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Reliable high-bandwidth rural communications have been a significant challenge since early Intelligent Transportation Systems (ITS) deployments at Caltrans. There is an effort to install fiber-optic broadband services on select rural highways throughout the state; however, it will take years before the service is useable, the service won't be installed on every rural state highway, and it will be in areas highly susceptible to damage from wildfire, floods, and landslides. Reliable communications are critical to the dependability of ITS elements for the traveling public. ITS elements cease to function as intended when communications systems fail, which poses a problem in rural areas where ITS elements are deployed to mitigate the effects of non-reoccurring congestion due to snow, fire, floods, and other major incidents. Most of the selected rural Caltrans field sites have been impacted by the lack of available high-bandwidth communications options. These ITS field sites include infrastructure related to changeable message signs, video sites, and roadside weather information systems. Caltrans needs to find an alternative, reliable high-bandwidth wireless communications option that is less susceptible to weather-induced incidents. The AHMCT Research Center procured, installed, operated, and evaluated five SpaceX Starlink satellite broadband communication services for various ITS elements in Caltrans District 2, and one in District 6. This research evaluated the procurement, construction, installation, integration, operation, and maintenance of the six selected rural sites. This is the final report of this project.

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# Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

## SpaceX Starlink Satellite Broadband Communications for ITS

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Dave Torick: Principal Investigator

Report Number: CA25-4059
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June 30, 2025

# California Department of Transportation

Division of Research, Innovation and System Information

# Executive Summary

Based on this project's testing and evaluation, the Starlink satellite communication system (specifically the product lineup as of 2025) performs well under ideal weather conditions for the California Department of Transportation's (Caltrans) rural communications. However, performance is degraded when factoring in issues, such as heavy rainstorms and snow accumulation, and the lack of constant physical access to maintain the field devices during extreme conditions. The system's reliability and uptime fail to surpass old low-bandwidth ground communications in most remote areas with heavy snow and limited sky visibility. As field element information, e.g., camera images, is most critical in those conditions, the system, as currently constructed, may not be a good match for all rural field element applications.

Starlink and satellite internet communication technology in general is a new and fast-evolving industry that has yet to target non-household consumers. At the beginning of this project, Starlink barely offered any support for commercial use, mostly serving households that mounted Starlink in their homes with easy and quick access to wipe snow, resecure wires, or reset the device. Caltrans rural communication requires a more reliable hardware suited for remote application and capable of withstanding more extreme weather conditions with less maintenance.

## Problem, Need, and Purpose of Research

Reliable high-bandwidth rural communications have been a significant challenge since early Caltrans Intelligent Transportation Systems (ITS) deployments. Caltrans is working to install fiber-optic broadband on select rural highways; however, it will take years before the service is useable, the service won't be installed on every rural highway, and it will be installed in areas prone to wildfires, floods, and landslides. Reliable communications are critical to the public's dependable use of ITS elements. These elements cease to function as intended when communications systems fail, which is particularly problematic in rural areas where ITS elements are deployed to mitigate effects of non-recurring congestion due to snow, fire, floods, and other major incidents. Most of the rural Caltrans field sites selected for this research are impacted by the lack of available high-bandwidth communications options. These sites include infrastructure for changeable message signs, closed-circuit TV (CCTV), and roadside weather information systems. Caltrans needs to find a reliable, high-bandwidth wireless communications option that is less susceptible to weather-induced incidents.

In the current research, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center procured, installed, operated, and evaluated five SpaceX Starlink (https:/www.starlink.com/) satellite broadband communication services for CCTV field elements in Caltrans District 2 and one site each in Districts 3 and 6. This research evaluated the procurement, construction, installation, integration, operation, and maintenance at four field (spoke) sites and one central (hub) site in District 2. The Standard Rectangular kit lent to Districts 3 and 6 was activated with a Mobile Priority service and tested at multiple locations throughout District 6 for rural communication with a similar application as District 2 has for Starlink.

# Methodology

The research methodology involved the following tasks:

- Procure Starlink systems
- Document Starlink system configuration and installation
- Exercise the Starlink systems
- Evaluate the Starlink systems and develop needed design and maintenance documentation
- Develop final report

# Major Results and Recommendations

The key deliverables for the project include:

- The Starlink systems
- Documentation of procurement issues in an interim report
- Raw video footage of system installation and configuration
- Raw pictures and video footage of available system testing
- System testing continued through June 2025 for District 2
- Support further testing across District 3 and 6
- System evaluation
- Final Report

The major results include:

- The current Starlink line-up and service plans are becoming more suitable for commercial purpose; however, the standard kits are meant for household use. High performance kits require further advancement to become viable for businesses, especially in remote applications where a user will have limited access to the system.

- Starlink also does not offer any professional high-end routers that allow businesses to set up VPNs or secure proxies.
- The Starlink system appears well-suited for rural communications for Caltrans under ideal conditions but has some drawbacks under heavy snow conditions.
- Extended testing in Districts 3 and 6 showed promise for high-bandwidth applications but led to similar issues in deployment, e.g., the challenge of finding a suitable third-party router that can be integrated with both the Starlink and Caltrans networks, lack of static public IP, and limited remote control over the antenna and router.
- SpaceX Starlink is a young company with a Silicon Valley mindset. Products, services, and policies often change. Usually, these changes are for the better. Users must have the ability to adapt to change.
- The Starlink High Performance kit with the flat non-actuated antenna is best suited for field installation due to its superior wind specifications.
- Priority service, which is tied to a location, with 40 GB of high-speed data was deemed sufficient for application in District 2. The more expensive Mobile Priority service, which allows for relocating the system, is available at any time in case a system is used in multiple locations. Mobile Priority service was useful during the initial testing that occurred in Davis and District 2, but Priority (non-mobile) service was used for all five District 2 sites throughout field testing.
- Mobile Priority services provide the greatest flexibility. Priority systems provide the most priority data for a given price. Choice between these services depends on the prioritization of mobility vs. data budget; hence, it is left to the user to decide which service is appropriate on a case-by-case basis. This service was used to test the SR kit across Districts 3 and 6 at any location, providing public Internet Protocol version 4 (IPv4) that may change when moving Starlink from one site to another.
- Lack of static public IPv4 turned out to be problematic and demanded use of custom routers and a dynamic host configuration protocol (or other means of handling changes of IP). Fortunately, Starlink kits support use of most third-party routers and Caltrans District 2 managed to integrate Starlink with their current network architecture after some testing and fine tuning.
- When the monthly priority data budget is exhausted, there is no added cost, and data communication continues until the end of billing month, but at slower speeds matching the Standard (fixed) plan in the area, unless the user subscribes to the Automatic Top Up priority data

plan. Starlink specifications[1] note the expected speed per service plan. Back in 2024, the download and upload speeds for the Priority (fixed) plan were 40-220 Mbps and 8-25 Mbps, respectively, while the same numbers for Standard fixed plan were 25-100 Mbps and 5-10 Mbps. Considering the application of Starlink in District 2, subscribing to a monthly priority of 40 GB of data is generally sufficient while the Top Up priority data plan was deemed unnecessary.

- The results from the field test showed that additional data is not required as the non-priority data provided by Starlink had sufficient download/upload speeds for the image and video transmission needs of District 2.
- The main reason for subscribing to a Priority Plan was to gain public IP for remote access.
- Obstruction from trees or extreme humidity at some field sites, especially Lassen Park and Sims Road, resulted in higher ping drop rates compared to other locations. Overall, these obstructions did not result in extended downtime.
- While outside of the project scope, AHMCT designed a custom mount to provide a more integrated, aesthetically appealing option by request of the Project Manager. This design is provided in Appendix D.

[1] https://www.starlink.com/legal/documents/DOC-1400-28829-70

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# Tables

# Acronyms and Abbreviations

| Acronym | Definition |
|---|---|
| ACH | Automated Clearing House |
| AHMCT | Advanced Highway Maintenance and Construction Technology Research Center |
| ASN | Autonomous System Number |
| ATIRC | Advanced Transportation Infrastructure Research Center |
| AUX | Auxiliary |
| Caltrans | California Department of Transportation |
| CCTV | Closed-Circuit Television |
| CGNAT | Carrier-Grade Network Address Translation |
| CIF | Common Intermediate Format |
| COTS | Commercial Off-The-Shelf |
| CMS | Changeable Message Sign |
| CSV | Comma-Separated Value |
| CVV | Card Verification Value |
| CWWP | Commercial Wholesale Web Portal |
| DDNS | Dynamic Domain Name Service |
| DHCP | Dynamic Host Configuration Protocol |
| DNS | Domain Name Service |
| DOT | Department of Transportation |
| DRISI | Caltrans Division of Research, Innovation and System Information |

| Acronym | Definition |
|---|---|
| ER-X | EdgeRouter-X |
| FEA | Finite Element Analysis |
| FoS | Factor of Safety |
| HP | High Performance |
| ICC | International Code Council |
| ISP | Internet Service Provider |
| IP | Internet Protocol |
| IPSec | Internet Protocol Security |
| IPv4 | Internet Protocol v4 |
| IPv6 | Internet Protocol v6 |
| ITS | Intelligent Transportation Systems |
| JPEG | Joint Photographic Experts Group |
| LAN | Local Area Network |
| LTE | Long-Term Evolution |
| NAT | Network Address Translation |
| OD | Outer Diameter |
| PoE | Power over Ethernet |
| POP | Point of Presence |
| POTS | Plain Old Telephone Service |
| PM | Project Manager |
| RJ | Registered Jack |
| RV | Recreational Vehicle |

| Acronym | Definition |
|---|---|
| RWIS | Road Weather Information System |
| SMB | Server Message Block |
| SMTP | Simple Mail Transfer Protocol |
| SNR | Signal to Noise Ratio |
| SR | Standard Rectangular |
| TCP | Transmission Control Protocol |
| TIG | Tungsten Inert Gas |
| TMC | Transportation Management Center |
| UTC | Universal Coordinated Time |
| VPN | Virtual Private Network |
| WAN | Wide Area Network |

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# Chapter 1: Introduction

## Problem

Reliable high-bandwidth rural communications have been a significant challenge since early deployment of Intelligent Transportation Systems (ITS) by the California Department of Transportation (Caltrans). There is an effort to install fiber-optic broadband services on select rural highways throughout the state; however, it will take years before the service is useable. In addition, the service will not be installed on every rural state highway and will be located in areas highly susceptible to damage from wildfire, floods, and landslides. Reliable communications are critical to the reliability of ITS elements for the traveling public, which poses a problem in rural areas where ITS elements are deployed to mitigate the effects of non-reoccurring congestion due to snow, fire, floods, and other major incidents. Most of the selected rural Caltrans field sites have been impacted by the lack of available high-bandwidth communications options. These ITS field sites require infrastructure related to changeable message signs (CMS), closed-circuit TV (CCTV) video sites, and road weather information systems (RWIS). Caltrans needs to find an alternative, reliable high-bandwidth wireless communications option that is less susceptible to weather-induced incidents.

## Objectives

In the current research, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center procured, installed, operated, and evaluated six SpaceX Starlink (https:/www.starlink.com/) satellite broadband communication services for CCTV field elements that belong to Caltrans. This research evaluated the procurement, construction, installation, integration, operation, and maintenance of four flat (non-actuated) High Performance (HP) kits at the selected field sites and a single actuated HP kit for one central (hub) site in District 2. Additionally, the actuated SR kit with Mobile Priority service was used across Districts 3 and 6 to test rural satellite communication in line with the District 2 application. Mobile Priority service was used to test the Standard Rectangular (SR) kit at multiple locations, providing a public Internet Protocol version 4 (IPv4) that may change when moving Starlink from one site to another.

The evaluation plan originally included three types of Starlink system as shown in Table 1.1.

**Table 1.1: Starlink systems – initial plan**

| System | Data speed category | Location | Device Cost | Quantity |
|---|---|---|---|---|
| **Residential** | 1x | Fixed | $599 | 2 |
| **RV** | 1x | Mobile | $599 | 2 |
| **Business** | 2x | Fixed | $2,500 | 1 |

As will be discussed in Chapter 2, the RV system was eliminated from the evaluation at the procurement stage. The final field testing was carried out using the systems noted in Table 1.2.

**Table 1.2: Starlink systems procured for pilot test – updated plan (as of January 2024)**

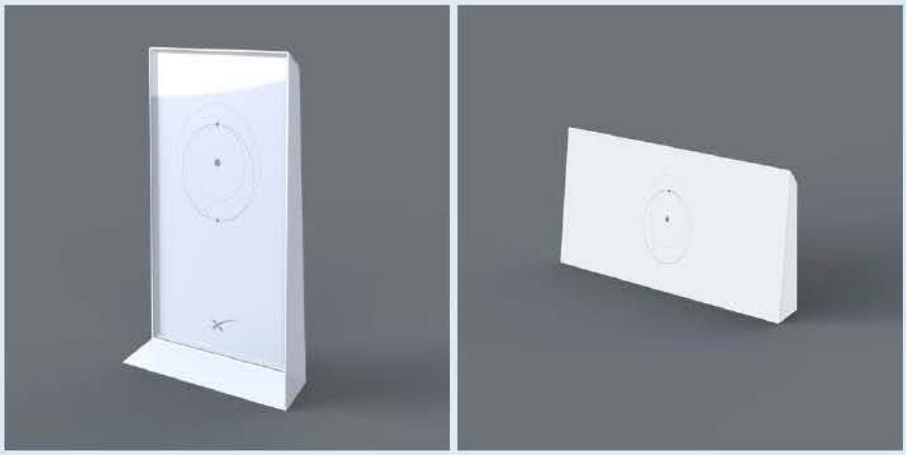
| Kit | Service | Bandwidth | Mobility | Device Cost | Quantity |
|---|---|---|---|---|---|
| **HP kit** | Priority | High | Fixed | $2,500 | 1 |
| **Flat HP kit** | Priority | High | Fixed | $2,500 | 4 |
| **SR kit at D3 and D6** | Mobile Priority | High | Multiple locations | $599 | 1 |

Table 1.3 provides a visual guide to the assorted Starlink hardware systems and key accessories discussed in this report.

**Table 1.3: Starlink systems and accessories featured in this report**

| Item | Photo |
|---|---|
| **Standard Rectangular (SR) kit (actuated)** |  |
| **Standard kit (non-actuated 2024 model)** |  |
| **Flat HP kit (non-actuated 2023 model)** |  |

| Item | Photo |
| --- | --- |
| **HP (actuated) kit** |  |
| **Ethernet adapter** |  |
| **Power supply** |  |

| Item | Photo |
| --- | --- |
| **Starlink Gen2 and Gen3 Wi-Fi routers** |  |
| **HP pipe adapter and Flat HP wedge** |  |
| **Starlink ground pole** |  |

# Chapter 2:
# Starlink Procurement and Deployment

Starlink procurement was generally problem-free. Full documentation of the system procurement is provided in the corresponding interim report [1], which is included in Appendix A for convenience.

The Task 2 interim report was complete and accurate at the time of its publication. However, Starlink policies, services, and systems evolve rapidly. As such, updates and new information are provided in this chapter. Where no revisions are provided, the reader is referred to [1] and Appendix A.

Since the September 2023 procurement interim report [1] was finalized, a few changes have been made in Starlink line-up and services with more changes expected in the future:

- Upon completion of field installation, AHMCT left three additional kits—one SR, one HP, and one Flat HP kit—at the District 2 warehouse plus other mounting equipment for future deployment or spare parts.
- It was suggested by the Project Manager and accepted by the customer that the SR kit would be lent to District 6 and later District 3 for further field testing under the Mobile Priority plan, while the field testing of systems in District 2 remain HP and Flat HP kits with Priority service. Refer to Table 1.2 for the updated plan.
- The additional priority data available for subscription upon exhaustion of priority data capacity became cheaper, from 2$ down to $0.5/GB in 2024. This rate has again changed according to the Starlink dashboard during 2025 to a dynamic rate that depends on the service plan.
- The older HP kit is being replaced with the Flat HP kit in Starlink's product line-up. We suspect the HP kit will be discontinued soon. It is not known for how long Starlink will continue selling the longer cables for the HP kit in their online store.
- Since the start of this project, Starlink has added two new kits to their product line-up. The first addition was the Starlink Flat HP kit in early 2023, which occurred before our procurement and field testing. As discussed in the interim reports, it was decided to procure four Flat HP kits and incorporate them in initial testing at Advanced Transportation Infrastructure Research Center (ATIRC) and later in the field. In early 2024, Starlink introduced another system into their line-up, which they refer to as simply the ***Standard kit***. Since the introduction of this new system, the old

Standard Rectangular kit is now referred to as the ***Standard Actuated kit*** by Starlink.

- The new Standard kit, showcased in Figure 2.1, is similar to the Standard Rectangular kit (in terms of technical features and kit price) with one major difference: the lack of an electric motor to rotate the antenna. This difference means that the user must manually adjust the antenna roughly towards a direction that is optimal to establish satellite connection in any given area. This adjustment is done through a combination of the Starlink mobile app and trial and error. With this device, users who primarily use Starlink on a vehicle/boat can subscribe to standard mobile plans, i.e., personal roam service with lower subscription costs compared to other kits.
- The new Standard kit does not include a separate power supply module and comes with an updated Starlink Gen3 Wi-Fi router that has a built-in RJ45 port for wired connectivity. The Starlink shop has several adapters for this new kit, including the standard pipe adapter to mount the antenna on top of a pole. While this kit has no moving parts, similar to the Flat HP kit, it is overall a downgrade from the old Standard Rectangular kit, and Starlink is promoting it since this kit costs significantly less to produce. This lower production cost is key for Starlink as the company has been selling kits with price tags lower than final production costs.
- The new Standard kit is not deemed appropriate for application in District 2 as it has all the limitations of the Standard Rectangular kit plus the manual adjustment requirement. District 2 requires a commercially available fixed-location priority service (with access to public IP and reliable hardware) rather than the household or roaming services intended for personal users.

**Figure 2.1: Starlink Standard kit and Gen3 router introduced in early 2024**

# Chapter 3:
# Starlink Testing

Starlink testing began at the AHMCT ATIRC facility. AHMCT researchers first demonstrated that the system was feasible for use with the Starlink public IP option and could be configured within the AHMCT network domain to share CCTV video. Then, AHMCT researchers worked with Keith Koeppen to fully emulate a single hardware and network configuration from District 2 within ATIRC. This test included two routers provided by District 2, and their corresponding configuration for a hub/headquarters and a field site. This setup was tested and confirmed on August 23, 2023. Following confirmation, AHMCT coordinated with District 2 for site installations, and extended field testing was initiated.

Initial testing occurred from early October 2023 through December 2023. The results of this testing are included in this final report and the corresponding evaluation. AHMCT also supported continuing field testing by Districts 2, 3, and 6 through June 2025 to allow District 2 to track and include the conditions encountered throughout the year in the final evaluation. At the end of the extended field testing period, AHMCT researchers worked with Caltrans management to survey the appropriate personnel to determine their impressions of the system. The results of this survey are included in this report.

The test plan and preliminary testing details are provided in the corresponding interim report [2], which is included in Appendix B for convenience. The extended testing details are provided in the next section.

## Extended Starlink Field Testing

Extended testing included the operation of the District 2 hub and field devices throughout summer of 2024 and winter of 2025 in addition to application of the SR kit with Mobile Priority plan across Districts 3 and 6 for about a year. In June 2025, the ownership of all purchased systems and their dashboard access was officially transferred to Caltrans.

# Chapter 4:
# Starlink Evaluation

The Starlink evaluation incorporated all findings from procurement through the initial testing as documented in interim reports [1] and [2]. The results of initial evaluation in the first six months of pilot testing was presented in full in a third interim report [3], which is included in Appendix C for convenience.

## Results of Extended Testing

Table 4.1 presents the Starlink performance stats during summer 2024 (May 15 to September 14) according to the data collected from Starlink dashboard on five-minute intervals. We can compare these summer data with the stats reported for the previous winter (Table C.3 of Appendix C).

**Table 4.1: Starlink performance stats during summer 2024 (May 15 to September 14, 2024)[2]**

| Kit | Location | Ave. Obstruction (%) | Ave. Signal Quality (%) | Ave. Ping Loss (%) | Ave. Latency (ms) |
|---|---|---|---|---|---|
| **HP** | Redding Fiber Hub | <0.01 | 99 | <0.01 | 30 |
| **Flat HP** | Sims Road | 2.5 | 99 | <0.01 | 29 |
| **Flat HP** | Lassen Park | 28 | 98 | 3.3 | 36 |
| **Flat HP** | Cedar Pass | <0.01 | 99 | <0.01 | 27 |
| **Flat HP** | SR70-SR89 | <0.01 | 99 | <0.01 | 31 |

[2] These statistics are reported as averages for all data records including periods of time when Starlink was idle or disconnected from the network.

Generally, all performance stats have improved for all systems compared to six months prior. Interestingly, the obstruction levels are lower across the board, which is partially due to less precipitation in the spring and summer months compared to winter. In the case of Lassen Park, where the sky is partially blocked by nearby trees, it may be the result of improved satellite coverage. Small obstruction, such as the situation in Sims Rd, has not led to significant loss of signal.

There was no confirmed overheating incident during the summer. However, there were more issues with wire connections and surge suppression devices resulting in downtime and in-person repairs. Extended testing though the winter of 2025 showed similar downtime behavior as the previous winter. The most significant incident was caused by the unnotified change of public IPs fifteen months into deployment, which required readjusting the set IPs on each router to the ones assigned in the Starlink dashboard.

# Field Testing Overview

AHMCT deployed one Starlink system near District 2 headquarters and four Starlink systems in District 2 field sites. The field systems were connected to CCTV cameras as part of each site's local network. The configurations at each site were based on standard District 2 field network configuration. Details of the test setup are provided in an interim report [2]. For the period covered by this addendum, District 2 essentially operated independently, with minimal support from AHMCT. The Starlink service accounts were managed by AHMCT throughout the project.

Based on this project's testing and evaluation, the Starlink satellite communication system performs well under ideal conditions to meet Caltrans' rural communications needs. However, when factoring in issues, such as snow accumulation and melt time, performance is degraded. As field element information, e.g., camera images, is most critical in these conditions, the system may not be a good match for Caltrans' rural communications needs. With respect to deployment, SpaceX Starlink is a young company with a Silicon Valley mindset. Products, services, and policies often change. Usually, these changes are for the better. Users must have the ability to adapt to change.

It should be noted that the product line-up and the service plan terms of use became more commercially available during the study period; however, the standard kits were always more suited to household use. HP kits, while making progress, require further advancement and reliability for commercial use, especially in remote applications.

The Starlink Flat HP Kit is best suited for field installations due to its superior wind specifications. Mobile Priority service provides the greatest flexibility, but it is currently too expensive to justify subscription or its use except for applications

on portable systems or moving service vehicles. Choice between priority and mobile priority services depends on mobility requirements vs. data budget, and it is left to the user to decide which service is appropriate on a case-by-case basis. If the monthly priority data budget is exhausted, there is no added cost for standard data, and data communications continue at slower downlink and uplink speeds.

By June 2025, five systems across District 2 were tested in the field for about twenty months. Longer operation by Caltrans is recommended to establish full confidence in the results. Mainly because Starlink has recently introduced and expanded their commercial plans and more changes are expected for both hardware and services.

A simple off-the-shelf mounting setup was used for deploying five Starlink systems across District 2 for pilot testing. This mounting solution is functional but not appealing for long-term deployment. The AHMCT team designed a custom mount which is far more suited to long-term Caltrans deployment. This mount has not been tested in the field. The design is provided in Appendix D.

# Survey Questions

An anonymous survey was distributed among Caltrans staff and Transportation Management Center (TMC) personnel at the end of the project. The raw survey responses are provided in Appendix E. The following provides an overview of the questionnaire.

1. Which Starlink kits were tested under your supervision? Check all that apply.

☐ Standard Actuated ☐ High Performance Actuated ☐ Flat High Performance

2. How long have you tested Starlink for Caltrans field elements?

☐ Less than 6 months ☐ 6-12 months ☐ Over 12 months

Please roughly specify the dates you started and ended the Starlink testing:

_____

3. I had enough time interacting with Starlink to understand its operation.

☐ 0- Not Sure ☐ 1- Strongly disagree ☐ 2- Disagree

☐ 3- Neutral ☐ 4- Agree ☐ 5- Strongly agree

4. Briefly describe your main application of Starlink for Caltrans ITS elements. What was connected to Starlink and monitored as part of your testing?

_____

5. What would you change about Starlink hardware or service to make it more suitable for stated Caltrans application. Please explain:

_____

6. The satellite communication service, as currently offered by Starlink, provides high uptime for remotely monitoring ITS field elements.

☐ 0- Not Sure ☐ 1- Strongly disagree ☐ 2- Disagree

☐ 3- Neutral ☐ 4- Agree ☐ 5- Strongly agree

7. The satellite communication hardware requires more maintenance than the old ground communications that support similar ITS elements.

☐ 0- Not Sure ☐ 1- Strongly disagree ☐ 2- Disagree

☐ 3- Neutral ☐ 4- Agree ☐ 5- Strongly agree

8. The satellite communication service is a better alternative compared to the old communications existing in some (but not all) Caltrans stations.

