COLORADO

Center of Excellence for Advanced Technology Aerial Firefighting

Department of Public Safety

Data Link Radio Evaluation:

Ground Test Report

CoE-16-001

Scope of the Report

The Center of Excellence for Advanced Technology Aerial Firefighting (CoE) is charged with researching, testing, and evaluating technologies related to aerial firefighting. This report represents a preliminary analysis of devices with the potential to transmit data files from an aircraft. These devices were made available to the CoE free of charge. On March 17, 2016, the CoE analyzed the devices in furtherance of the CoE's statutory mission. The analysis performed by the CoE was limited and recommendations will not be made based upon this analysis.

The CoE has published a request for information (RFI) concerning technologies that can provide data connectivity for wildland firefighters operating in cellular-denied environments. A more detailed and broader analysis of the devices addressed in this report may be performed in connection with the evaluation of information received by the CoE in response to the RFI. Any conclusions or recommendations with respect to the technologies will be based upon all of the information received by the CoE.

Executive Summary

The Center of Excellence for Advanced Technology Aerial Firefighting (CoE) has begun the process of evaluating technologies that can provide data connectivity for wildland firefighters operating in cellular-denied environments. The Colorado Division of Fire Prevention and Control Multi-Mission Aircraft program creates fire-related intelligence and can serve as a platform for disseminating that intelligence using a radio-based data link. To test the ability of data radios to function across long distances, such as the distance between aircraft and ground, the CoE conducted a ground test of two data-transmitting radios.

The data radios consisted of the Silvus SC3500 and the goTenna. The Silvus radio is designed for video broadcast and mesh-networking applications and is capable of transmitting large amounts of data or extending an Internet connection. The goTenna is designed to transmit small sets of data, such as text messages or GPS coordinates. The performance of these two radios was compared to that of portable voice radios, which are familiar equipment to many wildland firefighters. The two voice connections tested were an 800 megahertz (MHz) digital system operating in simplex mode and a very high frequency (VHF) analog system.

Testing was conducted in rural areas surrounding the CoE in Rifle, Colorado. A stationary team, referred to in this report as the Mountainside Team, was deployed on a high point and a Roving Team tested radios at various distances. Testing occurred at 11 sites—starting with 0.25 mile of separation between teams and working out to 16.3 miles, at which point a lack of plowed roads prevented further tests. All tests were conducted with a line of sight between the teams.

The performance of analog voice radios cannot be directly compared to digital data radios. However, the CoE developed a quality index to measure the ability of each radio to accomplish the goal of successfully transmitting voice traffic, small data files for the goTenna, or large/streaming data files for the Silvus radio. The 800 MHz radio sustained voice conversations with complete success across all distances. The goTenna performed second best, though past 9.6 miles the antennas required some adjustment to maintain a connection. The VHF voice radio came in third, with antenna adjustment also required after 9.6 miles to mitigate scratchy voice conversations. The Silvus radio came in fourth and was unable to stream video beyond 1.25 miles with an omnidirectional "whip" antenna. However, the Silvus radio was also tested with a highly directional panel

antenna, which—when aimed properly—allowed for video streaming up to 6.1 miles and facilitated file transfers at 16.3 miles.

Background

Wildland firefighters currently rely on handheld radios for voice communication and digital or paper maps of the terrain for navigation when fighting fires in remote areas. Firefighters use voice communication with aircraft and their experience, intuition, and maps to make decisions that directly affect the safety of other firefighters and the containment of the fire. To further improve decision-making and safety, the Center of Excellence for Advanced Technology Aerial Firefighting (CoE) has evaluated technologies that will allow firefighters to access digital fire information in areas where reliable Internet connections are unavailable.

The CoE has identified three distinct wildland-fire-related missions in Colorado that will benefit from accessing reliable digital data:

Mission 1: Support from the Multi-Mission Aircraft (MMA) to individual firefighters during initial attack. This support consists of rapidly accessible points and lines showing the size of the fire, location of spot fires, values at risk, and predicted fire growth overlaid on existing terrain maps, all viewed on a firefighter's smartphone or tablet.

Mission 2: Internet connectivity for Colorado Division of Fire Prevention and Control (DFPC) Fire Management Officers during initial and extended attack. An Internet connection allows Fire Management Officers to access the Colorado Wildfire Information Management System for tactical information, including MMA data, and submit administrative paperwork related to the fire—all from their laptop and work truck.

