



Improving Safety For Miners By Providing A Wireless Real Time Locating System

NIOSH Grant 1R43OH008952-01A1

Final Report

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Executive Summary:

Improving Safety for Miners by Providing a Wireless RTLS

This document presents the results of a research and development effort funded by the National Institute for Occupational Safety and Health (NIOSH) under SBIR Grant 1 R43 OH008952. The goal of the effort is to develop a tracking and location system to help localize miners in the event of a mine accident. Our work established several key principles:

- 🔑 Vertical polarization performs better than horizontal polarization in underground environments.
- 🔑 A power law roll-off of about r^{-5} is a reasonable estimate for mine propagation.
- 🔑 Phase response is distorted by mine infrastructure but in a gradual, slowly varying fashion that lends itself well to an RF mapping or fingerprinting approach to tracking.
- 🔑 Current NFER prototypes could be the basis of a tracking system with a range of about 150-200m (450-600ft). Reasonably foreseeable improvements could substantially extend the range to about 600-800m or 1800-2400 feet. With this kind of range, we can envision deploying a relatively limited number of receivers and obtaining accurate location information throughout mines of substantial size.

Specific accomplishments of the Phase I effort included:

- 🔑 Completion of a computer (HFSS) model of propagation along a shaft.
- 🔑 Collection of propagation data at 575 kHz in a linear cave (Cave Mountain Cave, AL), an abandoned limestone mine (Three Caves, AL), and the Bruceton Safety Research Coal Mine.
- 🔑 Establishment of baseline performance metrics.
- 🔑 Initial modification Q-Track NFER[®] systems for proof-of-concept application in mines.
- 🔑 Demonstration and evaluation of the proof-of-concept system at the Safety Research Coal Mine near Pittsburgh.

Furthermore, Q-Track identified a significant system improvement that should roughly double the robustness and performance of NFER tracking. This improvement is the subject of a provisional patent application filed February 25.

The Q-Track Corporation has assessed the feasibility of applying Near-Field Electromagnetic Ranging to the difficult problem of location awareness within coal mines. The Q-Track team believes that our Phase I experience demonstrates the feasibility of NFER tracking in coal mines. We will soon be submitting a proposal for a Phase II effort to implement a prototype system for tracking in a mine environment.

Table of Contents:

Improving Safety for Miners by Providing a Wireless RTLS

1.0 Introduction and Background	1
2.0 Propagation Modelling	4
3.0 Propagation Testing	7
3.1 Propagation Testing: Cave Mountain Cave	7
3.1.1 Background on Cave Mountain Cave	7
3.1.2 Cave Mountain Test Results: Summary	8
3.1.3 Cave Mountain Test Results: Details.....	9
3.1.4 Cave Mountain Conclusions.....	13
3.2 Propagation Testing: Three Caves	14
3.2.1 Background on Three Caves.....	14
3.2.2 Three Caves Test Results: Summary	15
3.2.3 Vertical Polarization	15
3.2.4 Horizontal Polarization	19
4.0 Upgrades, Improvements, and Optimization of Q-Track Hardware	21
4.1 Power Amplifier	21
4.2 Antenna Improvements	25
5.0 Initial Proof-of-Concept Demonstration.....	29
5.1 Pittsburgh Research Lab Safety Research Coal Mine	29
5.2 Experimental Set-Up	30
5.3 Experimental Results.....	31
6.0 Conclusions	36
Appendix 1: Cave Mountain Results	37
Appendix 2: Three Caves V-Pol Results.....	41
Appendix 3: Three Caves H-Pol Results	45
Appendix 4: Safety Research Coal Mine-Phase Delta Response	47

1.0 Introduction and Background

Recent tragedies at the Sago Mine,¹ the Aracoma Alma Mine No. 1,² and the Darby Mine No. 1³ have brought renewed attention to an old problem: situational awareness in mine emergencies.⁴ Improved communication is a partial, but not complete, solution to the problem. Mine emergencies often involve dense smoke and dust that impair visibility and disorient even those familiar with the mine layout. And miners overcome by carbon monoxide cannot communicate useful information to potential rescuers. Location awareness is an important aspect of the overall problem of situational awareness. In too many cases, mine fatalities might have been avoided if rescuers knew the location of trapped or disabled miners.

Decades of investigation have identified Medium Frequency (MF) radio waves as the most promising medium for within mine signalling. The MF band includes the frequencies 300kHz-3MHz. “MF transmission is advantageous since it couples into, follows and is radiated from existing mine wiring.”⁵ In fact, ranges of several miles have been reported for the case where two radios are in entries sharing connected conductors.⁶ Ranges are substantial even in conductor free areas.

In conductor free areas, Cory reported achieving maximum ranges of 180-260m between 200-300kHz when limited by receiver noise. Under median mine noise conditions, Cory reported 115-140m range between 400-800kHz. In the presence of conductors, Cory reported achieving 890m at 900kHz as a best case with minimum range around 570m in the vicinity of 1MHz as a worst case.⁷ Elsewhere, Cory reported

¹ Richard Gates et al, U.S. Dept. of Labor Mine Safety and Health Administration Coal Mine Safety and Health; “Report of Investigation: Fatal Underground Coal Mine Explosion, January 2, 2006; Sago Mine, Wolf Run Mining Company, Tallmansville, Upshur County, West Virginia, ID No. 46-08791.” At the time of this writing, this report was available at:
<http://www.msha.gov/Fatals/2006/Sago/sagoreport.asp>

² Kenneth Murray et al, U.S. Dept. of Labor Mine Safety and Health Administration Coal Mine Safety and Health; “Report of Investigation: Fatal Underground Coal Mine Fire, January 19, 2006; Aracoma Alma Mine #1, Aracoma Coal Company, Inc. Stollings, Logan County, West Virginia, ID No. 46-08801.” At the time of this writing, this report was available at:
<http://www.msha.gov/Fatals/2006/Aracoma/aracomareport.asp>

³ Thomas E. Light et al, U.S. Dept. of Labor Mine Safety and Health Administration Coal Mine Safety and Health; “Report of Investigation: Fatal Underground Coal Mine Explosion, May 20, 2006; Darby Mine No. 1, Kentucky Darby LLC; Holmes Mill, Harlan County, Kentucky; ID No. 15-18185.” At the time of this writing, this report was available at:
<http://www.msha.gov/Fatals/2006/Darby/darbyreport.asp>

⁴ R. Larry Grayson (Chair), Mine Safety Technology and Training Commission, “Improving Mine Safety Technology and Training: Establishing U.S. Global Leadership,” December 2006. At the time of this writing, this report was available at:
http://www.eme.psu.edu/Faculty/grayson/msttc_report.pdf

⁵ Terry S. Cory, Propagation of EM Signals in Underground Metal/Non-Metal Mines, Contract J0308012 (1981) Bureau of Mines p. 30.

⁶ Terry S. Cory, “Propagation of EM Signals in Underground Mines,” Rockwell International/U.S. Bureau of Mines Contract No. H0366028. NTIS No. PB/289-757, 1977, p. 13.

⁷ Terry S. Cory, “Electromagnetic Propagation in Low Coal Mines At Medium Frequencies,” Rockwell International/U.S. Bureau of Mines Contract No. H0377053, 1978, p. 13.

closing a 500kHz link at a range of up to 1200ft (366m),⁸ and identified 200-500kHz as optimal for propagation remote from conductors, and 500-700kHz as optimal for propagation in the presence of conductors.⁹ These communications systems typically have a bandwidth of about 10kHz. A narrow bandwidth ~500Hz tracking system should have roughly 13dB lower noise, 13dB greater signal-to-noise ratio, and correspondingly greater range.

Lagace reported 200-900kHz or 200-600kHz as an optimal region for radio wave propagation in a coal mine.¹⁰ Figure 1 presents Lagace's results for attenuation versus frequency. Past about 500kHz, attenuation begins to increase markedly.

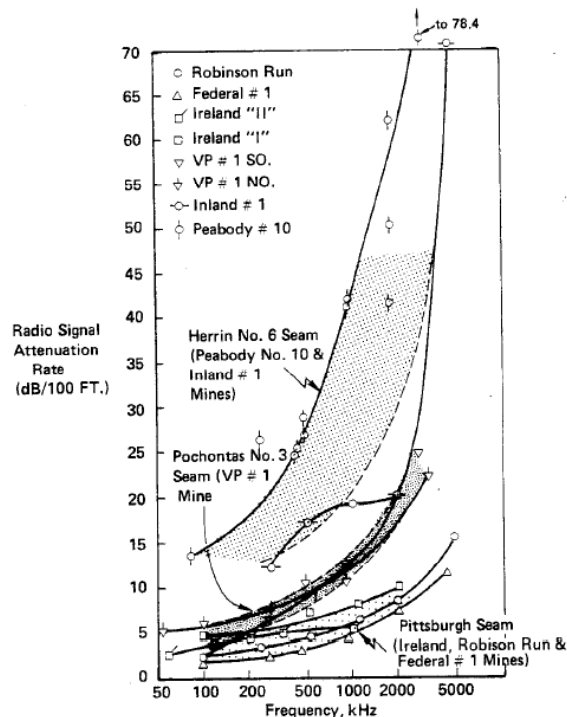


Figure 1: Attenuation versus frequency in typical coal mines.

Since 2002, the Q-Track Corporation has been pioneering a novel approach to real-time location systems (RTLs) called Near-Field Electromagnetic Ranging (NFER[®]) technology. Operating in the AM broadcast band (530-1710kHz) under Part 15 power levels, NFER[®] systems achieve tracking accuracies on the order of 1-3ft (30cm-1m) or better at ranges of 100-200ft (30-60m) in complicated indoor environments. NFER[®] systems take advantage of the far greater complexity of near-field signals to track on multiple signal characteristics such as the phase difference between electric and

⁸ Terry S. Cory, "Propagation of EM Signals in Underground Mines," Rockwell International/U.S. Bureau of Mines Contract No. H0366028. NTIS No. PB/289-757, 1977, pp. 9-10.

⁹ Ibid., p. 13.

¹⁰ Robert L. Lagace et al, "Modelling and Data Analysis of 50-5000kHz Radio Wave Propagation in Coal Mines - Supplement to Final Report," Arthur D. Little/U.S. Bureau of Mines Contract No. H0346045, 1980, p. 26, 66.

magnetic signal components. Transmitting at the higher power levels allowed in coal mines and operating at lower frequencies, range can be extended substantially relative to what Q-Track has achieved in above-ground tracking. We chose 575kHz as a good starting point for initial prototypes and testing. Additional information on Q-Track is available at the Q-Track website (<http://www.q-track.com>).

This report details both theoretical calculations and measurements in caves and mines that confirm the feasibility of applying NFER[®] systems in mine environments. Our work established several key principles:

- 🔑 Vertical polarization performs better than horizontal polarization in underground environments.
- 🔑 A power law roll-off of about r^{-5} is a reasonable estimate for mine propagation.
- 🔑 Phase response is distorted by mine infrastructure but in a gradual, slowly varying fashion that lends itself well to an RF mapping or fingerprinting approach to tracking.
- 🔑 Current NFER prototypes could be the basis of a tracking system with a range of about 150-200m (450-600ft). Reasonably foreseeable improvements could substantially extend the range to about 600-800m or 1800-2400 feet. With this kind of range, we can envision deploying a relatively limited number of receivers and obtaining accurate location information throughout mines of substantial size.

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2.0 Propagation Modeling

We created a model of the Cave Mountain Cave using Ansoft HFSS. The model assumes a 500ft long 7ft high by 6ft wide passage. Figure 2a shows a large scale version of this model, while Figure 2b shows close-up detail, including the electric antenna structure used to generate the RF signals into the passageway. The bulk medium was assumed to be limestone with dielectric constant $\epsilon_r = 7$ and no loss (due to the generally dry condition of the cave).