☐ 0- Not Sure ☐ 1- Strongly disagree ☐ 2- Disagree

☐ 3- Neutral ☐ 4- Agree ☐ 5- Strongly agree

9. The operation of Starlink was improved and downtime reduced after a few months (ramp-up period) as operators learned about Starlink and the appropriate configuration of hardware/software.

| | | |
|---|---|---|
| ☐ 0- Not Sure | ☐ 1- Strongly disagree | ☐ 2- Disagree |
| ☐ 3- Neutral | ☐ 4- Agree | ☐ 5- Strongly agree |

10. I would like to see Starlink further deployed/tested to support communication with ITS field elements.

| | | |
|---|---|---|
| ☐ 0- Not Sure | ☐ 1- Strongly disagree | ☐ 2- Disagree |
| ☐ 3- Neutral | ☐ 4- Agree | ☐ 5- Strongly agree |

Further comments:

_____

# Starlink Field Testing Survey Summary and Analysis

The following is a summary of responses to the field testing survey:

1. Overall, the users agreed they had good familiarity with Starlink equipment within less than six months of operation.
2. The main challenges for remote applications were:
    - Inadequate heating during snowstorms to avoid freezing and obstruction
    - Lack of surge suppression system specific to the application of ITS field elements
    - Lack of a static IP; the IP can change every few months even without hardware changes
    - Lack of control in remote applications when physical access to Starlink kit and router is limited
    - Requiring a third-party router to secure end-to-end connections

- Requiring Dynamic Host Configuration Protocol (DHCP) or Virtual Private Network (VPN) connection to handle possible changes of public IP

3. All surveys attendees agreed that Starlink offers high uptime (low downtime) for remotely monitoring ITS field elements. However, the general opinion was that the current state of satellite communication technology is not meaningfully better than ground communications in terms of reliability and maintenance.
4. While long-term operation of Starlink led to higher uptime over the year, the interruptions caused by heavy rain and snowstorms remained a concern.
5. The common impression as of 2025 is that, given the choice, ITS field elements are better connected to their hub using old communication tools available in rural areas, mainly due to stability and the user control they offer compared to the remote application of Starlink.

# Chapter 5: Conclusions

The key deliverables for the project include:

- The Starlink systems
- Documentation of procurement issues in an interim report
- Raw video footage of system installation and configuration
- Raw pictures and video footage of available system testing
- System testing summarized in an interim report
- System evaluation and Caltrans-specific design and maintenance documentation presented in an interim report
- Final Report

The major results include:

- The Starlink system appears well-suited for rural communications for Caltrans under ideal conditions but has some drawbacks under heavy snow conditions.
- SpaceX Starlink is a young company with a Silicon Valley mindset. Products, services, and policies often change. Usually, these changes are for the better. Users must have the ability to adapt to change.
- The Starlink HP Kit with the flat antenna is best suited for field installations due to its superior wind specifications.
- Priority service with 40 GB of high-speed data was deemed sufficient for District 2's needs. The more expensive Mobile Priority service is available at any time in case a system is used in multiple locations, but this service was only applied to initial testing before the field test.
- Mobile Priority services provide the greatest flexibility. Priority systems provide the most priority data for a given price. Choice between these services depends on the prioritization of mobility vs. data budget; hence, it is left to the user to decide which service is appropriate on a case-by-case basis.
- When the monthly priority data budget is exhausted, there is no added cost, and data communications continue at slower speeds unless the user subscribes to a $0.5/GB priority data plan.
- The results from the field test showed that additional data is not required as the non-priority data provided by Starlink has sufficient

download/upload speeds for the image and video transmission by District 2. Starlink specifications[3] note the expected speed per service plan. At the time of initial testing, Priority (fixed) plan's download and upload speeds were 40-220 Mbps and 8-25 Mbps, respectively, while the same numbers for Standard fixed plan were 25-100 Mbps and 5-10 Mbps. Considering the application of Starlink by District 2, subscribing to 40 GB of monthly priority data is sufficient while subscribing to additional priority data has been deemed unnecessary.

- Obstruction from trees or extreme humidity at some of the field sites, especially Lassen Park and Sims Rd, resulted in higher ping drop rates compared to other locations. Overall, these obstructions did not result in extended downtime.
- While outside of the project scope, by request of the Project Manager, AHMCT researchers designed a custom mount to provide a more integrated and aesthetically appealing option. This design is provided in Appendix D.

# Future Evaluation

Extended District 2 field testing continues beyond this project as Starlink devices are used long term at the designated sites. The items to be evaluated in District 2's future field operations include:

1. The obstruction pattern and loss of signal caused by rain, extreme humidity, or snowstorms as Starlink expands satellite coverage and improves its technology. One major focus will be on an auto-heating feature to unfreeze the snow on the antenna and preserve satellite connection in remote areas with limited physical access to the antenna.
2. The auto-shutdown and restart system designed to protect the kit from overheating or freezing.
3. The quality of connection established between Starlink and the corresponding satellites, including ping drop rates in clear skies (canceling out other reasons for loss of connection) and the average latency that impacts the ergonomics of CCTV control.
4. Starlink coverage and hardware changes after the conclusion of this project.
5. The long-term sustainability of Starlink as a service provider for Caltrans.

[3] https://www.starlink.com/legal/documents/DOC-1400-28829-70

# References

[1] S. Delshad Sisi and T. Lasky, "SpaceX Starlink Satellite Broadband Communications for ITS: Procurement Issues," AHMCT Research Center, UCD-ARR-23-04-30-01, Apr. 2023.
[2] S. Delshad Sisi and T. Lasky, "SpaceX Starlink Satellite Broadband Communications for ITS: System Testing," AHMCT Research Center, UCD-ARR-23-09-30-02, Sep. 2023.
[3] S. Delshad Sisi and T. Lasky, "SpaceX Starlink Satellite Broadband Communications for ITS: Evaluation," AHMCT Research Center, UCD-ARR-23-12-31-04, Dec. 2023.

# Appendix A:
# Starlink Procurement Issues Interim Report

## Removal of Starlink Residential and RV Services from Procurement and Evaluation

As shown in Table 1.1, the original plan was to evaluate the Residential, RV, and Business services provided by Starlink. By the time of procurement, the plan was updated to the list presented in Table 1.2. There were two main reasons for removing Residential and RV services (and subsequently the Standard Rectangular kit) from District 2 evaluation: Starlink RV availability for commercial and government use and Starlink public IP policy.

During the procurement investigation, AHMCT reviewed Starlink Terms of Service in December 2022. Since this evaluation may lead to further deployment, the terms (which are frequently updated) are important to Caltrans. During the procurement investigation, a key clause was read under Section 6, "Starlink for Recreational Vehicles (RVs)":

> "**6.3 Limitation and Requirements for RV Users**. Starlink for RVs is a consumer product only and is ***not available for purchase or use by commercial, enterprise, governmental or institutional users***. Starlink for RV can only be used within the same continent as the registered shipping address."

The emphasis beginning at "not available" was added here by AHMCT. This clause prohibited the use of Starlink RV system by UC Davis and more importantly, Caltrans. Based on this indication, AHMCT researchers consulted the Project Manager and the project panel in January 2023. AHMCT subsequently removed the RV system from the initial evaluation.

Additionally, since Residential and RV service plans lacked public IP, the AHMCT team did not subscribe to either plan meant for household users. Instead, the panel decided that the AHMCT team should focus on the Business service plan, which was broken down to Priority and Mobile Priority services in April 2023 by Starlink. As of September 2023, Residential and Roam/Mobile services only had a "Default" IP option, which does not offer any public IPv4 for customers.

Starlink Terms of Service evolve regularly. By September 2023, the above-mentioned Clause 6.3 had been removed. In fact, all Starlink services are now available for commercial use.

# Reserve Equipment

AHMCT is providing several spare kits and components to Caltrans, so they are available if needed for the pilot testing. These kits and components are not part of the planned pilot testing.

There are no plans to use the purchased Standard Rectangular kit for the pilot test at District 2. Under the new Starlink terms, one can subscribe to a priority service and take advantage of the Standard Rectangular kit for commercial use. Although subscribing to the priority data package removes the bandwidth restriction applied to Residential and Roam services, HP kits are expected to perform better than the Standard Rectangular kit with similar service due to their hardware advantages. As such, AHMCT has delivered and plans to transfer the ownership of the single Standard Rectangular kit that was purchased in October 2022 to Caltrans. Additionally, on October 16, AHMCT delivered one extra HP kit and one extra flat HP kit to the customer as reserves for the five kits that were installed and will be field tested beginning October 2023. All three reserve kits will remain inactive (paused service) until further notice.

Alongside the three noted kits, AHMCT delivered an extra ethernet adapter, surge protector, ground pole, flat HP antenna cable, wedge mount, and pipe adapter to District 2 as spare parts for contingency during the pilot test.

# Updated Procurement Plan Upon Starlink Change of Services

The biggest reason for changing the initial plan was the major change in services at Starlink. In April of 2023, Starlink updated the list of offered services significantly, introducing a new flat HP kit which enables users to access Starlink satellite internet in a truly mobile sense on moving vehicles and boats.

A new high-end service, called Mobile Priority, immediately became available for commercial use at the launch of Starlink flat HP antenna. This service was different from the RV service, which only added portability to the service address and allowed customers to use the Starlink standard rectangular antenna to access the internet at any location with satellite coverage while stationary.

After the change of services in April 2023, Starlink allows pairing hardware and services as presented in Table A.1. By June 2023, AHMCT collected this new information and discussed the options for procurement with the panel, with

focus on the necessity of public IPv4 for Caltrans application. It was then decided that AHMCT should perform initial testing at their shop, the Advanced Transportation Infrastructure Research Center (ATIRC), to confirm the feasibility of using HP and flat HP kits for the purpose of this project, i.e., establishing secure connection between Caltrans rural hubs and CCTV stations.

One recent change made to Table A.1 is the addition of priority services that Starlink started to offer in September 2023 to pair with the Standard Rectangular kit. This facilitates the use of cheaper hardware for District 2's application as priority services have no bandwidth restrictions and offer public IPv4. However, the Standard Rectangular antenna remains inferior to HP antennas in establishing satellite connections, and its power supply is not separate, so one cannot bypass the Starlink Wi-Fi router (powering the Standard Rectangular antenna) as easily as with the HP kits.

In September 2023, AHMCT confirmed that one HP kit (for Redding Fiber Hub) and four flat HP kits (for Sims Road, Lassen Park, SR70-SR89, and Buckhorn CCTV stations) would be used for the pilot test. In October 2023 at the time of installations, Buckhorn was replaced by Cedar Pass due to construction.

**Table A.1: Starlink kits and services available after April 2023 change of terms and services (updated in September 2023)**

| Kit/Antenna | Available Services | Mobility | Public IPv4 | Priority Data | Bandwidth |
|---|---|---|---|---|---|
| **Standard Rectangular** | Residential | Stationary with fixed service address | No | N/A | Limited download and upload speed. |
| **(Tilts towards North to establish satellite connection)** | Roam (Mobile) | Stationary without service address and available anywhere with capacity | No | N/A | Unlimited standard data. |
| | Priority | Stationary with fixed service address | Yes | Yes (for x price) | No restriction on bandwidth with priority data. |
| | Mobile Priority | Stationary without service address | Yes | Yes (for 5x price) | |

| Kit/Antenna | Available Services | Mobility | Public IPv4 | Priority Data | Bandwidth |
|---|---|---|---|---|---|
| **High-performance** | Priority | Stationary with fixed service address | Yes | Yes (for x price) | Location, weather, area capacity, and quality of antenna in establishing satellite connections will define the bandwidth.<br><br>Capped to Standard Residential bandwidth after priority data ends.<br><br>Unlimited standard data.<br><br>Additional priority data available to purchase in the middle of the period either by upgrading the plan or subscribing to $2.00 per GB priority data option. |
| **(Tilts towards North to establish satellite connection)** | Mobile Priority | Stationary without service address available anywhere with capacity | Yes | Yes (for 5x price) | |
| **Flat high-performance** | Priority | Stationary with fixed service address | Yes | Yes (for x price) | |
| **(Doesn't tilt, can connect with much limited view of the sky)** | Mobile Priority | Mobile, i.e., on the moving vehicle/boat without service address and available anywhere with capacity | Yes | Yes (for 5x price) | |

To guarantee service addresses and to save on costs, AHMCT will switch all devices to Priority service for the duration of the pilot test. There are several reasons for not making use of Starlink Mobile Priority service that can be activated on either kit:

- The Priority plan guarantees a service address unlike Mobile Priority, which is important as the ever-increasing customers pool added to the California area may eventually take satellite coverage beyond capacity.

- The pilot test is not expected to require any transfer of devices after installation.
- The Priority plan offers higher priority data with significantly less costly subscription plans compared to the Mobile Priority service.
- There are no technical differences between the two services except for where they are permitted to connect to the internet.
- Initial testing at AHMCT in August 2023 confirmed that both services are technically feasible for the pilot test and beyond as they both offer public IPv4 to be used for secure tunneling with Caltrans District 2 routers.
- There is no difference in speed or bandwidth policy between the two priority services.

# Guidance on the Starlink Online Procurement Process

Below are the screenshots for the step-by-step ordering of Starlink for the test site identified by Caltrans as Redding Fiber Hub. As specified in Table A.1 the Priority (Business) service requires a specific **Service Address** to check for availability and to initiate ordering. Note that the Starlink website recommends the service address from its directory based on customer suggestions. This suggestion often includes the name of road/street, a county/town, and a state. It can be a bit troubling to specify an acceptable service address that covers rural sites. Fortunately, there is no need to specify an accurate location for Starlink to allow connection. These addresses cover a large area on highways.

For example, the following are identified as appropriate service addresses for the sites used in the pilot test:

- Redding Fiber Hub/40° 35' 11.04" N 122° 21' 43.66" W: Cascade Wonderland Hwy, Redding, CA, USA
- Sims Road CCTV/41° 4' 41.83" N 122° 21' 21.38" W: Cascade Wonderland Highway, Castella, CA, USA
- Lassen Park CCTV/40° 32' 41.42" N 121° 34' 38.89" W: 44 Manzanita Lake Campground Road, Shingletown, CA, USA
- Cedar Pass CCTV/41°33'37.6"N 120°17'14.7"W: CA-299 Alturas CA 96101, USA
- SR70-SR89 CCTV/40° 2' 19.58" N 120° 59' 1.47" W: 23990 CA-70, Twain, CA 95984, USA

The steps of ordering process from the start screen to the final order page are provided in Figures A.1 to A.6. Where needed, clarification and emphasis are

provided for each step. These steps are accurate as of September 2023, and subject to change by Starlink.

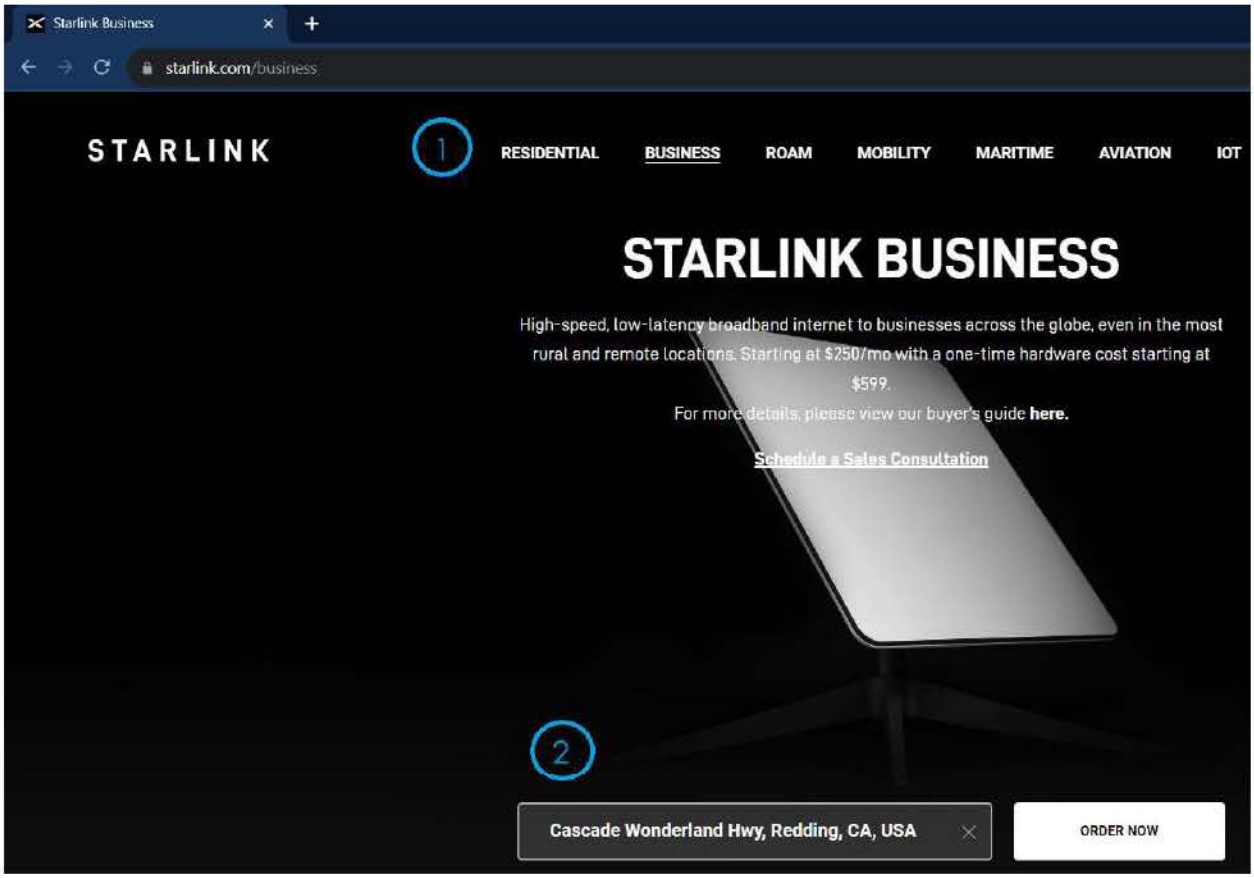



**Figure A.1: Starlink procurement Step 1: Starting page for service address and service type**

The order page and process has changed slightly since the beginning of the project up to September 2023. The first step is to click on the correct tab on the home page. For ordering Priority service, one needs to make sure they are on the "Business" tab, while to order Mobile Priority the "Mobility" tab must be selected. After confirmation of service address and clicking on "Order Now", Starlink will confirm the kit and its price on the second page. Figure A.1 shows the Starlink home page as the initial ordering screen. On this page and subsequent screens, key points are indicated by the light blue numbered circles. For this screen, at #1, choose the service type. At #2, enter the service location. Then, click "Order Now", which leads to the screen in Figure A.2.

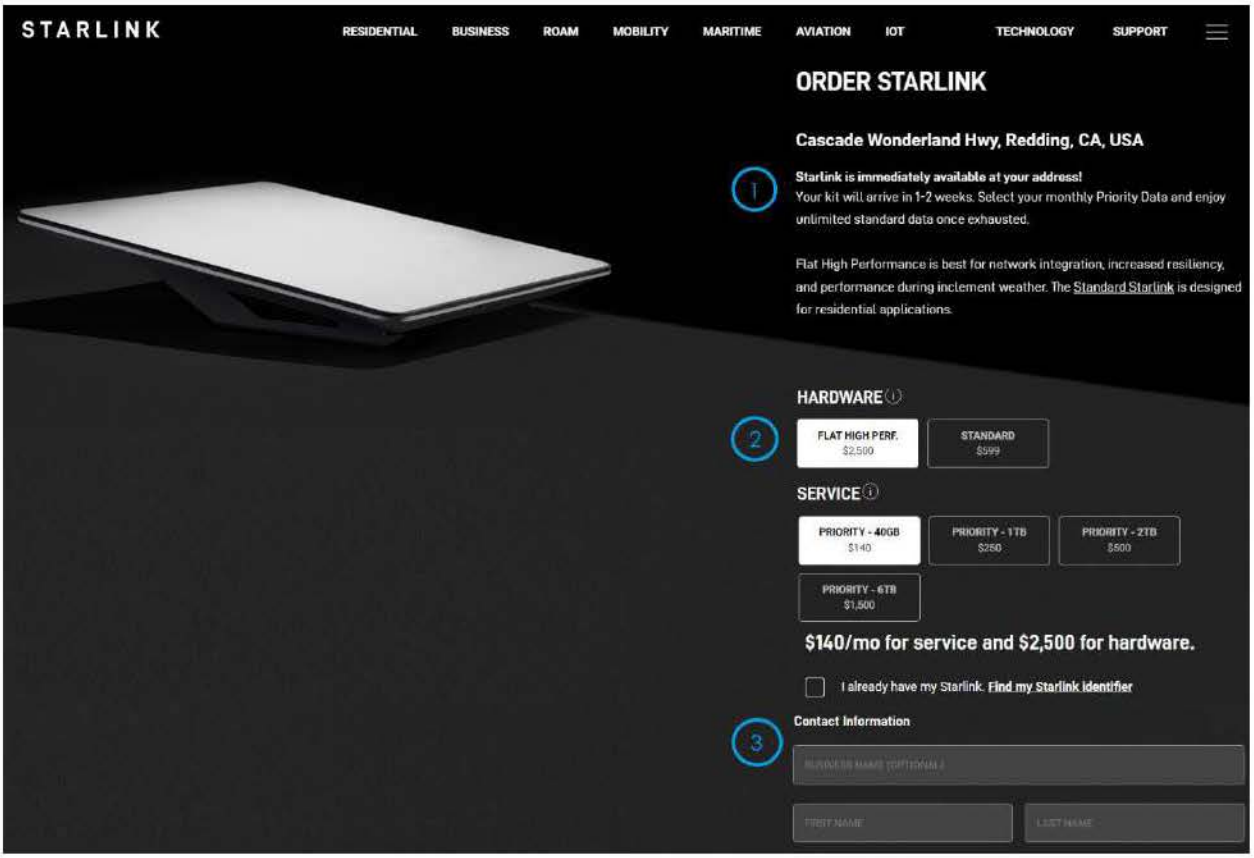



**Figure A.2: Starlink procurement Step 2: Starlink service availability, hardware, and service indications, and contact entry**

Figure A.2 provides Starlink service availability, indications, and contact entry. Here, the screen shows the selected location, followed by #1, which provides critical information about service availability. In this case, the service is immediately available, the ideal scenario. Another indication could be: (a) service is unavailable or (b) you will be in a queue to receive service. Other indications may be possible. The buttons at #2 show the types of kits and services available. Here, both Standard and Flat HP kits are available. Starlink allows customers to match different services with different kits from the order page. After the order is placed, the service can be changed at any point from the Starlink account (depending on the selected kit), but the kit itself is only replaceable for thirty days in cases when an incorrect kit was selected. At #3, enter the contact information for the service. This contact may be different than the purchaser's information, which is entered in a subsequent screen.

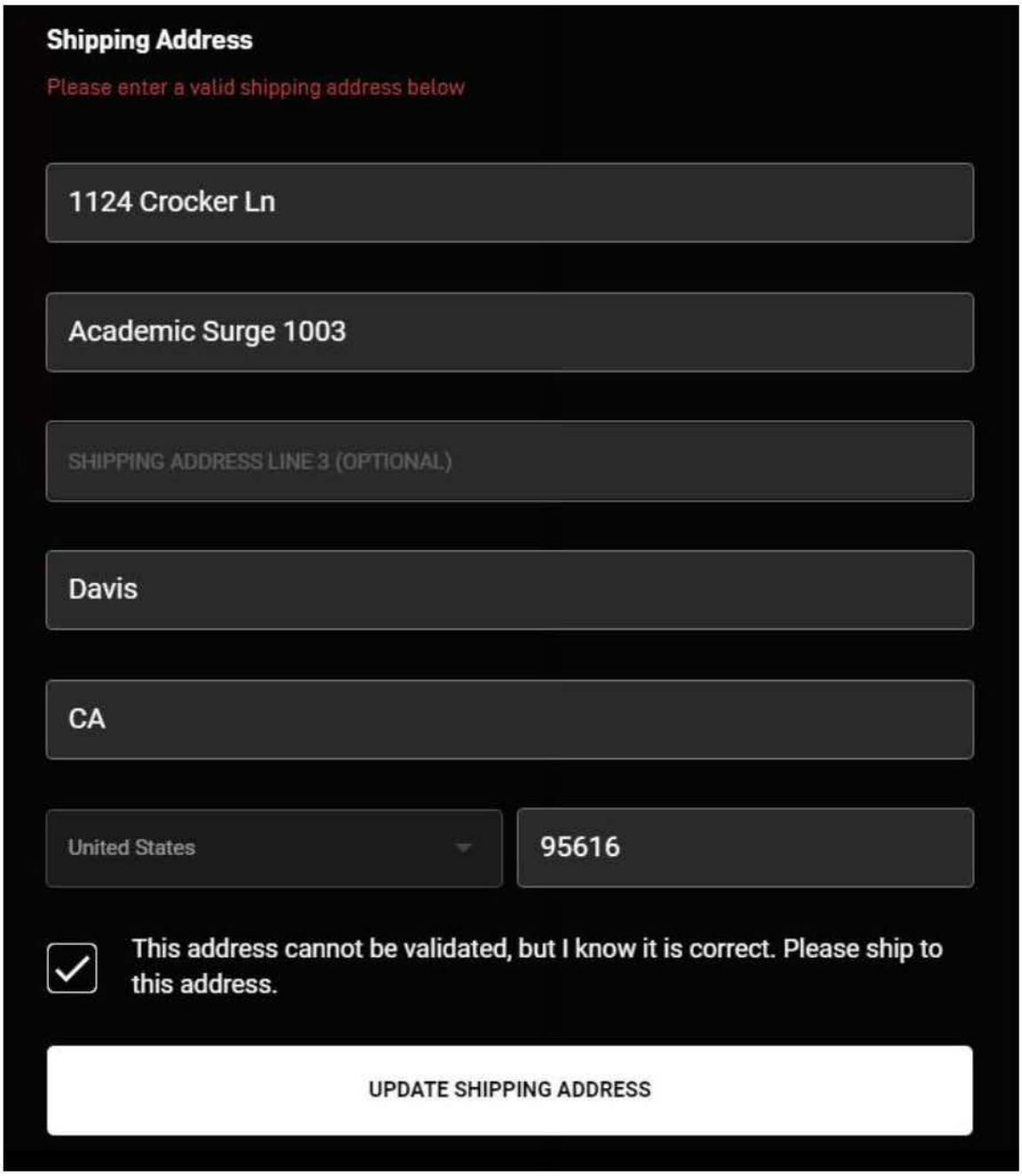



**Figure A.3: Starlink procurement Step 3: Shipping address for the Starlink hardware**

Figure A.3 shows the entry form for the shipping address for the Starlink hardware. This address may be different from the service location. Provide a valid shipping address to receive the shipment. If automatic validation of the address does not work, carefully confirm the address and then click the check box noting the address is correct.