Mission 3: High-quality video from the MMA during extended attack on large fires. Video allows incident commanders, who are often physically removed from the fire, the ability to view the status of the incident in real-time. By lifting the fog of war associated with large, complex fires, this technology will enhance the confidence level of decision-makers at the command post.

Missions 1 and 3, which require a data link from the MMA to firefighters on the ground, were selected as the highest priorities for further analysis by the CoE. Further testing is also needed on the technologies underlying Mission 2, but—as these result in the provision of full Internet access—a different testing methodology will need to be developed. One set of metrics can be used to compare the utility of preferred technologies identified for Missions 1 and 3; the development of these metrics was identified as a priority for the larger data-link project.

While aerial testing of the technologies will ultimately be necessary, a ground test was considered an important first step to verify that the radios involved could create a link over the distances encountered during MMA missions. The ground test was intended to simulate an aerial link by ensuring line of sight between the two testing parties and by orienting antennas in configurations common to an aircraft-based link.

Methods

The tests were performed by two teams. The Mountainside Team was set up in a fixed location at latitude 39.60688 and longitude –107.73259. This location—on an unimproved U.S. Bureau of Land Management road along slopes leading to the Grand Hogback north of Rifle, Colorado—was scouted prior to the test. Gentle slopes were found below the Mountainside Team's location, with steeper slopes leading into a narrow canyon above. While the Mountainside Team could have increased their elevation by proceeding up the road, the narrow canyon and muddy roads minimized the utility of doing so, particularly since the team was deployed in a light-duty pickup truck. This truck provided a platform for testing and electrical power for the Silvus radio.

Photo 1. View of the Mountainside Testing Location

The Roving Team also operated from a pickup truck and proceeded downhill from the Mountainside Team into the Colorado River Valley and then uphill on the opposite valley slopes into the Divide Creek Drainage. The Roving Team tested six transmission methods: (1) very high frequency (VHF) voice radio, (2) 800 megahertz (MHz) voice radio, (3) goTenna location transmission, (4) goTenna text exchange, (5) Silvus radio video-streaming, and (6) Silvus radio data-transmission speed (megabit per second [Mbit/s]). In addition to the devices, three antenna configurations were tested: (1) omnidirectional antennas oriented parallel to line of sight between teams, (2) omnidirectional antennas oriented perpendicular to line of sight between teams, and (3) a directional panel antenna pointed straight at the opposite team (for the Silvus radio only). The different orientations for the omnidirectional antenna were designed to simulate the orientations possible with an aircraft orbiting a firefighter on the ground, as well as the signal loss that could occur under this scenario due to the polarization of the signal. It should be noted that the omnidirectional antennas radiate primarily in a plane perpendicular to the antenna orientation; as a result, the parallel-to-line-of-sight orientation is expected to have degraded performance. However, this orientation is important for testing since it can occur due to relative location of the aircraft and ground teams during operations.

Photo 3. Omnidirectional Antenna Pointing Parallel to Line of Sight Between Teams

Photo 3.Omnidirectional Antenna Pointing Perpendicular to Line of Sight Between Teams

The VHF voice radio test was conducted with a Bendix King KNG series radio at the mountainside location and a Bendix King DPH series radio at the roving location. Both radios were set for a transmit power of 6 watts and the test was conducted on the DFPC TAC 1 frequency, located at 154.68 MHz. Each radio was equipped with an omnidirectional antenna.

The 800 MHz voice radio test was conducted using a Motorola XTS 2500 radio at the mountainside location and a Tait TP9400 radio at the roving location. Transmit power on these radios cannot be determined in the field, but the test was conducted on the SIMPLEX 1 frequency, which limits transmit power to 3 watts or less. This test was conducted at 851.10 MHz and each radio was equipped with an omnidirectional antenna.

The goTenna test was conducted with a pair of goTenna devices, each paired with an iPhone. The goTenna devices contain a 2-watt radio and the transmission power is not user-configurable. Both goTenna devices' internal batteries were fully charged before the test and neither device was connected to an external power source during the test. The goTenna's operating frequency is in the 151–154 MHz range and is not user-selectable.