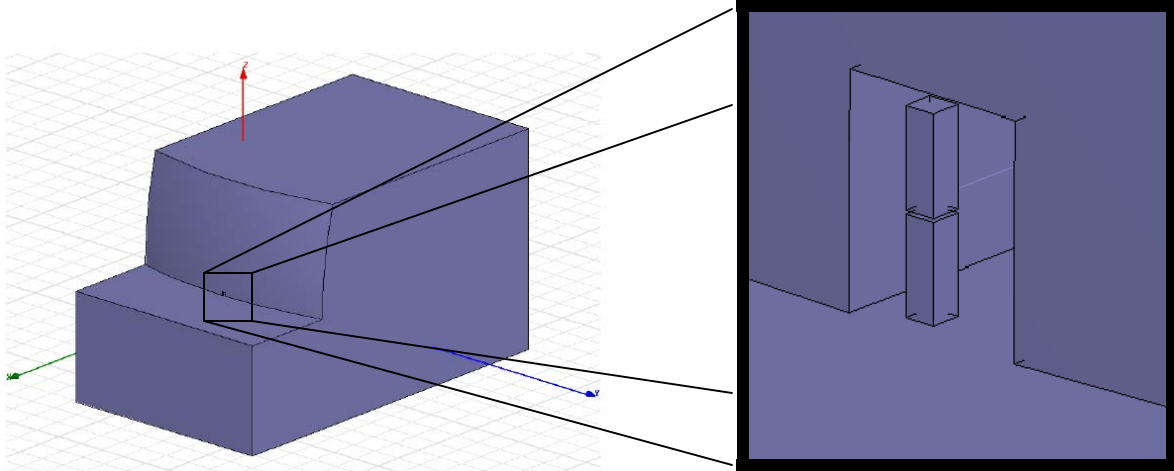


Figure 2a (left): Ansoft HFSS model of Cave Mountain Cave. **Figure 2b (left):** Close-up of cave mouth showing electric antenna used for excitation.

A few very interesting conclusions may be drawn from the results of Figure 3. First, in this numerical modelling, the breakpoint between near-field and far field appears to compress according to the wavelength. In limestone with a dielectric constant of $\epsilon_r = 7$, we expect the wavelength to be:

$$\lambda = \lambda_0 / \sqrt{\epsilon_r} \quad (1)$$

where λ_0 is the nominal free space wavelength.

In free space propagation, we expect the breakpoints between near-field propagation (in which fields vary as $1/r^3$ and $1/r^2$) and far field propagation (in which fields vary as $1/r$) to occur at $\lambda/2\pi$. Similarly, the E-H phase delta is 45 degrees at $\lambda/2\pi$. Taking into account the wavelength in the medium as defined by Equation (1), we predict the phase shift to be:

$$\Delta_\phi = \cot^{-1} kr = \cot^{-1} \frac{\lambda_0 r}{2\pi\sqrt{\epsilon_r}}. \quad (2)$$

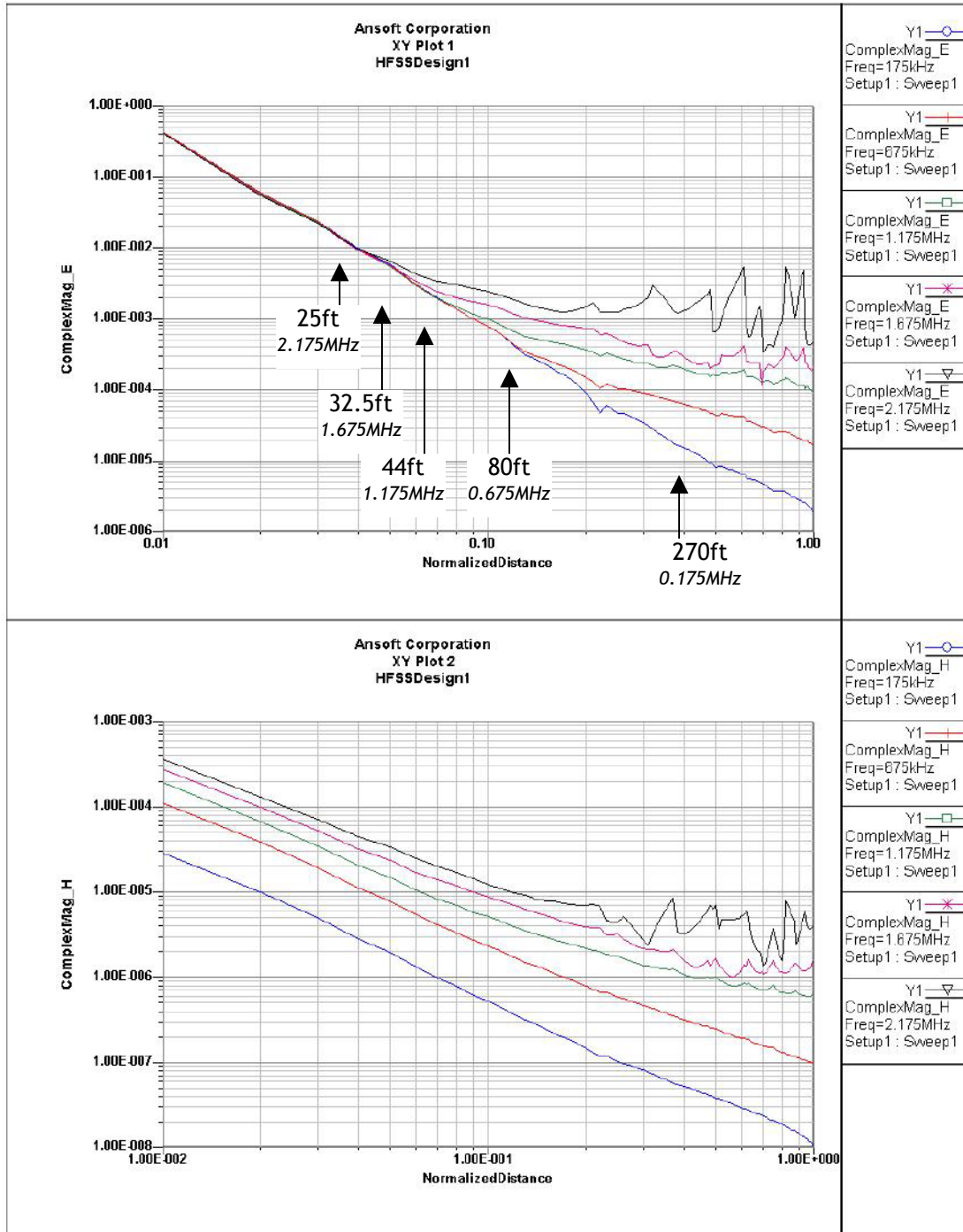


Figure 3a (top): Ansoft HFSS results for E-field in Cave Mountain Cave. The break points between $1/r^3$ and $1/r$ behavior occur at around $\lambda/2\pi$ for the frequency and medium. The “Normalized distance” is 500ft.

Figure 3b (bottom): Ansoft HFSS results for H-field in Cave Mountain Cave. The break points are more difficult to determine here because the transition is between $1/r^2$ and $1/r$ dependence.

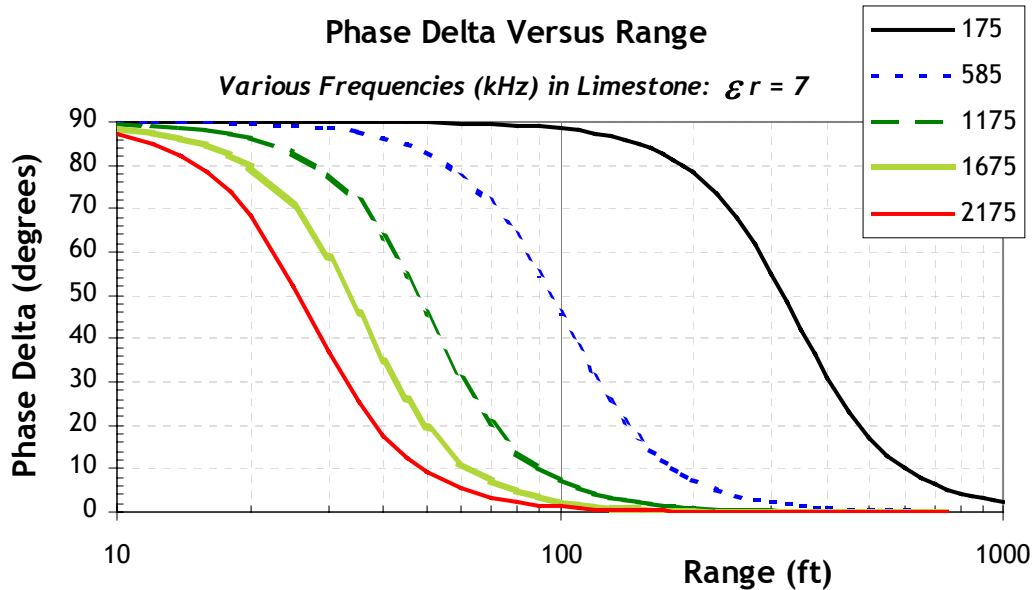


Figure 4: Theoretical phase behavior in limestone with $\epsilon_r = 7$.

Figure 4 plots the prediction of Equation (2). Table 1 compares the HFSS results for E-field breakpoints (in feet) and phase delta.

HFSS E-Field	HFSS Phase	Theory
25.0	27.5	28.5
32.5	30.0	37.0
44.0	50.0	52.7
80.0	90.0	105.9
270.0	175.0	354.1

Table 1: HFSS modeling and theoretical predictions for $\lambda/2\pi$ breakpoints show rough agreement.

This modelling and theory assumed that losses were negligible — not a valid assumption for most mine environments. In practice, we discovered that real-world propagation depends critically upon coupling to mine infrastructure. We thus decided to defer more elaborate modeling until we could gather additional data on propagation in actual mine environments.

3.0 Propagation Testing

Q-Track evaluated the behavior of near-field signals in two environments. Cave Mountain Cave provided a near linear shaft for testing propagation in an underground setting. This former saltpeter mine presented an excellent 1-D test environment. Three Caves, an abandoned limestone mine, provided us with a local 2-D test environment. Although passageways were substantially larger than in typical coal mines, Three Caves offered an opportunity to assess propagation in a complicated non-line-of-sight underground environment.

3.1 Propagation Testing: Cave Mountain Cave

In the Cave Mountain Cave Test, Q-Track personnel demonstrated the ability to track location up to 500-550 feet away from a locator-receiver in an occluded (non-line-of-sight) environment. Since the locator-receiver can detect angle-of-arrival as well, this means locator-receivers could be spaced approximately every 1000ft along a shaft. Closer spacing would be necessary to provide coverage of adjoining passages. Tracking accuracy was about 5-10ft. Comparable accuracy was obtained when an extension cord was laid along the shaft except for one point where a fifty foot error was observed.

3.1.1 Background on Cave Mountain Cave

North Alabama has a wide variety of caves suitable for evaluating RF propagation. In consultation with members of The Huntsville Grotto of the National Speleological Society, Q-Track chose to make measurements in Cave Mountain Cave, a dry, limestone cave on Tennessee Valley Authority (TVA) land near Guntersville dam (see Figure 5a). Q-Track received permission from the Guntersville office of the TVA to make measurements in Cave Mountain Cave. An “improved” cave (once exploited for saltpeter), Cave Mountain Cave has an approximately linear shaft with a walkable length of about 700 feet, and additional crawlway access. Figure 5b shows a tape and compass survey map of the cave generated by The Huntsville Grotto of the National Speleological Society. The cave is a desirable test environment for a variety of reasons:

-  Cave Mountain Cave is a single, generally linear shaft although true line-of-sight is limited to only a couple hundred feet at best. The cave has a flat even ground surface and uniform 6ft or higher ceiling allowing easy access in and out and rapid movement throughout the cave.
-  The cave comprises a single shaft with no side passages for relatively straightforward theoretical modeling and comparison of measured to theoretical data.
-  There are no conductors running along the shaft. This will allow Q-Track to assess the impact shaft wiring will have on propagation.