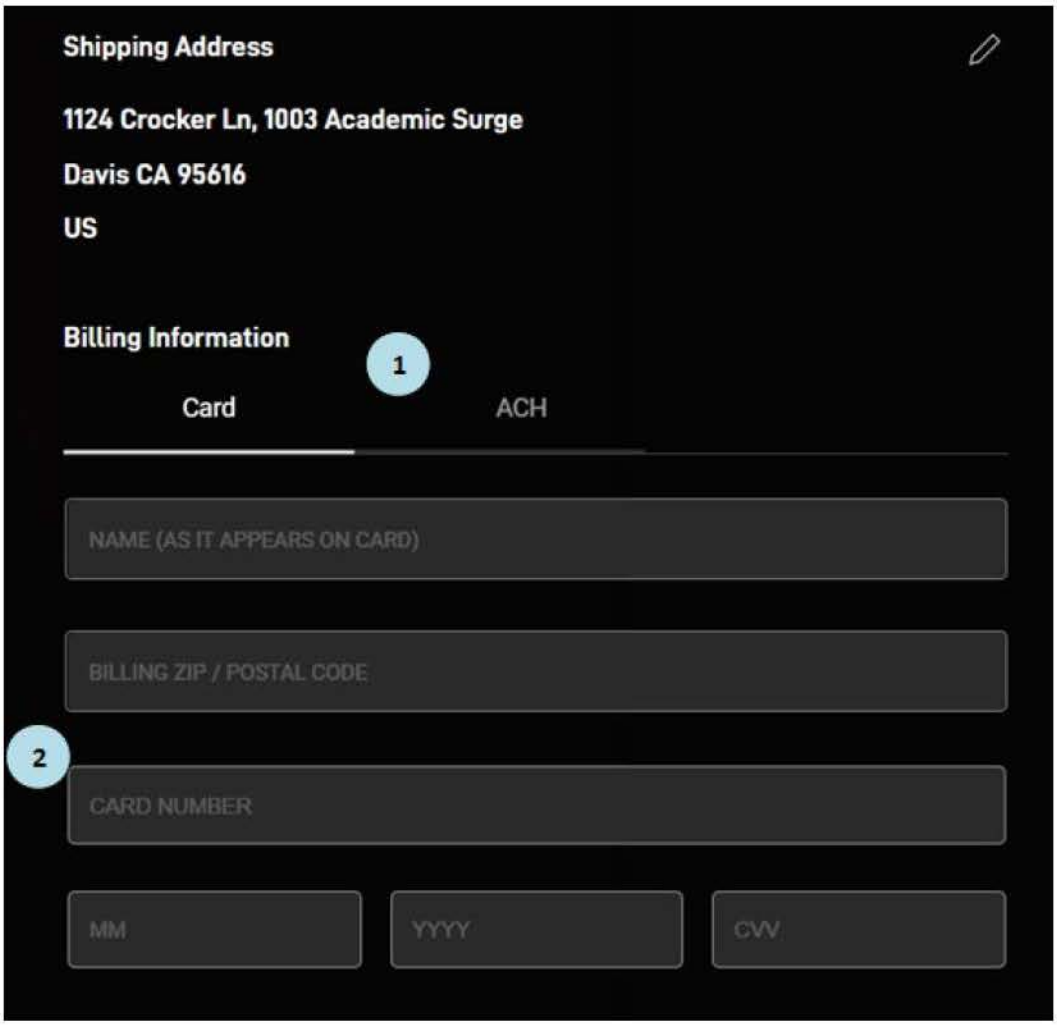



**Figure A.4: Starlink procurement Step 4a: Billing form for credit card payment**

Figure A.4 shows the billing form for credit card payment. The form will repeat the shipping address you have entered. It then includes two payment options at #1, credit card and Automated Clearing House (ACH), i.e., a direct charge to a bank account. In Figure A.4, credit card is selected. The key information for credit card is the card number, expiration, and Card Verification Value (CVV). For a typical state Department of Transportation (DOT), the information here will need to be for an authorized credit card purchaser. The purchaser will typically not be the contact or the user of the system.

Figure A.5 shows the entry form for the bank account ACH option. AHMCT has no experience with this approach. It may apply for some DOTs, but as with the credit card approach, only an authorized ACH purchaser can use this option, and the purchaser will typically not be the contact or the user of the system. Where ACH is applicable, the key information will be #1 routing number and #2 account number.

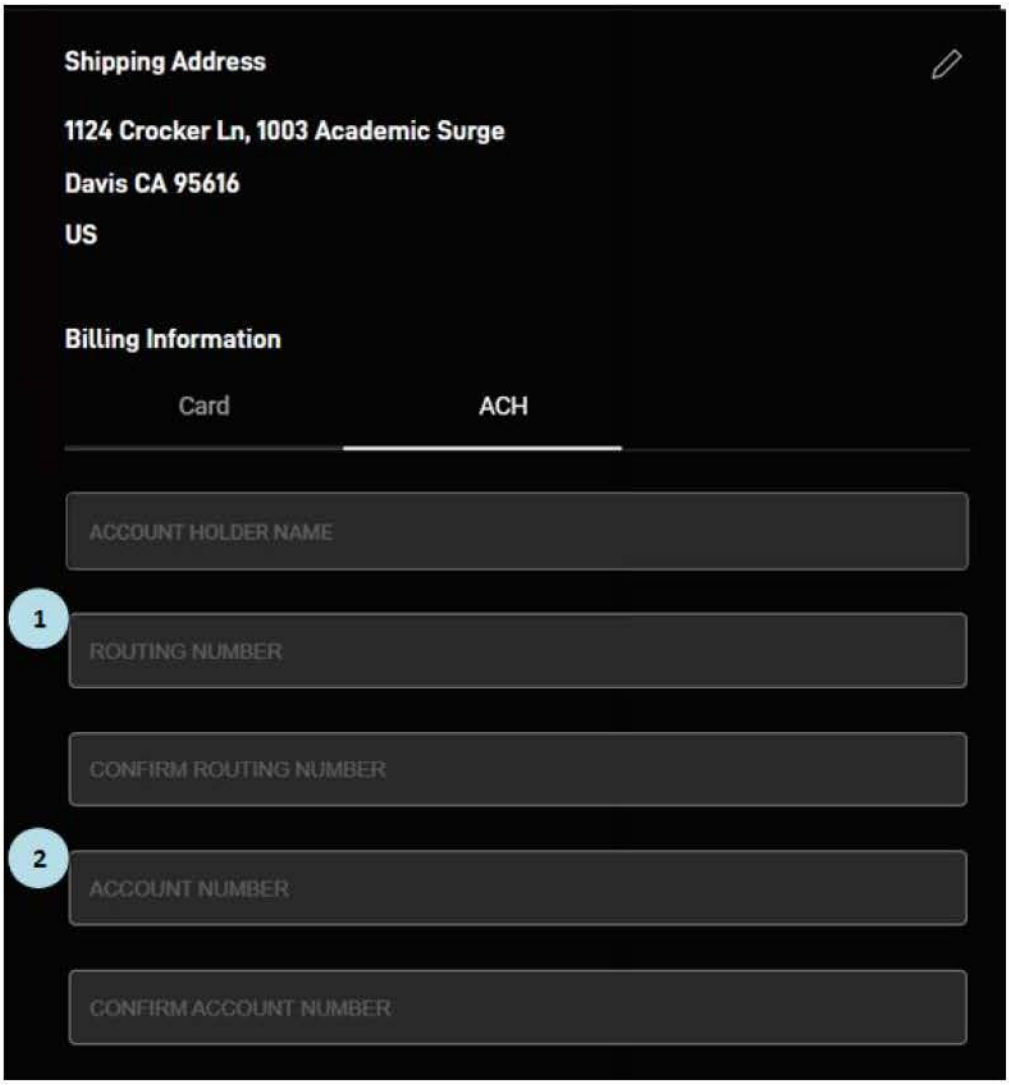



**Figure A.5: Starlink procurement Step 4b: Billing form for ACH payment**

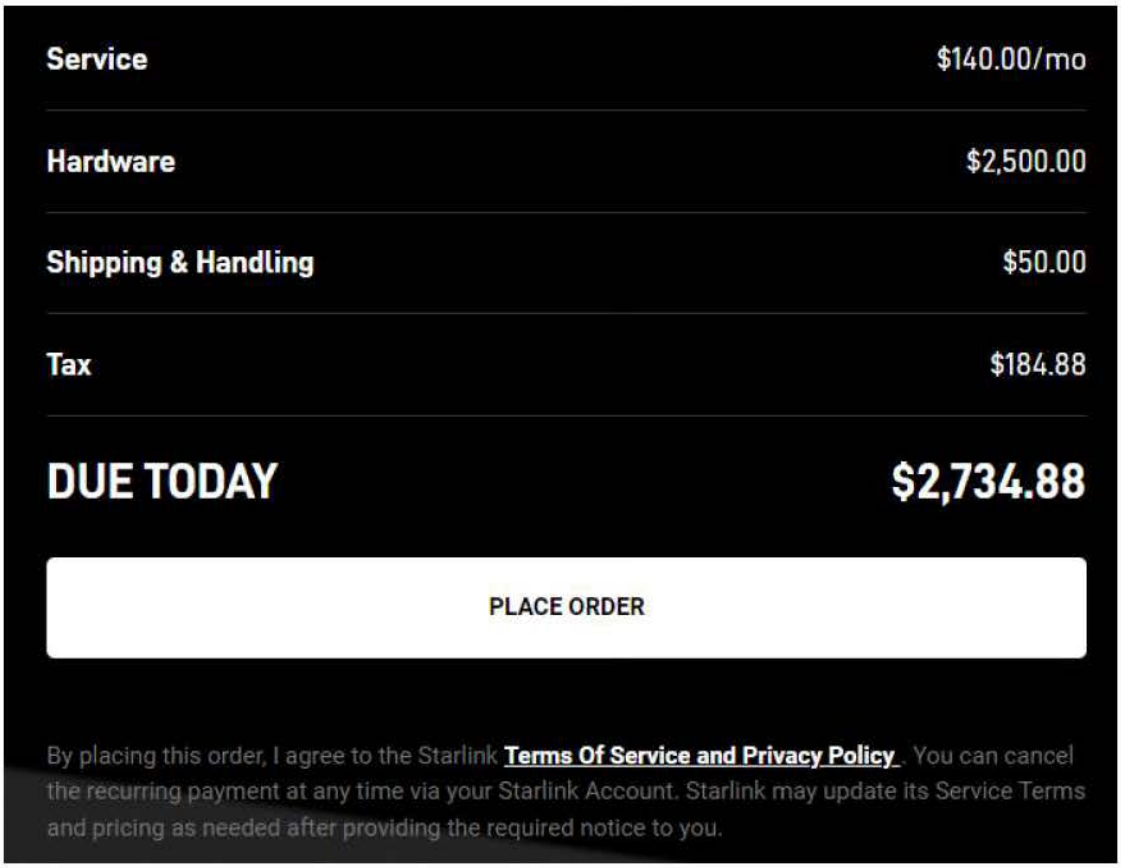



**Figure A.6: Starlink procurement Step 5: Starlink order summary including initial and on-going charges**

Figure A.6 shows the Starlink order summary, including initial and on-going charges. The initial charge includes the first month service payment (here $140), plus all up-front hardware, shipping & handling, and tax. The selected payment method will also be billed each month for the recurring service charge. This screen also includes a link to the Starlink Terms and Conditions and Privacy Policy. Review is recommended. The screen shown in Figure A.6 is the final section of the ordering page. Upon clicking "Place Order", the order will be submitted, the charge will be made, and Starlink will ship hardware within one to two weeks.

# Service Availability, Policy, and Pricing Updates

Since SpaceX Starlink is a fairly new and dynamic company, it did not, at the time of evaluation, have all business aspects firmly established as a more seasoned company typically would have. This gap was apparent in the service availability, policies, and pricing fluctuations during the study period.

In procuring the five systems for the evaluation, the researchers had to carefully check availability at the time of each system procurement. Sites were checked early in the procurement planning and selected in part for their

availability. As final procurement approached, availability was checked again, and sometimes service was no longer available. Typically, this is due to the popularity of the service in the given area, and limited bandwidth availability. If you have a guaranteed service address in an area, you will not lose it as the area gets crowded, but new users may not be able to get in. Thus, it is critical to check availability at the time of purchase and to procure service in a selected area as soon as you are certain you will need it.

Due to the primary mission of Starlink, the service is generally unavailable in more populated areas. The company is focused on providing service in underserved regions. Service availability in populated areas began increasing in the later part of this project.

Starlink is also prone to update policies fairly often. In the period of this evaluation, up to this report date, the team saw a few updates. Nothing was prohibitive to DOT use of the system, but it is important to be aware of the likelihood of such updates.

Pricing is also somewhat in flux and can change within a service period. DOTs would need to allow for some pricing uncertainty during the period of their contract.

# Surge Protection

For surge protection, AHMCT ordered five units of the Polyphaser Outdoor Twisted Pair Lightning Surge Protector model IXG-05 made for a four-pair power-over-ethernet (PoE) line with ground connection. This lightning surge protector/arrestor will help protect Caltrans equipment from surges in power that can be caused by lightning and other strong changes in electricity. The data line twisted pair surge protector product is manufactured for Gigabit Ethernet up to 1000 Mb/sec, PoE Data Turn-On Voltage of 75 VDC and used to protect sensitive electronic equipment.


**Figure A.7: Polyphaser surge protector IXG-05**

# Mounting and Installation

In this section, we focus on introducing all mounting equipment used for the pilot test installation planned for October 2023. AHMCT is designing an integrated HP pole mount for use at Caltrans installations. The design of this integrated mount will be documented separately. The mounting approach and hardware described below were procured and used for the project field testing.

In this plan, which works for both HP kits, we used a medium clamp with an extended arm and one set of crossover clamps to attach a pipe parallel to the CCTV pole or tower leg. Then we used a Starlink standard pipe adapter to mount the antenna on top of this pipe.

Table A.2 lists all the equipment required for installation of each flat HP kit in addition to what comes with the flat HP kit and Caltrans routers and Omnitron switches.

**Table A.2: Starlink updated mounting solution for each flat HP kit used in the pilot test with its overall cost estimate**

| Equipment | OD x Length | Qty | Price/Unit |
|---|---|---|---|
| Trylon/accessories SAS300L, medium backing fits | 2 3/8" x 3' arm<br>4 ½ " - 6" clamp | 1 | $175 |
| SitePro1 Valmont crossover clamp SSCK | 1.5" - 3.5" clamp | 1 | $50 |
| Starlink flat HP pipe adapter | Suitable for pipes up to 2.4" outer diameter (OD) | 1 | $120 |
| 2" x 2' galvanized pipe or Starlink ground pole | 1.75-2" x 2' | 1 | $75 |
| Flat HP 25-m Starlink cable | 0.5" x 82' | 1 | $165 |
| Polyphaser outdoor twisted pair lightning surge protector model IXG-05 | N/A | 1 | $190 |
| Total | | | $775 |

The flat HP kit shown in Figure A.8 comes with everything that the old HP kit had in its box plus a Wedge Mount kit (arrives in a separate box and can be used to mount the antenna on a flat surface). Both Starlink HP kits come with Starlink power supply, built-in Wi-Fi router, 8-meter Starlink (antenna) cable, 5-meter ethernet cable, 2-meter router cable, Starlink router & power unit AC power cables. We will need a 25-meter replacement Starlink cable to connect the antenna from the pole to Caltrans cabinets. This cable will be intercepted with a surge protector for additional safety.

**Figure A.8: Flat HP antenna attached to the wedge mount**

In addition to the kit, longer antenna cables, and the surge protector, installation requires the following equipment for mounting the antenna:

1. Trylon/Accessories SAS300L: 2 3/8" x 3' Single Arm Standoff with Medium Backing Kits, which fit up to 5 5/8" OD rounds and 6" (60°) angles or 5" (90°) angles. This item is hot-dip galvanized and weighs 22 lb. The Small Backing Kit weighs less but fits up to 4 1/2" OD round, which works for the tower leg but not the CCTV pole (with OD of 4 9/16"). Small-fit standard clamps/U-bolts support poles up to 4 1/2" OD. For any poles or tower legs above 4 ½" OD up to 6 ½", one can use either medium or large backing fits, with medium backing fits providing better support. Our test sites have poles 4 ½" to 5 ½" OD. As such, medium backing fits were acquired. It is also essential that the mounting solution gives us between 2' to 3' offset/standoff from the pole/tower leg depending on the surrounding area to allow for free movement of the Starlink dish.


**Figure A.9: Trylon/Accessories SAS300L with Medium Backing Kits**

2. SitePro1 Valmont SSCK: One set of hot-dip galvanized Crossover Clamp with 1.5" to 3.5" OD. This crossover clamp connects the Trylon/Accessories arm to the base of the Starlink antenna.

**Figure A.10: SitePro1 Valmont crossover clamp SSCK**

3. Starlink Flat HP Pipe Adapter: Designed to attach to any pole with a max diameter of 2.4" (62 mm). Slide the adapter over the top of the existing pole, fasten provided screws, and drop in the Starlink. Requires Wedge Mount Kit that comes with Flat HP Starlink.

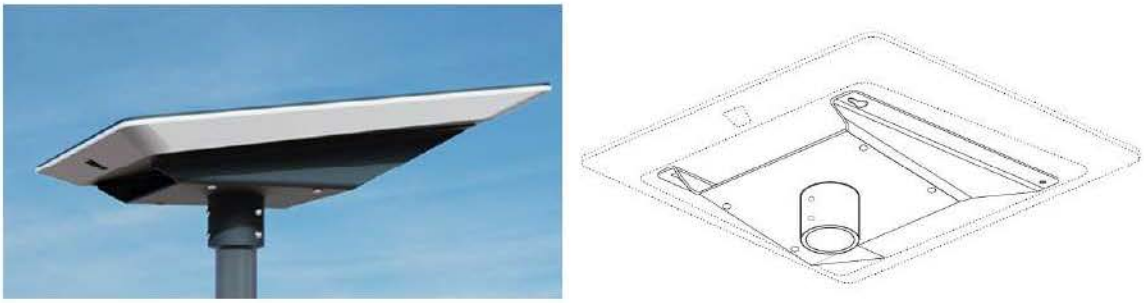


**Figure A.11: Starlink Flat HP Pipe Adapter attached to the Wedge Mount Kit, which is in part screwed to the bottom of the antenna**

4. Finally, we need a 2" x 2' galvanized pipe to support the Starlink pipe adapter and the antenna on top. Alternatively, as a low-cost and easily available option, we use the Starlink Ground Pole, which has 1.75" outer diameter plus six units of 1/4-20 x 1" flat countersunk head machine screws used to pressure fit the Starlink Flat HP Pipe Adapter to the bottom half of the pole. As shown in the left image in Figure A.12, the top half of this ground pole latches onto the Starlink HP antenna without any adapter required, making this a viable solution for mounting both HP antennas.
5. We used the Starlink ground pole shown in Figure A.12 with custom machine screws to secure the flat HP pipe adapter and the wedge mount on top. The HP kit latches to the HP antenna without any adapter. We used the top half of the Ground Pole (approximately 3 ft) for the Fiber Hub installation. We used an approximately 1.5-ft section at each field site.

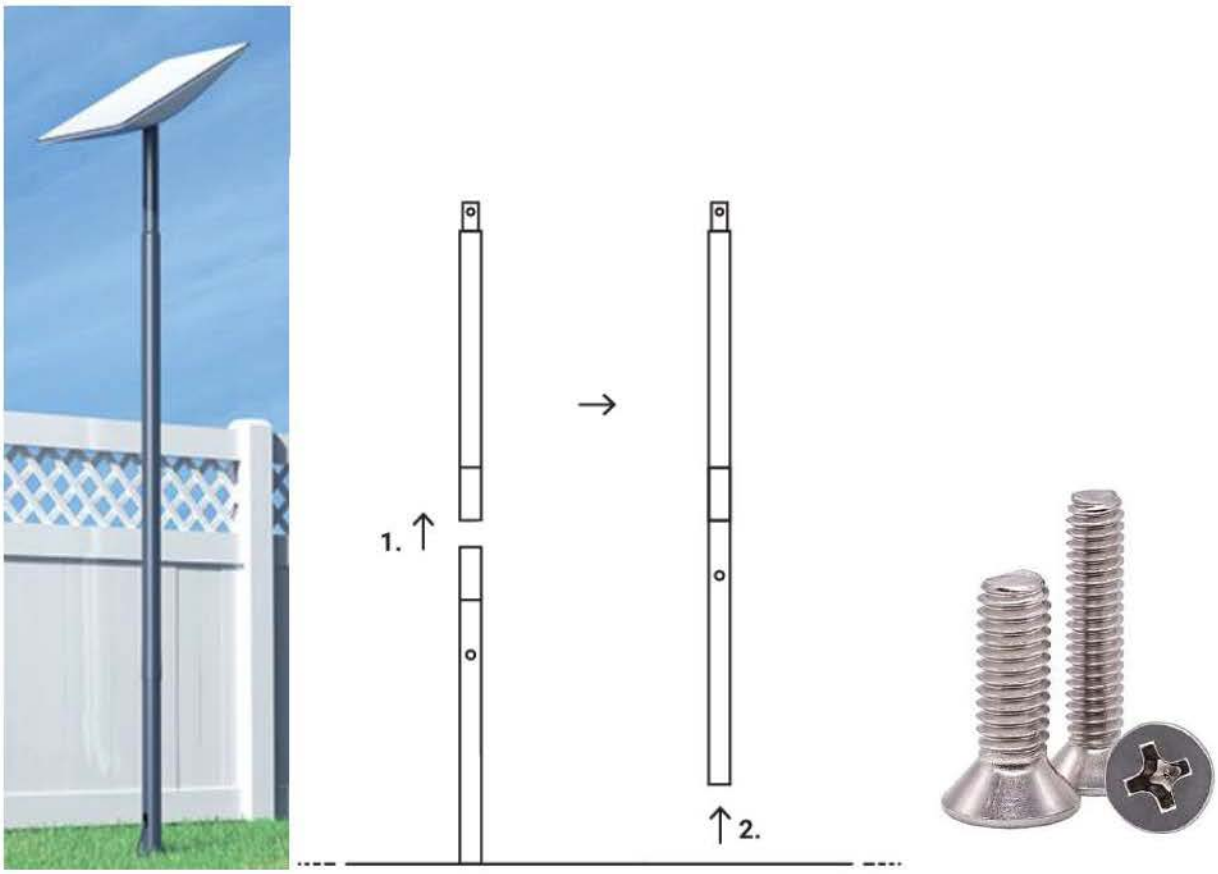



**Figure A.12: Starlink Ground Pole and 1/4-20 x 1" flat countersunk head machine screws**

Figures A.13 through A.16 provide various views of mounted HP and Flat HP kits across District 2.

**Figure A.13: The top half of Starlink Ground Pole being installed at Redding Fiber Hub as the base for the actuated HP antenna**

**Figure A.14: Starlink Ground Pole after installation at the Redding Fiber Hub**

**Figure A.15: First view of a complete Starlink Ground Pole installation at a field site**

**Figure A.16: Second view of a complete Starlink Ground Pole installation at a field site**

# Appendix B:
# Starlink Initial Testing Interim Report

## Test Plan Update

As fully elaborated in the Task 2 procurement interim report, the original plan was to test four Standard Rectangular (SR) kits as field systems (at four CCTV sites) and one High-Performance (HP) kit as the core system at the Redding Fiber Hub. By September 2023, it was decided that the SR kits would be replaced by new Flat HP kits which have the following features:

- The new Flat HP kit is equipped to connect to a wider range of satellites at once without mechanically tilting towards a specific direction. Both SR and HP kits have an electric motor which directs the antenna to look towards north (in the northern hemisphere) to establish optimized connection. This mechanical part for the standard SR and HP kits poses a reliability concern and was considered by the panel as a downside, especially at some of the sites where the north side of CCTV pole (where the antenna is supposed to be installed) could be blocked by hills or trees. This was a prime motivation for switching to the Flat HP kit, which uses a phased-array antenna rather than mechanical scanning.
- HP kits are equipped to have a higher bandwidth when priority data are available. Priority data comes with Priority and Mobile Priority services, which also reserve a public Internet Protocol (IP) v4 (IPv4) for users. Priority plans were exclusive to HP kits until September 2023. After a series of updates to Starlink Terms of Use and Services, SR kit users can now subscribe to commercial Priority services at the same monthly rates; however, SR kits still have their hardware limitation compared to HP kits as described in the Procurement Interim Report, e.g., moving parts, lower power, lower bandwidth, smaller antenna, and the lack of separate power supply module that makes it harder to bypass the Starlink router.
- Other than the antenna, HP and Flat HP kits were found to have similar hardware and compatibility features. Both HP and Flat HP kits come with a separate power supply that feeds relatively higher power to the antenna compared to the SR antenna which is powered by the Starlink Wi-Fi router. Since the power supply allows the connection of off-the-shelf routers (directly to the antenna) via Starlink Ethernet cable, HP kits allowed us to easily bypass the Starlink Wi-Fi router without needing the Starlink Ethernet adapter.

