COLORADO

Center of Excellence for Advanced Technology Aerial Firefighting

Department of Public Safety

FirstNet High Power User Equipment (HPUE) Test Results and Recommendations

CoE 22-001.5

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Executive Summary

In 2021 the Center of Excellence (CoE) tested a new cellular capability available to the First Responders on the AT&T FirstNet® Network, namely High Power User Equipment (HPUE). Offered under the "MegaRange™" moniker, this is a high-power cellular modem that can be installed either as a fixed or semi-fixed installation or in a vehicle. The HPUE operates at high power on FirstNet Band 14 in low coverage situations and provides a data connection that can be used as a network connection.

In the cellular industry "User Equipment" or "UE" refers to the devices, such as mobile phones, hotspots, and modems, used by the end-user. HPUE, or High Power User Equipment, is end-user equipment that emits a higher power radio signal.

The factor most often limiting cellular coverage in underserved areas is the Radio Frequency (Rf) signal traveling from the mobile device back to the tower. Standard mobile devices are limited to 23dBm (200mW) transmitted power due to potential interference with cellular systems, FCC regulations, and battery power/size (power class 3). While increasing the power of the mobile device has the potential to increase usable range and data rates by increasing the signal traveling back from the mobile device to the tower, increasing mobile device power is only viable in certain conditions. Specifically, higher power is only allowed on cellular Band 14. The HPUE devices tested here are classified as power class 1 and can operate up to 31dBm (1.25 W) on Band 14. Because Band 14 is prioritized for Public Safety, higher-power user equipment is allowed. Note: Band 14 does not currently provide 5G.

Cellular devices operate on specified ranges of Rf frequency ranges are called "bands".

The HPUE is only available to first responders, only operates on high power in certain circumstances, and then only on Band 14. When to operate the HPUE at high power is determined automatically by the FirstNet system and is not under the control of the user. While this places limitations on HPUE, the CoE found that, for the right user, HPUE can provide a significant benefit. However, performance in urban or suburban areas with better coverage is sometimes not as expected.

The HPUE provides a data connection operating as a cellular modem (data connection). It is not a cell phone. Phones used in VoIP or Wi-Fi calling mode on the HPUE Network do benefit from the improved coverage and data stream.

Recommendations

The CoE can recommend the HPUE equipment for public safety practitioners who operate in rural areas with Band 14 coverage. The benefit was significant and measurable. The only caveat is that determining the actual value is very location dependent and cannot be easily determined with consumer equipment. The CoE may be able, on a limited basis, to help first responders in Colorado measure coverage in areas of interest.

CoE Findings

The CoE found the HPUE provided meaningful and measurable benefit, as compared to the standard power user equipment, to first responders in certain cases.

HPUE Provides Benefit When:

- Using HPUE in remote or rural locations with limited cellular coverage can provide significant data connectivity benefits as long as that area does have Band 14 coverage and does not have strong (or even sometimes moderate) coverage in other bands.
- The HPUE provides a data connection operating as a cellular modem (data connection). It is not a cell phone. Phones used in VoIP or Wifi calling mode on the HPUE Network do benefit from the improved coverage and data stream.
- The CoE tested standard mobile devices and HPUE by conducting speed tests on connected devices. In addition, the CoE used professional Cellular Test and Measurement Equipment donated to the CoE by PCTel (pctel.com).

HPUE Provides Little or No Benefit When:

- Band 14 coverage is not available.
- Strong cellular coverage is available either from AT&T or other carriers.
- Other bands or frequencies have slightly higher signal strength than Band 14, causing the HPUE to operate at lower power on other bands.

Challenges with the HPUE:

- There is no user feedback on the power being used and because the power depends on factors not known to the user (coverage by other bands/carriers/etc.), the HPUE operation can change dramatically based on small geographic changes. *(Note: The CoE received information that no visual feedback was provided as a safety factor. There was concern that driving and observing signals could be a safety hazard. In addition, the goal was a simple and automatic tool for first responders.)*
- The process by which the AT&T cellular network determines if the HPUE should operate at higher power is still being refined. The net result is that in areas with good coverage, the CoE observed the HPUE sometimes operating significantly slower than standard mobile devices. This is as expected since HPUE is designed to improve connection in tough coverage areas, not high coverage areas.

Assured Wireless MegaGo

The HPUE, while called 'user equipment' is typically provided in a kit that is to be installed into a vehicle or fixed location - installation is required and may require significant work. Assured Wireless does sell the "MegaGo" preconfigured portable system. (https://www.assured-wireless.com/products/megago/)

Summary Statement

In the right conditions and for the right practitioners, the HPUE provides significant and meaningful improvement. HPUE will provide benefits for:

- Users operating in rural areas with low cellular signal strength (bars) and where Band 14 does have coverage.
- Users who are willing to install the HPUE in a vehicle, or construct/purchase a 'semi-portable' system. The CoE has constructed several of these lower cost systems and there are commercial, albeit expensive, options.

The CoE is happy to engage public safety cooperators in Colorado to help make a determination based on use model, coverage, and location. In the right conditions, the CoE may be able to come and use PCTel analytic equipment to test the area of interest.

Note: general information about where Band 14 is deployed can be found using the open-source site CellMapper (https://www.cellmaper.net/map). In addition, AT&T/Firstnet can help identify areas of improved coverage with HPUE.

Recommendation

The CoE can recommend the HPUE equipment for public safety practitioners who operate in rural areas with Band 14 coverage. The benefit was significant and measurable. The only caveat is determining the actual value is very location dependent and cannot be easily determined with consumer equipment. The CoE may be able, on a limited basis, to help first responders in Colorado measure coverage in areas of interest.

"HPUE benefit is less predictable than the CoE would have preferred. If using HPUE and having connection troubles, repositioning can have a dramatic effect. Unfortunately, since you likely do not know the location of the tower(s), it can be difficult to determine what location is best except driving around and trying which is tedious and error prone. The CoE was able to predict, with assurance, where good service was likely by using sophisticated cellular testing equipment designed to map cellular services as you drive."

"In those cases where HPUE operates at higher power, the benefit was real and significant."

Background - FirstNet

Due to communications challenges during the response to the 9/11 terrorist attacks, the 9/11 Commission recommended the establishment of a single, interoperable network for public safety. Congress established the First Responder Network Authority (FirstNet) in 2012.

The First Responder Network Authority, or FirstNet Authority, was created as part of the Middle Class Tax Relief and Job Creation Act (PUBLIC LAW 112–96), which was signed into law on Feb. 22, 2012. The law allocated 20 megahertz of Band 14 spectrum and $7 billion to establish a broadband network dedicated to the nation's first responders and gave the FirstNet Authority the mandate to ensure the building, deployment, and operation of the network. Congress also required that the network extend coverage in rural areas through buildout milestones. The inaugural meeting of the FirstNet Authority Board took place on Sept. 25, 2012. FirstNet Authority awarded a 25-year contract to AT&T in March 2017.

Many cell phone providers have a priority system for first responders which prioritizes registered users on their networks, however, only FirstNet/AT&T has access to Band 14.

For more information visit firstnet.gov and firstnet.com (AT&T)

Technical Implementation

FirstNet operates on an allocated band of frequencies known as Band 14, which was allocated in 2012, as well as on other commercial bands operated by AT&T. In March 2017, AT&T was awarded the contract to provide FirstNet for the US. Colorado opted into FirstNet on December 18, 2017. Band 14 can be utilized for normal civilian communications (normal cell phone), but provides priority for registered First Responders meaning that in emergencies, First Responders will have priority on the network. First Responder calls and data requirements will take precedence over the public to assure First Responders have the best access to any available system. This precedence operates on all bands, but Band 14 is treated specially to provide a dedicated set of frequencies.

Not all cell phones or cellular modems support the Band 14 frequency set so if you are a First Responder wanting Band 14 access, make sure your device support AT&T and Band 14.

2012: Congress creates the First Responder Network Authority

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High Power User Equipment

One of the potential advantages of a dedicated, prioritized spectrum for Public Safety is that specialized equipment can be developed that would not be allowed on the normal public cellular bands. In 2021 AT&T, through its partner Assured Wireless, released two Band 14 modems that operate as HPUE. HPUE can operate at significantly increased RF power on Band 14 when appropriate. This improves the ability of these devices to provide connectivity and, potentially, higher data speed when in a geographic area where Band 14 is implemented and where the cellular signal is weak. The HPUE equipment can operate at up to 1.25 watts on Band 14 (Power class 1) as compared to 200mW (power class 3) for mobile. These devices are data-centric - they are modems, not phones - but support VOIP voice communications so can be used to augment both data and voice communications.

To make phone calls, a phone must be connected to the HPUE via Wifi and operating in Wifi calling mode to benefit from the HPUE equipment's enhanced range. Phones and plans that do not support Wifi calling cannot operate using HPUE equipment for voice communications. If the phone is connected to the normal Cellular network, either Band 14 or other commercial bands, it is not utilizing the HPUE.

As of the date of this report, the only HPUE available are modems. No phones with HPUE have been announced, and given thepower requirements of HPUE, it seems a dedicated HPUE phone is not a priority. Power (battery) requirements would be significant.

General Discussion of Technologies

Cellular Systems

In the most general sense, a cellular phone is a portable data radio. A two-way radio signal is established between the phone and one or more fixed towers. Each tower serves a specific geographic area and communicates with cell phones within that area. The area served by a particular tower is a "cell", hence the name cellular phone system. At any time, a given phone may be connected (registered) with more than one cell tower, but communications are typically routed to the one with the strongest signal. As the phone moves, it will switch quickly, and typically seamlessly, between towers. Data that the tower receives from the phone will be forwarded to the global "system" using some type of backhaul connection (commonly fiber optic cables) where it is sent on to the tower where the receiving phone is connected, or in the case of a call to a landline, to the telephone system serving that phone. It is important to note that modern cell systems are digital. That means all the information sent or received by the phone is sent in digital form. Voices are converted to a digital signal, transmitted across the system then converted back to voice at the receiving end. Data traveling along the system could be digitized voice or actual data - such as web pages or digital video. This provides much higher bandwidth and reliability than old "analog" systems and provides for some level of error correction when signals are weak. The details of how digital data is transmitted and received is beyond the scope of this paper.