The Silvus SC3500 was utilized for video-stream and data-speed tests. The radios were set to transmit with 1 watt of power at 2.385 gigahertz with 5 MHz bandwidth. The link length was manually input into the radio configuration page at each test site using the distance estimated by the Avenza app. Both an omnidirectional antenna and a Wilson panel antenna were utilized for these tests.

Experiments were performed at each of 11 distances that were estimated in the field using the Avenza PDF Maps app and calculated following the test using QGIS. Devices were tested in the order listed with visual line of sight, which is the best-case scenario. Line of sight was estimated by comparing the Roving Team's location to a PDF Map showing the viewshed from the mountaintop site. This viewshed was calculated prior to the test using QGIS and a digital elevation model of the test area. The viewshed indicated all areas in the test site that were visible from the mountaintop location. Line of sight was confirmed during the test by the Mountainside Team conducting mirror flashes toward the Roving Team. Using a 2″ × 3″ signal mirror, line of sight was confirmed at all locations except Sites 2 and 3, where the piñon-juniper woodland obscured the view. However, at these sites the Mountainside Team was able to send a scout uphill to confirm the line of sight.

Table 1. Distance Between the Mountainside and Roving Teams for Each Test Location

Site #	Avenza-Estimated Distance (miles)	GIS-Calculated Distance (miles)
1	0	0.01
2	0.21	0.21
3	0.58	0.59
4	1.25	1.26
5	2.27	2.31
6	4.25	4.29
7	6.11	6.11
8	9.60	9.61
9	11.43	11.40
10	13.10	13.06
11	16.29	16.25

Note that, for the first three locations, the panel antenna was incorrectly positioned such that the antenna pattern was focused directly away from the signal source (i.e., focused away from the other team). The antenna configuration error was recognized and further results were valid. Since the first three locations represent minimal-distance tests, the overall result of the test is not impacted. Failed experiments were not repeated; therefore, data using the panel are presented separately.

Initially, the team attempted to rate each test in a binary fashion—1 for transmission received and 0 for not received. However, some locations presented partial reception for the

VHF voice radio, which was rated as 0.25 for received, but not understandable; 0.50 for received, but substantial interference; and 0.75 for received, but some interference. Data was electronically recorded by the Roving Team. Each task was performed by a single team member to minimize variability due to technique.

The two teams performed tests in a controlled and consistent fashion, orienting the omnidirectional antenna of each device by either pointing parallel to line of sight or perpendicular to line of sight between the teams.

When the Roving Team arrived at each site, line of sight was confirmed using the viewshed maps and signal-mirror flashes. The latitude and longitude of the site location were entered into a spreadsheet in which all results were also logged. The VHF voice test was conducted first, followed by the 800 MHz voice, the goTenna, and then the Silvus radio. For all tests, the radios were held at arm's length by test operators who were standing in the bed of the truck (Mountainside Team) or standing several steps away from the truck (Roving Team).

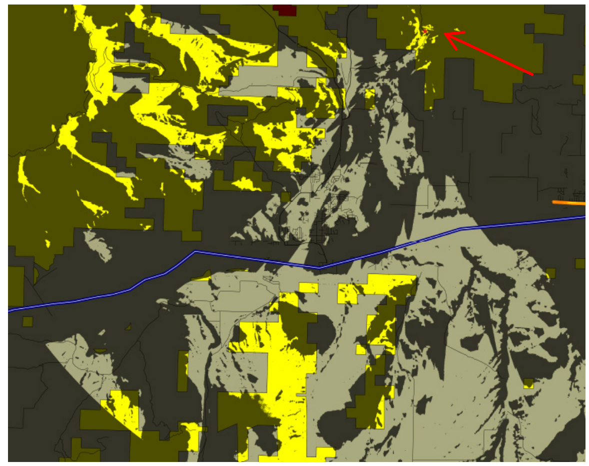

Figure 1. Viewshed from Mountainside Site with Arrow Pointing to Site Location

For both voice tests, the operators started by holding the radio with the antenna oriented parallel to the line of sight and then oriented perpendicular to the line of sight. Approximately 15 seconds of voice traffic were exchanged during each test, during which the quality index value of the signal was assessed by all team members and arrived at by mutual agreement. A repeated 800 MHz Talkgroup, using separate radios, was used to coordinate all tests and to ensure that all antennas were oriented in the proper direction.