Q-Track personnel completed a preliminary survey before selecting the cave. The cave does not appear to have any delicate geological features that might be damaged by our presence. In our initial survey, we did not observe any wildlife, however during our tests we discovered bats roosting about 500 ft from the entrance. We tried to minimize the potential disturbance by using red tinted lights in this area.

The cave appears to be heavily frequented as evidenced by the extensive spray paint and graffiti throughout. Figure 5c shows a representative cave interior picture. Q-Track's test involved no fixed infrastructure and did not in any way damage the cave. This NSS survey was the basis of our test diagram shown in Figure 9.

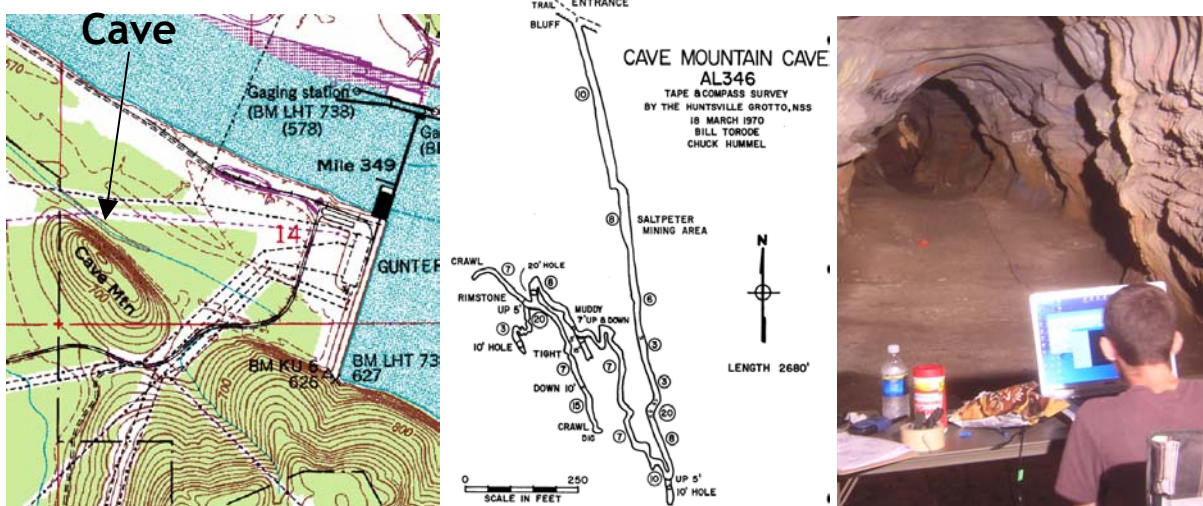


*Figure 5a (left): USGS map of Cave Mountain area (adjacent to Gunter's Dam).
Figure 5b (center): Survey map of Cave Mountain Cave. Circled numbers denote ceiling height in feet.
Figure 5c (right): Typical interior appearance of a Cave Mountain Cave passageway.*

3.1.2 Cave Mountain Test Results: Summary

We performed three experiments.

- 🔑 **Evaluation of WiFi Propagation:** We discovered our 802.11b wireless links would propagate more than 300ft along the shaft provided we had a substantially line-of-sight path. Signal strength plummeted once line-of-sight was lost.
- 🔑 **Low Frequency Propagation Along Rock Shaft:** We demonstrated that the Q-Track system could range accurately up to about 500 feet away along the shaft, even with no line-of-sight path.
- 🔑 **Propagation Along Rock Shaft With Conductor:** We demonstrated that the Q-Track system could propagate even further using coupling to a conductor placed in a shaft. Our test was limited by having only 400ft of extension cord, however.

3.1.3 Cave Mountain Test Results: Details

Test 1: Evaluation of WiFi Propagation: The first experiment involved measurement of WiFi propagation within the cave.

For Test 1, we placed a WiFi hub (router) just inside the mouth of the cave at the origin of the 1-D coordinate system. We positioned the hub on a tripod approximately equidistant between shaft ground and ceiling. We used a “Net Stumbler” equipped laptop to assess RSSI and SNR as a function of distance along the shaft, as shown in Figure 6.

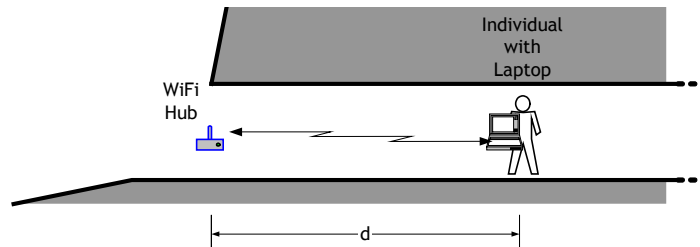


Figure 6: Conceptual Diagram of Test 1.

We found the signal strength “maxed out” at -20dBm according to the signal strength metric built into the computer’s WiFi network. The measured signal strength remained at the -20dBm level along the length of the shaft until the 314ft point. Between 314ft and 315ft, the signal strength dropped from -20dBm to -90dBm. At 320ft, the signal was completely lost. The cave was very quiet with a noise floor of -100dBm. This precipitous decline in signal strength coincided with entering an abrupt turn in the tunnel shaft that blocked the near line-of-sight path. Figure 7 plots the data.

We conclude that the shaft acts to duct the 2.4GHz wireless network signals along a substantially linear shaft. These microwave signals do not effectively diffract around corners and attenuate very quickly once line-of-sight is blocked.

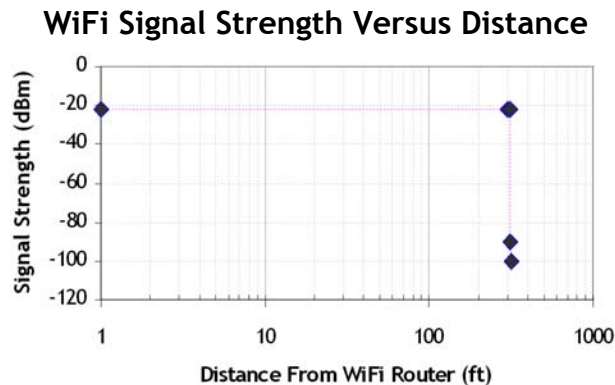


Figure 7: Signal strength versus distance. The cave acts so as to “duct” the signals along the shaft giving excellent signal strength for substantial distances (over 300ft). However, signal strength drops precipitously once line-of-sight is lost.

Test 2: Propagation Along Rock Shaft: The second experiment involved measurement of low frequency propagation along the cave. We deployed QTTM-400 Locator-Receiver (portrayed in Figure 8a) to track a vest-embedded experimental transmitter (portrayed in Figure 8b).

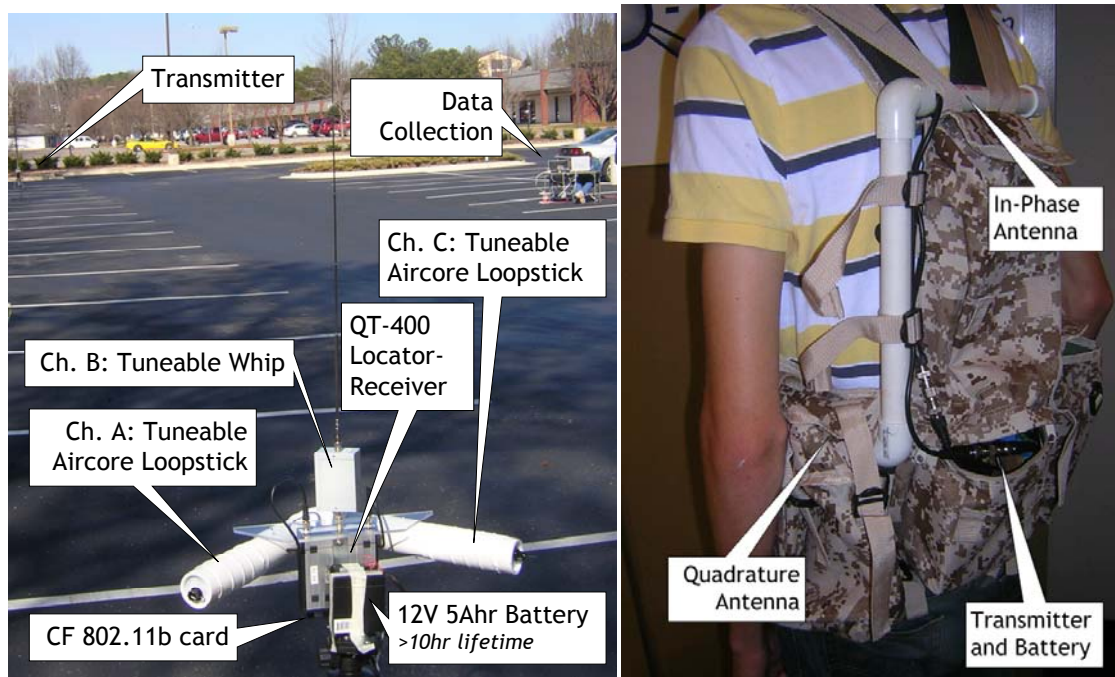


Figure 8a: QT-400 Locator-Receiver(left); **Figure 8b:** Experimental Transmitter (right).

Figure 9 shows our test set-up superimposed on the Huntsville Grotto survey map. We placed orange cones at fifty-foot intervals along the tunnel to serve as landmarks, and we deployed two Locator-Receiver to track the experimental transmitter.

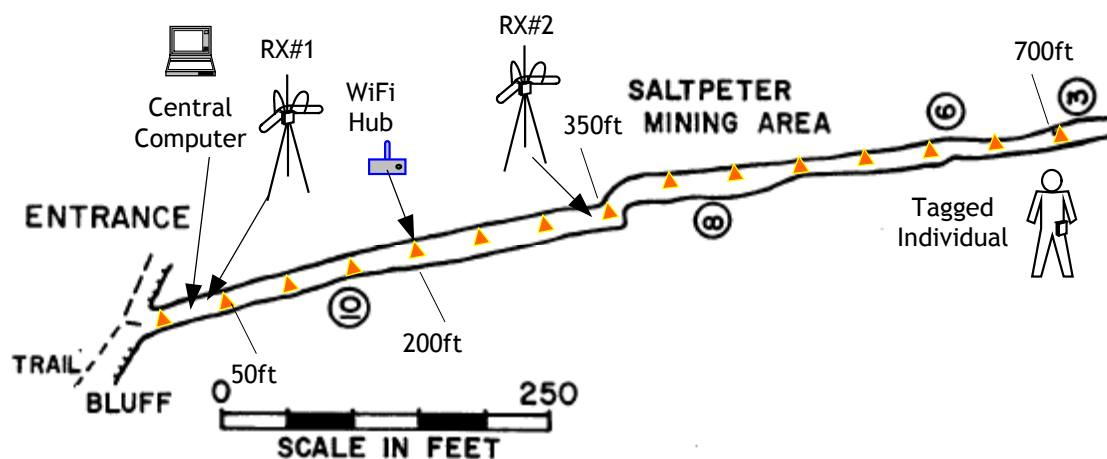


Figure 9: The first 750ft of Cave Mountain Cave, showing Q-Track's test set-up. We placed orange cones at 50ft intervals along the shaft (as shown) to use as landmarks. Circled numbers denote ceiling height in feet.