Limits to Cellular Reception

Cellular phones and, in this case, modems, are radios operating at very low power (200mW) and on very high frequencies, about 600 MHz through about 6 GHz (not including the so-called 5G millimeter wave which operates around and above 27GHz). As such, they are "line of sight" devices - meaning there needs to be a 'clear line of sight' between the phone and the tower. In this context, "line of sight" does not mean 'I see the tower' but 'can radio waves get from me to the tower?' Radio waves penetrate some things such as building materials, foliage, glass, etc. so phones may continue to operate even if you cannot actually see the tower. They can also 'bounce' off objects to a limited extent. However, if there is anything between the phone and the tower that blocks the radio waves, like a hill, metal buildings/ walls, etc. the phone will lose connection.

Cellular systems are two-way radios so communications must be established in both directions between the tower and the phone for the system to function. The tower sends a signal to the phone, and the phone sends back an answer (or vice-versa). If either direction fails, the connection is dropped.

In practice, the cell tower operates at much higher power than the phone, so the primary limit is the signal from the phone to the tower. The maximum effective radiated power (ERP) of a cellular tower is 500 watts, though nominal power is typically 20-60 watts. In contrast, a cell phone radiates at no more than 200mW or 0.2 watts, 500 times less than the tower. This means the signal from the phone to the tower is usually the limit. The phone can receive the

signal from the tower, but the tower cannot receive the, much smaller, signal from the cell phone.

One way to think of this is to imagine two people shouting across a noisy street to each other. If one person has a megaphone (the tower) and one does not (the mobile phone), then the person with the megaphone can be heard, but may not hear what the other person says back.

Detailed Discussion of Results

How HPUE Extends Reception Range

This is where HPUE becomes important. In cases where there is limited cell coverage, say in rural areas, the cell phone can probably "hear" the tower (big megaphone), but the tower cannot "hear" the phone answer (person shouting). With HPUE, which operates at 6 times more power than the phone, we have given the person a megaphone, albeit a small one, to shout back with.

During operation the HPUE will operate on standard cellular bands, using two antennas in a MIMO (Multi-Input, Multi-Output) configuration. MIMO antennas are often used to provide improved reception. In addition, the HPUE has a single dedicated Band 14 antenna to allow operation at higher power on Band 14 when conditions warrant. The HPUE also has a GPS antenna to provide required location information.

If the HPUE and the cellular system determine that high power can be utilized, it will ramp up the output power. The exact algorithm that is used by the HPUE to determine this switching process is proprietary and was not shared with the CoE. However, our general understanding is that the HPUE will increase transmit power when:

- Band 14 is available, but at low relative power and the signal detected at the tower drops below some minimum level, in which case the tower instructs the HPUE device to increase power (in small steps).
- Other cellular bands are not available or are also at low relative power.

This last point is key. If you have an 'acceptable' connection to a standard band, the HPUE will not operate at high power. This may result in conditions where HPUE at high power might help, but the HPUE stays at low power because of a slightly stronger signal from other bands, or to prevent the high output power from interfering with other cellular signals. It would be possible for an HPUE operating at higher power to create noise or interference on other frequencies.

Benefits of HPUE

When in use, the HPUE will monitor the relative strength, noise, and stability of signals to/ from all cells it is connected to. Based on that information, the HPUE may increase output power on Band 14 from 200mW to as much as 1.2W - a 6-fold increase.

When the HPUE ramps up to a higher power, the signal from the HPUE to the tower increases dramatically which provides a much more robust connection.

- Data rates increase dramatically, as much as 100 times.
- Voice calls using VOIP (Wi-Fi calling) can be made with much greater success.
- Phones, *from other carriers*, that can use Wi-Fi calling may be able to make calls.
- *Note - it is not clear that, for all phones, SMS data (texts) will be sent over Wi-Fi. You may find yourself in a situation where you can email and call, but not text.*

HPUE Higher Power "Algorithm"

The exact algorithm that is used by the HPUE to determine its output power is proprietary and was not shared with the CoE. The end-user has no control over the HPUE power setting, and there is no way of knowing at what power the HPUE is operating as that information is not provided to the user. Because the state of power of the HPUE is not visible to the user, the CoE can only infer the operating state based on the performance seen. In addition, AT&T is continually optimizing system performance.

Our general understanding is that the HPUE will increase transmit power when:

- Band 14 is available but at low relative power.
- Other cellular bands are not available or are also at low relative power.
- Switching to a higher power on Band 14 is done 'conservatively' (based on observations).
- It seems that if there are multiple cells, even with very low signal strength, the HPUE may remain at low power (based on observations).

The net result of this means:

- In marginal areas where there is weak coverage from multiple Bands, the HPUE may not ramp to higher power quite as quickly as might be optimal.
- Small positional changes, moving as little as a few hundred yards, can make significant differences in the system operation by causing the HPUE to ramp up to higher power.

Limitations of HPUE

While the HPUE provides a dramatic improvement in some cases, the HPUE is not without limitations. For a number of technical and practical reasons, HPUE cannot always provide better reception.

For instance:

- HPUE operates only on cellular Band 14 frequencies. The FCC does not allow operating at higher power on anything but Band 14. If Band 14 is not available, then there is no benefit to the HPUE.
- Band 14 is still being deployed and may not be available in many areas.
- While Band 14 can be utilized by the public (if they have a phone that supports Band 14), FirstNet services and HPUE are limited to authorized Public Safety Operators. You must be subscribed to Firstnet as a public safety operator and have an authorized HPUE data plan.
- HPUE will not provide benefits in all cases. For instance:
    - HPUE will operate at high power only when weak Band 14 signals are available.
    - HPUE will not switch to high power in many cases, such as when signals are stronger or multiple signals are present. This is because the high power output may disrupt other communications. The user has no way to specify or control high power operation and no feedback as to current power state. The cellular system makes that determination.

    - If there are strong cellular signals on other bands (not Band 14), the HPUE will operate at standard power on those bands, not Band 14.
    - If a phone can connect to a tower using Band 14 or other Bands, it may use that connection instead of the HPUE Wifi connection unless you specifically configure the phone to use WiFi and WiFi calling.
    - *This last point is especially important if you have a cellular amplifier, such as a WeBoost, installed in your vehicle. This may cause a phone to connect to a 'weaker' cell signal rather than the HPUE-provided wireless network.*
- Because of the line-of-sight nature of cellular signals, a small position change can dramatically change performance.
    - *As an example, the CoE found very good Band 14 performance at a given location on a rural county road, but at a higher location 1/2 mile away, there was no signal at all, even though the higher location would seem to have made up for the distance.*

The net result of this is that:

"HPUE benefit is less predictable than the CoE would have preferred. If using HPUE and having connection troubles, repositioning can have dramatic effects. Unfortunately, since you likely do not know the location of the tower(s), it can be difficult to determine what location is best except driving around and trying which is tedious and error prone. The CoE was able to predict, with assurance, where good service was likely by using sophisticated cellular testing equipment designed to map cellular services as you drive."

"In those cases where HPUE operates at higher power, the benefit was real and significant. "

Consequently:

- In marginal areas where there is weak coverage from multiple Bands, the HPUE may not ramp to higher power quite as quickly as might be optimal.
- Small positional changes, moving as little as a few hundred yards, can make significant differences in the system operation by causing the HPUE to ramp up to higher power.

Testing Methodology

The CoE performed this testing using a methodology that relied on both analytical signal test equipment and speed tests on end-user equipment. The process is best described as an analytic directed test process.

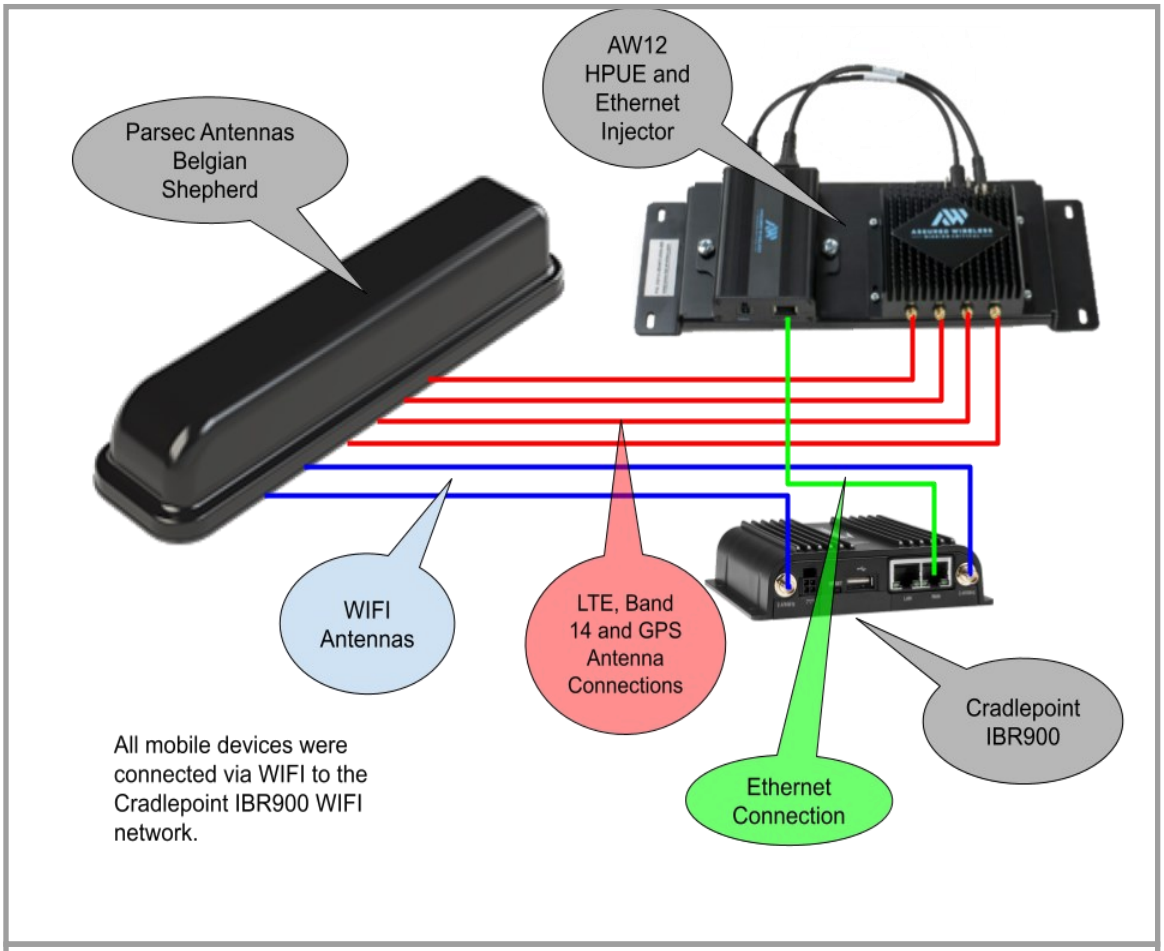
Test Procedure:

- A predetermined test route was driven based on:
    - Prior knowledge of cell tower locations in the area
    - Viewshed information from those towers that provide predicted shading. Viewshed maps for key towers are shown in this report.
    - Previous spot checks based on familiarity with the cell service along the route
    - Analytical signal strength data were collected using the PCTel Ibflex scanner as we drove.
    - The PCTel system was configured in "drive test mode" where regular signal checks were performed on specified bands. Representative signal maps are provided.
- Data transfer speed tests were performed at locations expected to have high, medium, low, and no service based on cell tower location, PCTel Ibflex measure data, and previous testing.
    - At each spot, various speed tests were performed using devices configured to use different channels.
    - At each spot, the measured signal strength on relevant cellular bands was recorded.

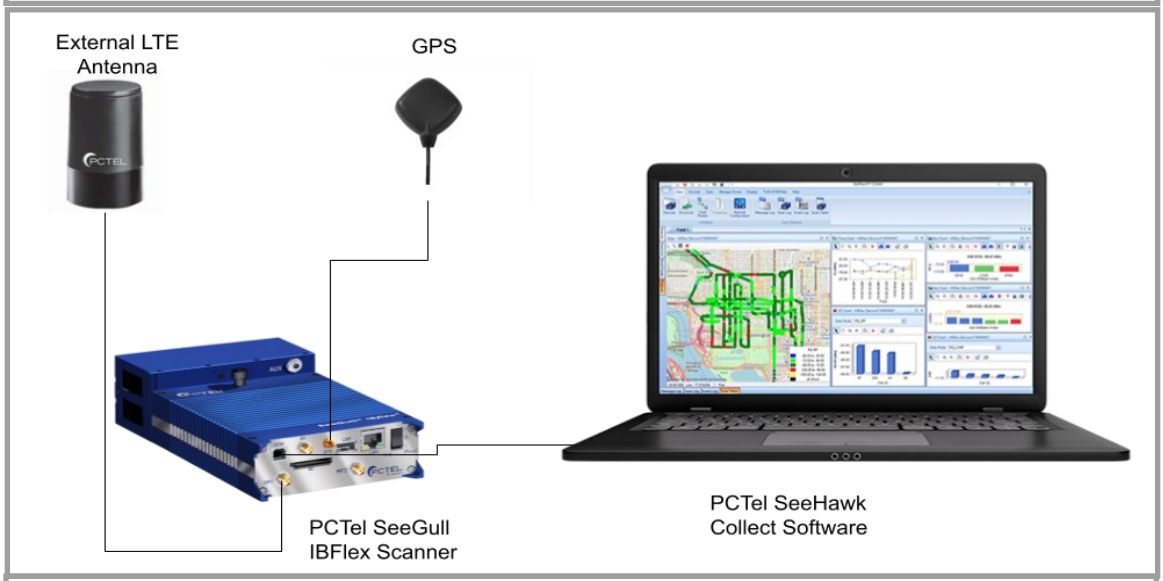
Equipment Configuration:

- An HPUE Airgain Connect Antenna Modem[1] was installed on the top of a State fleet pickup.
    - Airgain Connect was installed on top of an aluminum 'topper' on a 2019 Dodge Ram 1500 pickup.
    - Wireless connectivity to the HPUE was via a CradlePoint IBR-900 wireless access point connected via the Ethernet port on the HPUE.
- Motorola G-stylus (2021) Android Smartphone operating on Verizon
- HP laptop computer operating on Wi-Fi connection to the HPUE
- PCTel IBFlex scanner with SeeHawk Collect and SeeHawk Touch software

1. https://airgain.com/products/airgainconnect-antenna-modem/fleet/airgainconnect-ac-hpue/
2. https://www.pctel.com/products/test-measurement/scanning-receivers/ibflex-scanning-receiver/



Configuration of the HPUE equipment tested in this process.

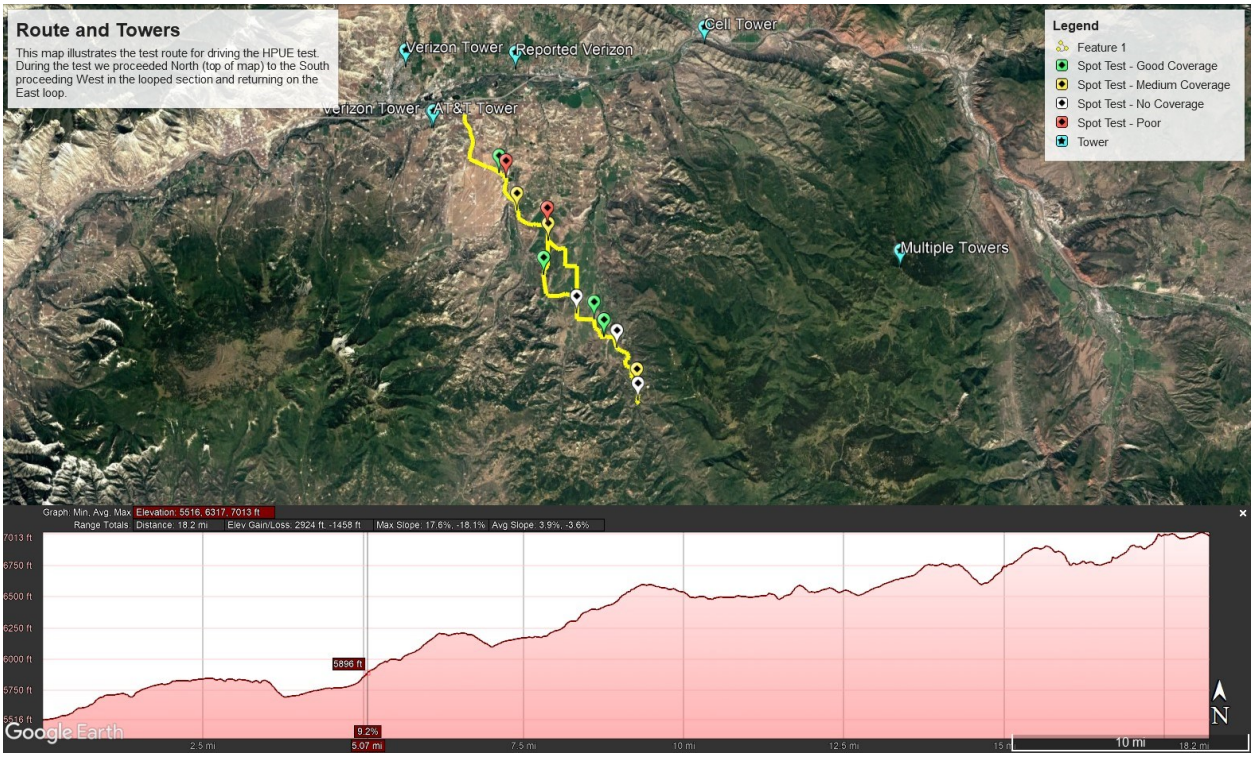


PCTel Test Equipment.

- The IBFlex Scanner and Software were donated to the CoE by PCTel[2].
- Samsung Galaxy S10+ AT&T FirstNet Phone
- Android Automotive Head Unit

Testing Route and Tower Locations

The following figure shows the approximate test route, identified cell towers, and markers for spot tests showing relative coverage levels. Also shown is the elevation profile of the test route including the elevation profile of the route. The test route started at the Garfield County Regional Airport (CoE Office) and proceeded south on county roads to an area with no coverage.