- The Flat HP antenna is the only hardware that allows for a connection in a true mobile sense on moving ground vehicles and boats, but this feature was not a factor in this research as all testing in this project was carried out when the antenna was stationary.

After the launch of the new Flat HP kit in April 2023, the panel decided to carry out a series of testing at AHMCT's Advanced Transportation Infrastructure Research Center (ATIRC). First, AHMCT, with the help of their IT expert Travis Swanston, tested the viability of using the public IPv4 offered by Starlink and an off-the-shelf wired router to remotely access a live camera footage connected to the web via Starlink. Upon the success of this test, the panel went forward with simulating the conditions of the field test at ATIRC where one HP kit (representing the core) and one Flat HP kit (representing the field) were used to check the compatibility of District 2's commonly used Cisco routers and switches with Starlink systems. Upon confirming the feasibility of using existing equipment at District 2's hubs and CCTV cabinets, AHMCT and the customer proceeded to install five kits in D2 for field/pilot testing early October 2023.

Another update to the plan was switching the Buckhorn test site to Cedar Pass due to ongoing construction at Buckhorn at the time of installation and testing. District 2 staff, with the help of the AHMCT team, successfully installed and activated five kits using Starlink hardware, off-the-shelf surge protectors, and mounting equipment, all procured in Task 3. This interim report documents the system testing of Task 4 carried out at the ATIRC and District 2 field sites.

# SR Kit Testing

AHMCT acquired an SR kit with Residential service in October 2022. During the first site visit, the portability option was added to the service to test its connection at the Sims Road and Lassen Park CCTV sites. The initial testing late in 2022 was promising. The connection quality was deemed sufficient at both sites under the Residential plan which had no restrictions on bandwidth. Since Starlink did not offer any plans with public IPv4 for SR users until late 2023 and also due to the emergence of more advanced Flat HP kit, the panel indicated no further testing the SR kit.

AHMCT sees potential benefit in using the SR kit at District 2's CCTV sites possibly under Priority service, which now offers public IPv4 for SR kits. The technical challenges for using the SR kit remain, specifically needing a clear view of the sky to the north of the pole where the antenna is mounted and the lack of power supply as the antenna is powered directly by the Starlink Wi-Fi router. Therefore, unlike HP kits, the SR kits need to keep the Wi-Fi network on (causing security issues) while using the Starlink ethernet adapter to connect additional off-the-shelf wired routers. Further testing is required to investigate the possibility of bypassing the Starlink Wi-Fi router for SR systems.

# HP Kit Testing

This kit was first tested late in 2022 during the first site visit at the Redding Fiber Hub under the Business plan, which was later renamed Priority service. The same device was simulated as the core system during testing at ATIRC and eventually selected to be permanently mounted on the Redding Fiber Hub tower for field testing.

# Flat HP Kit Testing

This device was first tested at ATIRC to check the viability of using IPv4 to remotely access devices using the Starlink network. Later, the Flat HP kit simulated the spoke system (field devices) to tunnel live camera footage to the HP kit simulating the core at ATIRC. Upon success of this test, the panel chose to equip four CCTV sites (namely Sims Rd, Lassen Park, SR70-SR89, and Cedar Pass) with Flat HP kits for field testing.

# Viability Test Results at ATIRC

As of November 2023, Starlink support reads regarding their IP policy[4]:

*"Starlink provides two IP policies, "default" and "public". The default IP configuration is Carrier Grade Network Address Translation (CGNAT) using private address space assigned to Starlink clients with DHCP from the 100.64.0.0/10 network. Network Address Translation (NAT) translates between Starlink private and public IPs.*

*The Starlink public IP policy is an optional configuration available to Priority and Mobile Priority customers. A public IP is reachable from any device on the internet and is assigned to Starlink network clients using DHCP. While we do not provide a static IP option at this time, we utilize a reservation system so that the public IP address is reserved even when your Starlink is turned off or rebooted. Our system is dynamic where moving the Starlink to another location and Starlink software updates may cause the public IP to change. Starlink does not currently offer the ability for Standard or Mobile customers to receive a public IP. The public IP option can be enabled from the account dashboard.*

*Each Starlink is allocated one IPv4 address and delegated a /56 IPv6 prefix for network clients. All Starlink network clients are assigned an IPv6 address. IPv6 is supported on all Starlink routers.*

---

[4] Acronyms and abbreviations used in this excerpt: Dynamic Host Configuration Protocol (DHCP), Internet Protocol v6 (IPv6), Server Message Block (SMB), Simple Mail Transfer Protocol (SMTP), Transmission Control Protocol (TCP)

*The default IP policy using CGNAT blocks all inbound ports. Customers requiring inbound ports should consider products with a public IP option. The following outbound ports are blocked for all customers per information security best practices: TCP/25 (SMTP) and TCP/445 (SMB).*

*As Starlink continues to expand and upgrade our global internet service infrastructure and rollout new capabilities, some users may see different IP address behavior (for example, publicly routable addresses, IPv6, non-CGNAT)."*

# Stage 1 Viability Testing

To make sure that the above IP policy will not be a problem for this project, the District 2 customer asked AHMCT researchers to facilitate a test at ATIRC before initiating the field testing to confirm the viability of using HP and Flat HP kits to tunnel a secure connection from rural field CCTV sites to the core Fiber Hub at Redding. AHMCT suggested two stages of testing during the summer of 2023 to confirm the feasibility of using off-the-shelf wired routers for District 2's application.

In the first stage, a single Flat HP kit was utilized to test the stability of public IPv4 offered by Starlink for Priority service users. Travis Swanston from AHMCT supervised this test, proposing the system architecture shown in Figure B.1 and the configuration code for the ER-X wired router.

The system included two links to remote access the AXIS camera footage from any computer: one using the actual external public IPv4 (e.g., 98.97.123.148:40080/) assigned to ER-X and the other using a link generated by a 3rd-party (free) account at No-IP.com (https://www.noip.com/), which operates ddns.net. This Dynamic Domain Name Service (DDNS) scheme was supported by the ER-X router configured to use the created noip.com account and allowed a fixed link (e.g., sl1-ahmct.ddns.net:40080) to be translated into the assigned dynamic IPv4 so that the link would always forward the user to the right IP. Both links remained operational for the duration of the test. In the future, if Starlink offers static public IP, Caltrans will not need to use any DDNS scheme, and instead one can just set up a Domain Name Service (DNS) provider at the host server.

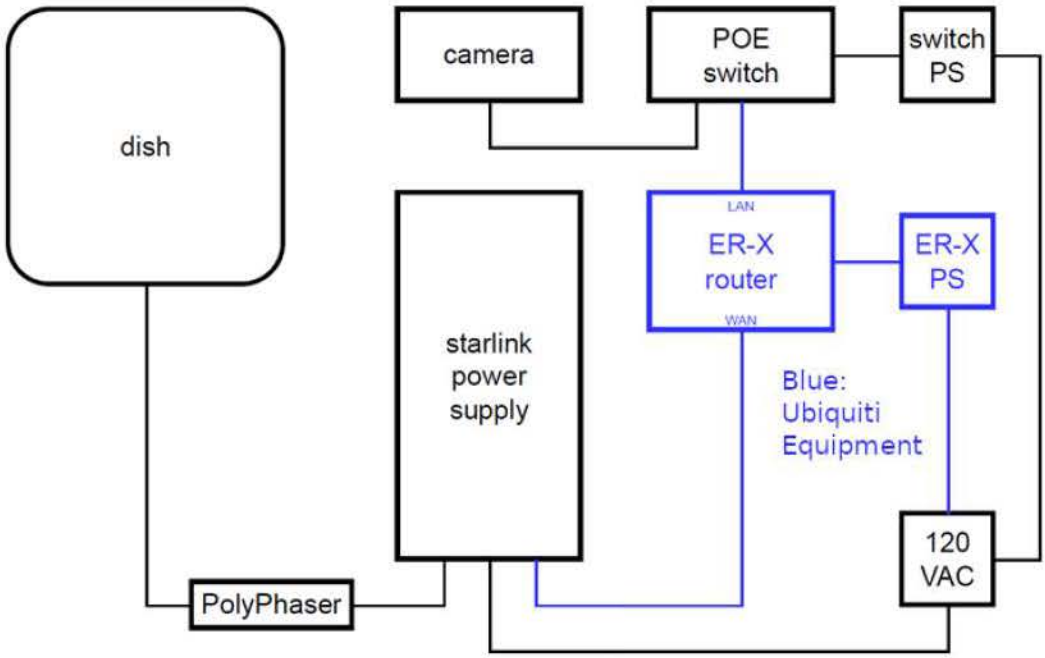



**Figure B.1: System architecture for testing public IPv4 to remote access camera footage with one Flat HP kit and Ubiquiti EdgeRouter-X wired router and power switch replacing Starlink Wi-Fi router (Courtesy of AHMCT and Travis Swanston)**

In conclusion, the Starlink Flat HP kit proved to be flexible for using off-the-shelf routers, while the public IPv4 remained unchanged throughout the test for as long as the same router was connected to the power supply. The test duration was approximately six weeks. The system was not moved/relocated during the test to model District 2's application. AHMCT unplugged the system for one week during that period. Upon switching the system back on, it was confirmed that rebooting the system did not lead to change of the reserved IPv4; although, Starlink does not guarantee static IP for any users as of November 2023. That said, Travis investigated Starlink's IP approach, discovering:

- Starlink currently issues 5-minute DHCP leases, leaving themselves with the flexibility to quickly change IP addresses if/as needed.
- From Starlink's Autonomous System Number (ASN) records, it looks like they currently have less than 240,000 IPv4 addresses assigned to them. Starlink currently has over 1.5 million subscribers and that number increases by thousands each day. Of course, the vast majority of users have the default CGNAT IP, so these numbers are not particularly indicative of what to expect in the future.
- AHMCT's conclusion is that unless static IPs become part of the service offering, it is best to assume that the IPs are dynamic. If Caltrans plans

around that assumption and handles it correctly, there should not be any serious problems.

## *Stage 2 Viability Testing*

In the second stage, a Flat HP kit was used to simulate the spoke (field device) and a HP kit was utilized to represent the hub (core device) as depicted in Figure B.2. This test was carried out using the Cisco 1920 and 1921 routers and switches connected to both systems.

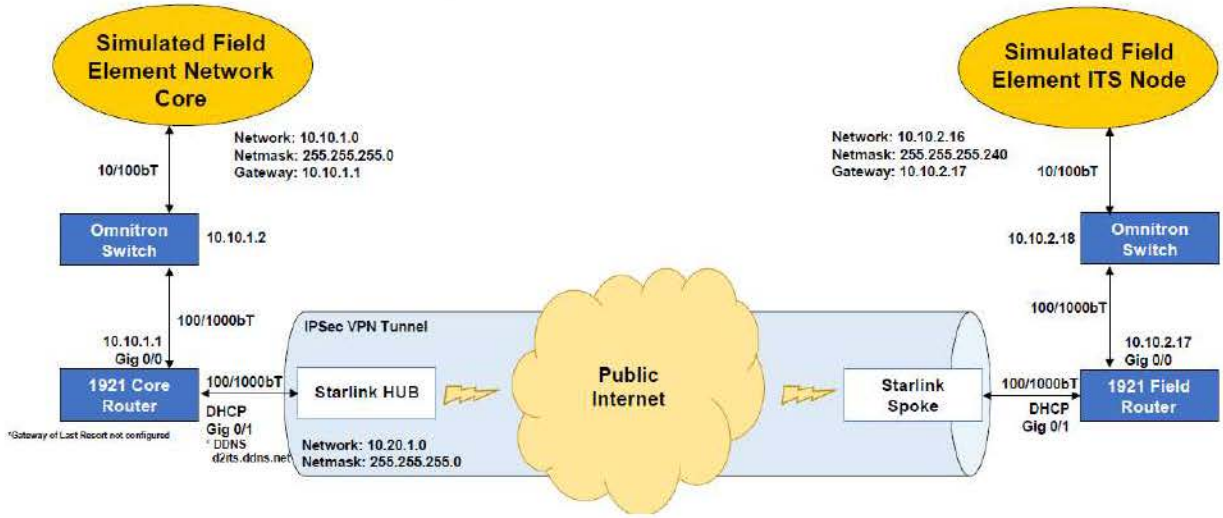



**Figure B.2: Starlink end-to-end network architecture including hub and spoke systems (Courtesy of Caltrans D2 and Keith Koeppen)**

Keith Koeppen from District 2 set up the configuration for both routers and set manual local IPs for the camera and other devices in the network to forward the camera stream out from the spoke to the hub. The Cisco wired routers and switches are standard with the majority of District 2 cabinets and hubs; hence, this test showed significant promise that the same setup would work for District 2 field testing. For field testing (described in the next section), the only difference would be that there are four spoke systems tunneling streams into the hub simultaneously, meaning that the core metrics are Uplink Throughput for spoke systems and Downlink Throughput for the hub system.

# Initial Field Testing Results

Field testing officially started on October 9, 2023, with the first kit mounted and activated at the Redding Fiber Hub. Since then, District 2 has been managing the data exchange from field sites to the core hub.

There are two main applications that require the transfer of data from field sites to the core hub, e.g.,

1. *Periodic image grabs by the CCTV Information Relay (hosted at the District 2 head office pulling data from the field site) that are forwarded to the Caltrans Commercial Wholesale Web Portal (CWWP) for traveler information dissemination*. Since the Fiber Hub receives images from multiple CCTV field sites, District 2 personnel had to adjust the downlink given its known bandwidth. To that end, they would occasionally decrease the frequency of image grabs to as low as one JPEG (at 2-CIF [Common Intermediate Format] resolution) image per hour to avoid network contention at the hub. When needed depending on weather conditions, snow, fire, traffic, or other events, the District 2 district office would raise the frequency at one or more field sites up to one image per ten minutes.
2. *Transportation Management Center (TMC) streaming video from the CCTV site onto the video wall at the District 2 district office*. This feed is also adjusted (video protocol, compression, resolution, framerate, etc.) to avoid surpassing the bandwidth capacity at the Fiber Hub. District 2 can limit the number of simultaneous CCTV streams to the field using the TMC's CCTV control software.

District 2 sets fixed parameters for image frequency and video parameters at the CCTV sites based on the bandwidth requirements at the Fiber Hub. Another factor considered in this project is the amount of subscribed priority data, currently selected as 40 GB per month for each field device. For field testing, District 2 has also considered the amount of data usage in the first few weeks of testing in an effort to stay within this data limit as we expect lower download/upload speeds after exhausting the month's priority data. To that end, District 2 throttled down the video bandwidth to 200 kbps, which resulted in using 50 GB of data at Fiber Hub from November 21, 2023 to December 20, 2023. The last 10 GB was supported by Starlink's unlimited standard data plan as it was decided not to subscribe for additional priority data.

Figure B.3 shows the mounted HP antenna and the cable management outside the hub building. The suppressor is recommended to be grounded outside the building. For the long term, District 2 recommends modifying a lightning suppressor (surge cable landing) unit tailored to the Starlink cable.

**Figure B.3: HP Starlink mounted on the Hub tower (Courtesy of District 2)**

**Figure B.4: Flat HP Starlink mounted on CCTV pole (Courtesy of District 2)**


**Figure B.5: Starlink power supply and PolyPhaser surge protector housed temporarily in highway cabinets next to CCTV poles (Courtesy of District 2)**

Figure B.4 shows the Flat HP antenna mounted about 6' below the CCTV camera, so it minimally blocks the view of the road below, and the Starlink cable stretching inside through the hole made on the side of pole. The cable is routed underground to enter the cabinet from the bottom where a lightning suppressor unit intercepts the cable before connecting to the power supply as depicted in Figure B.5.

District 2 uses the system architecture depicted in Figure B.6 to connect multiple roadside Local Area Networks (LANs) to the core network. For field testing, the only change made for the five field networks was to switch the Internet Service Provider (ISP) from Long-Term Evolution (LTE) to Starlink and manually reconfiguring the system IPs.

The AHMCT team used the Starlink account to set up Priority 40 GB plans for all five devices for the duration of the field test and is planning to transfer the account entirely to District 2 upon project conclusion. Starlink provides an online portal that allows customers to shop for replacement equipment, see billing, and most importantly access the dashboard which lists all active and inactive devices as presented in Figure B.7. By clicking on each of the service lines, the user can access the subscription management and data usage report (Figure B.8) and device management toolkit and data transfer report (Figure B.9). These tools collectively allow users to modify service or remote control the hardware by rebooting, stowing, and changing the configuration. The dashboard also allows download of comma-separated value (CSV) files for each device providing network performance, including downlink throughput, uplink throughput, latency, ping drop rate, signal quality, and obstruction. The available data duration and corresponding sample period are shown in Table B.1.

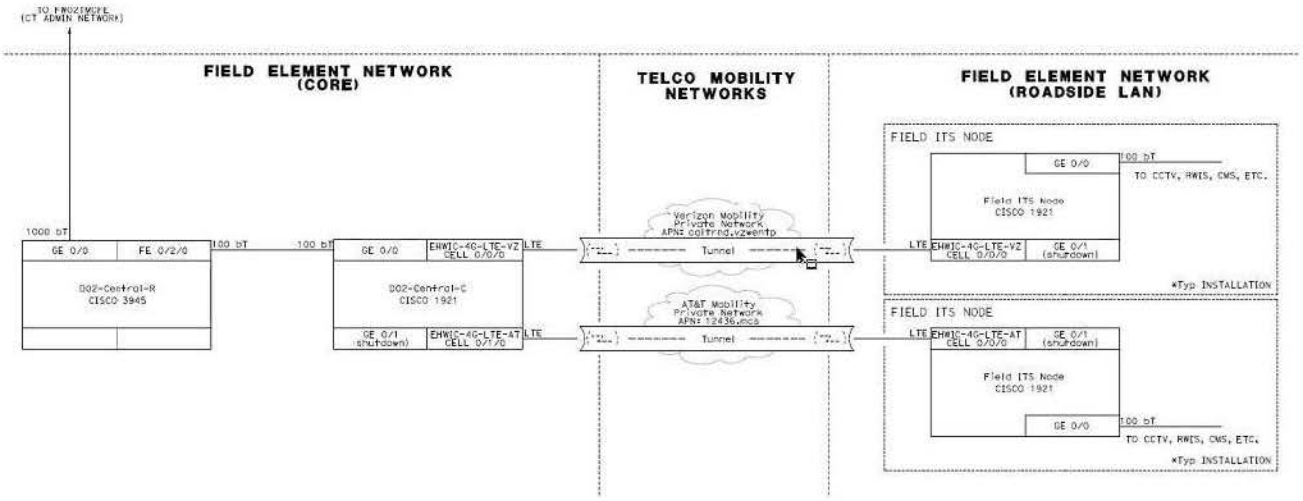



**Figure B.6: D2 system architecture (Courtesy of Caltrans District 2)**

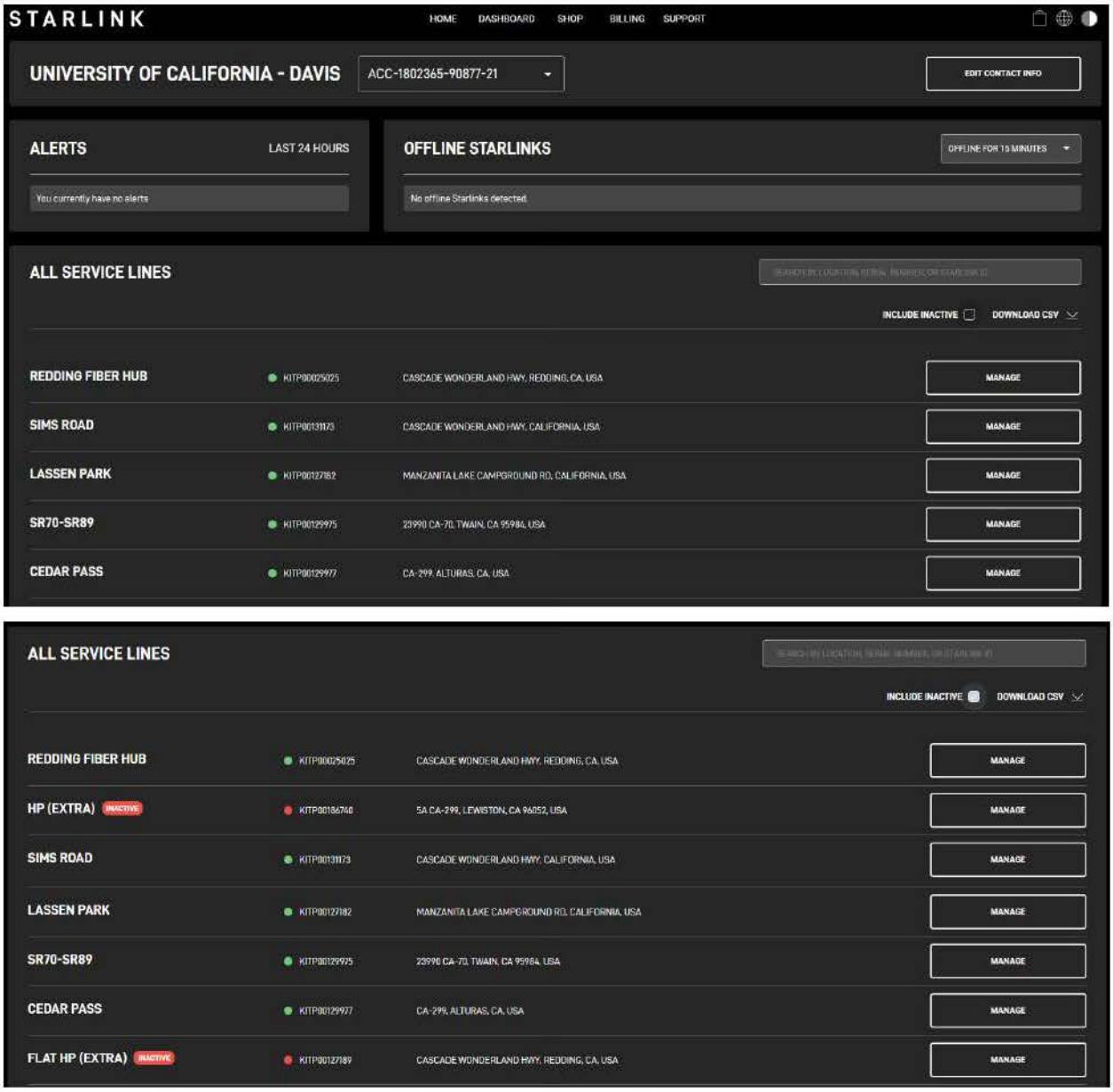






**Figure B.7: Starlink dashboard listing active systems - plus inactive devices if checked (Source: Starlink Account Dashboard)**

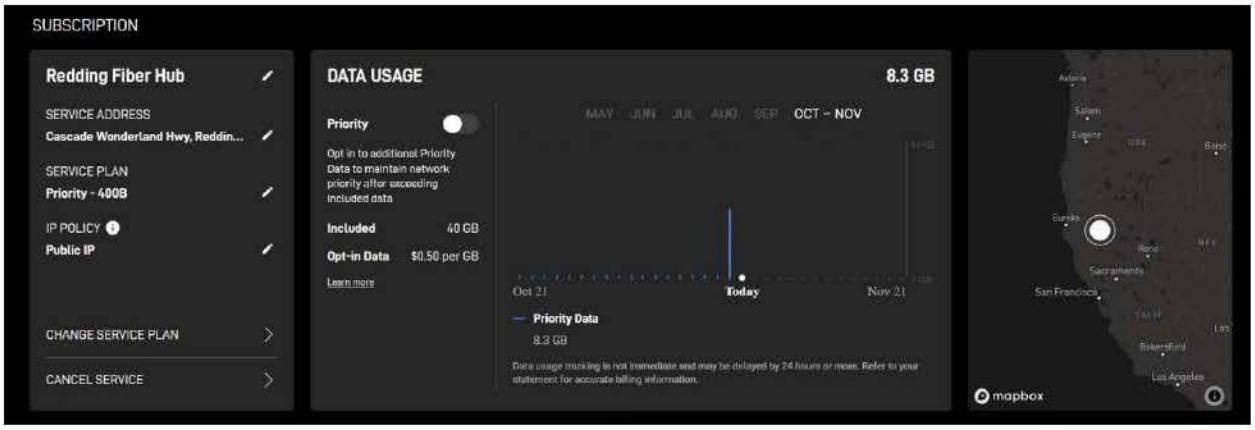



**Figure B.8: Starlink subscription management and data usage report including tools to change/cancel service plan, service address, IPv4 setup (public vs. default), and Priority opt-in-data updated from $2.00 to $0.5 per GB in 2024 (Source: Starlink Account Dashboard).**

**Table B.1: Starlink dashboard network performance data duration and corresponding sample period**

| Collection duration | Collection sample period |
|---|---|
| **15 min** | 15 sec |
| **3 hour** | 1 min |
| **24 hour** | 5 min |
| **7 day** | 15 min |
| **30 day** | 1 hour |

As of November 2023, the only source of testing/operation data can be accessed by downloading the CSV datasheets for each device on an hourly, daily, weekly, or monthly basis. Starlink also depicts the data in each query by six graphics as shown in Figure B.9. For instance, we can see how the graphs below for the last 24 hours show a period of low signal quality between 3 PM and 1 AM. This low signal occurs despite the antenna not detecting much obstruction during this period (mostly under 20% with the maximum of 50% for a few minutes) and is able to send/receive data with a slightly higher latency than average. In the obstruction chart, the rate (and not percentage) of obstruction is showcased corresponding to the data query that can be downloaded using the link above the graphs. In the Starlink portal chart, obstruction of 1 (range 0 – 1) corresponds to 100%. The ping drop rate is the best indicator of lost

communication here happening for reasons beyond obstruction, such as the position of satellites and their access during that period or excess data traffic in the region.