Figure 10a shows where we set up our “Base Camp” just inside the mouth of the cave. Figure 10b shows the “Base Camp” featuring a video camera setup to record the tracking display on the central computer. Figure 10b also shows the transmitter tag and the first Locator-Receiver (RX#1). Figure 10c is a close-up of the first Locator-Receiver, placed at approximately 40ft. Figure 10d shows the WiFi hub placed at 200ft. Figure 10e shows the second Locator-Receiver placed at about 340ft. WiFi signals would not propagate past the slight bend in the tunnel at the 350ft mark. In fact, we also found that our FRS handheld radios (~462MHz) would not propagate through the bend at 350 feet. This required us to set up a voice relay to transmit commands and messages the length of the cave.



Figure 10a (left): “Base camp” just inside the cave mouth.

Figure 10b (right): Video camera to record tracking display in foreground, James Fluhrer wearing vest tag, and first Locator-Receiver (RX#1) at 40ft mark in background.



Figure 10c (left): First Locator-Receiver (RX#1) at 40ft.

Figure 10d (center): WiFi Router at 200ft (note orange cone landmark).

Figure 10e (right): Second Locator-Receiver (RX#2) at 340ft.

The two Locator-Receivers detected the signals from the Transmitter Tag and sent their data to the Central Computer over the 802.11b (WiFi) network. Figure 7 shows how the system displayed the current location of the tagged individual as a red dot on the tracking map. The central computer updated the tracking map as the tagged individual moved through the cave. The video camera recorded the central computer's tracking display.

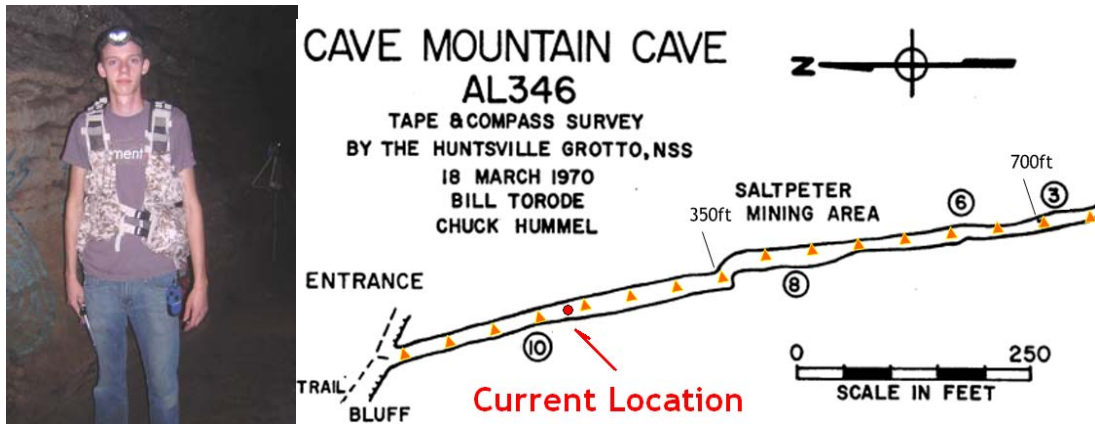


Figure 11a (left): Tagged individual at 180ft.

Figure 11b (right): Tracking map with red dot showing location at 180ft.

In Test #2, we were able to track to an accuracy of about 5-10ft throughout the entire length of the cave. RX#1 lost lock on the transmitter signal past the 550ft point (a range of 510ft). RX#2 tracked the entire 700ft length (350ft on a side).

Test 3: Propagation Along Rock Shaft with Conductor: The third and final experiment involved measurement of low frequency propagation within the cave. We repeated Test 2, having first deployed an extension cord along the length of the cave. Figure 12a shows a typical extension cord splice. Figure 12b shows the end of the extension cord at 400ft. We lacked sufficient cord to extend the remaining length of the cave.

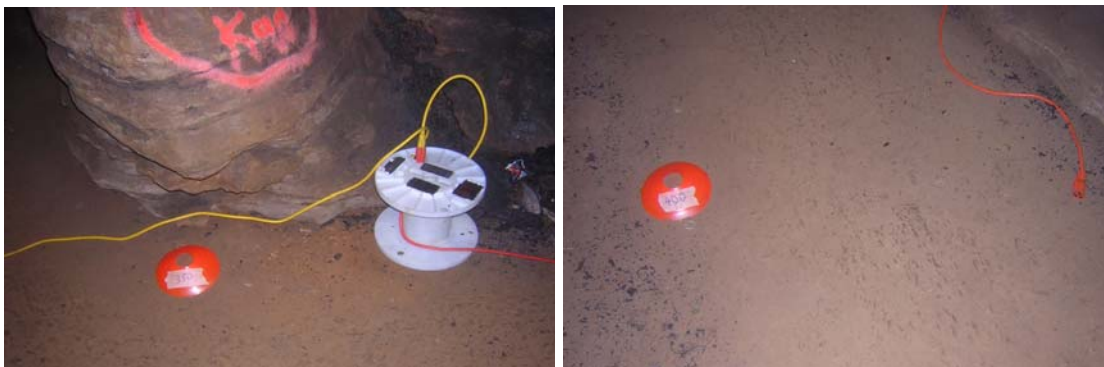


Figure 12a (left): Extension cord extended past 350ft.

Figure 12b (right): Extension cord ended at 400ft for the "with conductor" tests.

In Test #3, we were able to track to an accuracy of about 5-10ft throughout the most of the cave, however near RX#2 the system suffered from aliasing and became unable to determine which side the transmitter was on relative to RX#2. This resulted in an error of about 50 feet in this vicinity. RX#1 lost lock on the transmitter signal past the 600ft cone (a range of 560ft). RX#2 tracked the entire 700ft length (350ft on a side). Raw data are in Appendix 1.

3.1.4 Cave Mountain Conclusions

In this preliminary test, we were able to demonstrate accurate tracking (within 5-10ft) in a 1-D cave environment at ranges of about 500ft even in a non-line-of-sight environment.

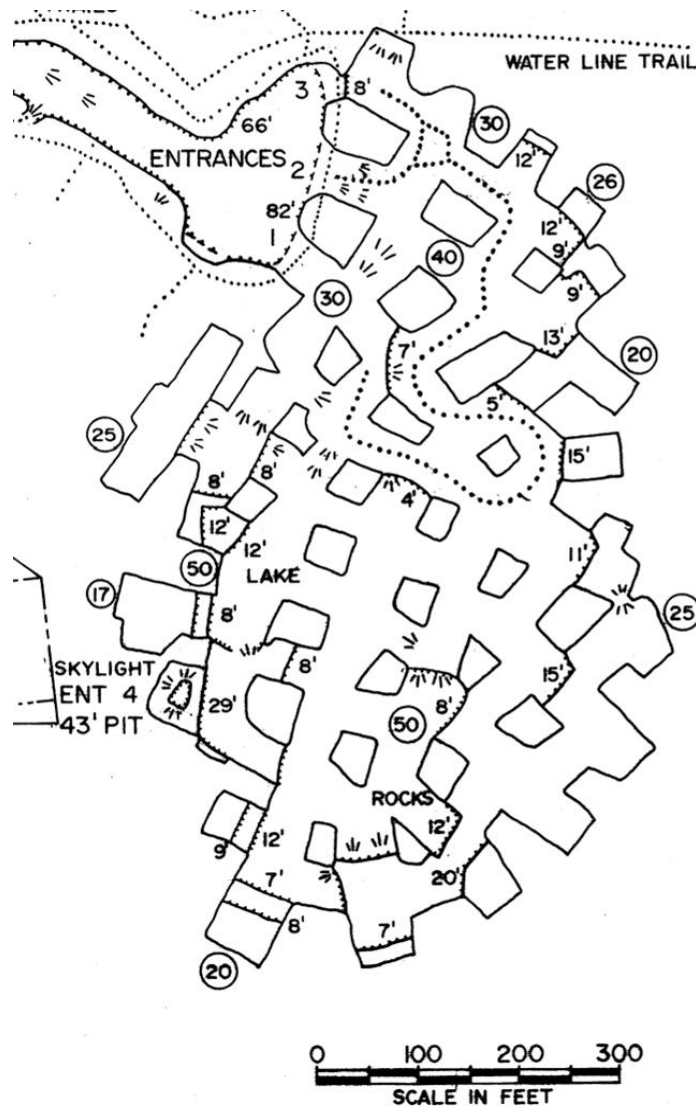


Figure 13: Survey map of Three Caves, an abandoned limestone mine approximately 900 ft long by 400 ft wide. Circled numbers denote ceiling height in feet.

3.2 Propagation Testing: Three Caves

Q-Track personnel demonstrated the ability to track location in two dimensions in this underground environment to an accuracy of about 20 ft at ranges of 450-600 ft. Vertical polarization appeared better behaved than a higher power horizontal polarization system.

3.2.1 Background on Three Caves

Q-Track was unable to secure permission to test propagation characteristics within a working coal mine in North Alabama. As an alternate test venue, Q-Track tested system performance within the Hermitage Street Quarry, in Huntsville Alabama, also known as “Three Caves.” Three Caves was a limestone mine active between 1945 and 1954. Now abandoned, the property is currently owned and managed by the Huntsville Land Trust. More information on the property is available online.¹¹ Passageways within Three Caves are substantially larger than in typical coal mines, however the facility provides a good test of the ability of Q-Track’s NFER systems to track in non-line-of-sight underground environments. Figure 13 shows a survey map. The overall dimensions of the mine are approximately 400ft by 900ft. Figure 14 shows a typical interior view.



Figure 14: Interior view of the Three Caves limestone mine.

¹¹ http://www.landtrust-hsv.org/three_caves.htm

3.2.2 Three Caves Test Results: Summary

We performed two experiments.

- 🔑 **Evaluation of Propagation with Vertical Polarization:** We deployed four vertically polarized receivers around the abandoned mine. We found typical ranges of 450-600ft. Phase behavior was remarkably similar to open field results. Additionally we demonstrated tracking throughout about 75% of the mine with typical accuracy better than about 20ft.
- 🔑 **Evaluation of Propagation with Horizontal Polarization:** We deployed two horizontally polarized receivers around the abandoned mine. The magnetic channel achieved only about 400ft range and the electric field channel range was only about 250ft. We conclude that vertical polarization is preferred.

3.2.3 Vertical Polarization

The first series of tests we conducted in Three Caves used vertical polarization. We used the same receiver and transmitter configuration as in the Cave Mountain tests (see Figures 8a and 8b). Figure 15 shows the configuration of our testing.

We set up our “Base Camp” about fifty feet inside Entrance 1. We deployed our WiFi node nearby where we would have a line-of-sight to the four receiver locations. The red lines in Figure 15 denote the lines-of-sight from the WiFi node to the receivers and base camp. The blue squares in Figure 15 show the locations at which we took propagation measurements. We attempted to take data at each intersection between orthogonal passageways as well as between each column. We were able to take data throughout most of the mine except in the far back where the floor lies submerged in a pool of water.

From Receiver #143 to the furthest data point in the back of the mine was about 700ft. Figure 16 presents a variety of photos of our testing and the Three Caves environment.