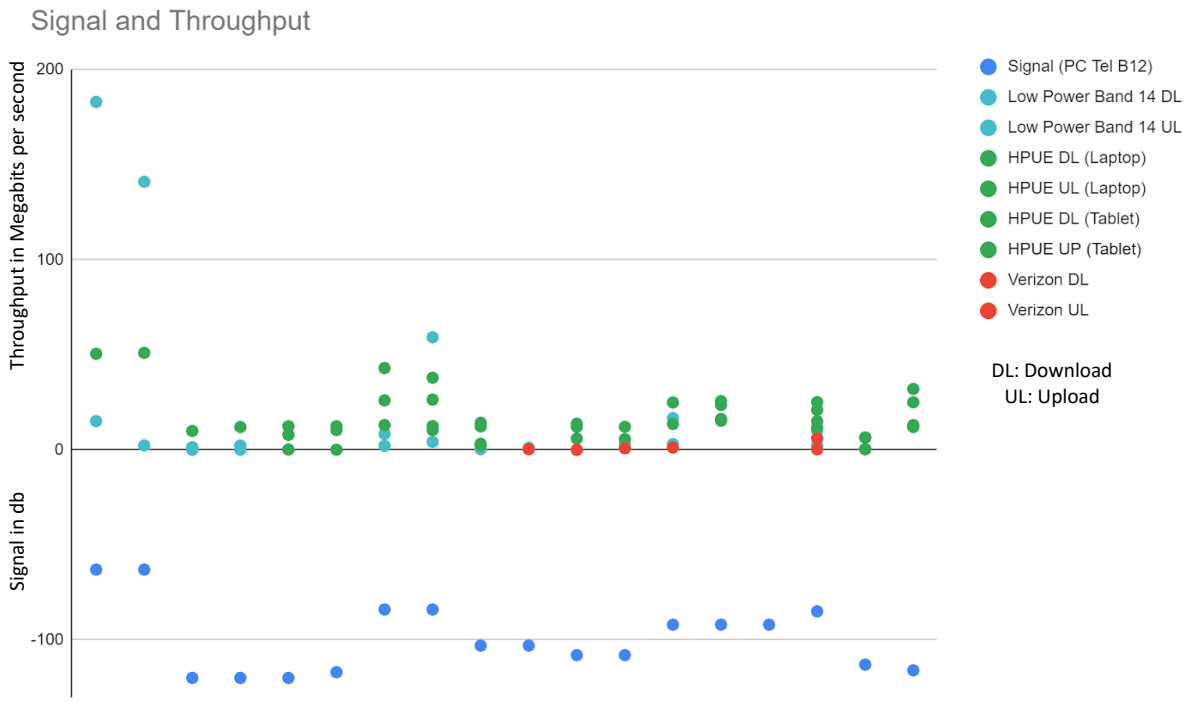


Signal Analysis

The following sections detail the analytical cell signal analysis and provide cell tower viewsheds relative to the test route.

Measured Speed Results

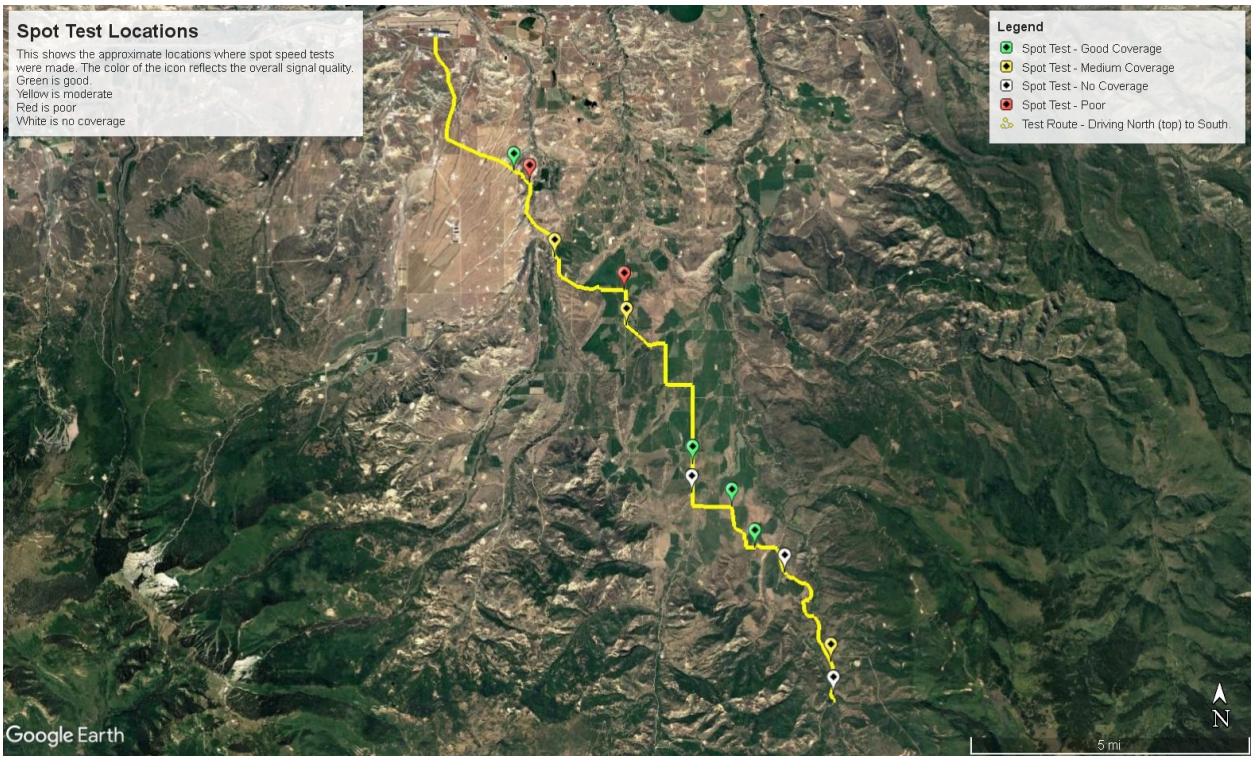
At specific locations during the test run, the test vehicle was stopped and speed tests were taken using various devices, including the HPUE equipment. The following graph shows the speed and signal on various channels during the test run. The green dots are HPUE speed tests. Note the two cyan dots which are lower power Band 14 (cell phone on band 14)



The following table lists the results of those tests. The numbers are Upload (UL) or download (DL) speed in Mbps.

Descriptive	Subjective signal	Low Power	Low Power	HPUE DL	HPUE UL	HPUE DL	HPUE UL	Verizon DL	Verizon UL
Hunter Mesa at top of hill above Mamm Creek.	Good	183	15.1			50.5			
		141	2.31			51			
Hunter Mesa at Mamm Creek.	Very Low	1.38	0.01			9.92			
		2.27	0			12			
				7.89	0.17	12.4			
				10.4	0.04	12.4			
Past Cow	Medium	8.3	2.08	26	13	43			
		59.2	4.2	26.4	10.4	37.9	12.5		
Jenkins Cutoff-	Very Low	0.3		12.3	2.43	14.2	3.16		
		1.07	0.3					0.35	
Colbran Cutoff	Very low			13.7	5.87	12.1		0	0
		3.24	1.3			12.1	5.6	0.77	-
1st Water Pipe	Low	16.7	3.06	24.9	13.6			1.19	
				25.6	16.2	23.6	15.3		
Ganns	Nill								
Duke 1st 90	Medium	9.91	2.25	21	11.6	25.1	15	5.99	0.24
Below Duke				6.4	0.3	6.5	0.34		
Past Duke				32	13	25	12		

The following map shows approximate locations where the tests were performed. Note that the spot test locations were chosen based on experience with cell service at those locations and based on geography. Where no coverage was noted, there are no spot tests.



Analytical Cell Signal Measurements

Measurement of the cell signal was performed using a PCTel IBFlex (IBFlex Device release 3.5.0.) scanner with an external antenna. Scans were performed in a blind scan mode which looks at a wide variety of cell channels and bands. Data was captured using PCTel SeeHawk Touch 2.9.1.11.

The following table summarizes the blind scan results during the test run. Of note is the Detection Count which reflects the number of times a signal was detected.

Protocol	Band	Channel Range	Measurement Mode	Total Sweeps	Avg Time/ Sweep (seconds)
LTE	EB 02: 1900 (PCS) DL	605 - 1195	High Speed	44	27.217
LTE	EB 04: 2100 (AWS) DL	1955 - 2395	High Speed	44	27.237
LTE	EB 05: 850 (Cellular) DL	2405 - 2645	High Speed	44	27.258
LTE	EB 12: US Lower 700-A/B/C Blocks DL	5005 - 5175	High Speed	44	27.319
LTE	EB 13: US Upper 700-C Block DL	5185 - 5275	High Speed	43	27.595
LTE	US Upper 700-C/D Blocks DL	5185 - 5275	High Speed	43	27.65
LTE	EB 14: Upper 700-D Block DL	5285 - 5375	High Speed	43	27.67
LTE	EB 17: US Lower 700-B/C Blocks DL	5735 - 5845	High Speed	43	27.756
LTE	EB 29: US 700 DL	9665 - 9765	High Speed	43	27.693
LTE	EB 66: AWS-3 DL	66441 - 67331	High Speed	43	27.782
TD-LTE	EB 41: TDD 2.5 GHz	39655 - 41585	High Speed	43	27.797
TD-LTE	EB 41: TDD 2.5 GHz Lower	39655 - 40615	High Speed	43	27.746