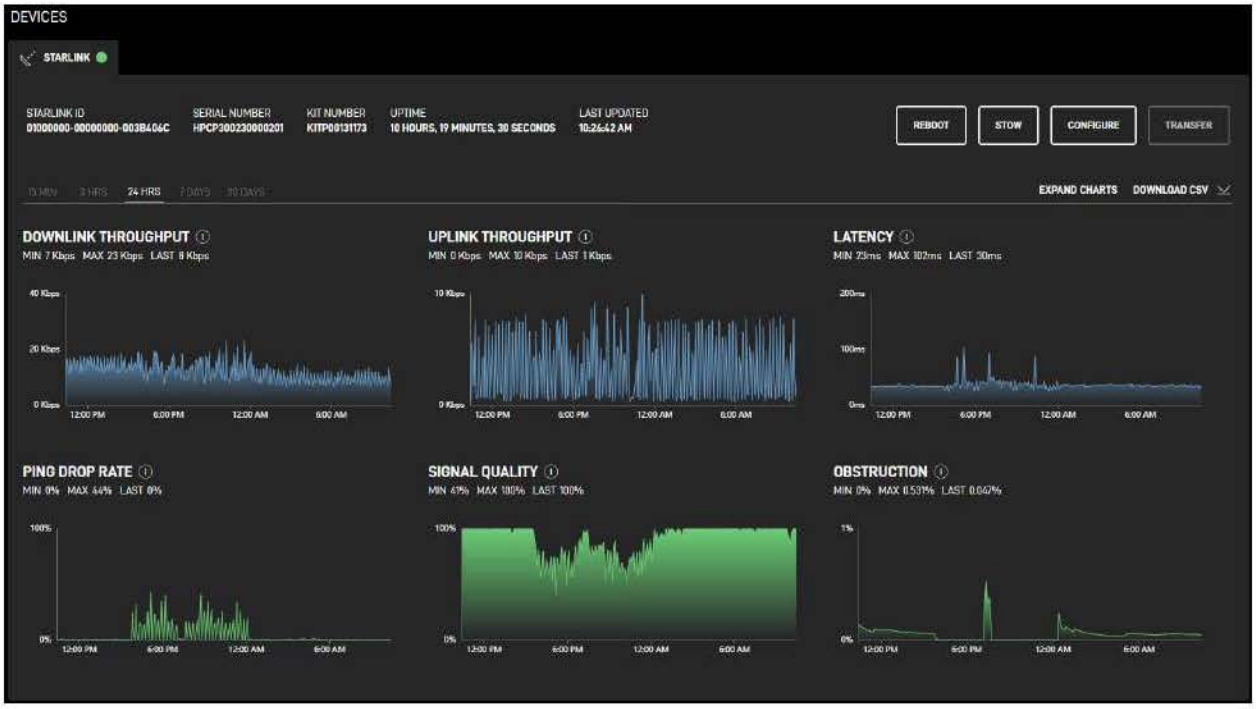



**Figure B.9: Starlink device management toolkit and data transfer report (Source: Starlink Account Dashboard[5])**

[5] Note that the percentage sign on the left side legend of the bottom right graph in Figure B.9 is a misrepresentation. In fact, Starlink is plotting the *Obstruction Ratio* in this chart, and value 1 corresponds to 100%.

# Appendix C:
# Starlink Evaluation Interim Report

## Evaluation Process

This chapter documents the system evaluation of Task 5. Although this task was scheduled in sequence following Tasks 2 through 4, the presented results were gathered throughout the project beginning from the initial test of a Standard Rectangular (SR) kit during the first site visit in late 2022 all the way to installation and field testing of a High Performance (HP) kit at Redding Fiber Hub and four Flat HP kits at Sims Road, Lassen Park, SR70-SR89 intersection, and Cedar Pass up to February 2024. This report reintroduces the significant features of Starlink devices, equipment, and online account (excluding items irrelevant for this project) following recent changes made to Starlink hardware and terms of use.

## Evaluation of Starlink Shop and Customer Service

The Starlink Shop, like other aspects of Starlink, has evolved throughout the project. As of January 2024, the Starlink Shop is still only available to current Starlink customers, and the list of available equipment and their prices change frequently. While many accessories made by Starlink are available from other online vendors, such as Amazon, AHMCT recommends purchasing equipment directly from Starlink as prices are typically lower in the Starlink Shop and delivery times are often within 2 to 7 days.

Starlink customer service has been quite responsive to inquiries made by AHMCT as a business customer. Starlink customer service is not reachable outside of the customer portal. However, since the purchase of the first kit, AHMCT's experience with Starlink customer service has been positive, specifically:

- AHMCT could obtain more detailed information regarding Starlink policies for public IP.
- Starlink customer service gave AHMCT advance notice regarding the upcoming policy changes before the April 2023 overhaul of hardware and services.

- Starlink customer service accepted the return and replacement of three HP kits with Flat HPs even after the one-month return period was over.
- Starlink customer service was very cooperative regarding multiple missing items in shipment and did not charge AHMCT for the replacements.
- Starlink customer service managed to respond to most inquiries made by AHMCT within 1 to 3 business days.
- AHMCT was able to quickly resolve mistakes made in subscription billing that resulted in overcharging for services.

The shop provides replacement kits in case the antenna fails. While all other accessories are available to buy individually from Starlink, one cannot buy the dish separately. It is expected that the Flat HP kit will completely replace the older HP kit in the Starlink Shop. As of January 2024, Starlink still sells replacement material for the older HP kit, but Starlink seems to have removed the older HP kit from the production line-up as the new Flat HP kit surpasses the older kit's performance.

There is also additional connectivity and mounting equipment for different kits. Most of the cables and adapters are specific to only one of the kits (SR, HP, or Flat HP) and cannot be used interchangeably. There are longer cables available in the Starlink Shop with different lengths to provide flexibility regarding connectivity between the antenna and router.

# Testing Results

Here, we provide an overall evaluation of testing Starlink systems in the field at the Redding Fiber Hub and the four CCTV sites. We focus on the overall results, important distinctions between systems, and specific events that occurred during field testing. Further results are expected from District 2 systems as testing continues through 2024 and from the SR kit upon testing across District 6. AHMCT will support further testing across District 2 and District 6 until the end of 2024 and present further results in the final report.

The Starlink dashboard provides several statistics for each system while they are communicating with the server. These data, which include the metrics listed in Table C.1, were sampled for five systems during six weeks from December 12, 2023, to January 23, 2024; the results are summarized in Table C.2 and further expanded in the following sections.

Starlink has posted a support/guide document elaborating what these metrics mean and when one should reference them. Table C.1 is based on a blog post prepared by the Starlink support team for Starlink users. One of the key metrics is throughput, which is the transmission rate at which data are being exchanged in/out of the router/computer connected directly to Starlink, i.e., the download/upload speed the user experiences at any given time.

**Table C.1: Network statistics definitions (Source: Starlink Guide for Customers[6])**

| Metric | Description |
|---|---|
| **Downlink Throughput** | Download speed in Mbps (the rate at which the user is transmitting data out of Starlink) |
| **Uplink Throughput** | Upload speed in Mbps (the rate at which the user is receiving data through Starlink) |
| **Latency** | Round trip time to the Starlink Point of Presence (POP) |
| **Ping Loss (drop rate)** | Percentage of "pings" sent that did not get a response from the POP. You should not experience any effects while ping loss is less than 3% |
| **Signal Quality** | Signal Quality is an indication of Signal to Noise Ratio (SNR) which we represent as a percentage from 0% - 100% |
| **Obstruction** | Check to see where you may have obstructions causing intermittent service. Any obstruction level is bad for performance. If you see obstruction percentage greater than 20%, your install location or current surroundings is having a negative effect on performance. Anything more than 27% obstruction will cause enough outages for the end user to notice. In this case, please consider adjusting your install location or raising up your Starlink to improve your performance. A Starlink should have a clear view above 20 degrees elevation, in ALL directions 360 degrees around the azimuth. |

***Note:*** Starlink Support/Guide, "Monitoring Your Starlink." (https://starlink-enterprise-guide.readme.io/docs/monitoring-your-starlink)

There is a negative correlation between signal quality and ping drop rates. Although the maximum downlink/uplink throughput can be limited by obstruction, registering obstruction does not always lead to loss of signal quality as Starlink does not require an absolute clear view of the sky for nominal operation. This is apparent from the results expanded below for Sims Road and Lassen Park, which experienced constant physical obstruction by surrounding trees, yet registered 100% signal strength quite often. Additionally, rain and high humidity can lead to small obstruction values but usually these factors do not

[6] Starlink Support/Guide, "Monitoring Your Starlink." (https://starlink-enterprise-guide.readme.io/docs/monitoring-your-starlink)

impact signal strength. On the other hand, accumulation of snow and especially a layer of ice on top of the antenna, which is resistant to melting in extremely low temperatures, can result in high obstruction values and even automatic shutdown. Such an event probably occurred at Cedar Pass as we elaborate below.

We first focus on the results of this study and later move on to the results found from District 2 CCTV Relay data. As a reminder, below are the two main applications that require transfer of data from field sites to the core hub at District 2:

3. *Periodic image grabs by the CCTV Information Relay (hosted at the District 2 district office pulling data from the field site) that are forwarded to the Caltrans Commercial Wholesale Web Portal (CWWP) for traveler information dissemination*. Since the Fiber Hub receives images from multiple CCTV field sites, District 2 personnel had to adjust the downlink given its known bandwidth. To that end, they would occasionally decrease the frequency of image grabs to as low as one JPEG (at 2-CIF [Common Intermediate Format] resolution) image per hour based on the communications type and field element type. The images are grabbed within 10 to 60 minutes, e.g., a stand-alone CCTV utilizing POTS/ISDN is always grabbing one image per hour. An RWIS or CCTV/RWIS site utilizing POTS grabs one image every 15 minutes. A CCTV on microwave or fiber grabs one image every 10 minutes.
4. *Transportation Management Center (TMC) streaming video from the CCTV site onto the video wall at the D2 district office*. This feed is also adjusted (video protocol, compression, resolution, framerate, etc.) to avoid surpassing the bandwidth capacity at the Fiber Hub. District 2 can limit the number of simultaneous CCTV streams to the field using the TMC's CCTV control software.
5. District 2 personnel set the image retrieval frequency based on the availability of network resources and set fixed video parameters at the CCTV sites based on network bandwidth. We need to establish the definition of some of the terms used in this report to describe Starlink, e.g.,
    - ***Throughput*** is the term used by Starlink to describe the transmission rate at which data are being exchanged in/out of the router/computer connected directly to Starlink, i.e., it is simply the download/upload speed user experiences at any given time across all devices using Starlink. The value of downlink and uplink throughput registered by Starlink is non-zero even when the system is idle. Unfortunately, Starlink records non-zero values for throughput even when the user is disconnected due to Starlink automatic shutdown, high obstruction, power outage, etc. Additionally, periodic image grabs from District 2 CCTV sites (with periods from 10 minutes up to one hour) often are not

clearly captured in the Starlink log data as the Starlink data have a 5-minute resolution at best. Statistics for streaming video to the TMC video wall (lasting for several hours/days) can be captured for hub and field devices in Starlink throughput data, as presented in Figures C.1 to C.5.

- ***Bandwidth*** refers to the rate of data exchange established by the Starlink system. Bandwidth is determined by the physical specifications of Starlink antenna, data traffic in the region, obstruction levels, satellite coverage, etc. Higher bandwidth is expected from high-performance Starlink systems compared to standard systems. Also, priority service plans offer the maximum download/upload speeds while standard plans have a software cap on both. Although data speed and latency are inconsistent and highly volatile, applying the Starlink Wi-Fi router allows users to access the public net at high download speeds up to 250 Mbps and upload speeds as high as 35 Mbps with latency as low as 25 ms in many remote areas. Bandwidth depends on Starlink antenna capacity, time, location, type of data, system hardware, antenna cable conditions, and network architecture. Starlink has guidelines regarding network configuration, mounting, and cable management that help achieve maximum bandwidth.
- ***Data usage*** is the monthly downloaded plus uploaded data recorded by Starlink. It includes monthly priority and standard data used by District 2 at each site.

The average throughput was evaluated for each system. For the spoke systems, the relevant metric was uplink throughput, while for the hub system it was downlink throughput. Figure C.1 to Figure C.5 provide the throughput vs. time and the throughput histogram for each of the systems over the six-week test period. Except for Sims Road (Figure C.5), the spoke site histograms show a very clear grouping into idle/low-speed bins and high-speed bins corresponding to streaming. The Sims Road histogram shows no such pattern due to the difficulties noted in the detailed discussion for this site below.

The Redding Fiber Hub site histogram results are more interesting. There is a large grouping around the same high-speed range of the spoke sites. In addition, there is a smaller grouping at a much higher speed, around 450 kbps, which may be related to how District 2 streams different a number of CCTVs simultaneously or due to configuration changes made by District 2 for this site during the six-week period. Further testing is needed in the extended pilot test period to assess whether this is true.

For the hub and three spoke sites (omitting Sims Road), the throughput was calculated by considering data above a select threshold (140 kbps for each case). This threshold restricts the throughput results so that they are based upon streaming periods, which is more representative of system performance.

Table C.2 provides the throughput results based on this approach. For transparency, the calculated uplink throughput for Sims Road based on an arbitrary threshold of 10 kbps was 12.6 kbps; this value is not representative due to the noted issues.

**Table C.2: Average throughput for four Starlink sites during six weeks of testing in December 2023 and January 2024**

| System | Samples | Throughput (kbps) |
|---|---|---|
| **Redding Fiber Hub (HP, Downlink)** | 4055 | 281 |
| **Lassen Park (Flat HP, Uplink)** | 3023 | 208 |
| **Cedar Pass (Flat HP, Uplink)** | 1539 | 210 |
| **SR70-SR89 (Flat HP, Uplink)** | 375 | 216 |

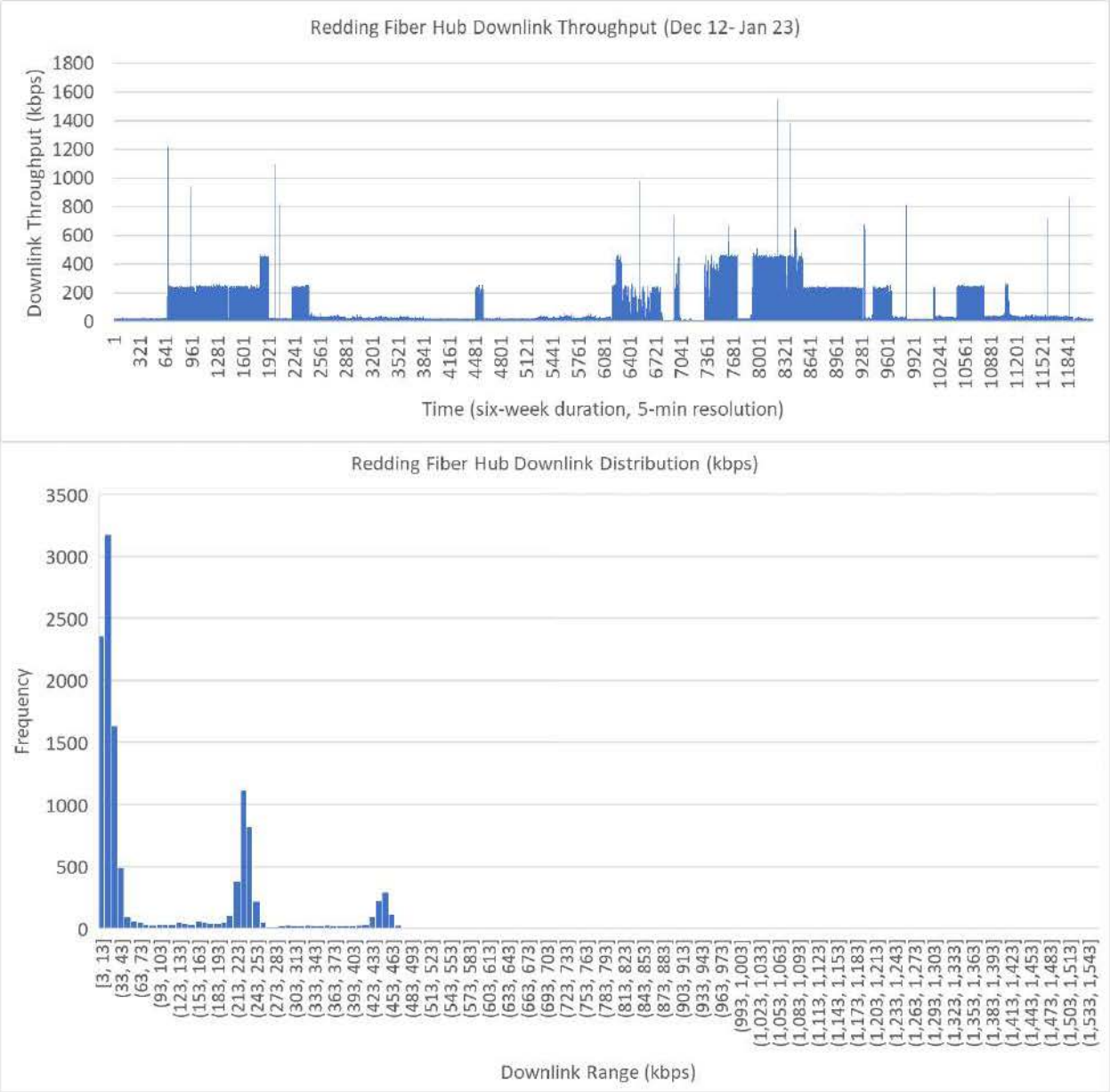



**Figure C.1: Downlink throughput vs. time and histogram for Redding Fiber Hub over the six-week test period in December 2023 and January 2024**

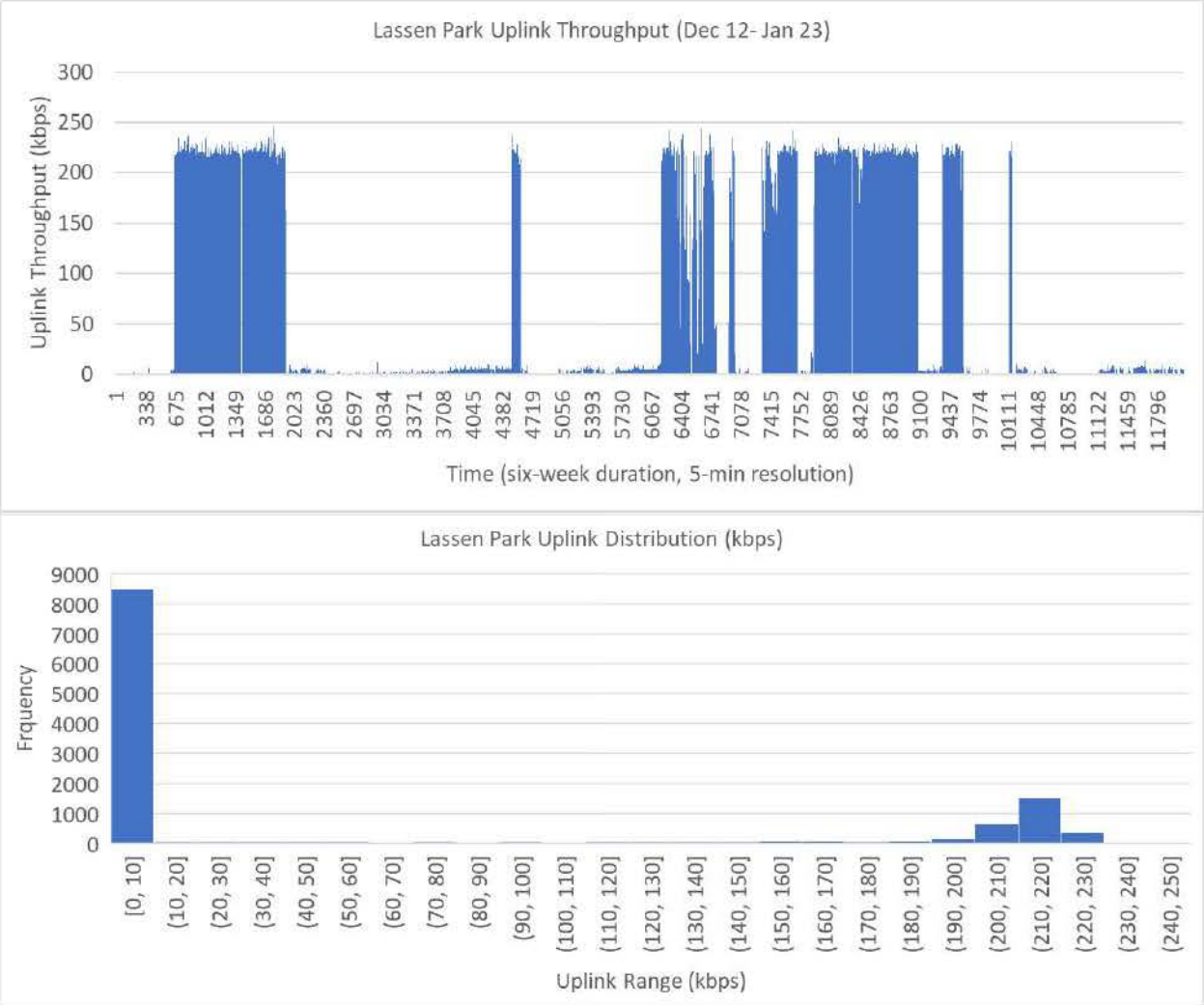



**Figure C.2: Uplink throughput vs. time and histogram for Lassen Park over the six-week test period in December 2023 and January 2024**

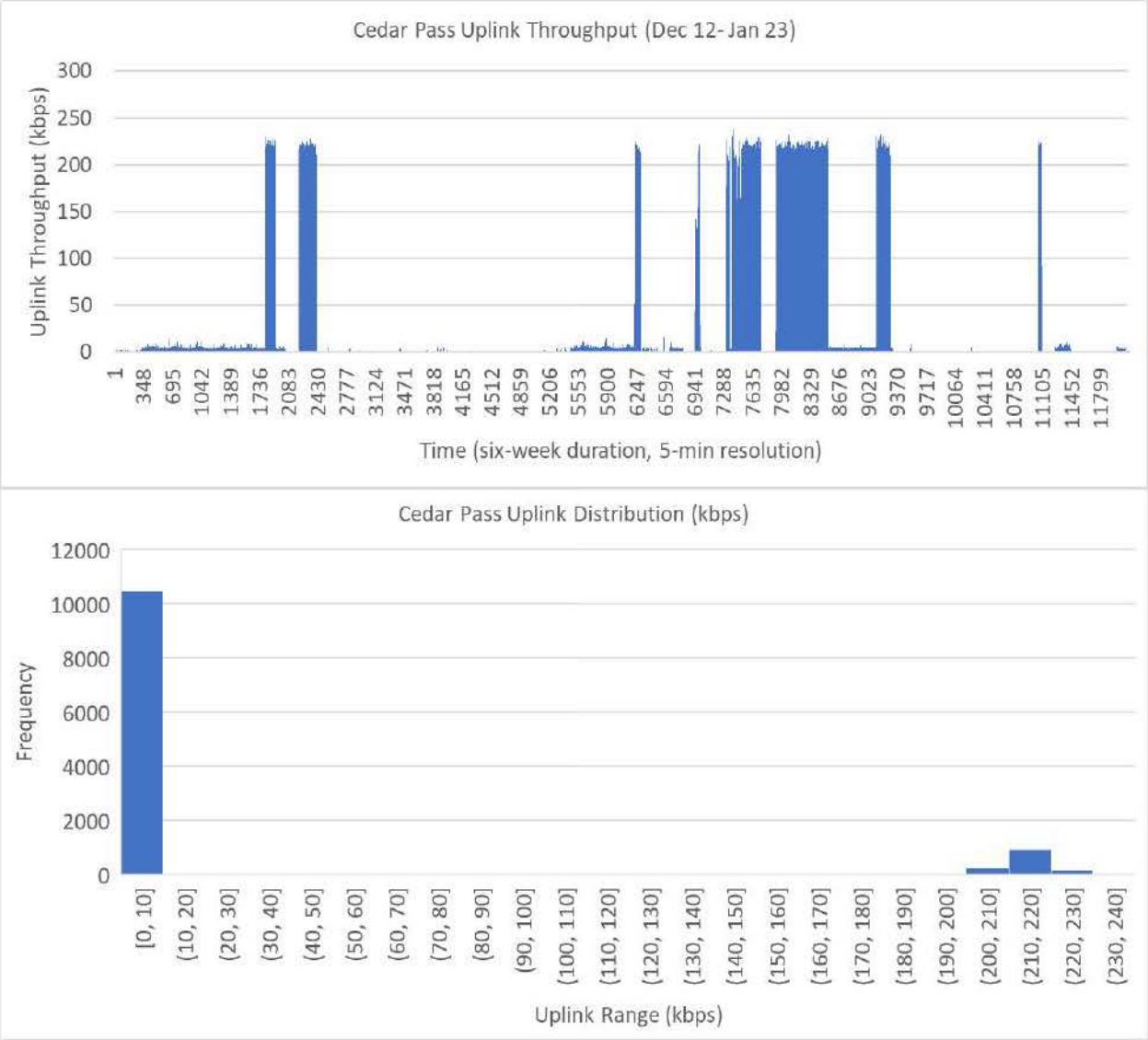



**Figure C.3: Uplink throughput vs. time and histogram for Cedar Pass over the six-week test period in December 2023 and January 2024**