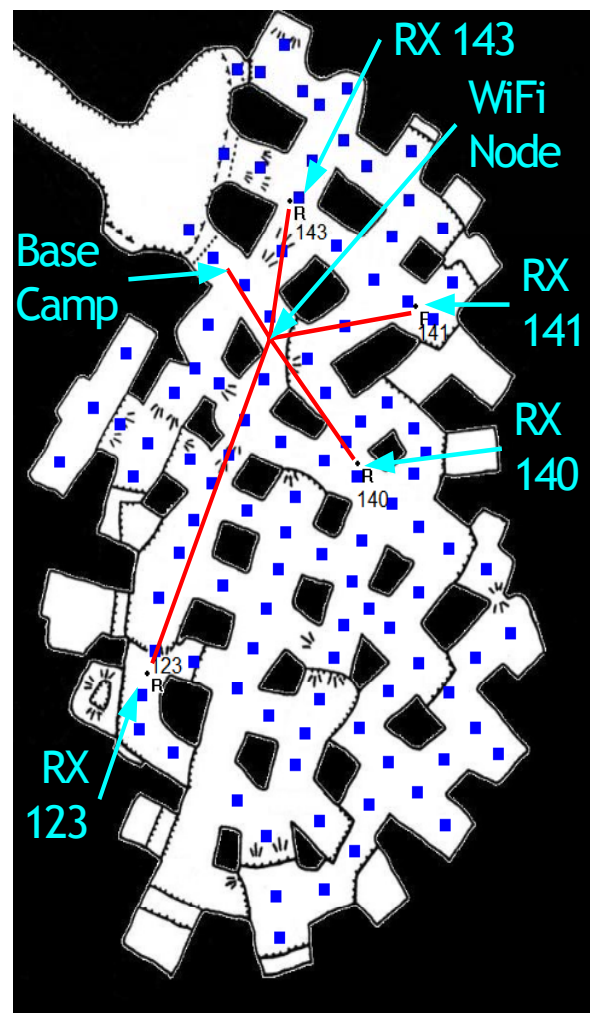


Figure 15: Vertical polarization testing showing WiFi node location, receiver deployment, and locations of field measurements (blue squares).

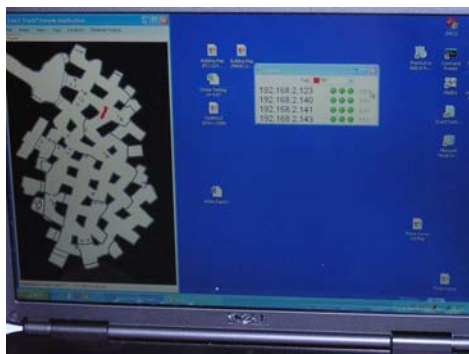


Figure 16a (top-left): Two of “Three Caves” three entrances.

Figure 16b (top-right): Base camp, just inside the right entrance shown in Fig. 14a.

Figure 16c (center-left): Tracking display showing map and red history trail.

Figure 16d (center-center): Nick wearing prototype transmitter (shown in more detail in Fig. 8b).

Figure 16e (center-right): Interior photo of Three Caves showing limestone columns.

Figure 16f (bottom-left): John guiding Nick during gathering of propagation data.

Figure 16g (bottom-right): Receiver 123.

The transmitter operated at 575kHz with vertically polarized signals. The wavelength was 1711ft. Typical noise levels were between -130dBm and -125dBm. Figure 17 shows received signal strength for Receiver 143. The boundary between the light and dark purple contours is the limit of useable signal. By that criteria, the magnetic channels (A and C) have a maximum range of between 450-500ft. Channel A exhibits a null to the lower right while channel C exhibits a null to the lower left. Range is necessarily less for each channel in these null directions. The electric channel (B) has a maximum range of about 600ft.

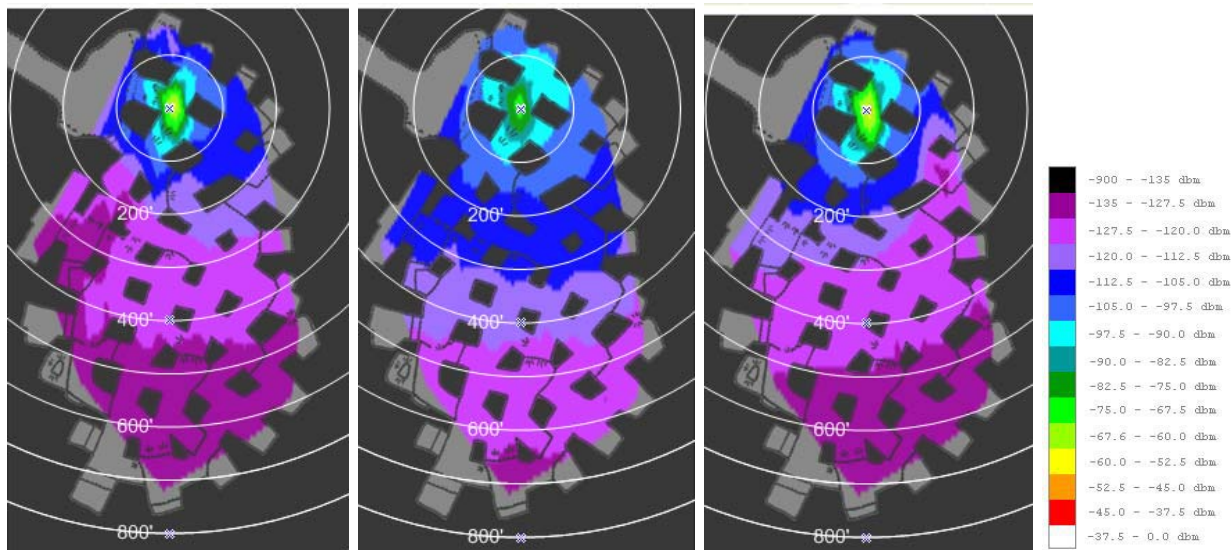


Figure 17a (left): Signal strength contours for the first magnetic (A) channel. Range is ~400ft.

Figure 17b (left-center): Signal strength contours for the electric (B) channel. Range is ~600ft.

Figure 17c (right-center): Signal strength contours for the electric (B) channel. Range is ~450ft.

Figure 17d (right): Color code for the signal strength contours.

Figures 18a-c show the theoretical open field phase behavior and the measured phase behavior in the mine. The qualitative agreement is very good, particularly for Phase BC. Deviations are in part due to the influence of the propagation environment, but are mostly due to imperfections in the antennas and mutual coupling between antennas. Even with these imperfections relative to ideal open field behavior, the phase is generally monotonic and slowly varying. Thus, by using a calibration or fingerprinting scheme, we can obtain accurate tracking. Complete results are in Appendix 2.

Figure 19 shows typical screenshots from our calibrated tracking in this environment. Tracking accuracy was within 20ft over 90% of the time. The region shown in the screenshots of Figure 19 was over two hundred feet away from any receivers. The red history trails show 30 seconds of motion.

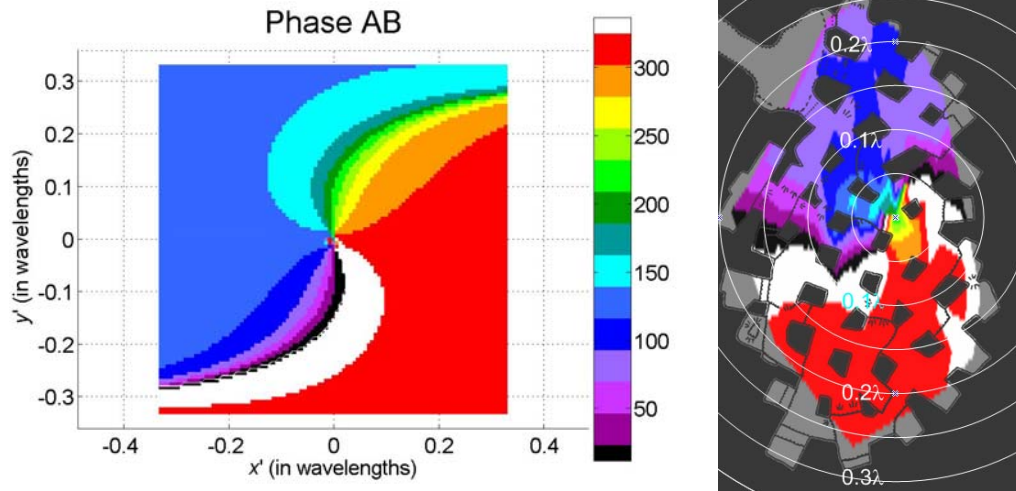


Figure 18a: Phase AB - Ideal open field results (left) and measured results (right).

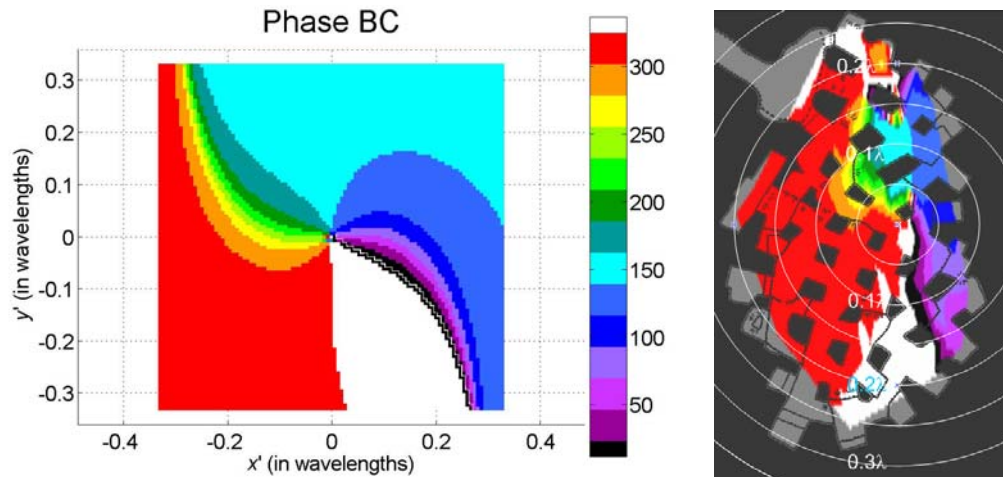


Figure 18b: Phase BC - Ideal open field results (left) and measured results (right).

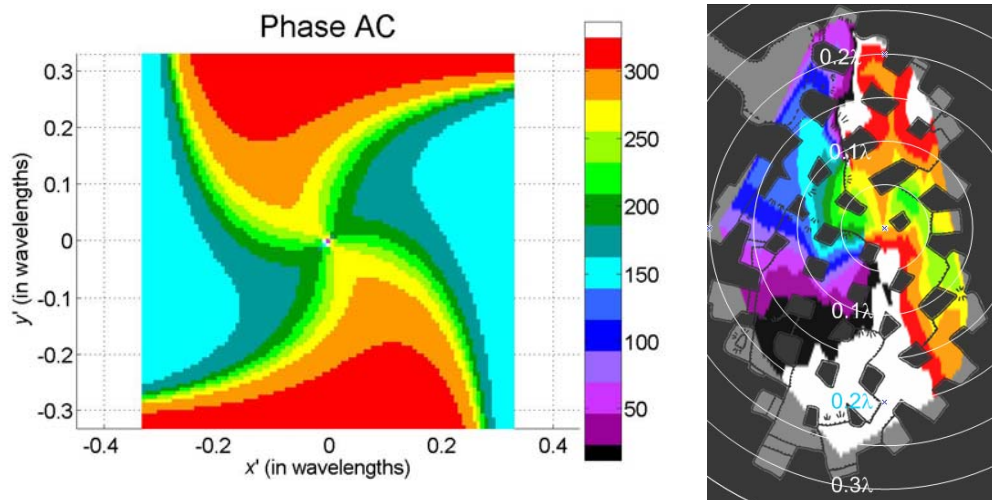


Figure 18c: Phase AC - Ideal open field results (left) and measured results (right).