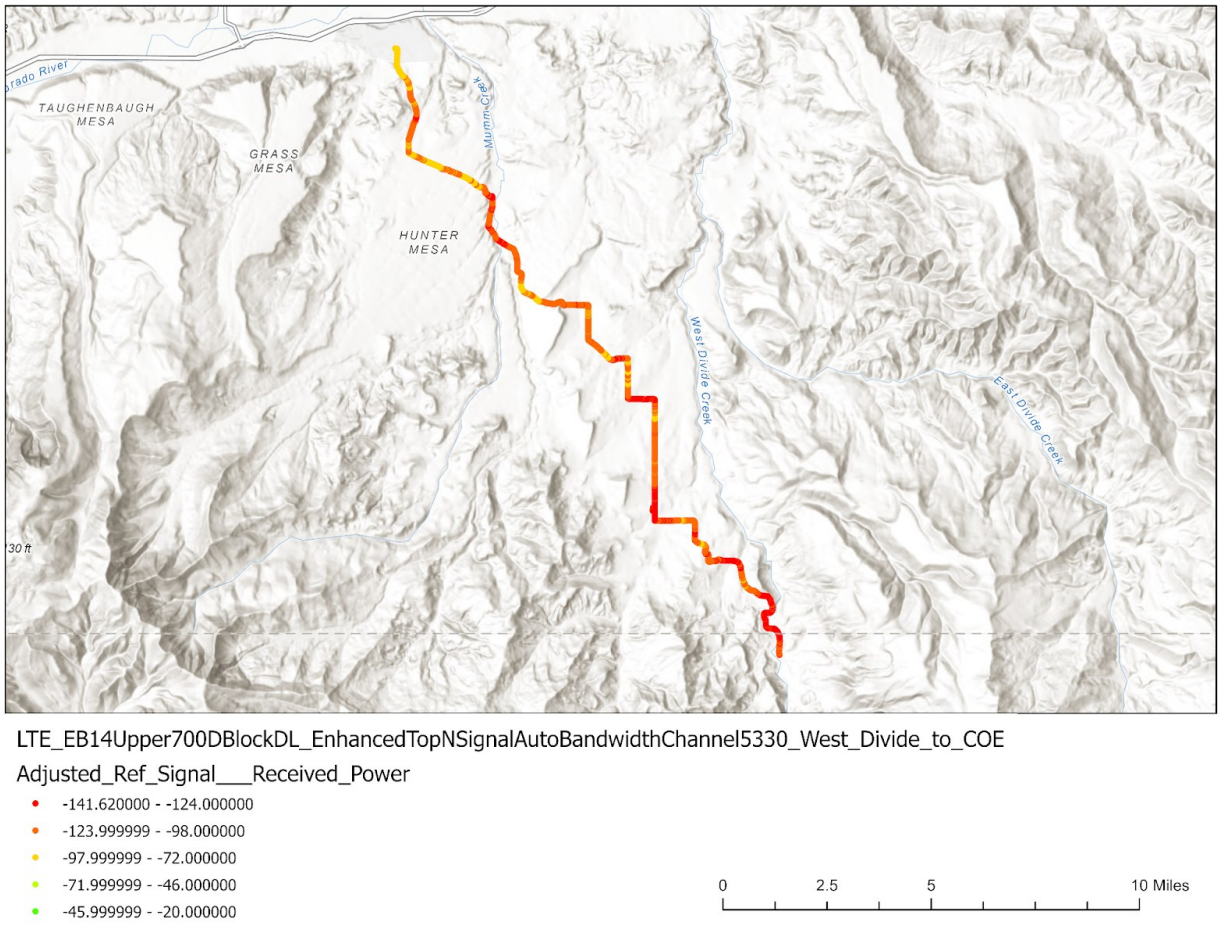
The following table shows the frequency ranges and bands swept during a typical run.

Protocol	Band	Chan#	Detection Count	Bandwidth	Network
LTE	EB 02: 1900 (PCS) DL	700	36	20 MHz	First Responder Network Authority
LTE	EB 02: 1900 (PCS) DL	875	29	15 MHz	Sprint
LTE	EB 04: 2100 (AWS) DL	2050	37	20 MHz	Verizon Wireless
LTE	EB 04: 2100 (AWS) DL	2225	32	15 MHz	First Responder Network Authority
LTE	EB 05: 850 (Cellular) DL	2425	32	5 MHz	First Responder Network Authority
LTE	EB 12: US Lower 700-A/B/C Blocks DL	5035	40	5 MHz	Sprint
LTE	EB 12: US Lower 700-A/B/C Blocks DL	5090	42	5 MHz	Commnet Wireless LLC
LTE	EB 13: US Upper 700-C Block DL	5230	43	10 MHz	Verizon Wireless
LTE	US Upper 700-C/D Blocks DL	5230	43	10 MHz	Verizon Wireless
LTE	EB 14: Upper 700-D Block DL	5330	41	10 MHz	First Responder Network Authority
LTE	EB 17: US Lower 700-B/C Blocks DL	5760	43	5 MHz	Commnet Wireless LLC
LTE	EB 66: AWS-3 DL	66536	36	20 MHz	Verizon Wireless
LTE	EB 66: AWS-3 DL	66711	32	15 MHz	First Responder Network Authority
LTE	EB 66: AWS-3 DL	67086	27	10 MHz	Verizon Wireless
TD-LTE	EB 41: TDD 2.5 GHz	40978	17	20 MHz	Sprint
TD-LTE	EB 41: TDD 2.5 GHz	41176	21	20 MHz	Sprint
TD-LTE	EB 41: TDD 2.5 GHz	41347	16	15 MHz	Sprint

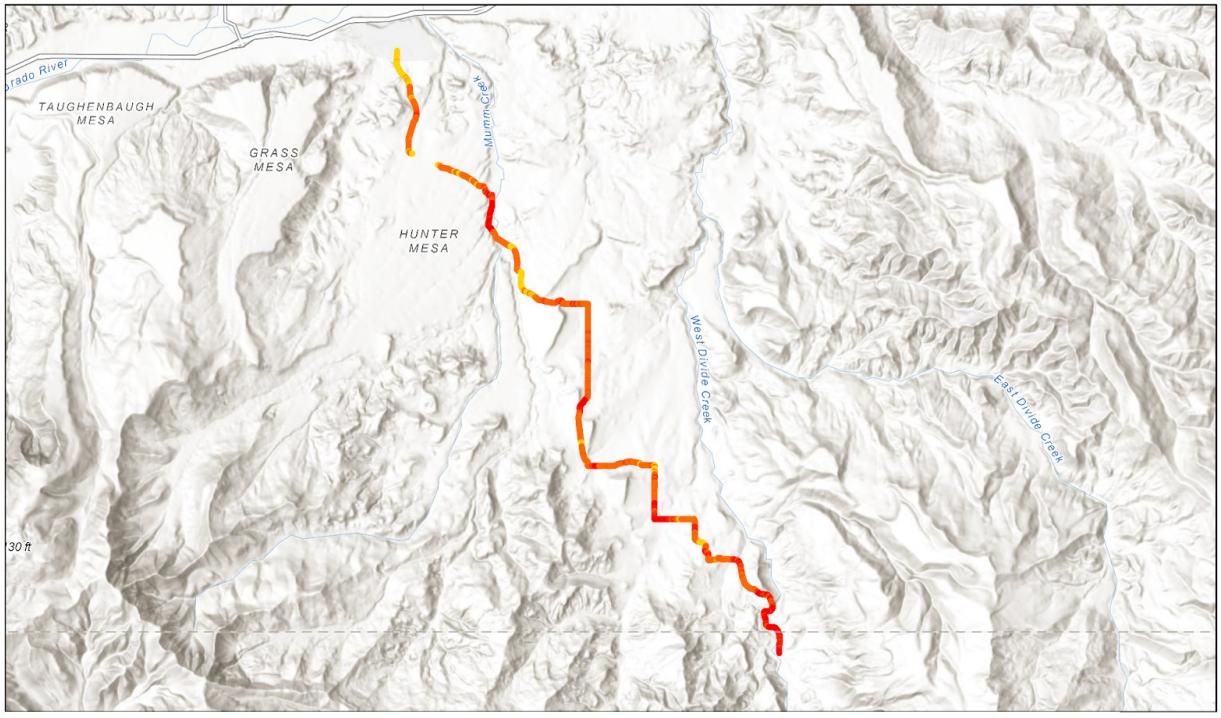
For each band, a wide variety of measurements were made. The analysis reviewed all these parameters, however, for brevity only Reference Signal - Received Power (RS-RP) for a few representative bands is presented here as it is representative of the data.

Georeferenced Signals Along Test Route

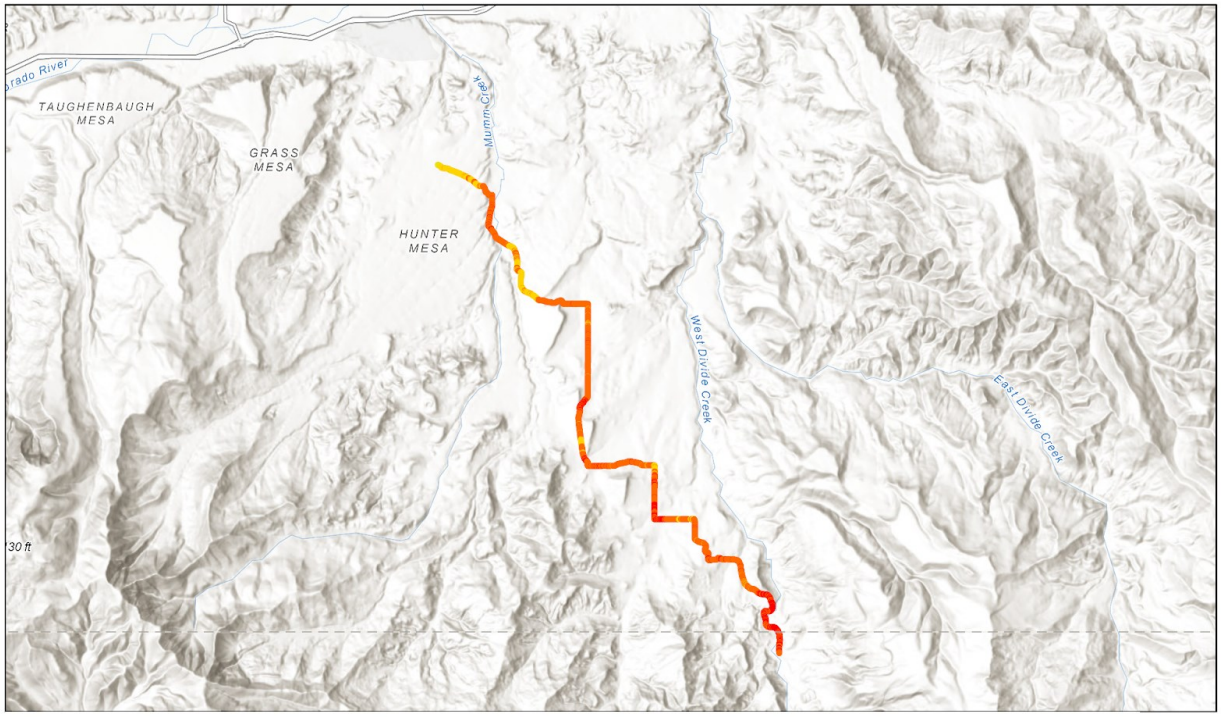
The maps on the following pages show the relative signal strength as measured by the PCTel IBFlex scanner. Each colored dot shows the RS-RP for the channel at that location. These are signal strengths, not speed tests. During testing it was found that signals below about -85 to -90 dBm resulted in little or no data transfer with the exception of Band 14 using HPUE.