The goTenna was assessed in a similar fashion, with the antennas first parallel to the line of sight and then perpendicular to line of sight. Prior discussions with goTenna engineers revealed that person-to-person text messages were smaller in size, and thus easier to send than text messages with a GPS location attached. As a result, the team sent both types of messages in both antenna configurations. A successful exchange of data was given a quality index value of 1, while an unsuccessful exchange was given a value of 0.

Data-transfer speeds for the Silvus radios were measured using iPerf3, a widely used, open-source network-performance-measurement tool. The Mountainside Team ran the server and the Roving Team queried it to obtain a speed test. The speed of the connection was used directly for the quality index. The video stream was assessed using an MP4 video clip of MMA imagery, which was served over the network using VLC and the UDP streaming protocol. The Roving Team operated the server and the Mountainside Team connected to the stream and assessed its quality. A video stream was given a quality index score of 1 when the receiving team judged it to be of usable quality with minimal dropped frames. A stream was given a score of 0 when the receiving team could not sustain the stream, or it became unusable due to dropped frames.

Results

The 800 MHz voice radio performed perfectly at all distances and under all antenna configurations. The digital nature of this voice link tends to result in a connection that is either clear or garbled to nonexistent and, as a result, the line of sight between teams was a significant contributing factor toward the success of this radio system. When driving between test sites, the Roving Team attempted to contact the Mountainside Team in a non-line-of-sight environment and experienced either a highly garbled connection or no connection at all.

The goTenna received the second-highest quality rating and no difference was found between sending text messages only and sending text messages with locations attached. The goTenna performed perfectly out to 9.6 miles; however, starting at 11.4 miles the device only sent messages successfully when the antenna was oriented perpendicularly to the line of sight between test teams. A successful connection when oriented parallel to the line of sight was not achieved at 11.4 miles and 13.1 miles. At 16.3 miles, successful transmissions occurred regardless of the device's orientation. It is likely that at the 16.3 mile-point a multi-path transmission occurred and brought the signal to a threshold that allowed successful transmission in the parallel orientation case.

The VHF voice radio received the third-highest quality rating and received several ratings of partial reception, which indicated that the voice traffic was scratchy but still intelligible. Starting at 9.6 miles, the VHF radio transmitted scratchy traffic when the antennas were pointed parallel to line of sight, and by 16.3 miles the conversations were barely intelligible in this orientation. However, when antennas were pointed perpendicularly to the line of sight, the quality of the signal significantly improved, with mild intermittent static occurring starting at 11.4 miles and continuing to 16.3 miles.

The Silvus radio presented the most complicated set of results since it was tested with three different antenna configurations and the first three tests with the panel antenna had to be disregarded due to the incorrect aiming of the antenna. Video streaming was not successful at any distance when using the omnidirectional antennas pointed parallel to line of sight; however, streaming was successful with perpendicular omnidirectional antennas out to 1.25 miles. After this point, some video frames were still transmitted, but not enough to create a usable video stream. Using the directional panel antennas, video streaming became possible up to 6.1 miles if the panel antennas were properly oriented. If one panel antenna was deflected 30 degrees off line of sight the connection was significantly degraded or lost.

Photo 4. Silvus Radio and Panel Antenna

Speed tests showed that file transfers were possible up to 2.3 miles with the Silvus radio when omnidirectional antennas were pointed parallel to line of sight and up to 9.6 miles when the antennas were oriented perpendicularly to the line of sight. With the directional panel antennas, file transfers were possible at 16.3 miles. To verify the speed test data, at 16.3 miles the team successfully exchanged a 34 megabyte PDF file using FTP.

Discussion

The purpose of this test was to determine the suitability of tested devices for use by wildland firefighters in remote areas where other means of data communication are not available. An important component of the envisioned information ecosystem is data provided by DFPC's MMA, two Pilatus PC-12's with sensor suites capable of mapping wildfire perimeters and providing a variety of data useful to firefighters on the ground. To exploit this data to its full potential, a solution needs to be developed to deliver the data in near real-time to firefighters on the ground. The degree to which a particular solution will be optimal cannot be fully captured by the numerical results of this test. The best solution will depend on a combination of factors, including the ability to transmit data in conditions similar to those faced by wildland firefighters, the weight and size of the equipment, the cost of the equipment, the ease of integrating the equipment with mission-critical hardware and software on the MMA, the ease of use of the equipment by firefighters in real-world conditions, and the spectrum of other benefits provided by each solution. This initial test allowed the test team to become familiar with the equipment being evaluated. The relative benefits and detriments of the Silvus Multiple Input Multiple Output (MIMO) radio and the goTenna are outlined below.