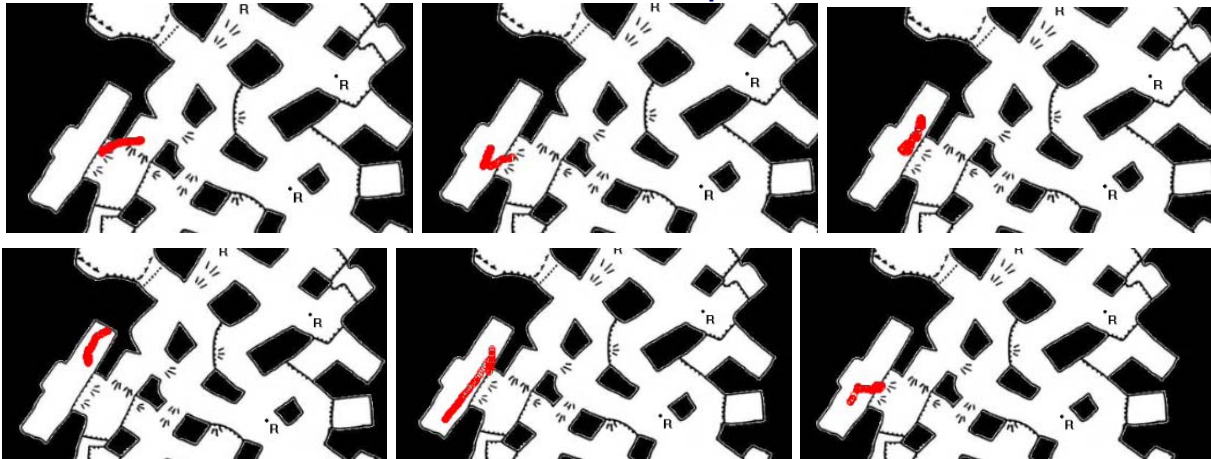


Figure 19: Tracking results obtained during vertical polarization testing. The red history trail shows 30 seconds of motion. The three closest receivers are 200-300 ft away.

3.2.4 Horizontal Polarization

The second series of tests we conducted in Three Caves used horizontal polarization. Figure 20a shows the layout of the two receivers we deployed in this configuration. The horizontal polarization receiver used two orthogonal electric dipoles and a vertically oriented magnetic loopstick antenna. Figure 20b shows one of the two receivers. For a transmitter, we used an air core loopstick of the same kind as was used for the vertical polarization receivers as our transmit antenna. We chose this aircore loopstick to ensure that there would be no saturation to limit transmit efficiency as might have happened with a ferrite core. Figure 20c shows the transmitter configuration.

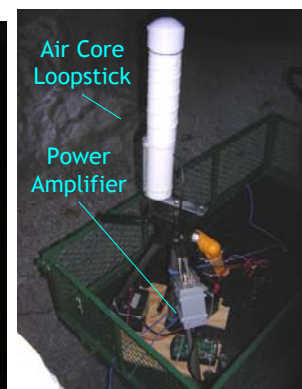
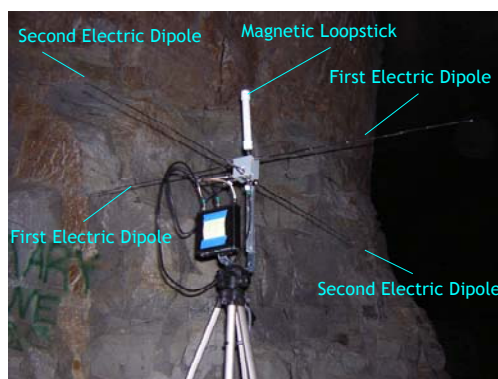
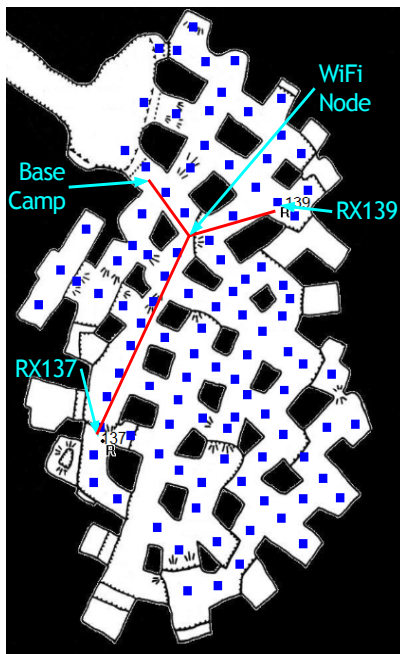


Figure 20a (left): Horizontal polarization testing showing WiFi node location, receiver deployment, and locations of field measurements (blue squares).

Figure 20b (center): Horizontal polarization receiver showing two orthogonal electric antennas and a vertical ferrite loaded loopstick antenna.

Figure 20c (right): Horizontal polarization transmitter showing air core loopstick and power amplifier.

The horizontal polarization system had a moment of $NIA = 0.47Am^2$, about 24dB stronger than the $NIA = 0.00174Am^2$ moment of the standard vertical polarization vest antenna transmitter system. Despite this 24dB improvement over the vertical polarization system, performance was substantially worse. The magnetic channel exhibited a range of about 400ft, and the electric channel worked only out to about 250ft. We conclude that horizontal polarization is not as good a choice as vertical polarization in this environment. Figure 21 shows results for an electric and a magnetic channel. Complete results are in Appendix 3.

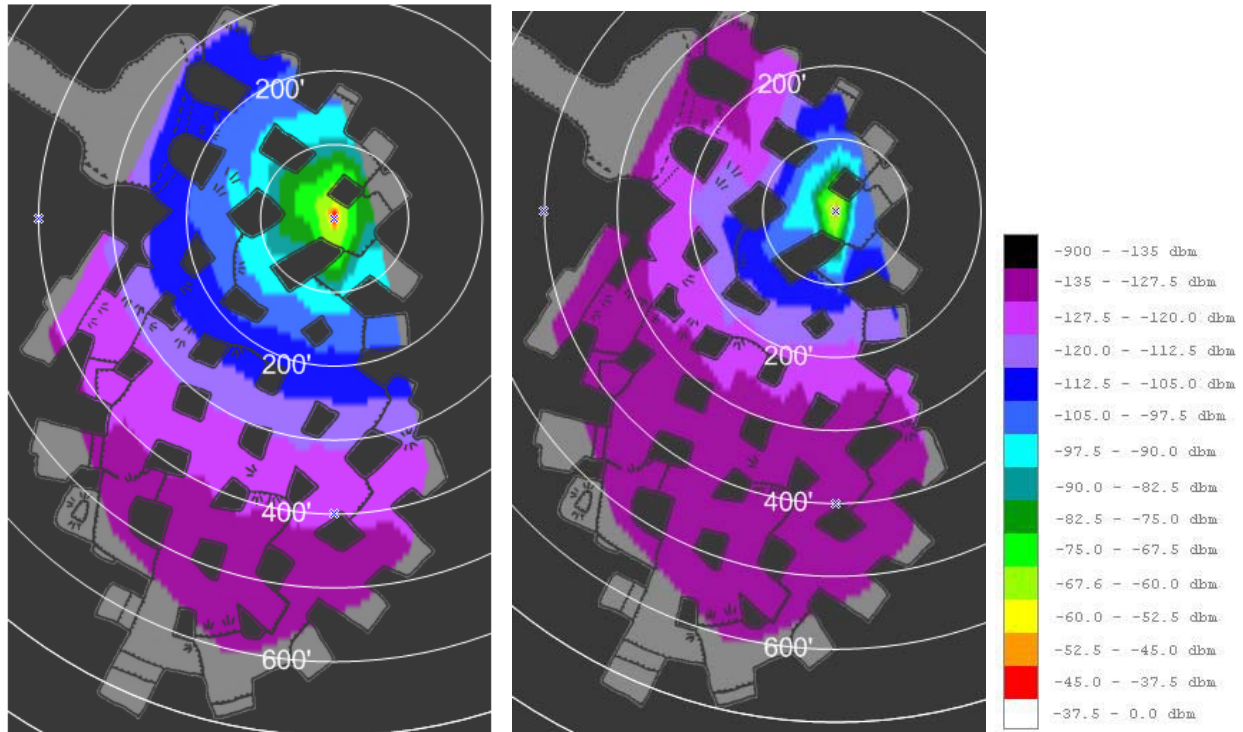


Figure 21a (left): Magnetic field measurements from RX #139.

Figure 21b (center): Electric field measurements from RX #139.

4.0 Upgrades, Improvements, and Optimization of Q-Track Hardware

Initial tests of Q-Track equipment in a cave were extremely promising. With a 500mW transmitter, the range was in excess of 500 ft, which included bends in the tunnel shaft. If the transmit power were increased to 5-10 watts, it is likely that the tracking range in this environment could be extended to 1500ft and possibly beyond.

Researching the commercial equipment market showed no availability of amplifiers that could operate 1) from batteries, 2) at the required frequencies, 3) at the required drive and 4) load levels, and that could be adapted to be 5) intrinsically safe (IS). Q-Track then decided to design an amplifier that could meet these requirements.

4.1 Power Amplifier

The amplifier was designed around a power MOSFET that met requirements for 1) power dissipation, 2) input capacitance, 3) operating frequency, and 4) operating voltage. The selected device was an IRF5111, which was readily available and economically feasible. It was further decided to drive the amplifier from an existing Q-Track transmitter and to connect an antenna with a similar load impedance.

The input drive was around 7 volts rms into the 220Ω antenna, which amounted to 227 mW. The desired output power was 10 watts into a 220Ω antenna. The output voltage then need to be 46.9 volts rms. The battery source would be 24 volts, but since it could not drive a 46.9 volt rms load, it was decided to connect the antenna to a 4:1 step-up transformer. The load reflected back to the transistor would then be $220\Omega/4^2 = 13.75\Omega$. The power that would then be dissipated in the transistor would

be $P_o = \frac{V_{cc}^2}{2 \cdot R_L} = \frac{24^2}{2 \cdot 13.75} = 20.95 \text{ watts}$. The amplifier efficiency would be

$\frac{\text{OutputPower}}{\text{DissipationPower}} = \frac{10\text{watts}}{20.95\text{watts}} = 47.7\%$. It was further decided to limit the power

dissipation in the device to 10 watts, so two of the devices were paralleled so as to limit the temperature rise consistent with the specifications of an available heat sink. The input capacitance for the IRF511 is specified to be 145 pF nominal, which calculates to $-j1876\Omega$ at 585 kHz. This value is almost ten times the input impedance, so it was decided to ignore the input capacitance in the design.

We decided to run the amplifier in Class C to achieve the highest possible efficiency, although at the expense of harmonic distortion. To reduce the distortion at the antenna, we placed a Chebyshev lowpass filter at the output. The calculated design of the output filter is shown in Figure 22 below:

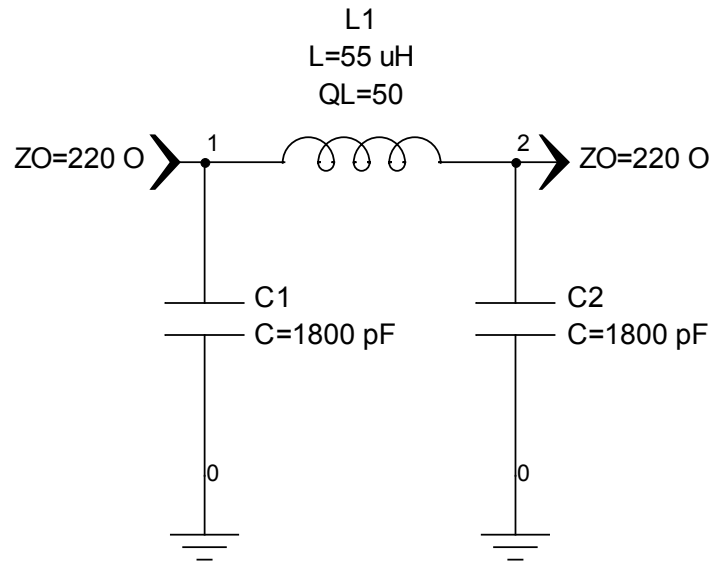


Figure 22: Design of the transmitter output filter.

Figure 23 shows the filter response. This output filter will have a transfer response (S21 in dB) as shown in red, and signal reflection characteristics (S11 in dB) as shown in blue in Figure 6 below. This filter will suppress the second harmonic by 12 db, and the third harmonic by 27.5 db.