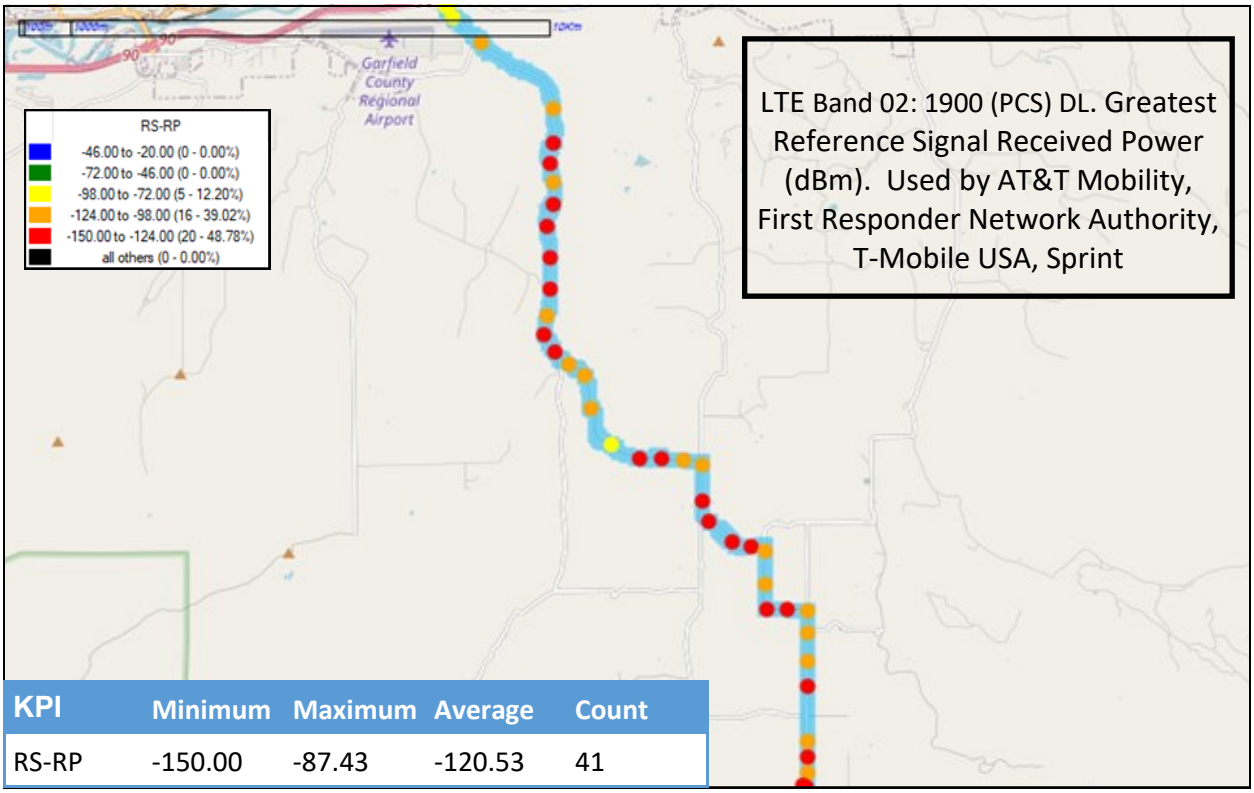
LTE Band 14: First Responder Network Authority (AT&T/HPUE). Reference Signal Received Power (dBm). Traveling generally northbound from West Divide Creek to the CoE Office.



LTE Band 14: First Responder Network Authority (AT&T/HPUE). Reference Signal Received Power (dBm). Traveling generally southbound from CoE office to West Divide Creek.

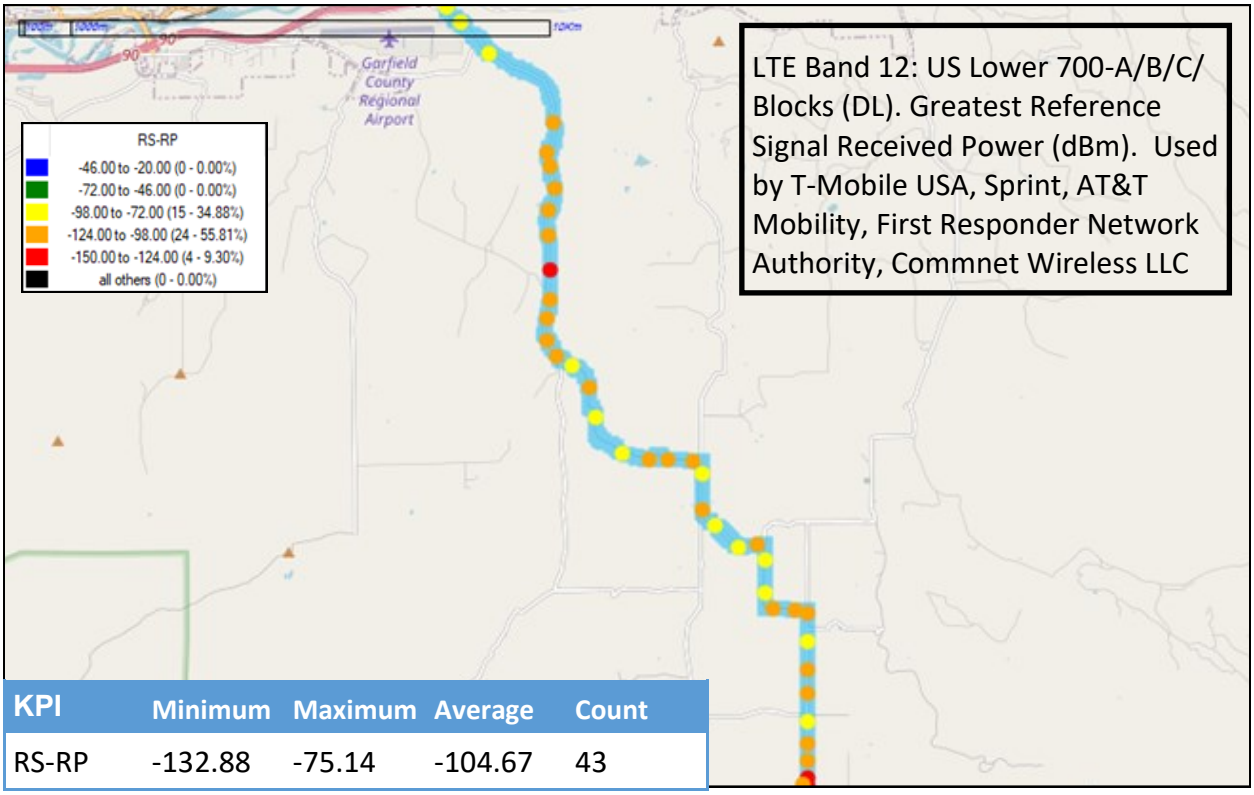


LTE Band 17: Commnet Wireless LLC. Reference Signal Received Power (dBm). Traveling generally northbound from CoE from Hunter Mesa to West Divide Creek.