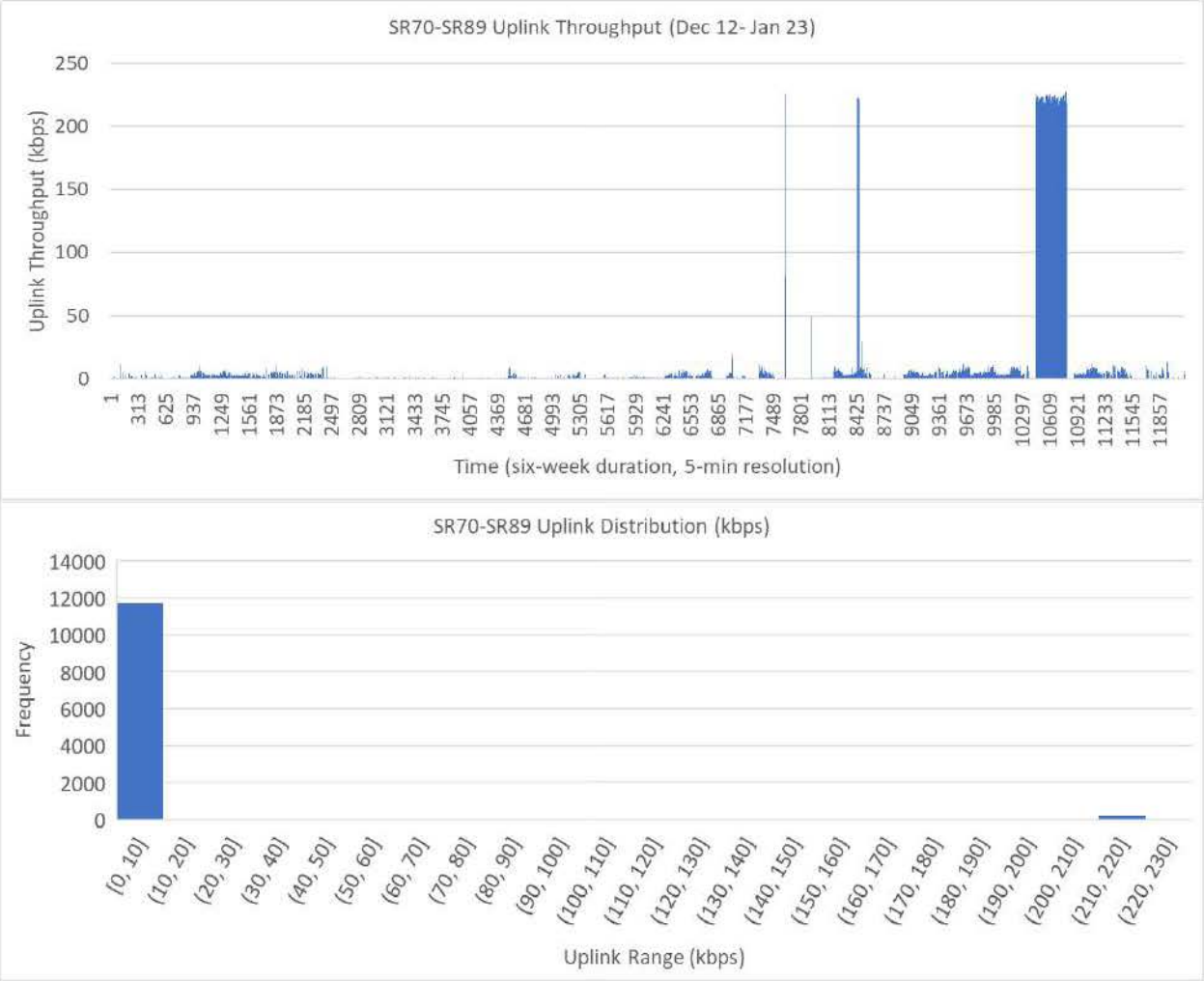



**Figure C.4: Uplink throughput vs. time and histogram for SR70-SR89 over the six-week test period in December 2023 and January 2024**

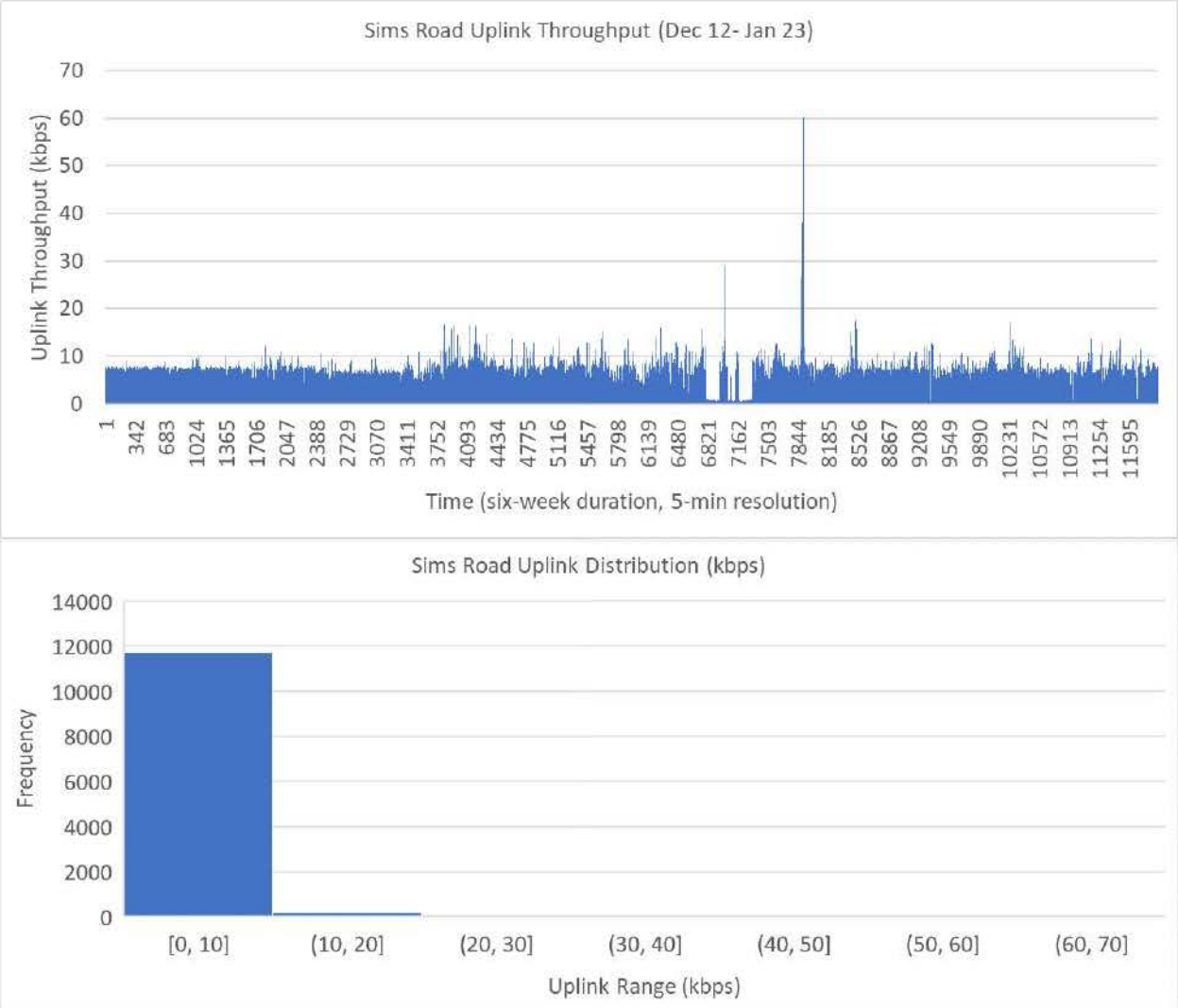



**Figure C.5: Uplink throughput vs. time and histogram for Sims Road over the six-week test period in December 2023 and January 2024**

Table C.3 provides additional statistics for all systems. While the Starlink guide in Table C.1 does not mention this directly, snow and high humidity increase the obstruction percentage recorded in the dashboard, and physical objects near the antenna (while stationary) do not always lead to the same obstruction levels. In both Table C.1 and Table C.3, obstruction values have been multiplied by 100 as Starlink reports the obstruction ratio rather than percentage. This is obvious from the graphs in the dashboard, which has a maximum of 1 (one) for obstruction (see the bottom right plot in Figure C.8).

**Table C.3: Starlink performance stats during six weeks of testing in December 2023 and January 2024[7]**

| Kit | Location | Ave. Obstruction (%) | Ave. Signal Quality (%) | Ave. Ping Loss (%) | Ave. Latency (ms) |
|---|---|---|---|---|---|
| **HP** | Fiber Hub | 0.3 | 99 | 0.3 | 32 |
| **Flat HP** | Sims Road | 7 | 95 | 2.5 | 36 |
| **Flat HP** | Lassen Park | 30 | 90 | 4.5 | 41 |
| **Flat HP** | Cedar Pass | 1 | 99 | 0.3 | 35 |
| **Flat HP** | SR70-SR89 | 1.2 | 95 | 1.4 | 35 |

# *SR Kit Evaluation*

While the SR kit had not yet been used in field testing as of January 2024, initial test result showed promise for establishing high-speed connections in Sims Road and Lassen Park. Considering that Starlink now allows SR users to subscribe to Priority and Mobile Priority plans and make use of public IP options, Caltrans can consider using the SR kit for similar future applications.

As far as the bandwidth is concerned, under the same priority service, the SR system is likely sufficient for the applications required by District 2 as it registers high download/upload speeds with low latency. For example, at Sims Road in October 2022 (at the time of initial testing), the SR system achieved download and upload speeds as high as 120 Mbps and 15 Mbps, respectively, with latency as low as 25 ms. At Lassen Park, we recorded download and upload speeds as high as 55 Mbps and 6 Mbps, respectively, with latency as low as 35 ms. These numbers were registered using the Starlink Gen 2 Wi-Fi router accessing public network.

However, the SR antenna (like the HP antenna) requires tilting toward the north using the electric motor included at the antenna bottom. The mechanical part creates a reliability concern. Also, wind resistance is lower for the SR and HP dishes than for the new Flat HP kit (according to Starlink specifications, exact

[7] These statistics are reported as averages for all data records including periods of time when Starlink has been idle or disconnected from the network.

numbers not confirmed) and both require a clear view of the sky towards the north (northeast to northwest) to establish any connection.

Additionally, the SR antenna is powered directly by the Starlink Wi-Fi router (the same router shipped with HP and Flat HP kits) rather than a separate power supply unit which powers HP and Flat HP antennas and provides a direct wired connection to a third-party router. To remedy this on the SR kit, one can use the Starlink Ethernet adapter (in between the antenna and the Starlink Gen 2 router) or use Starlink Gen 3 router (with a built-in RJ45 port) to connect a third-party router and use the Starlink app to access settings and enable "Bypass mode". In bypass mode, the Starlink router will disable wireless functionality. Nevertheless, the user cannot remove the Wi-Fi router altogether as it is still required to power the SR antenna. Further testing is required to confirm if the SR antenna can be powered with any Power over Ethernet (PoE) device. The SR antenna is more power-friendly as it uses less power (75-150 W) compared to HP antennas (150-250 W). Figure C.6 illustrates the setup required to use a third-party router accompanied by the SR kit to establish a secure local area network (LAN).

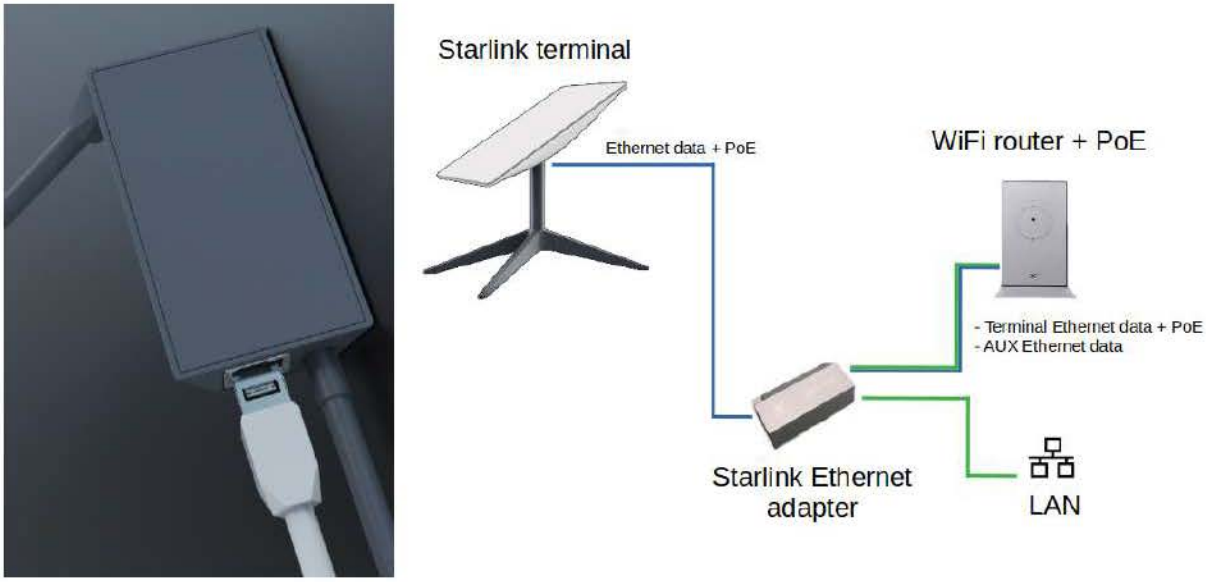



**Figure C.6: Required setup to apply the SR kit with Starlink Ethernet adapter (Source: Oleg Kutkov blog[8])**

For the following sections, AHMCT researchers used the data extracted from Starlink for the five field devices during six weeks of testing between December 12, 2023 and January 23, 2024. These data are provided in five comma-separated value (CSV) files with approximately 12,000 total records (5-

[8] Reverse engineering of the Starlink Ethernet adapter (https://olegkutkov.me/2022/03/07/reverse-engineering-of-the-starlink-ethernet-adapter/)

minute resolution) that report Universal Coordinated Time (UTC) timestamp, data uplink and downlink (Mbps), latency (ms), ping drop rate, obstruction, and signal quality (all three in range 0 to 1). To better present these data in this report, data speeds are reported in kbps, and the last three measures are rounded to closest percentage. AHMCT will share the archive for these data with District 2 as a compressed zip file containing CSV files along with a text log file.

## *HP System Evaluation*

The HP device was tested at AHMCT's Advanced Transportation Infrastructure Research Center (ATIRC) and at the Redding Fiber Hub for extended field testing. Overall, this device performed well and operated normally except for a few minor incidents discussed below. In both locations, this system had a clear view of the sky towards the north from east to west, while the south side was obstructed by a wall or a tower leg. Unlike the Flat HP antenna, this antenna does not scan the surrounding sky in all directions and has a smaller field of view, which is partly why the Starlink dashboard registered less than 0.3% obstruction and ping drop rate and around 99% signal quality on average during six weeks of data collection. This device performed better than the other four systems across District 2 in terms of maintaining a stable connection.

During this period, one of the highest ping drop rates was recorded on December 28, 2023, at around 15% with signal quality of 79%, for which the obstruction was registered at only 0.26%. This high drop rate followed more than one inch of precipitation in the Redding area. Note that signal quality and ping drop rate depend on several factors, e.g., obstruction (by physical objects, frozen surface, and high humidity), position of satellites, and data traffic in the region. The data loss at Redding Fiber Hub, while insignificant and extremely rare, was not due to obstruction. This data can be used as a baseline for latency and loss of connection for reasons besides obstruction. To that end, the latency throughout the testing period at Fiber Hub was around 32 ms with maximum of 66 ms, while the downlink throughput across 5-minute intervals reached as high as 1550 kbps during the six-week span.

By the end of October 2023, District 2 adjusted the video bandwidth of the encoder at the field locations (used by TMC operators on an as-needed basis, i.e., not streamed continuously) down to 300 kbps to avoid network contention at the hub and reduce data consumption (considering 40 GB of available monthly priority data). Based on careful consideration of data needs and available monthly priority data for the Fiber Hub Starlink system, District 2 set the video bandwidth for all field sites at 192 kbps. While uplink speed is not a concern for the Fiber Hub, a small portion of data is consumed on data upload, averaging less than 10 kbps.

The most significant incident at the Fiber Hub occurred between December 21, 2023 and January 5, 2024, when only 6.4 GB of priority data were used. Normally, Fiber Hub, which receives data from multiple sites, would exhaust its 40 GB of priority data maxing at 45-55 GB in cold months. Upon investigation by AHMCT and troubleshooting by District 2, it was discovered that the HP Starlink was operating normally but the interface between the Starlink router and the network switch at the Hub location was not negotiating. While the reason remains uncertain, District 2 set the port to force it to negotiate at "100 Mbps/Full" rather than "Auto". This resolved the issue as data usage significantly increased after January 5, 2024 (30 GB of data used between January 5 and January 21, 2024).

The highest daily precipitation in the Redding area during the six weeks of data collection was 2.45 inches on December 18, 2023 followed by 0.39 inches on December 19, 2023. These weather conditions led to a ping drop rate of 13% with a signal quality of 91% and 0.3% obstruction during those two days.

The average minimum daily temperature at Redding was 42°F over December 2023 and January 2024 with lowest temperature 32°F in December and 29°F in January. These temperatures are not critically low; therefore, Starlink devices would be expected to perform as normal. Of the five sites, the Redding Hub received the least amount of snow, which minimized HP system obstruction during field testing.

While the HP system performed satisfactorily at the Redding Fiber Hub, it is very likely that the production of this kit will soon be discontinued by Starlink, creating a level of risk as the supporting equipment and accessories (such as cables and mounting adapters) between the SR, HP, and Flat HP kits are not cross-compatible.

## *Flat HP System Evaluation*

The Flat HP device was tested at ATIRC and four District 2 sites. There was some physical obstruction by nearby trees and hills at Sims Road and Lassen Park sites, leading to lower signal quality and higher ping drop rates compared to SR70-SR89 and Cedar Pass, even in clear weather. Additionally, winter storms and precipitation led to higher data loss at Lassen Park, Sims Road, and to a lesser extent, Cedar Pass. Since the Flat HP phased-array antenna scans the sky in all directions with a 140° field of view, the obstruction numbers received from Flat HP systems are usually higher than HP systems in the same location. However, that does not necessarily mean that Flat HP antennas experienced a lower bandwidth as the hardware is designed to maintain more satellite connections at any given time.

While incorporating the same phased-array technology used in SR and HP antennas, the Flat HP antenna works with a fixed orientation and has the benefit

of having no moving parts as it does not require tilting to scan the sky for available satellites. While unconfirmed, according to Starlink the new Flat HP antenna survives wind speed of 280 kph+ or 174 mph+ (equivalent of a Category 5 hurricane). These numbers do not account for the wind resistance of off-the-shelf mounting kits used for installation. Currently, Starlink only offers a pipe adapter (to attach the antenna to a tailored bracket) for customers who do not intend to secure the antenna on a flat surface. Hence, as far as installation is concerned, SR and HP antennas are more versatile and are compatible with cheaper off-the-shelf mounting solutions.

Additionally, HP kits are reported to have operating temperature of -22°F to 122°F and snow melting capability of 3 inches per hour. While all three antennas are capable of downloading and uploading at high speeds, the Flat HP kit is the only viable system in locations where the north view is partially blocked (in the northern hemisphere) as the SR and HP kits will most likely fail to establish a stable connection.

Next, we review the performance of the Flat HP antenna at each of the four rural CCTV sites.

## Sims Road

The Flat HP kit at Sims Road experienced multiple temporary incidents with loss of connectivity and ping drop rates close to 100% (which usually corresponds to temporary disconnection). Unfortunately, the logged performance data for Sims Road have missing or outlier numbers, especially for obstructions, making it difficult to report average numbers accurately. Excluding the missing data, obstruction was on average around 7% with a maximum of 99%, while the ping drop rate was on average around 2.5% with a maximum of 99%. Sims Road had partial physical obstruction from nearby trees and hills, while also being exposed to harsher weather conditions than the Redding area. Fortunately, ping drop rates above 50% were rare and short-lasting, accounting for less than fifty timestamps in six weeks.

Between December 18 to 20, 2023, there were 5 inches of precipitation in the Sims Road area leading to frequent low signal quality with ping drop rates as high as 70%. The Sims Road Starlink managed to maintain an average uplink rate of 3.5 kbps with a latency of 40 ms during this time. On January 20, 21, and 22, 2024, the Sims Road area had 2, 2, and 4 inches of precipitation, respectively, in the form of rain and snow, causing frequent ping drop rates as high as 90%. The uplink and latency respectively averaged around 3.3 kbps and 36 ms in this this period.

Unfortunately, Starlink does not record when and how long the snow melting feature has been active to melt snow off the antenna and the only way to know if this feature is active (in real time) is to use the mobile app in combination with the Starlink Wi-Fi router. Since we are not using either in our testing, we do not

have any records for the snow melt feature. In the Starlink dashboard, the user can set the Snow Melt Mode to *auto, always on, or always off* as showcased in Figure C.7. During the pilot test, this was set on *auto* by default. It is recommended to switch this feature to *always on* when expecting snow but that setting could lead to overheating in hot temperatures.

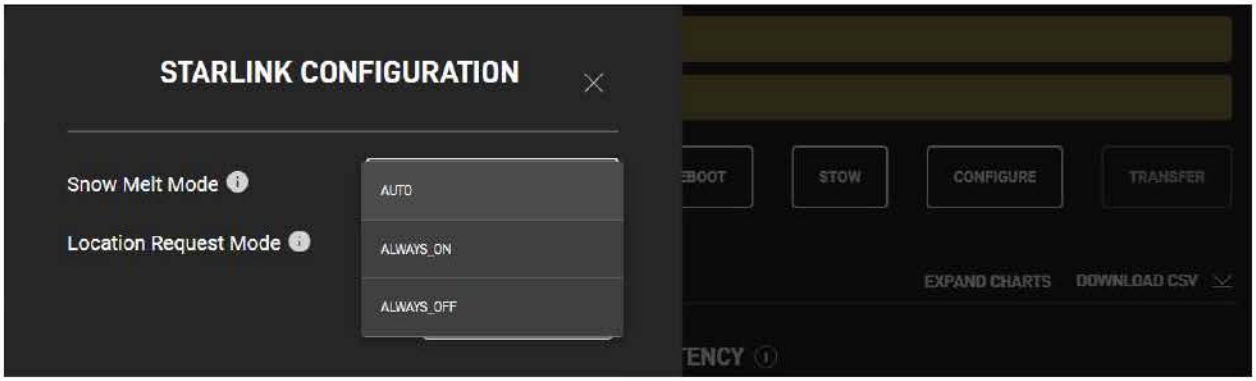



**Figure C.7: Clicking on Configure in Starlink dashboard allows setting Snow Melt Mode to Auto, Always on, or Always off**

While ping drop rates were significantly higher during these two 72-hour periods, the uplink and latency were fortunately maintained close to normal values for this area, partly because District 2 kept the video bandwidth low. Even with partial obstruction and loss of signal, the Flat HP Starlink seems capable of maintaining higher uplink throughput than for what it is currently configured. Additionally, District 2 has consumed less than 4.5 GB of priority data in each month of testing at Sims Road. One reason for this underusage is to avoid network congestion and high data usage at Fiber Hub, which is receiving multiple feeds at any given time.

## Lassen Park

Lassen Park had the highest bandwidth demand among all field sites while dealing with more connectivity issues than other sites due to heavy snowfall, physical obstruction by surrounding trees, and one-time incidents such as a power outage in the area and loss of negotiation between the router and network switch.

The Lassen Park logged network statistics also has many missing and outlier values due to loss of connection between the system and the Starlink servers caused by extreme weather causing obstruction, power outage, hardware failure such as antenna cable failure or technical issues related to the surge protector, Cisco routers, and switches. In the following, some notable instances of data loss are discussed. Excluding those records, the Lassen Park Starlink had an average obstruction of 30% during the six-week data collection with maximum of 100% obstruction, which is expected from snowfalls heavier than 3" in a short period. The ping drop rate and signal quality on average were about

4.5% and 90%, respectively. This drop rate led to latency of 41 ms on average. The data usage ranged between 25 and 30 GB each month.

Inclement weather (i.e., temperatures lower than 10°F combined with snowfall and humidity) during December and January could have resulted in failing weather stations in the area. Consequently, accurate localized snowfall levels are unknown. The only confirmed snow event from weather.gov was 5" of new snow in the afternoon of December 30, 2023. The ping drop rate reached a high of 98% during this day with latency averaging 51 ms. The obstruction level during this day is unknown due to the high number of missing data. Missing data for an extended period are associated with complete loss of communication between the system and Starlink servers either because Starlink had probably shut down to protect the hardware or high obstruction is disrupting communication. While we cannot confirm whether power loss occurred, the automatic reboot suggests that this was done by Starlink to protect the device.


**Figure C.8: Lassen Park connectivity data for 24 hours starting at noon of December 30, 2023. Obstruction levels are not showcased due to missing data in the query from noon to midnight of December 30 (Source: Starlink dashboard).**

A power outage occurred at 4:45 AM on February 3, 2024, causing the Starlink system to remain offline even after the outage ended in the area. The reason for the extended outage remains to be investigated. The system did not power on as expected until a District 2 operator manually restarted the system from the cabinet.

## SR70-SR89

The Cedar Pass and SR70-SR89 systems had a different situation than the Sims Road and Lassen Park systems as they both have a very clear view of the sky from all directions with no physical obstruction when the weather is clear. These

differences helped with isolating the reason for obstruction periods related to heavy snow and high humidity in general. From the data, sometimes loss of signal or ping drop rates occur when zero obstruction is detected, and the weather is also clear. These events are rare and can be associated with the connection of the antenna with the Starlink satellite constellation and data traffic in the region. In the case of these two locations, the number of Starlink users is low, which also helps maintain high quality connections.

