Environmental Meter with Link (Anemometer)	1	2.2.1	Support
DJI	DJI		Mini 2 (UAS)	1	2.2.3	Support
Costco	Firman		3200 Watt Dual fuel generator/inverter	1	2.2.3	Support
Amazon	Anker	Anker 521 portable station	Ground power station	1	2.2.3	Ground Station
Amazon	Anker	Anker 555 portable station	Ground power station	1	2.2.3	Ground Station
Lenovo	Lenovo	34IAZ7	Lenovo, Lenovo Legion T7 34IAZ7 workstation	1	2.4	Support
Amazon	TP Link	150603397	TP Link Deco X90 Mesh WiFi router 2 pack	1	2.4.1	Ground Station
Amazon	TP Link	0153800841	TP Link EAP610 Outdoor	2	2.4.1	Ground Station
USAT LLC	Sierra Wireless	1104073	Airlink MP70 4G LTE-Advanced Router/Gateway	2	2.4.1 - 3	Payload
DSLR Pros	DJI		Zenmuse H20 camera	1	2.5	UAS System
DSLR Pros	DJI		Zenmuse H20T thermal IR camera	1	2.5	UAS System