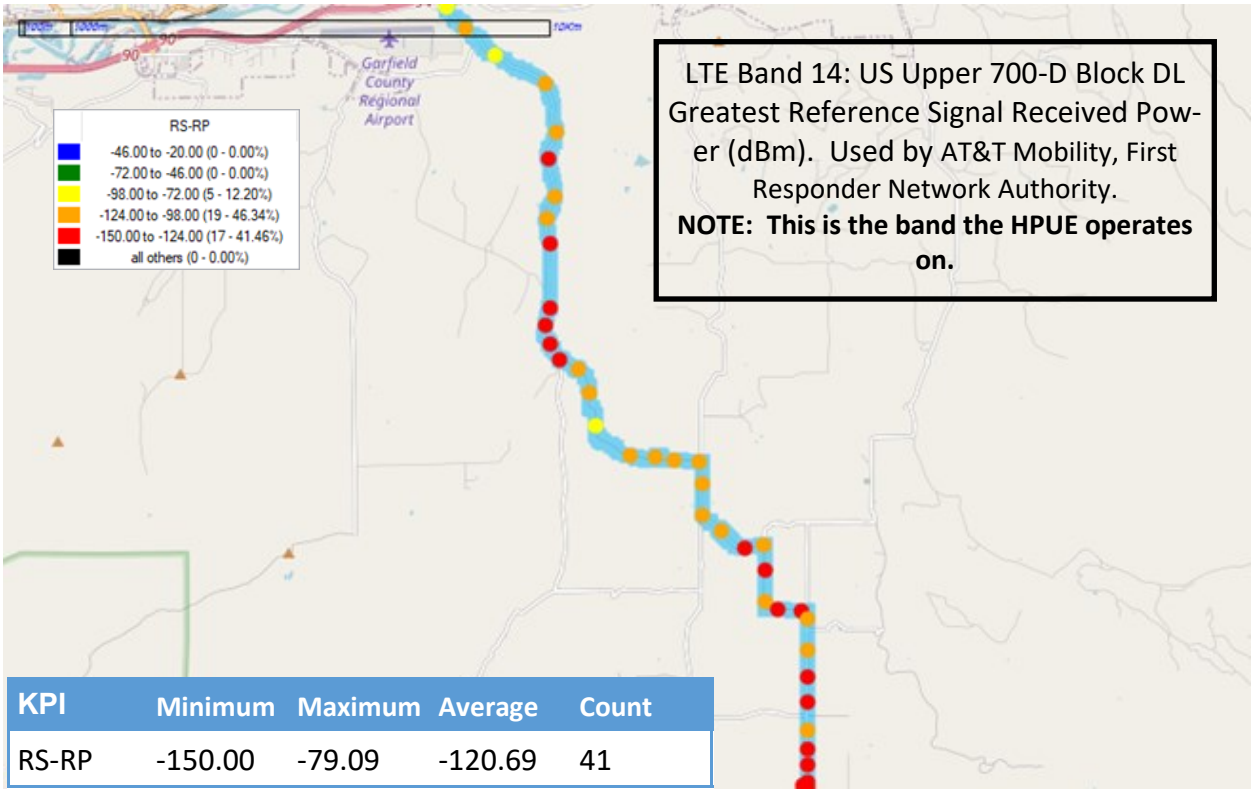
LTE Band 02: 1900 (PCS) DL. Greatest Reference Signal Received Power (dBm). Used by AT&T Mobility, First Responder Network Authority, T-Mobile USA, Sprint

KPI	Minimum	Maximum	Average	Count
RS-RP	-150.00	-87.43	-120.53	41



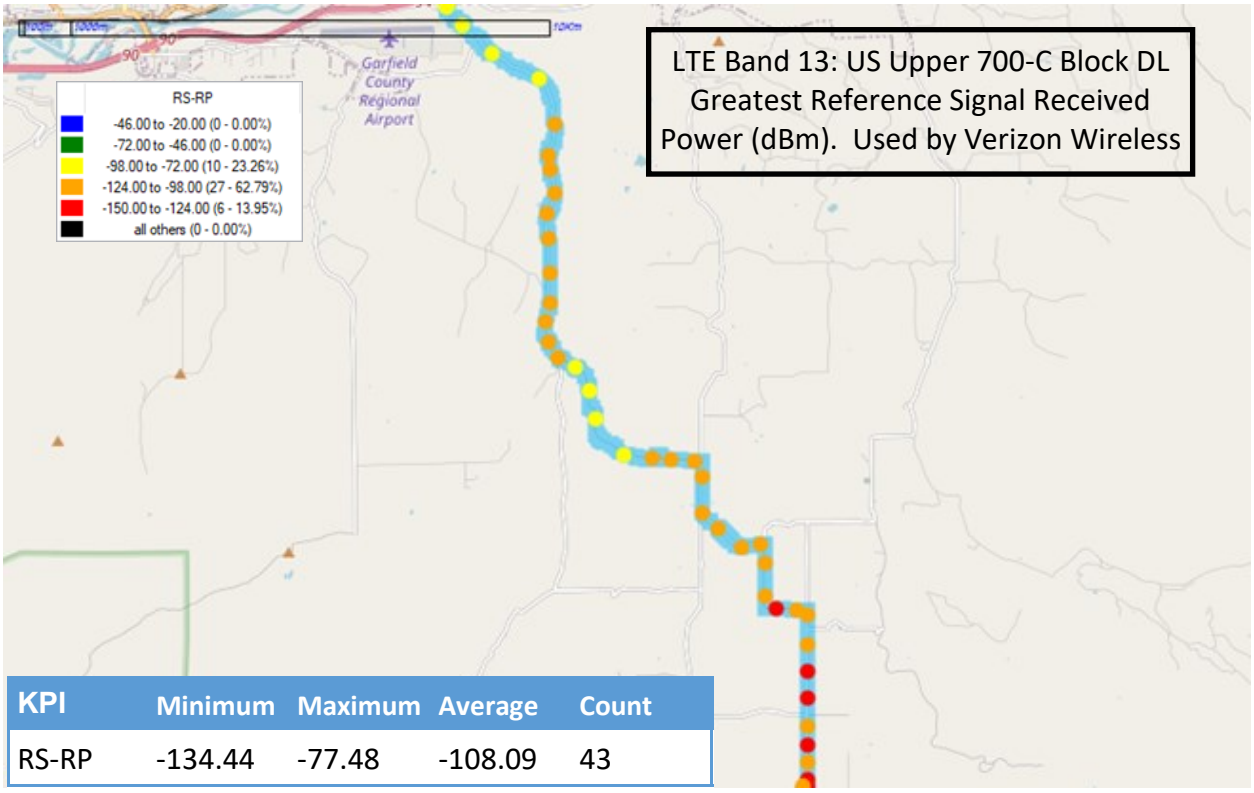
LTE Band 12: US Lower 700-A/B/C/ Blocks (DL). Greatest Reference Signal Received Power (dBm). Used by T-Mobile USA, Sprint, AT&T Mobility, First Responder Network Authority, Commnet Wireless LLC

KPI	Minimum	Maximum	Average	Count
RS-RP	-132.88	-75.14	-104.67	43



LTE Band 14: US Upper 700-D Block DL Greatest Reference Signal Received Power (dBm). Used by AT&T Mobility, First Responder Network Authority.
NOTE: This is the band the HPUE operates on.

KPI	Minimum	Maximum	Average	Count
RS-RP	-150.00	-79.09	-120.69	41

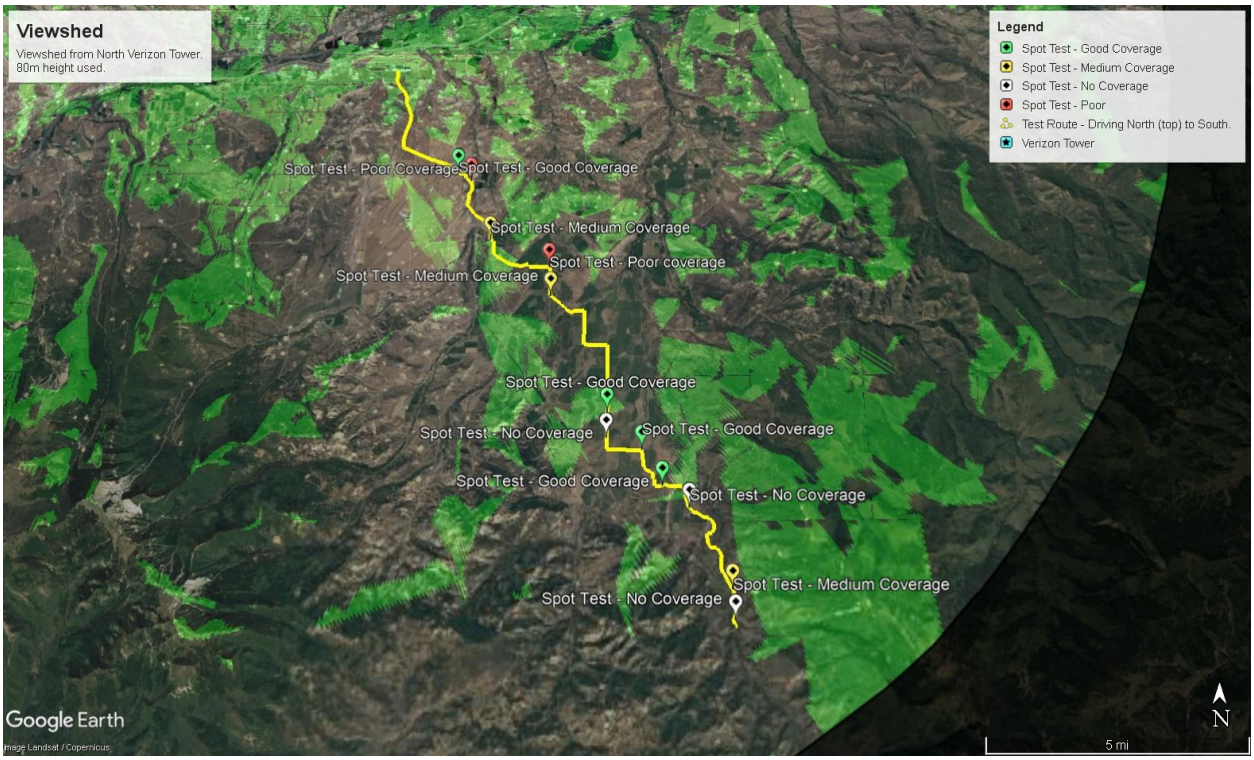


LTE Band 13: US Upper 700-C Block DL Greatest Reference Signal Received Power (dBm). Used by Verizon Wireless