For SR70-SR89, the six-week statistics indicate 1.2% of obstruction on average with maximum of 53%, while the average ping drop rate and signal quality were 14% and 95%, respectively.

The most significant event at SR70-SR89 occurred during the first half of February 2024 when Starlink system had red warning on the dashboard stating *"Poor cable connection. Internet speed may be slower than expected"*. Red warnings often mean critical issue that cause the system to go offline. This is unlike yellow warnings on the dashboard, which indicate partial obstruction or other non-critical errors when Starlink is still able to communicate.

In the case of this event, Starlink was experiencing regular (even periodic) loss of connectivity. In the network stat data, the Obstruction column had many zeros or missing data in the second week of February. Figure C.9 shows the recorded statistics during this time. As seen consistently with other sites, extended missing data indicate periods with total loss of connection. The unseen strange part of this event was that the system was getting back online and then going offline again. Remote restart was disabled as the system appeared offline in the dashboard although some data was periodically received.

Considering this lasted for some time, District 2 personnel suspected there might have been a mechanical failure caused by weather conditions resulting in intermittent outages. Hence, District 2 sent their electrician to check. The onsite District 2 tech reported that the ethernet interface on the router was going up and down, similar to what happened at Fiber Hub. However, by changing the configuration to 100 Mbps/Full Duplex, the symptoms did not settle down. After that, they temporarily replaced the cable between the antenna and the cabinet modem. That seemed to settle the symptoms with the interface remaining up for 20 minutes. To find out the root cause of the problem, the District 2 tech then changed the configuration of the router's interface to 10 Mbps under the presumption that there might have been crosstalk in the Polyphaser box and retried the existing cable again. The interface had the same symptoms as before. Therefore, the electrician completely replaced the existing cable with the new cable and brought the Polyphaser cable assembly back to the District 2 shop/lab for further testing, which resolved the issue completely. This was the first time any field device had a downtime due to failure of antenna cable and/or possibly the Polyphaser

surge protector that intercepted the cable. Similar issues occurred with other devices while also getting several warnings in Starlink dashboard regarding inappropriate cable connection throughout the testing.

Starlink has recently added some descriptions to their warnings/errors appearing in the dashboard to help users better understand the cause of problems. Two instances of such descriptions are presented in Figure C.9 and Figure C.10, taken a few days after the above-mentioned issue was resolved at SR70-SR89. The updated status indicated temporary partial obstruction up to 50%, which can be due to weather as SR70-SR89 Starlink has no physical obstruction nearby.

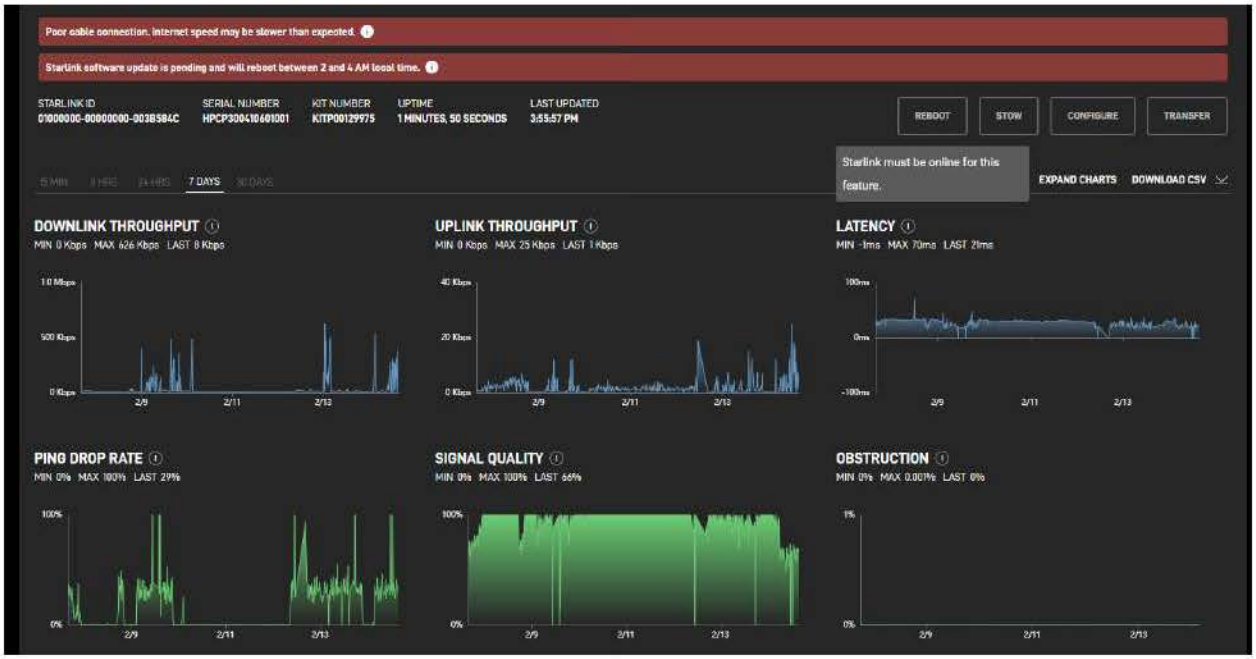



**Figure C.9: SR70-SR89 network statistics during February 7th-14th, 2024 (Source: Starlink dashboard)**

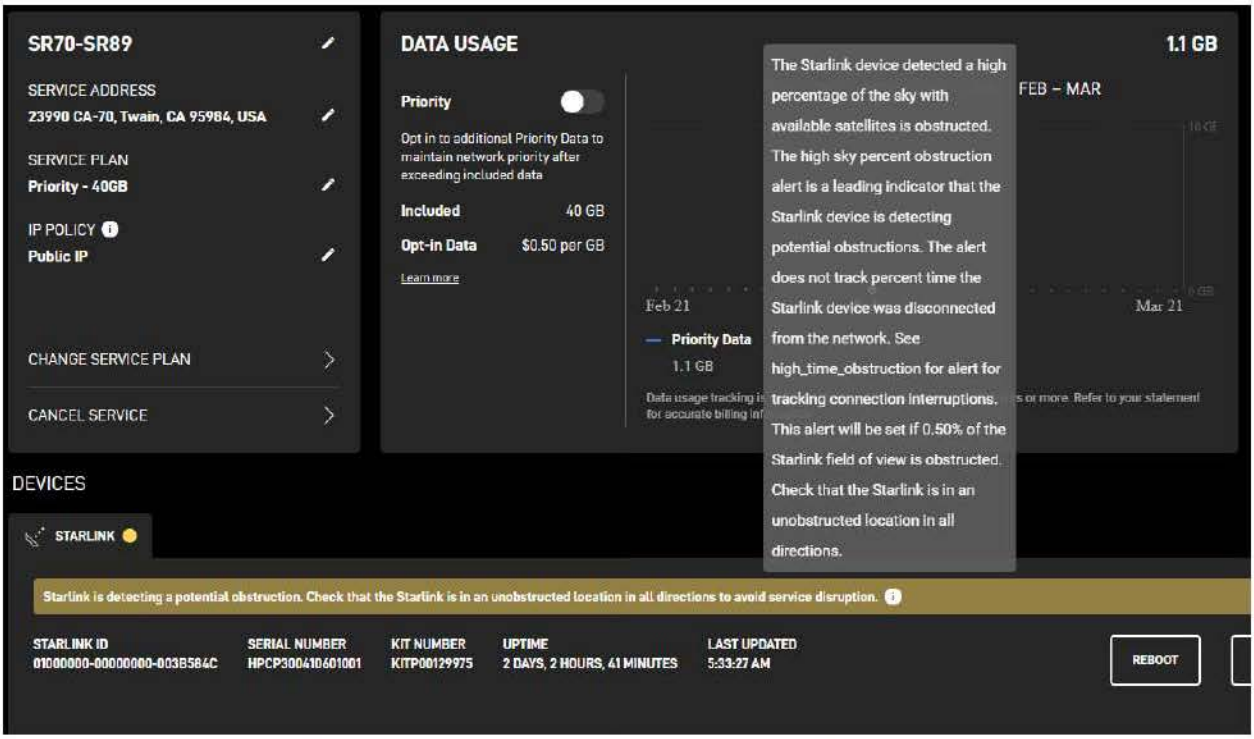



**Figure C.10: SR70-SR89 updated status early March 2024 after fixing the warning about partial obstruction (Source: Starlink dashboard)**

## Cedar Pass

During six weeks of testing, Cedar Pass recorded less than 1% obstruction on average with a maximum of 12% on December 31, 2023, which resulted in average ping drop rate and signal quality of 0.3% and 99%, respectively. The data uplink throughput at Cedar Pass reached a maximum of 238 kbps. The latency over this period was on average about 35 ms.

The latest update from this site was in March 2024 when the dashboard had a warning for Cedar Pass as shown in Figure C.11. This error regarding 100 Mbps/Full Duplex configuration is inconsistent as other sites have the same setting, and we do not always see this warning on the dashboard for any site. Also, the yellow warnings seem to be omitted by Starlink after some time without notice.

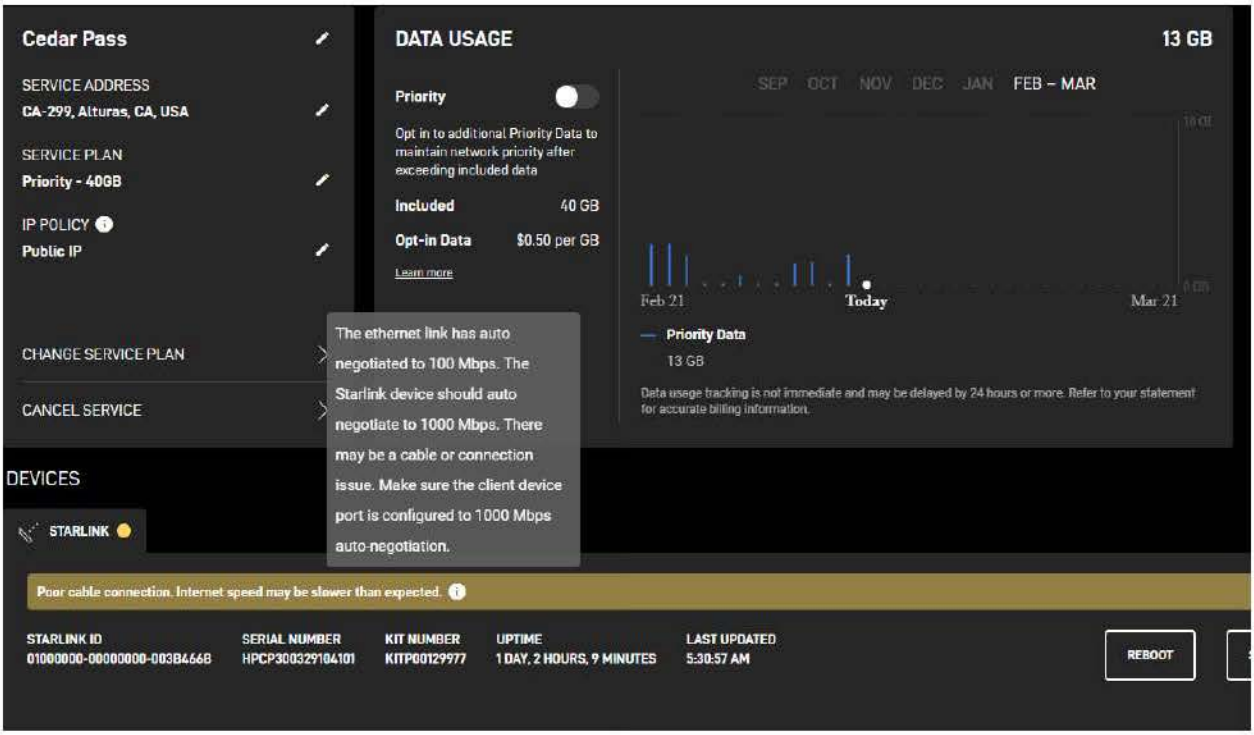



**Figure C.11: Cedar Pass status on March 2024 warning about 100 Mbps/Full Duplex configuration potentially affecting connection speed (Source: Starlink dashboard)**

As for the most significant event at Cedar Pass, District 2 personnel reported a longer than normal disruption on November 7, 2023. Unfortunately, the precise weather history for Cedar Pass is difficult to access due to the lack of nearby weather stations. Starlink data for this day at Cedar Pass are missing obstruction data that would illustrate extreme weather conditions and lack of communication for this entire day. Starlink data (from November 7, 2023 provided to District 2 in a separate CSV file) indicate "zero" or an empty cell for missing values. Excluding the missing data, the ping drop rate was around 25% at Cedar Pass, while data uplink was less than 1 kbps. These numbers indicate complete loss of communication for over 24 hours at Cedar Pass, matching the observation made by District 2 personnel that "the outage persisted longer than the usually observed occasional outages and correlated with a snow event". The snow accumulation at Cedar Pass was minimal according to District 2 data, less than 2 to 3 inches. The reason for minimal snow leading to complete disruption over 24 hours can be extreme cold temperatures that can create a layer of ice over the antenna and perhaps initiating a shutdown to protect the device.

# Additional Results from District 2

The above results are from the Starlink network statistics. Below, we provide additional results from the data report by the District 2 CCTV Information relay that summarize the daily measured availability (i.e., percentage of uptime) for one year preceding the Starlink deployment up to March 14, 2024. The data are tabulated in a spreadsheet for four spoke sites reporting uptime and downtime in minutes as recorded by CCTV Information relay.

To account for weather conditions, we compare the performance of Starlink systems versus the previous Internet Service Provider (ISP) used at each site during the corresponding period, i.e., we compare the ISP uptime of each system during October 15, 2022 to March 14, 2023 versus the Starlink uptime during October 15, 2023 to March 14, 2024.

Table C.4 and Table C.5, respectively, illustrate the change in daily uptime hours and the change in availability percentage on average throughout each month, compared to the previous year. The last row presents the results for the entire five months. These records indicate significant improvement in availability at SR70-SR89 (with more than 50% increase in uptime) and a slight decrease in availability for the other three sites as a result of implementing Starlink. Note that Table C.4 and Table C.5 compare uptime and availability of satellite-based communications vs. landline Plain Old Telephone Service (POTS). This comparison may be skewed towards POTS, and it is surprising that there is any increase for satellite, indicating a special situation as noted below for the SR70-SR89 site.

Alongside these results, the overall feedback received from District 2 personnel indicates a drop in reliability and availability for cold seasons as a result of using Starlink satellite communications. The latency of receiving images and videos from field sites also did not improve by using satellite vs. ground communications.

It is worth noting that these numbers do not capture the amount of maintenance and support required from District 2 to maintain communications between hub and spokes. These data only account for the first five months of Starlink deployment when District 2 was still learning more about the appropriate configuration and setup of Starlink as a new technology. Differences in weather conditions and wildfire occurrence from a year before also impacted these results. For instance, the aftermath of wildfires near SR70-SR89 and its impact on ground communications is the reason Starlink made a great improvement in performance compared to a year before. A similar study repeated for hot seasons and multiple years (larger sample size) can shed more light on advantages and disadvantages of shifting from ground-based to satellite-based communications.

Further analysis of Starlink's performance for ITS rural communications is needed for the following reasons:

- The first few months of testing occurred during winter without using the Starlink preheating feature to better tackle the impact of snowstorms. It is recommended that next year, we change the Starlink setting for snow melt feature to "Always on" during cold seasons, especially at Lassen Park and Cedar Pass.
- Multiple failures occurred in surge suppressors used in District 2's cabinet, interrupting connections. We do not know how much this circumstance impacted on the final availability of Starlink. A new solution for surge protection is needed for future testing.
- District 2 changed the configuration of field routers and switches multiple times during the testing period in response to connectivity issues. District 2 can potentially improve the performance of Starlink by reconfiguring the hub and spoke devices in future testing.

**Table C.4: Mean daily uptime change (hours) achieved by Starlink compared to previous ISP at each spoke site (average daily uptime during October 15, 2023 to March 14, 2024 minus average daily uptime during October 15, 2022 to March 14, 2023)**

| Period | Lassen Pk | Sims Rd | SR70-SR89 | Cedar Pass |
|---|---|---|---|---|
| **2nd half of October (2023 minus 2022)** | -0.11 | -0.11 | 7.72 | -4.6 |
| **November (2023 minus 2022)** | -0.49 | -0.23 | 17.74 | -0.08 |
| **December (2023 minus 2022)** | -0.4 | -0.45 | 15.16 | 0.44 |
| **January (2024 minus 2023)** | -2.88 | -1.88 | 12.36 | -2.22 |
| **February (2024 minus 2023)** | -3.9 | -0.5 | 9.15 | -0.25 |
| **1st half of March (2024 minus 2023)** | 7.41 | 1.3 | 12.04 | 5.69 |
| **During all 5 months** | **-0.8** | **-0.5** | **13.5** | **-0.43** |

**Table C.5: Mean uptime change (percentage) achieved by Starlink compared to previous ISP at each spoke site (average uptime percentage during October 15, 2023 to March 14, 2024 minus average uptime percentage during October 15, 2022 to March 14, 2023)**

| Period | Lassen Pk | Sims Rd | SR70-SR89 | Cedar Pass |
|---|---|---|---|---|
| **2nd half of October (2023 minus 2022)** | -0.5% | -0.5% | 32% | -19% |
| **November (2023 minus 2022)** | -2% | -1% | 74% | -0.5% |
| **December (2023 minus 2022)** | -1.7% | -1.9% | 63% | 1.7% |
| **January (2024 minus 2023)** | -12% | -7.8% | 51% | -9% |
| **February (2024 minus 2023)** | -16% | -2% | 38% | -1% |
| **1st half of March (2024 minus 2023)** | 31% | 5.4% | 50% | 24% |
| **During all 5 months** | **-3.3%** | **-2.1%** | **53.6%** | **-1.8%** |

# Appendix D:
# Custom Mount Design for Starlink Field Installation

This appendix describes a custom-designed mount implemented for the Starlink project to provide better integration and more pleasing aesthetics. It was designed to withstand the expected wind loads in District 2. The design criteria for the mount included a five-times factor of safety (FoS), which dictates that the stress experienced by a part does not exceed 20% of its yield strength [1]. To achieve this FoS, the expected wind loads were first calculated. Next, measurements were taken from the Starlink antenna and accessories for initial tube sizing. This process was followed by a preliminary design and subsequent iterations based on finite element analysis (FEA) conducted in SolidWorks.

Caltrans design constraints were a primary consideration. Caltrans requested that the mount be compatible with both a tower leg and a CCTV pole. Best practices also dictate that the optimal material for antenna mounts is coated steel, which resists rust and related part failure. Galvanized steel was utilized for the Starlink mount, but powder-coated steel was also considered.

## Wind Loading Calculations

The primary forces that the mount is expected to experience are wind loading and gravitational forces from its weight. Wind loads were calculated by use of windspeed data found in the International Code Council (ICC) City of Los Angeles Building Code [2]. Only windspeeds from District 2 and adjacent regions were considered.

Equation (D.1) defines the wind loading $F_W$ experienced by antennas of varying cross-sectional profiles. Several common cross sections for antennas and their respective profile drag coefficients can be found in the formulation below. The values used for this calculation are tabulated as follows.

$$F_w = \tfrac{1}{2} \cdot \rho \cdot (C_{dp} \cdot \lambda) \cdot V^2 \cdot A$$

Where:

- $F_w$ = Force due to wind (lbf, N)
- $\rho$ = Air Density (.075lb/ft$^3$, 1.22 kg/m$^3$)
- $C_{dp}$ = Profile Drag Coefficient (from text or experimental data)
- $\lambda$ = Length/Width Aspect Ratio Correction Factor
- V = Wind Velocity (ft/s, m/s)
- A = Cross Sectional Area Normal to wind direction (length*width) (ft$^2$,m$^2$)

(D.1)

**Table 1. Drag Coefficients For Various Antenna Profiles.**

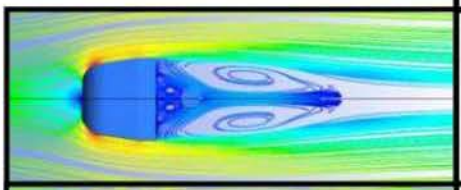
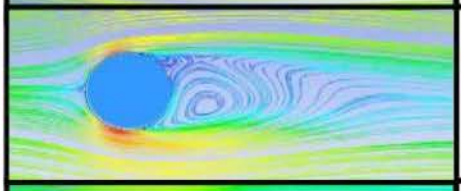
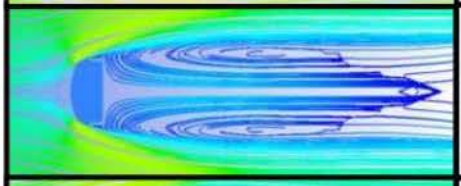
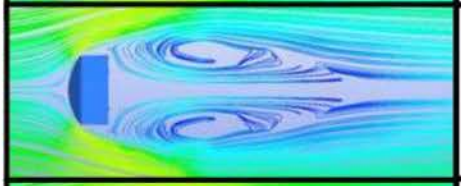
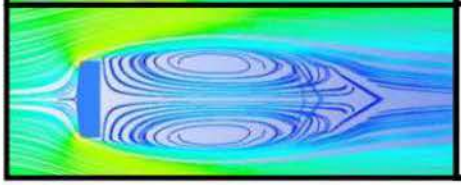
| | Profile Drag Coefficient* |
|---|---|
|  | 1.0 |
|  | 1.2 |
|  | 1.6 |
|  | 1.7 |
|  | 1.9 |

**Figure D.1: Drag coefficients for various antenna profiles [3]**

**Table D.1: Values used to calculate wind loads [3]**

| Term | Value (Lateral) | Value (Longitudinal) |
|---|---|---|
| $\boldsymbol{\rho}$ | $1.22\ kg/m^3$ | $1.22\ kg/m^3$ |
| $\boldsymbol{C_{dp}}$ | 1.90 | 1.90 |
| $\boldsymbol{\lambda}$ | 13.2 | 13.2 |
| $\boldsymbol{V}$ | Varied from min to max windspeed (m/s) | Varied from min to max windspeed (m/s) |
| $\boldsymbol{A}$ | $0.0192\ m^2$ | $0.0185\ m^2$ |

The Starlink antenna profile is a rectangular cross section, which corresponds to a profile drag coefficient of 1.90. The length/width aspect ratio was calculated by creating a projected surface in SolidWorks. Wind load calculations accounting for both lateral and longitudinal cross sections were conducted by varying wind velocity values and solving for the force due to wind. These values were tabulated and can be visualized in the following graph (Figure D.2).

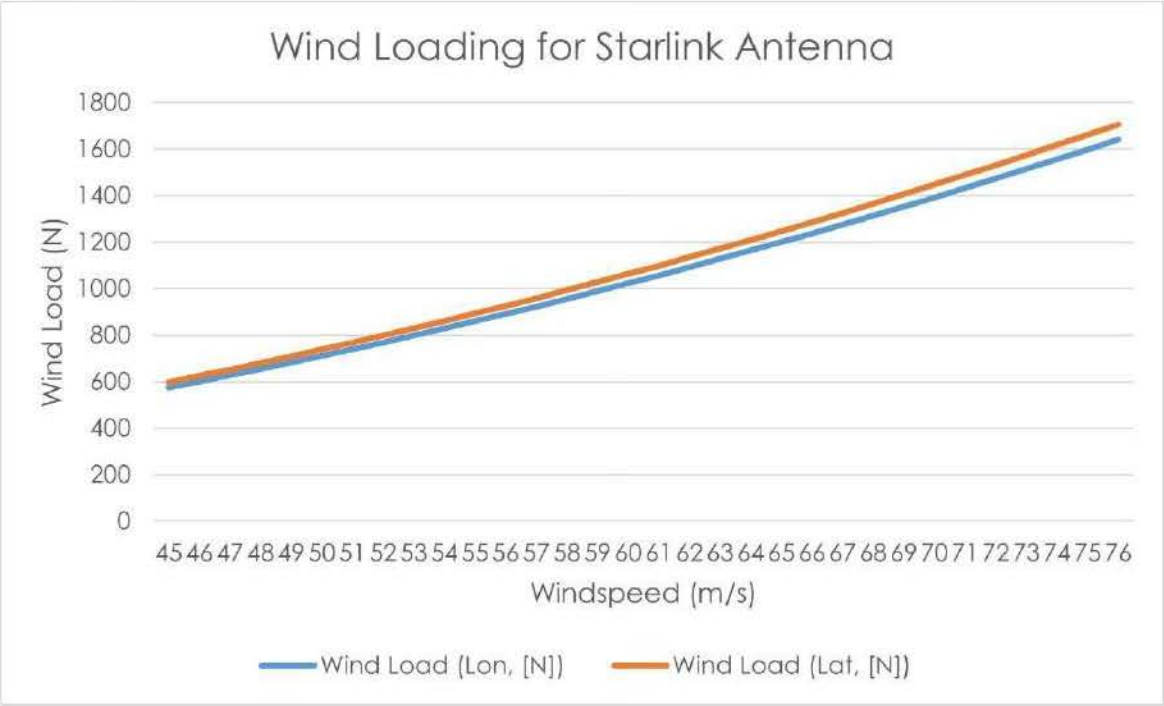



**Figure D.2: Graph of wind loading vs. windspeed for Starlink antenna**

The resulting load envelope accounts for the minimum through maximum values for District 2 seen in the ICC Building Code and is detailed in the "Analysis" section.