The Silvus MIMO radios offer sophisticated capabilities that should be a suitable solution for the intended-use scenario. However, the test team's actual experience with the equipment in the field revealed that the equipment's sophistication could limit its usefulness since the intended users may not have the time and skills to operate the radios to their maximum potential.

Silvus radios create a TCP/IP network, allowing any computer to use the radio as a standard network adapter. This eliminates the need for special software to transmit data over the connection. The test team was able to use standard network testing tools to assess data throughput and stream video using the UDP protocol. Under ideal conditions, the connection was sufficient to satisfy the needs of the intended-use scenario. However, practical limits to the widespread adoption of the Silvus radio system are apparent from several aspects of the system. First and most obvious is the physical size and weight of the radios. Without a power supply, the radio measures 3.25″ × 5.75″ × 4″ and weighs 3.7 pounds. In its existing form, the radio also requires a wired connection to the device to connect to the network. This limits the ability to integrate the Silvus MIMO system with ubiquitous devices, such as popular smartphones and tablets. The test team also found that the radios require a considerable level of technical knowledge and attention in the field. The configuration of the radios, managed through a web interface, needed several adjustments as distance changed and the radios had to be rebooted several times to resolve connection problems. The omnidirectional antennas needed to be oriented vertically at 4 miles and greater distances and the panel antennas proved to be quite sensitive to alignment. When panel antennas were pointed even a few degrees off the direct line between them, the connection disintegrated. Automated antenna alignment systems exist to address the problem, but further add to the cost, weight, size, and complexity of the setup. Nevertheless, the Silvus MIMO radios offer a unique solution that is well suited to an application in which a well-trained operator can be devoted to optimizing the radio's performance in the field, and in which weight, size, and power supply are not significant barriers.

The goTenna device offers a limited set of capabilities, but the limits do not adversely affect its suitability for the intended-use scenario. Unlike the Silvus radio, the goTenna does not create a standard TCP/IP connection. This means that communication via the goTenna is limited to information that can be sent via the smartphone or tablet app provided by goTenna. Another current limitation of the device is the fact that, under Federal Communications Commission regulations, the frequency band on which it currently operates is limited to ground-to-ground communication. Further development would be required to adapt the device to its intended use aboard aircraft. The goTenna's advantages for the intended-use scenario are its small size (7″ × 1″ × 0.5″ when extended), low weight (1.8 ounces), long operating time on the rechargeable internal battery, and its simple and intuitive operation in the field.

Next Steps

A considerable amount of work remains to be done before any device can be fielded by wildland firefighters. The CoE has issued a Request for Information regarding this need and is looking forward to working with vendors to determine if existing devices can be further developed to address the limitations outlined above. Further tests of these and other brands of radios will be necessary to assess the performance of the data links in field conditions, including terrain where the line of sight between devices is obstructed by vegetation. Tests to assess performance of the devices on radio frequency bands suitable for air-to-ground communication will also be necessary. These tests will require a carefully designed testing procedure to determine the effects of both the vertical and horizontal distances between radios, as well as the effects of different kinds of vegetation canopies, on the equipment's performance. In addition, software development will be necessary to integrate data radios with existing wildland-fire mapping and awareness tools. Finally, the most suitable device may need to be integrated into the MMA in compliance with Federal Aviation Administration regulations.

Appendix A

Statistical Methods

The original intention was for the distribution of the outcome variable (i.e., "received") to be binomial. Conditions in the field dictated a more granular scale, with the values of: 0, 0.25, 0.5, 0.75, and 1.00. Thus, multinomial logistic regression was used to analyze the device type and antenna direction; however, the 800 MHz radio scored all 1's under all conditions and distances, which means that the device cannot be evaluated with logistic regression since there is no variable in the score and a logit cannot be calculated due to the inability to divide by zero. However, this analysis was performed with the known limitation. To look at the analysis in another way, the received variable was then treated as a continuous variable and a two-factor analysis of variance (ANOVA) with an interaction was performed, even though the distribution was not normal, with a Tukey-Kramer p-value adjustment for multiple comparisons. Least square means and standard errors were reported. A p-value < 0.05 was considered significant for the omnibus test and an adjusted p-value < 0.05 was considered significant for pairwise comparisons. One-factor ANOVA was used to test transmission speed among the three antenna positions and linear regression was used to determine whether there was a relationship between transmission speed and GIS-calculated distance in meters.