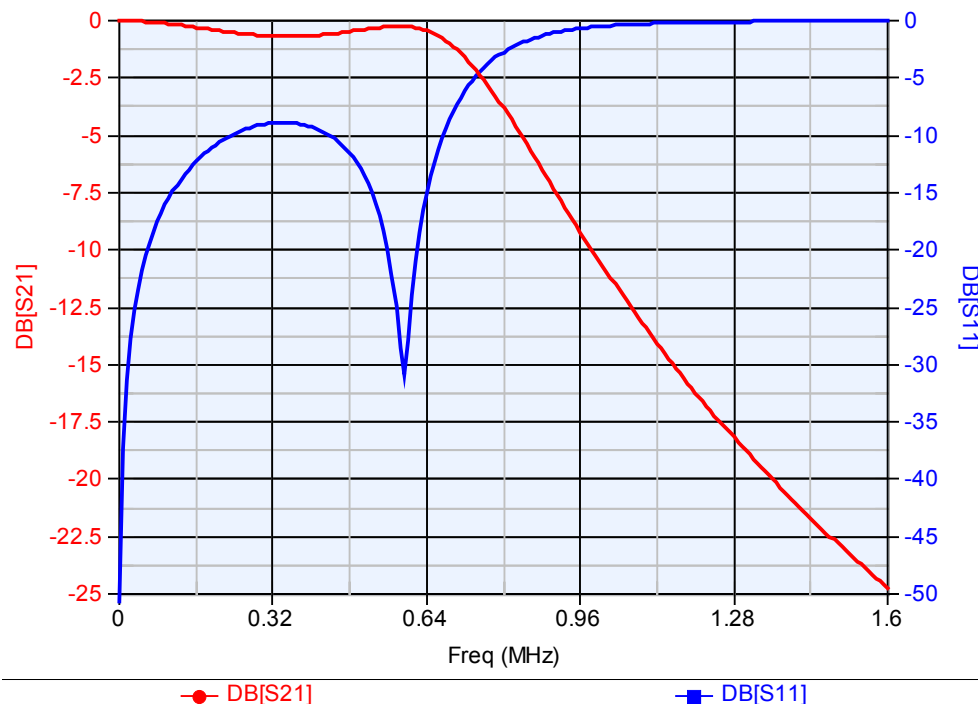


Figure 23: Output filter response characteristics.

Circuit performance was verified in PSPICE simulations prior to construction. The basic circuit is shown next in Figure 24.

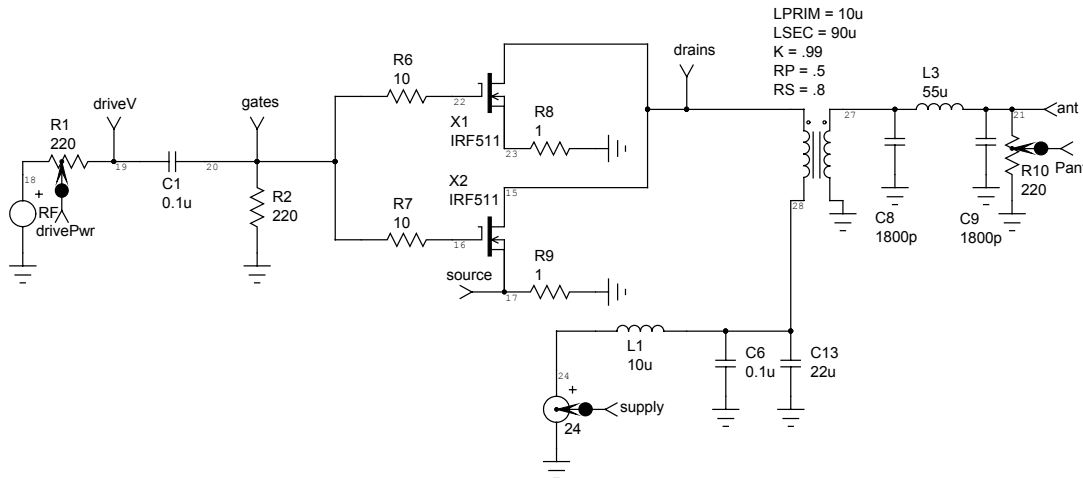


Figure 24: Basic amplifier circuit for simulation.

Figure 25 depicts the Bode plot for the amplifier. Note that it is nicely tuned for 585 kHz, and that there is only a single pole at work. The gain goes to 1 long before the phase inversion goes to -180 degrees. Thus the amplifier will be unconditionally stable.

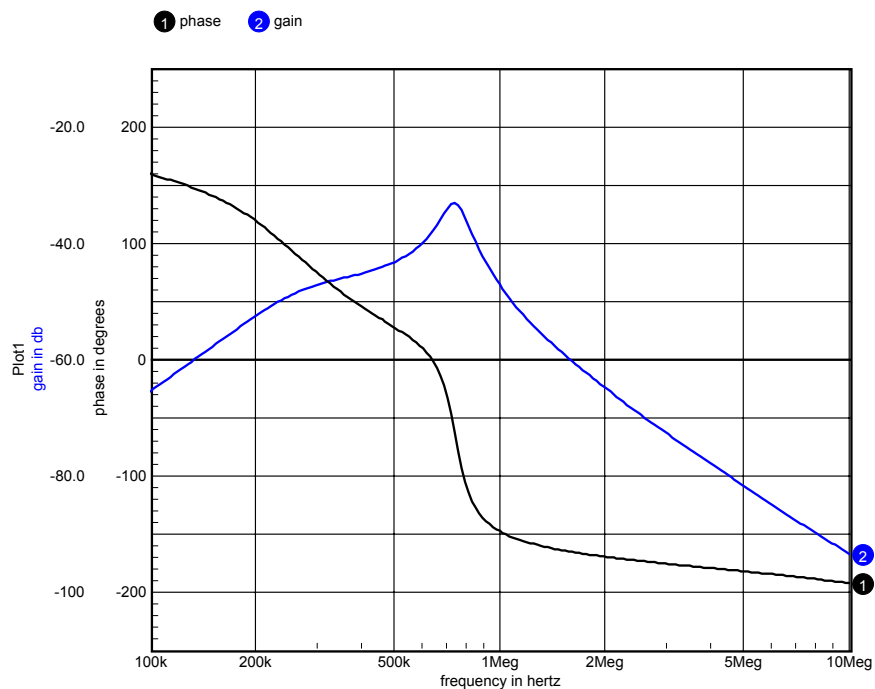


Figure 25: Bode Plot for the amplifier.

The first transient response simulation showed a high frequency spur on the drain voltages (see Figure 26), which we considered objectionable. We added ferrite beads to the drain leads to eliminate the problem.

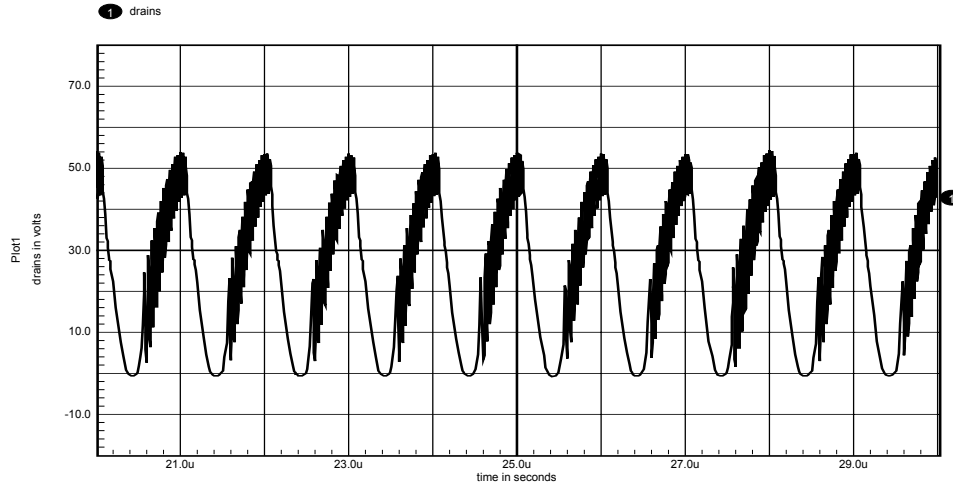


Figure 26: Drain voltage with spurious response.

Figure 27 shows the circuit with the ferrite beads added. Not only do they seriously attenuate the interference, but the peak-to-peak voltage at the drains is increased from 56.6 volts to 85.9 volts, a 3.6 dB improvement.

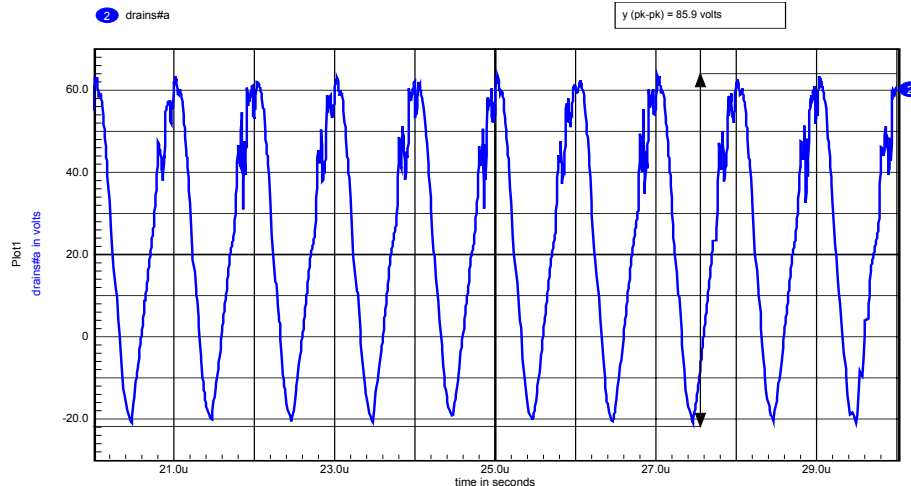


Figure 27: Drain voltages with ferrite beads added.

Figure 28 next shows the output signal at the antenna port. It is a very clean sinewave with a peak-to-peak of 157 volts. The Fourier Transform of the output is also shown. It maximum output is 66.7 volts rms, which corresponds to an output power of 20.2 watts, which is considerably greater than originally hoped. The transform shows the worst harmonic to be 25.2 dB below the carrier, which easily satisfies FCC Part 15 requirements. The simulation also shows 35 watts drawn from the power supply, so the efficiency is then computed as 57.7%.

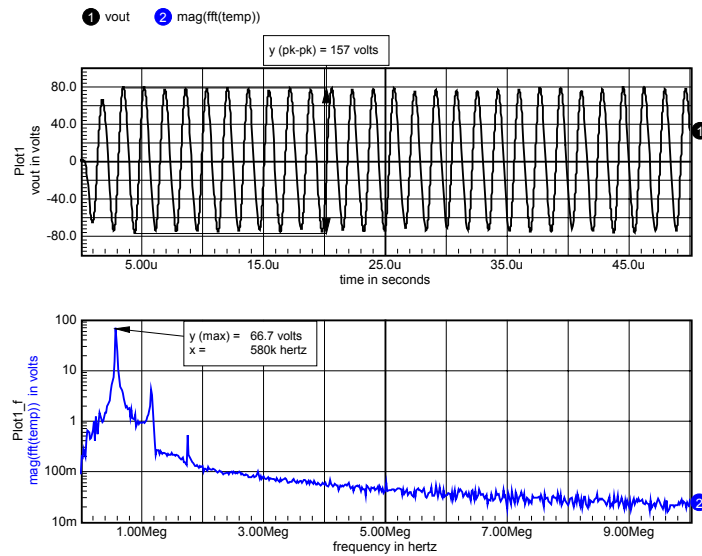


Figure 28: Output signal for the amplifier.

Unfortunately, we were unable to get the improved amplifier ready in time for the final demonstration at the Pittsburgh Research Lab Safety Research Coal Mine.