# Mount Design

The Starlink mount is comprised of three members and a back plate. The diagonal and horizontal members possess a square cross section, yielding better longitudinal and lateral stiffness. The bottom member also has weep holes to ensure proper water drainage. The vertical member is made of round tubing and is compatible with both the Starlink Pipe Adapter and the Starlink Flat Mount. The back plate has mounting holes compatible with commercial off-the-shelf (COTS) U-bolt clamps.

The members and the back plate are all tungsten inert gas (TIG) welded with a filler rod and then hot-dipped. The hot-dip process must occur after all machine operations, including cutting, drilling, and welding, are completed. Ending with hot-dip ensures that the part has an even coat, increasing its longevity [4].

# Analysis

FEA was completed on the part via SolidWorks simulations to ensure proper tube sizing for the load case. Iterative static studies were conducted such that stress singularities did not occur. The following load cases were considered:

- Lateral Loading Scenario
    - 652 N force along top face of vertical tube in *x*-direction to simulate wind loading
    - 86 N force along top face in negative *y*-direction to simulate the weight of the antenna
    - Fixture in fastener holes and on face of mounting plate
- Longitudinal Loading Scenario
    - 627 N force along top face of vertical tube in z-direction to simulate wind loading
    - 86 N force along top face in negative *y*-direction to simulate the weight of the antenna
    - Fixture in fastener holes and on face of mounting plate

As indicated in the tabulated $F_W$ values, the wind load values seen above correspond to a wind speed of 47 m/s, which was the maximum wind speed in District 2 according to the ICC Building Code. The following figures display where these loads were placed on the part as well as the fixtures for both simulations.

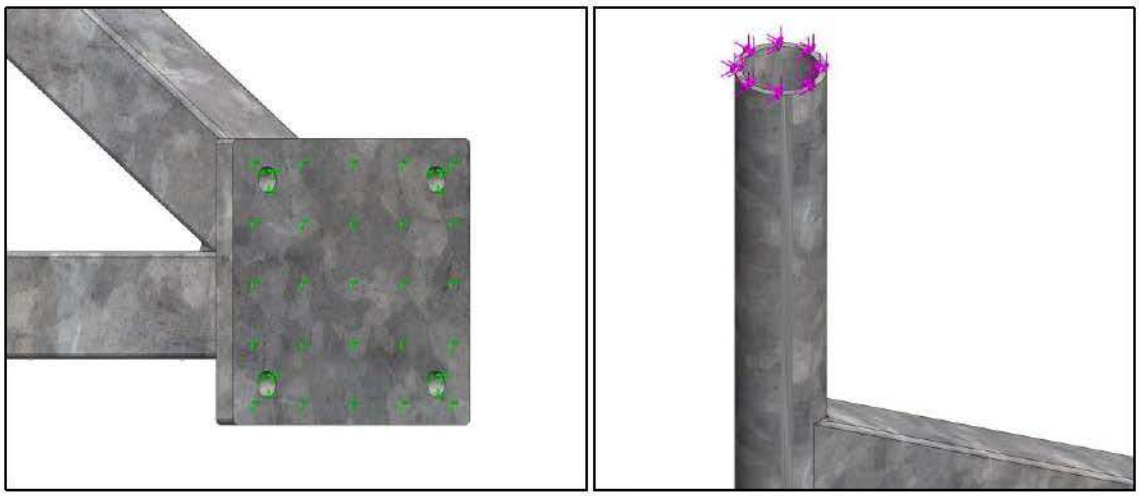


**Figure D.3: Fixtures for mount in FEA simulations**

As mentioned in the introduction of this appendix, the design criteria for the mount is a five-times FoS. Table D.2 outlines the Von Mises stresses seen in each loading scenario and how they compare to the yield strength of galvanized steel.

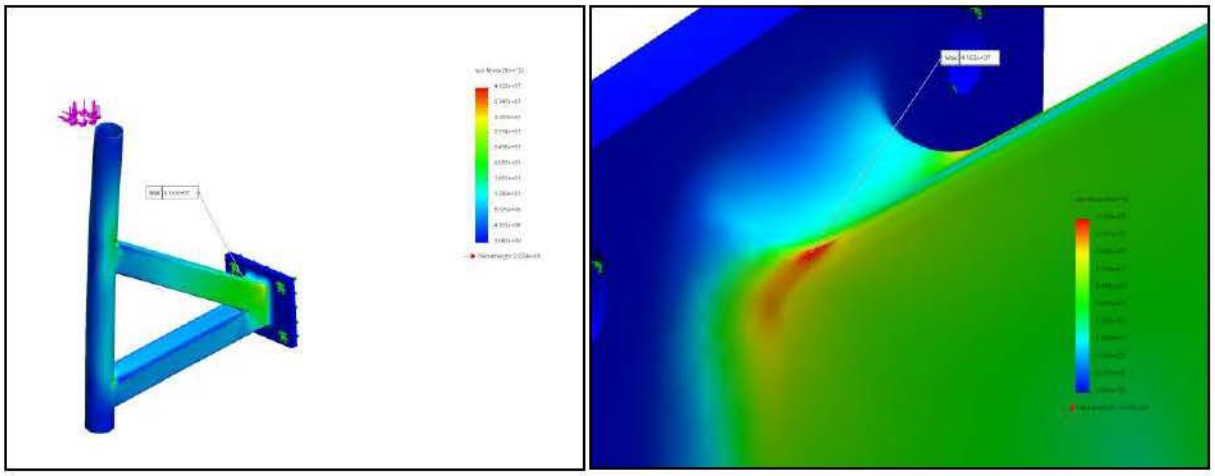


**Figure D.4: FEA Von Mises stress results for lateral loading scenario**

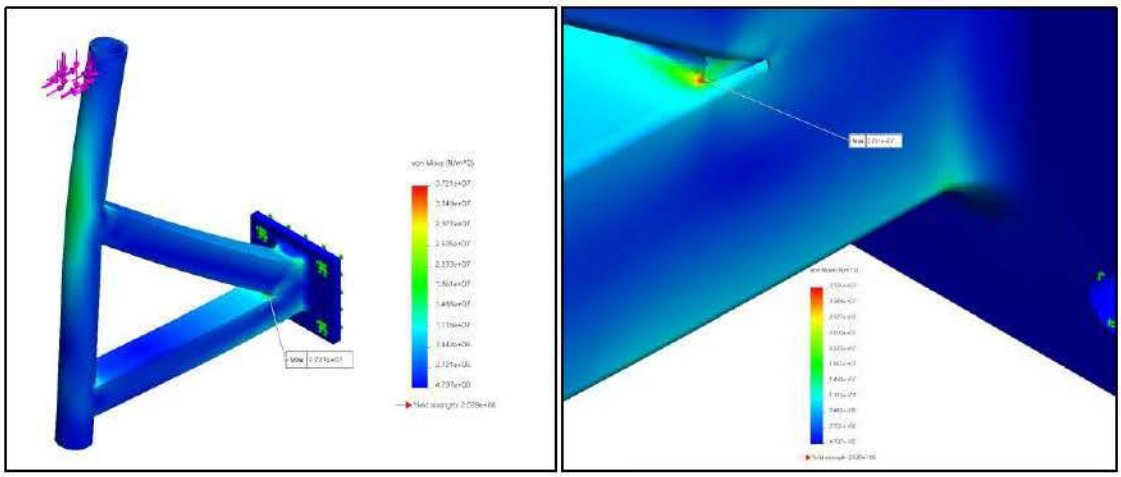


**Figure D.5: FEA Von Mises stress results for longitudinal loading scenario**

**Table D.2: FEA stress results**

| | **Longitudinal** | **Lateral** |
|---|---|---|
| $\sigma_{VM,max}$ **[MPa]** | 37.2 | 41.6 |
| $\mathbf{20\%}\ YS_{galv.\ steel}$ **[MPa]** | 94.0 | 94.0 |
| **Meets criteria?** | Yes | Yes |

Under these loading scenarios, the maximum Von Mises stresses never exceeded 20% of the yield strength of galvanized steel. Thus, the mount meets the design criteria and will not fail under its expected load.

# Drawings

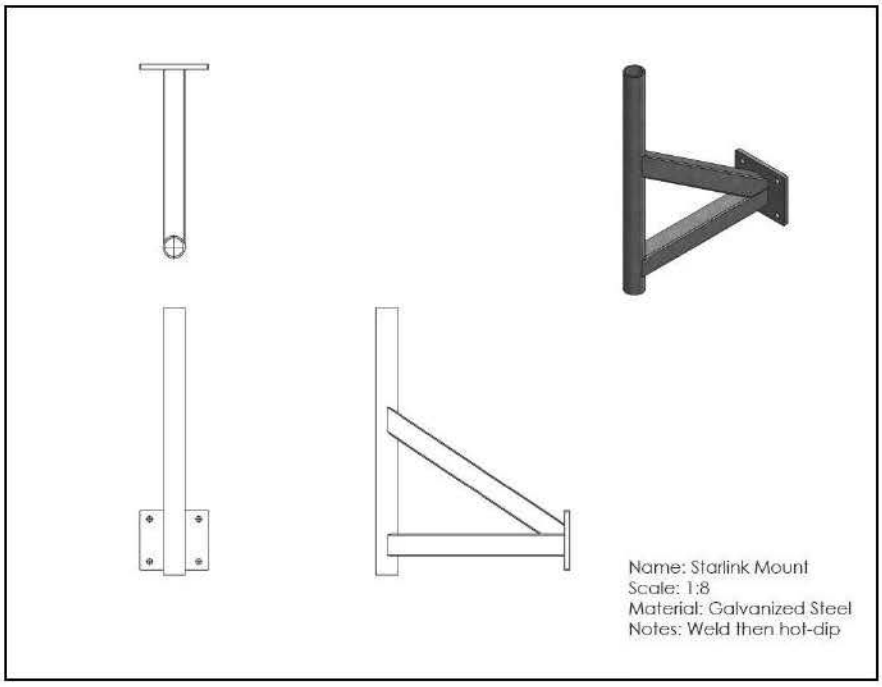



**Figure D.6: Engineering drawing for Starlink mount assembly**

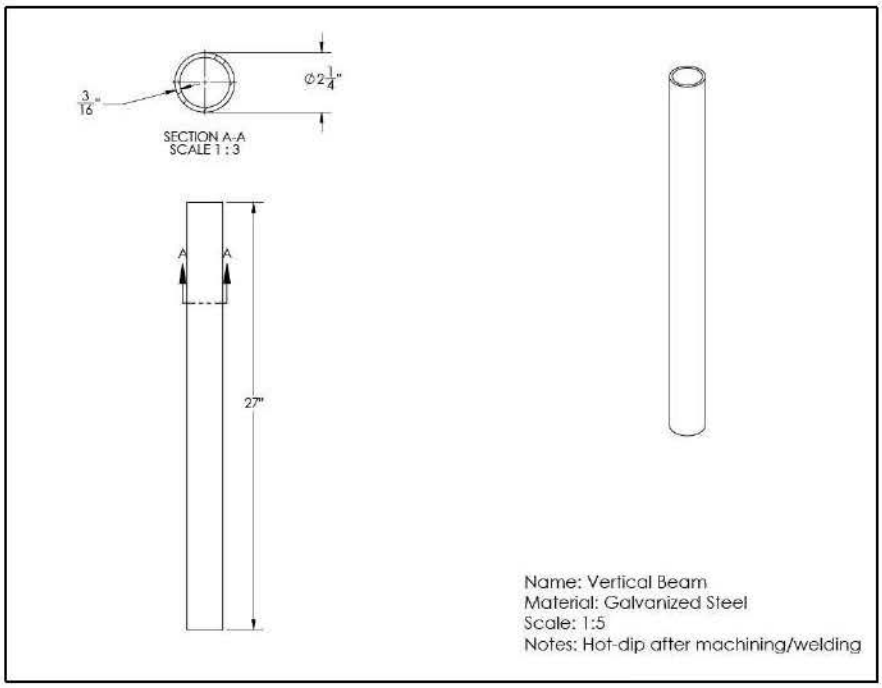



**Figure D.7: Engineering drawing for Starlink mount vertical beam**

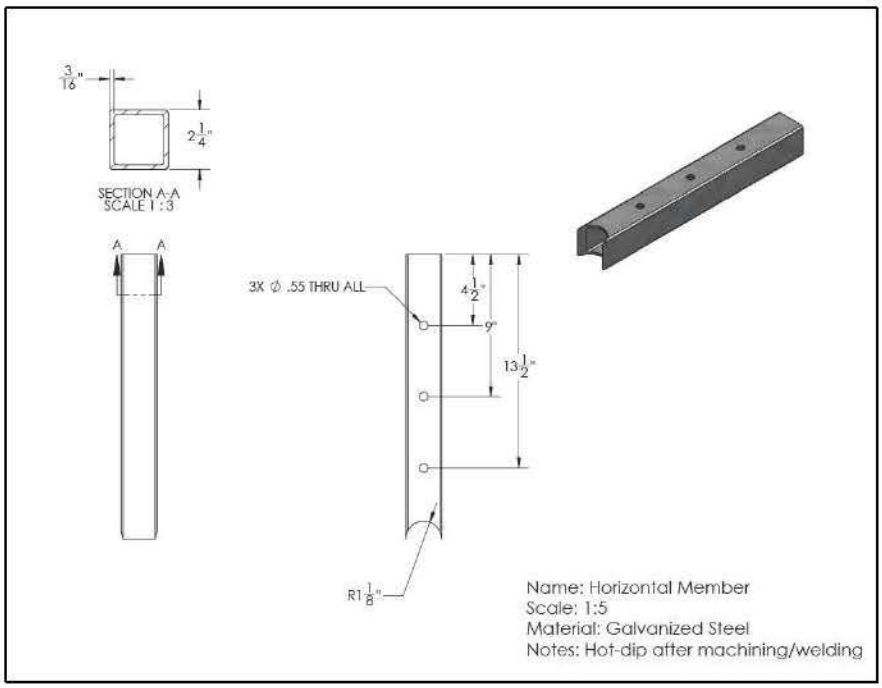



**Figure D.8: Engineering drawing for Starlink mount horizontal member**

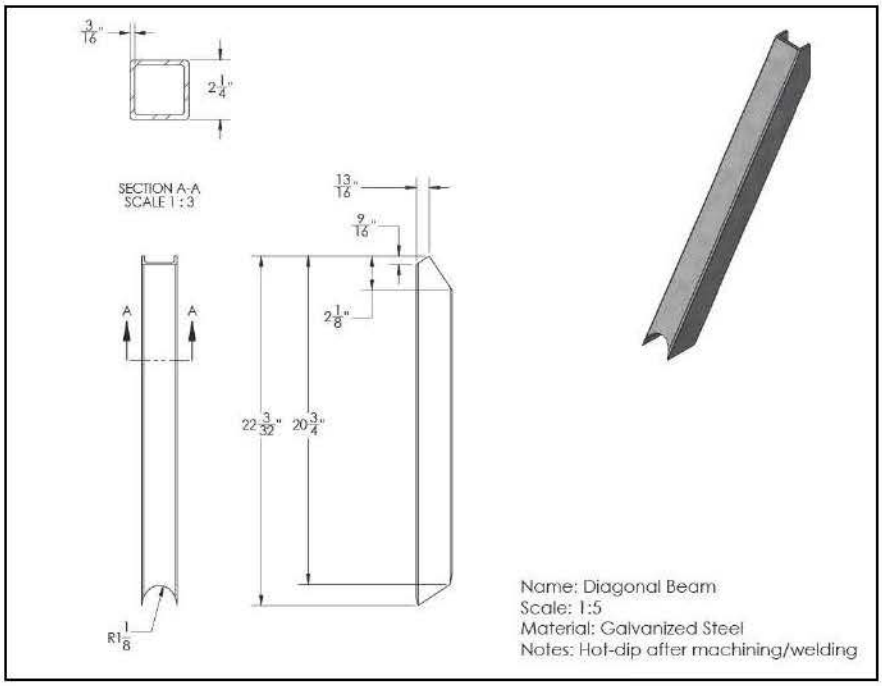



**Figure D.9: Engineering drawing for Starlink mount diagonal beam**

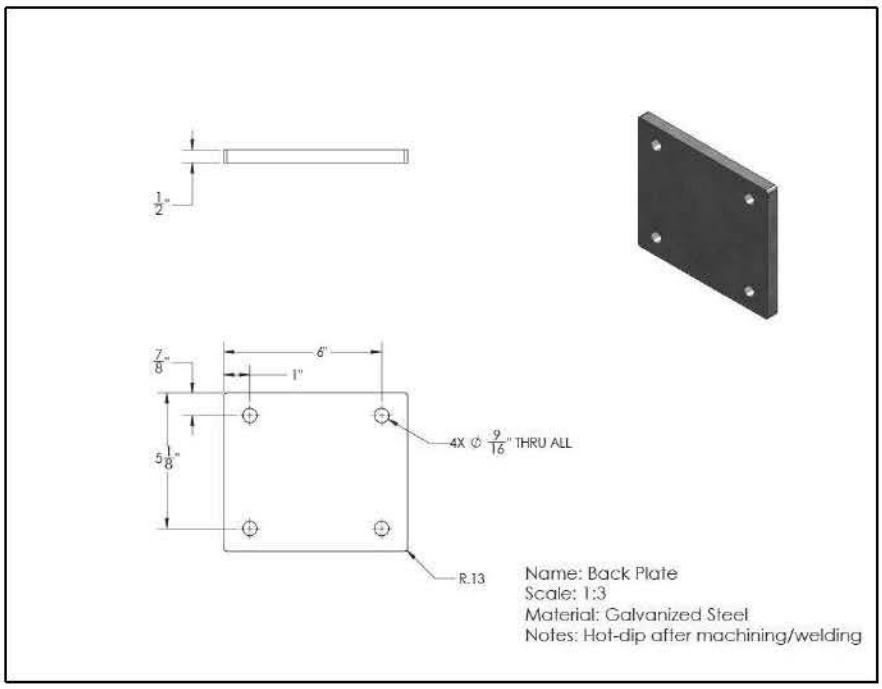



**Figure D.10: Engineering drawing for Starlink mount back plate**

# Processed Data

**Table D.3: Sample longitudinal and lateral wind loads for component FEA**

| | Longitudinal Loading | Lateral Loading |
|---|---|---|
| **Velocity (m/s)** | Wind Load (Lon, [N]) | Wind Load (Lat, [N]) |
| **45** | 575.17 | 597.83 |
| **46** | 601.02 | 624.69 |
| **47** | 627.44 | 652.15 |
| **48** | 654.42 | 680.19 |
| **49** | 681.97 | 708.83 |
| **50** | 710.09 | 738.06 |
| **51** | 738.78 | 767.88 |
| **52** | 768.03 | 798.28 |
| **53** | 797.86 | 829.28 |
| **54** | 828.25 | 860.87 |
| **55** | 859.21 | 893.05 |

# Appendix D References


[1] J. E. Shigley, *Mechanical Engineering Design*, 9th ed. McGraw Hill, 2011.

[2] International Code Council, "2020 City of Los Angeles Building Code." International Code Council, Jan. 2020. Accessed: Dec. 18, 2023. [Online]. Available: https://codes.iccsafe.org/s/CACLABC2020P1/chapter-16-a-structural-design/CACLABC2020P1-Ch16A-Sec1609A.3

[3] M. Ferris, "Wind Loading On Base Station Antennas." Jun. 2009. Accessed: Dec. 18, 2023. [Online]. Available: https://www.cosconor.fr/GSM/Divers/Equipment/Andrew/White%20papers/Wind%20loading.pdf

# Appendix E:
# Survey Raw Responses

There was a total of three responses collected from Caltrans staff who interacted with Starlink system across D2, D3, and D6. In the following, the raw responses of this anonymous survey are included.

## Survey Response 1

1. Which Starlink kits were tested under your supervision? Check all that apply.

| ☐ | ☐ | ☐ |
|---|---|---|
| Standard Actuated | High Performance Actuated | Flat High Performance (non-actuated) |

2. How long have you tested Starlink for Caltrans field elements?

| ☐ | ☐ | ☐ |
|---|---|---|
| Less than 6 months | 6-12 months | Over 12 months |

Please roughly specify the dates you started and ended your Starlink testing:

October 2023 to Present

3. I had enough time interacting with Starlink to understand its operation.

| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

4. Briefly describe your main application of Starlink for Caltrans ITS elements. What was connected to Starlink and monitored as part of your testing?

Closed Circuit Television (CCTV) Cameras and Road Weather Information System (RWIS) stations.

5. What would you change about Starlink hardware or service to make it more suitable for stated Caltrans application. Please explain:

Antenna heating processes to avoid downtime at the onset of winter weather.

Surge suppression system specific to the application.

6. The satellite communication service, as currently offered by Starlink, provides high uptime (low downtime) for remotely monitoring ITS field elements.

| ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

7. The satellite communication hardware requires more maintenance than the old ground communications that support similar ITS elements.

| ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

8. The satellite communication service is a better alternative compared to the old ground communications existing in some (but not all) Caltrans stations.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

9. The operation of Starlink was improved and downtime reduced after a few months (ramp-up period) as operators learned about Starlink and the appropriate configuration of hardware/software.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

10. I would like to see Starlink further deployed/tested to support communication with ITS field elements.

| ☐ | ☐ | ☐ | ☒ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

Further comments:

Overall (averaged over 365-days) uptime improved with Starlink. However, when considering the context of rural ITS deployments and monitoring winter conditions, Starlink doesn't appear to be any more reliable than other ground based telecommunications technologies.

# Survey Response 2

1. Which Starlink kits were tested under your supervision? Check all that apply.

| ☐ | ☒ | ☐ |
|---|---|---|
| Standard Actuated | High Performance Actuated | Flat High Performance (non-actuated) |

2. How long have you tested Starlink for Caltrans field elements?

| ☒ | ☐ | ☐ |
|---|---|---|
| Less than 6 months | 6-12 months | Over 12 months |

Please roughly specify the dates you started and ended your Starlink testing:

11/19/2024-- PRESENTLY RUNNING

3. I had enough time interacting with Starlink to understand its operation.

| ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

4. Briefly describe your main application of Starlink for Caltrans ITS elements. What was connected to Starlink and monitored as part of your testing?

TRAFFIC MONITORING STATION AND SOLAR POWER INVERTER MONITORING, VPN WITH CISCO 800, INCLUDING WAVETRONICS CLICKS, QFREE TMU4.

5. What would you change about Starlink hardware or service to make it more suitable for stated Caltrans application. Please explain:

ETHERNET DHCP LEASE RENEWING WAS NOT WORKING, GENERAL LACK OF CONTROL OVER THE ROUTER PROVIDED WITH KIT. PROPRIOTARY CONNECTORS DIFFICULTY TO RUN THROUGH CONDUIT.

6. The satellite communication service, as currently offered by Starlink, provides high uptime (low downtime) for remotely monitoring ITS field elements.

| ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

7. The satellite communication hardware requires more maintenance than the old ground communications that support similar ITS elements.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

8. The satellite communication service is a better alternative compared to the old ground communications existing in some (but not all) Caltrans stations.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

9. The operation of Starlink was improved and downtime reduced after a few months (ramp-up period) as operators learned about Starlink and the appropriate configuration of hardware/software.

| ☒ | ☐ | ☐ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

10. I would like to see Starlink further deployed/tested to support communication with ITS field elements.

| ☐ | ☐ | ☐ | ☐ | ☐ | ☒ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

Further comments:

STARLINK IS A GREAT PRODUCT FOR COMMUNICATION IN REMOTE AREAS, BUT IF GIVEN THE OPTION BETWEEN OUR CURRENT WIRELESS COMMUNICATION VS STARLINK CURRENT ONES ADVANTECH/DIGI MODEMS PREFERED FOR STABILITY AND USER CONTROL.

# Survey Response 3

1. Which Starlink kits were tested under your supervision? Check all that apply.

| ☐ | ☐ | ☐ |
|---|---|---|
| Standard Actuated | High Performance Actuated | Flat High Performance (non-actuated) |

2. How long have you tested Starlink for Caltrans field elements?

| ☐ | ☐ | ☐ |
|---|---|---|
| Less than 6 months | 6-12 months | Over 12 months |

Please roughly specify the dates you started and ended your Starlink testing:

April to August 2024

3. I had enough time interacting with Starlink to understand its operation.

| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

4. Briefly describe your main application of Starlink for Caltrans ITS elements.

What was connected to Starlink and monitored as part of your testing?

We were trying to use it with a CCTV in a rural area. We were unable to finalize testing of the element because of the inability to obtain a static IP address from the provided router.

We did all of our testing at our District office with multiple networking tests.

5. What would you change about Starlink hardware or service to make it more suitable for stated Caltrans application. Please explain:

The #1 priority has to be the ability to obtain a static IP address from Starlink. Without that, the way we handle our ITS elements would not work.

6. The satellite communication service, as currently offered by Starlink, provides high uptime (low downtime) for remotely monitoring ITS field elements.

| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

7. The satellite communication hardware requires more maintenance than the old ground communications that support similar ITS elements.

| ☐ | ☐ | ☐ | ☒ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

8. The satellite communication service is a better alternative compared to the old ground communications existing in some (but not all) Caltrans stations.

| ☐ | ☒ | ☐ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

9. The operation of Starlink was improved and downtime reduced after a few months (ramp-up period) as operators learned about Starlink and the appropriate configuration of hardware/software.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

10. I would like to see Starlink further deployed/tested to support communication with ITS field elements.

| ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
|---|---|---|---|---|---|
| 0 – Not Sure | 1 - Strongly disagree | 2 - Disagree | 3 - Neutral | 4 - Agree | 5 - Strongly agree |

Further comments:

The bandwidth and speed of the unit is high quality. In our testing, the amount of satellite uptime was near 100%, which is very promising.