Statistical Results

Multinomial logistic regression revealed that the Silvus video stream was far less likely to be received compared to VHF radio ($p < 0.0001$) **(Table 2)** and that the antenna in perpendicular orientation was more likely to be received than the antenna pointed at the opposite team ($p = 0.0485$). Since the 800 MHz radio performed perfectly at every distance under every condition, a true odds ratio and p-value were not obtained. Two-factor ANOVA with an interaction demonstrated a strong main effect of device used ($p < 0.0001$) and a main effect of antenna position (perpendicular 0.84 ± 0.04 vs. pointing at the opposite team 0.73 ± 0.04, $p = 0.0476$). There was no significant interaction ($p = 0.6760$). P-value corrected pairwise comparisons demonstrated a significant difference between Silvus video stream and all other devices ($p < 0.0001$ all).

There was no difference in least squares mean transmission speed among the perpendicular antenna (4.39 ± 2.88 Mbit/s), the antenna pointed parallel to line of sight (3.97 ± 3.26 Mbit/s), and the Silvus-only panel antenna (4.83 ± 3.05 Mbit/s, $p = 0.9818$).

There was no significant relationship between transmission speed and GIS-calculated distance in meters in the perpendicular-to-line-of-sight position (-0.0005 ± 0.0004, $p = 0.2090$) **(Figure 3)**. In addition, there was no significant relationship between transmission speed and GIS-calculated distance in meters in the parallel-to-line-of-sight position (-0.0011 ± 0.0010, $p = 0.3326$) **(Figure 4)**. Finally, there was no significant relationship between transmission speed and GIS-calculated distance in meters with the panel (-0.0005 ± 0.0003, $p = 0.1375$) **(Figure 5)**. However, since only eight observations were performed, there was a lack of statistical power to detect a negative relationship.

Table 2. Multinomial Logistic Regression Results

	β ± SE	OR (95%CI)	P-Value
Intercept 1	1.27 ± 0.53	--	0.0167
Intercept 0.75	1.63 ± 0.55	--	0.0031
Intercept 0.50	2.19 ± 0.60	--	0.0003
Intercept 0.25	2.34 ± 0.61	--	0.0001
800 MHz vs. VHF	12.53 ± 188.3	>999.9 (< 0.001 - > 999.9)	0.9469
goTenna Location vs. VHF	1.127 ± 0.89	3.086 (0.545-17.492)	0.2029
goTenna Text vs. VHF	1.127 ± 0.89	3.086 (0.545-17.492)	0.2029
Silvus Video Stream vs. VHF	-3.60 ± 0.90	0.027 (0.005-0.161)	< 0.0001
Perpendicular vs. Parallel to Line of Sight	0.71 ± 0.36	4.119 (1.009-16.810)	0.0485

Table 3. Quality Comparison

Device	LSMEAN ± SE	P-Value Compared to Silvus Video Stream
800 MHz	1.0 ± 0.05	< 0.0001
VHF	0.89 ±.05	< 0.0001
goTenna Location	0.91 ± 0.05	< 0.0001
goTenna Text Exchange	0.91 ± 0.05	< 0.0001
Silvus Video Stream	0.21 ± 0.07	--