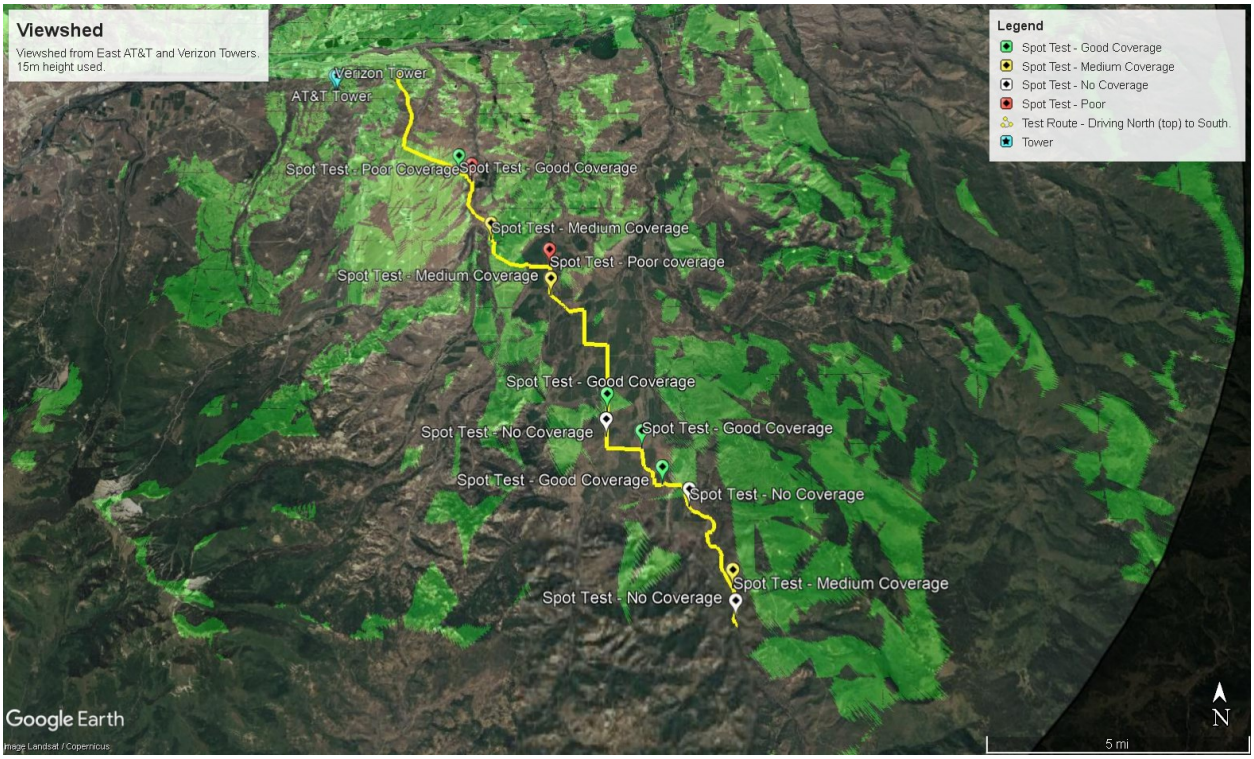
KPI	Minimum	Maximum	Average	Count
RS-RP	-134.44	-77.48	-108.09	43

Cell Tower Viewsheds

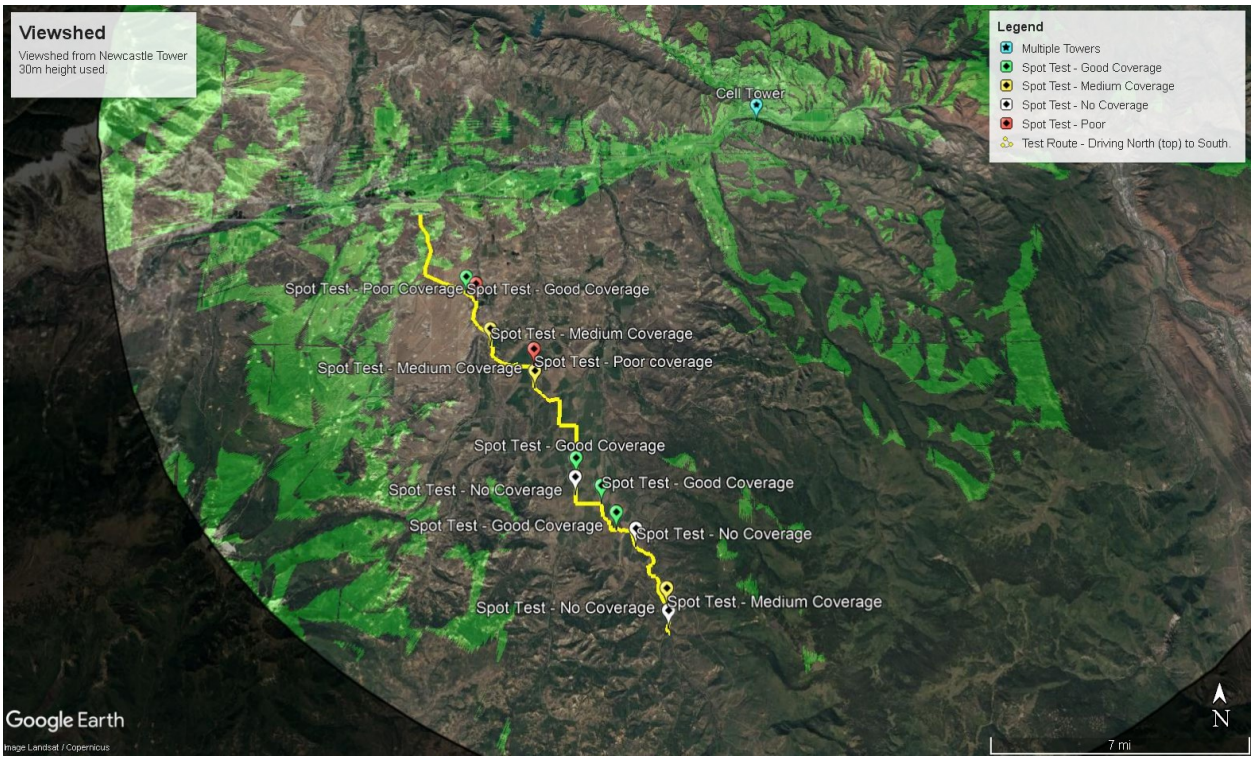
The following figures show approximate viewsheds from each primary presumed cell tower covering the test route. The areas shaded in green illustrate areas that should be 'in view' of the tower. Detailed information about antenna height was not available so the viewsheds assume the cellular antennas are located just below the maximum height of the tower per the FCC Tower Registration Database.



Coverage from the north Verizon tower.
This tower, while the highest, provided little coverage.

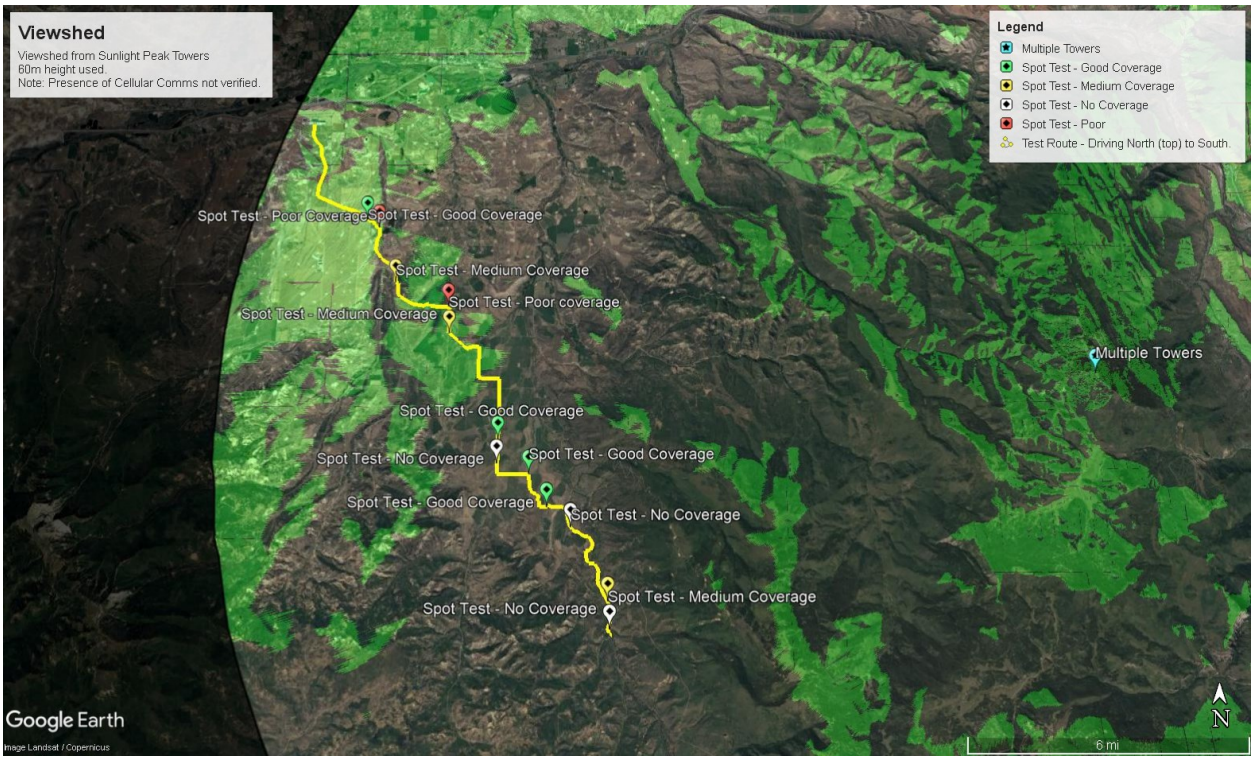


Coverage from the AT&T and Verizon Towers located to the east of the Airport.
These towers provide most of the measured coverage.



Coverage provided by the tower located south of I-70 near New Castle Colorado.
This tower provides nearly no coverage.

Viewshed from Reported Verizon Tower near Silt.
This tower has not been verified but is reported by CellMapper.



Potential coverage from towers located on Sunlight Peak.
Note: CellMapper shows towers here, but with coverage projecting east.
This viewshed would indicate coverage on the test route, but test results do not support that.