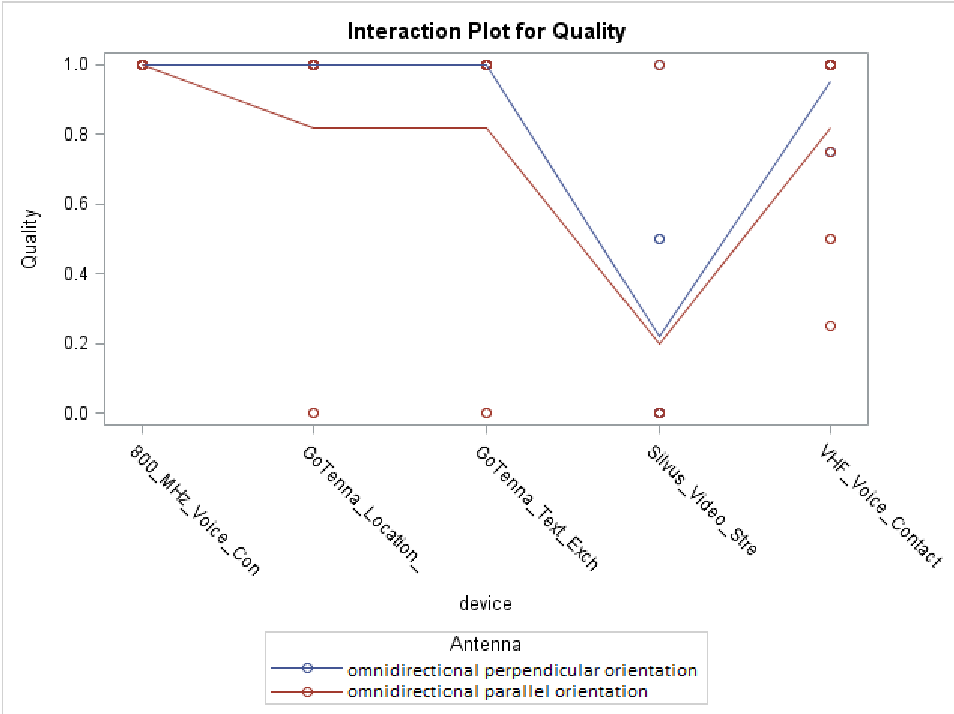

Figure 2. Overall Quality Index by Antenna Orientation

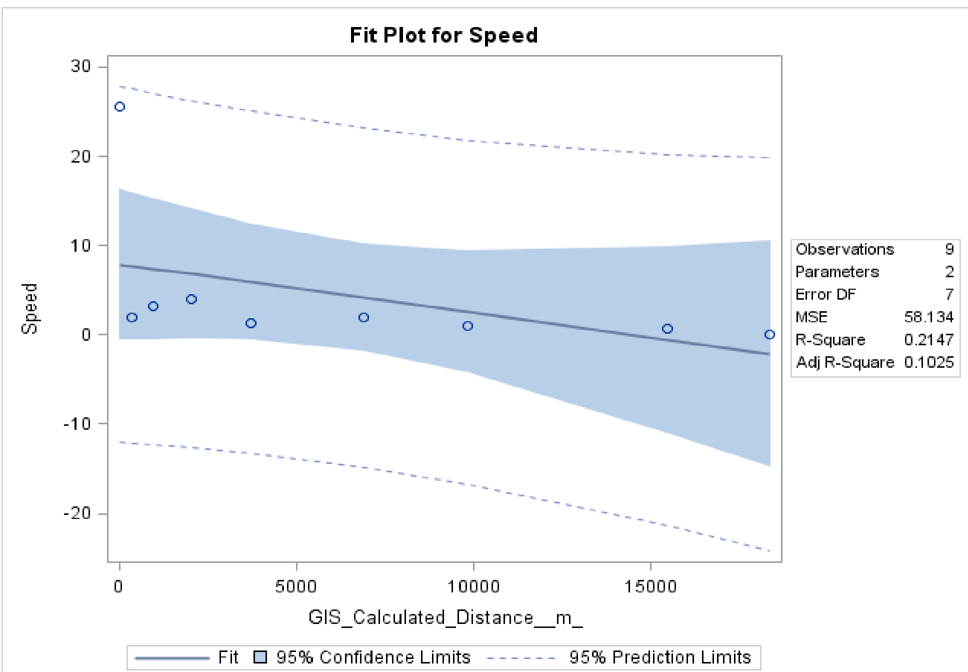

Figure 3. Silvus Speed (Mbit/s) in Perpendicular Orientation

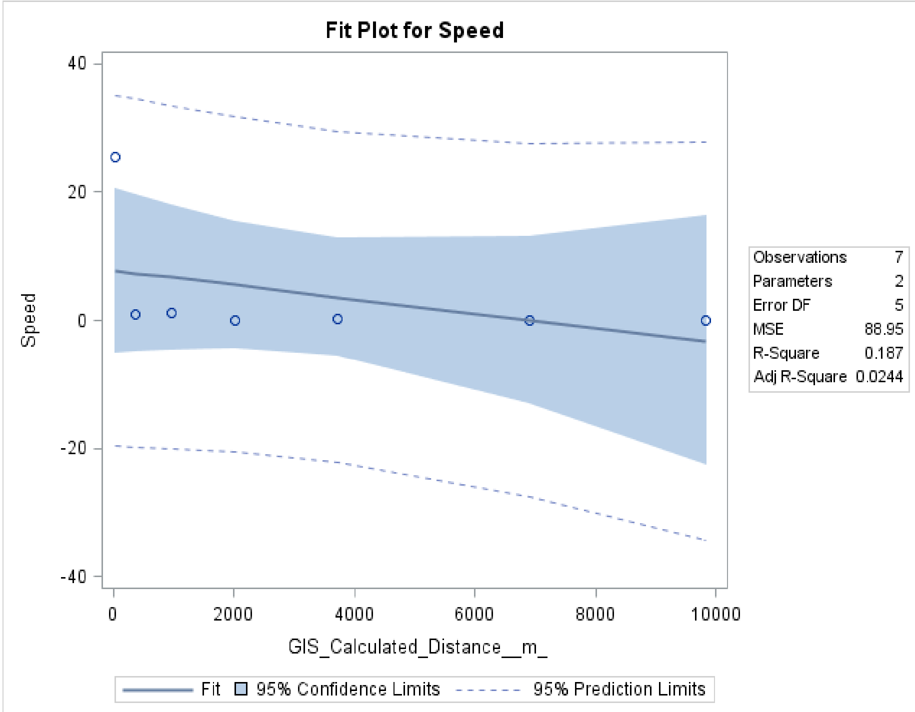

Figure 4. Silvus Speed (Mbit/s) in the Parallel-to-Line-of-Sight Orientation

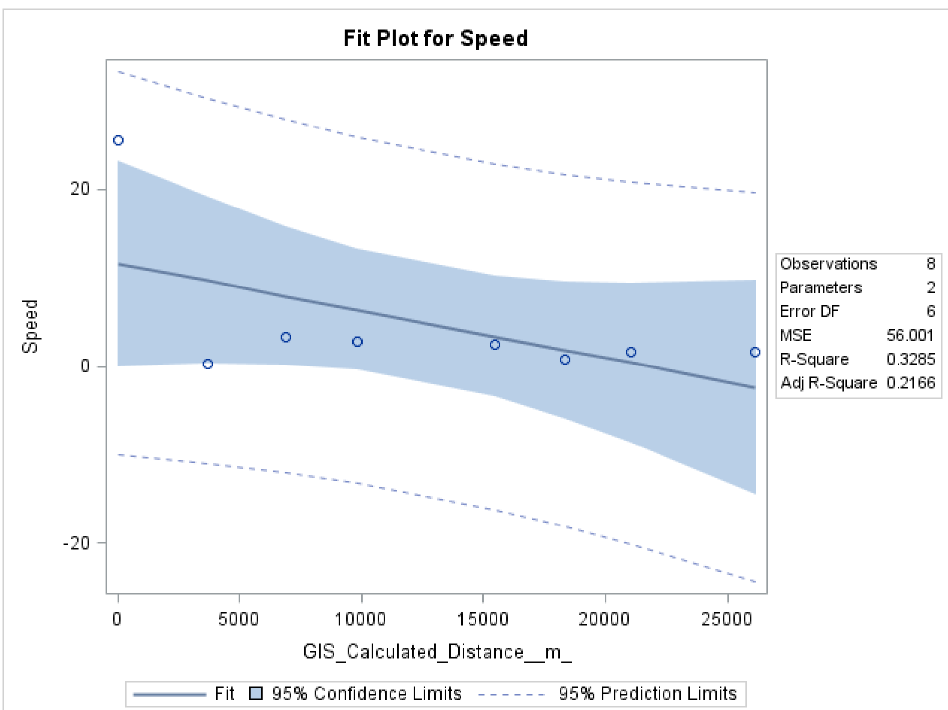

Figure 5. Silvus Speed (Mbit/s) with Panel Antenna