4.2 Antenna Improvements

One of the principal challenges of a NFER tracking system is developing compact, efficient antennas. Vertical polarization (V-pol) antennas exhibit superior performance because V-pol signals propagate better than horizontal polarization (H-pol) signals between the “parallel plate” arrangement of the floor and ceiling of typical building structures. As we confirmed in Three Caves, H-pol does not appear to propagate as well as V-pol, particularly H-pol electric field components.

Figure 29a shows an electric whip antenna with corresponding omnidirectional V-pol pattern. An electric antenna is prone to coupling with nearby objects, however, so a magnetic antenna is preferred. A typical magnetic antenna also has an omnidirectional dipole pattern, however the polarization is horizontal. Figure 29b shows a magnetic loop antenna and the corresponding H-pol dipole pattern.

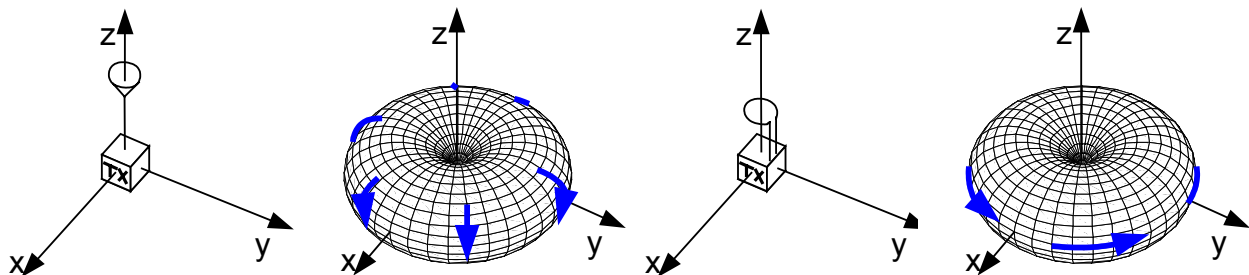


Figure 29a (left): Electric whip antenna and corresponding vertically polarized omni dipole pattern.

Figure 29b (right): Magnetic loop antenna and corresponding horizontally polarized omni dipole pattern.

The secret to a successful low frequency transmit antenna is to devise a magnetic antenna system with an omnidirectional vertically polarized pattern. Figure 30a shows how a loop antenna whose normal aligns with the x axis yields nulls along the x-axis and vertically polarized signals along the +y and -y-axes. Adding a second orthogonal loop antenna and phasing signals in quadrature between the two antennas yields a dipole pattern that rotates at the RF frequency yielding the desired effective omnidirectional vertically polarized pattern. The quadrature-fed orthogonal magnetic loop antenna system of Figure 30b was successfully demonstrated by Q-Track under a Phase I NSF Grant (0539073) in 2006.

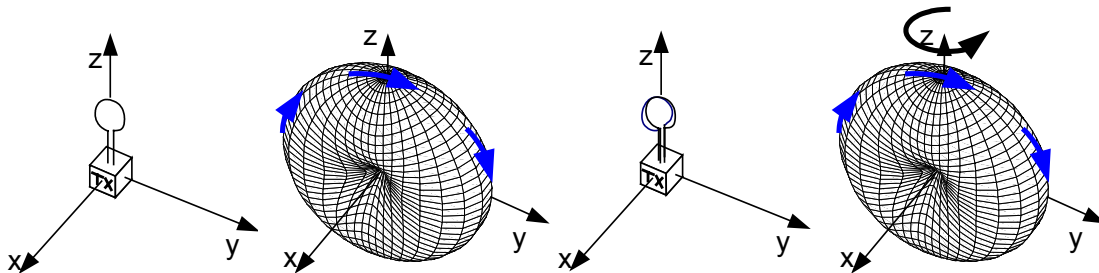


Figure 30a (left): Magnetic loop antenna and corresponding vertically polarized pattern.
Figure 30b (right): Quadrature fed magnetic loop antennas yield a rotating dipole pattern that is effectively omni-directional and vertically polarized, as desired.

Figure 31a shows a block diagram of how this antenna system is incorporated in Q-Track's QTTM-400 Tag. A PIC microprocessor controls a pair of direct digital synthesizers operating at the RF frequency. One (Q) is offset 90 degrees from the other (I) so as to be in quadrature. A power amplifier raises the signal level to the appropriate power level. These quadrature fed orthogonal antennas yield the rotating pattern of Figure 31b. The resulting time average pattern is vertically polarized on azimuth and circularly polarized in the vicinity of the poles. Figure 31b shows a NEC simulation of the 3D pattern.

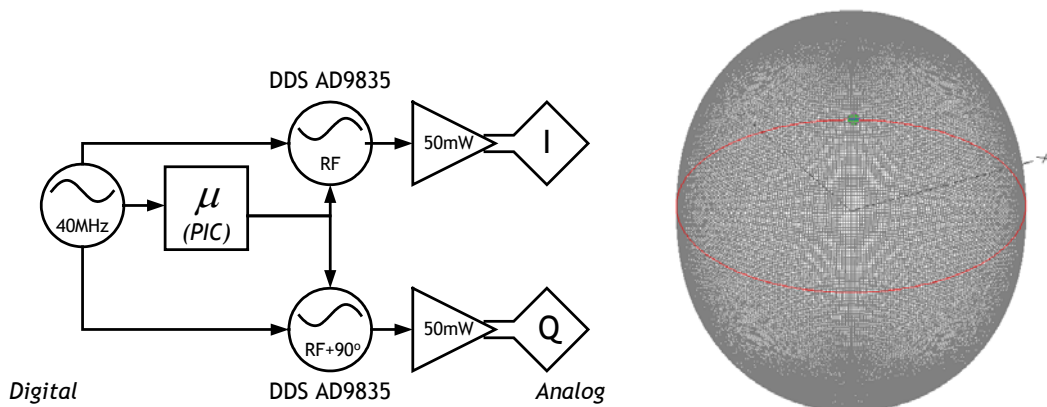


Figure 31a (left): Block diagram for the quadrature-fed orthogonal magnetic antenna system.
Figure 31b (right): NEC simulation of the resulting pattern. The rotating loop pattern of Fig. 7b yields a quasi-isotropic pattern that is vertically polarized on azimuth and circularly polarized in the vicinity of the poles.

In the course of analyzing the Three Caves data and comparing theoretical to actual data, Q-Track personnel further confirmed an interesting discovery. If the sense of rotation of the quadrature pattern is reversed, then the phase response surface toggles into an alternate state. This doubles the amount of phase information available for tracking yielding a substantially more robust tracking system

In practice, the transmitter imposes a BPSK modulation on one of the two channels. This modulation can carry digital data or voice. The receiver can detect the two distinct phase variations, measure each one, and not only demodulate the signal to recover the data but also take the two distinct values of the phase for use in a NFER location system. Instead of the three phase differences used in standard NFER tracking, this gives us six phase differences.

Figure 32a shows the alternate patterns and Figure 32b shows the phase response surfaces. On February 25, Q-Track filed a provisional patent application on this concept. Q-Track intends to file a regular patent application in the next few months.

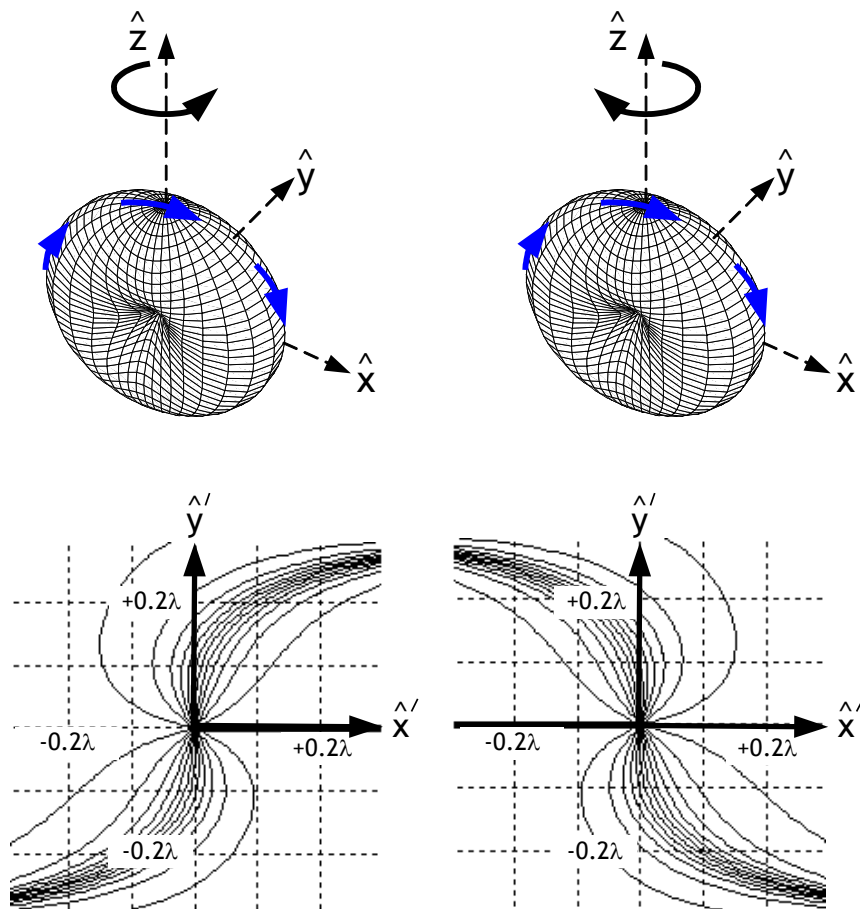


Figure 32a (top): Two rotation states for a quadrature fed orthogonal antenna system. The quadrature pattern can be made to rotate clockwise or counter-clockwise.

Figure 32b (bottom): Two distinct phase response surfaces that will be observed by a receiver located at the origin of the primed coordinate system.

Q-Track's NFER tracking systems have been optimized for operation indoors under FCC Part 15 power levels. In preparation for mine operation, we designed the experimental vest antenna system shown in Fig. 8b. In lab measurements, we found that the peak current was 0.174mA. Since this antenna had 78 turns and a diameter of 1.27cm, the product $NIA = 0.0016\text{Am}^2$ for the vest antenna. Typical high performance transmit systems achieve $NIA = 2.5\text{Am}^2$, about 32dB stronger. Thus there is substantial room for improvement in Q-Track's transmit system. Unfortunately, Q-Track was unable to complete an improved transmitter in time for our measurements at the Pittsburgh Research Lab Safety Research Coal Mine.

In preparation for this final experiment, Q-Track designed low frequency antennas optimized for 575kHz. The gain of these new magnetic "diamond" planar spiral loop antennas was about -68dBi at 600kHz. The aircore loopstick antennas we deployed for the Cave Mountain and Three Caves testing had a gain of -80dBi, so this represents a 12dB improvement. Figure 33 shows the receiver with the diamond planar spiral loop antennas in a lab setting.



Figure 33: Q-Track receive antenna array: orthogonal magnetic antennas and vertical electric dipole.

5.0 Initial Proof-of-Concept Demonstration

In February, we traveled to the NIOSH Pittsburgh Research Lab for a field test of an initial proof of concept system. We were able to deploy improved receivers in this test. We deployed the same transmitter system as was used in the Cave Mountain and Three Caves testing, and we gathered propagation data at 575kHz. Due to damage incurred in transporting our prototypes, we were only able to deploy two receivers. This limited our ability to do tracking, but still provided the opportunity to collect propagation data .

5.1 Pittsburgh Research Lab Safety Research Coal Mine

With the cooperation of NIOSH, we were able to secure two days for testing in the Pittsburgh Research Lab Safety Research Coal Mine. Figure 34a shows the mine entrance and typical interior views. Figure 34b shows a map of the mine. Entries were typically 6.5ft high and a 14ft wide. The mine is well ventilated and suitable for testing non-intrinsically safe hardware like Q-Track's prototypes.

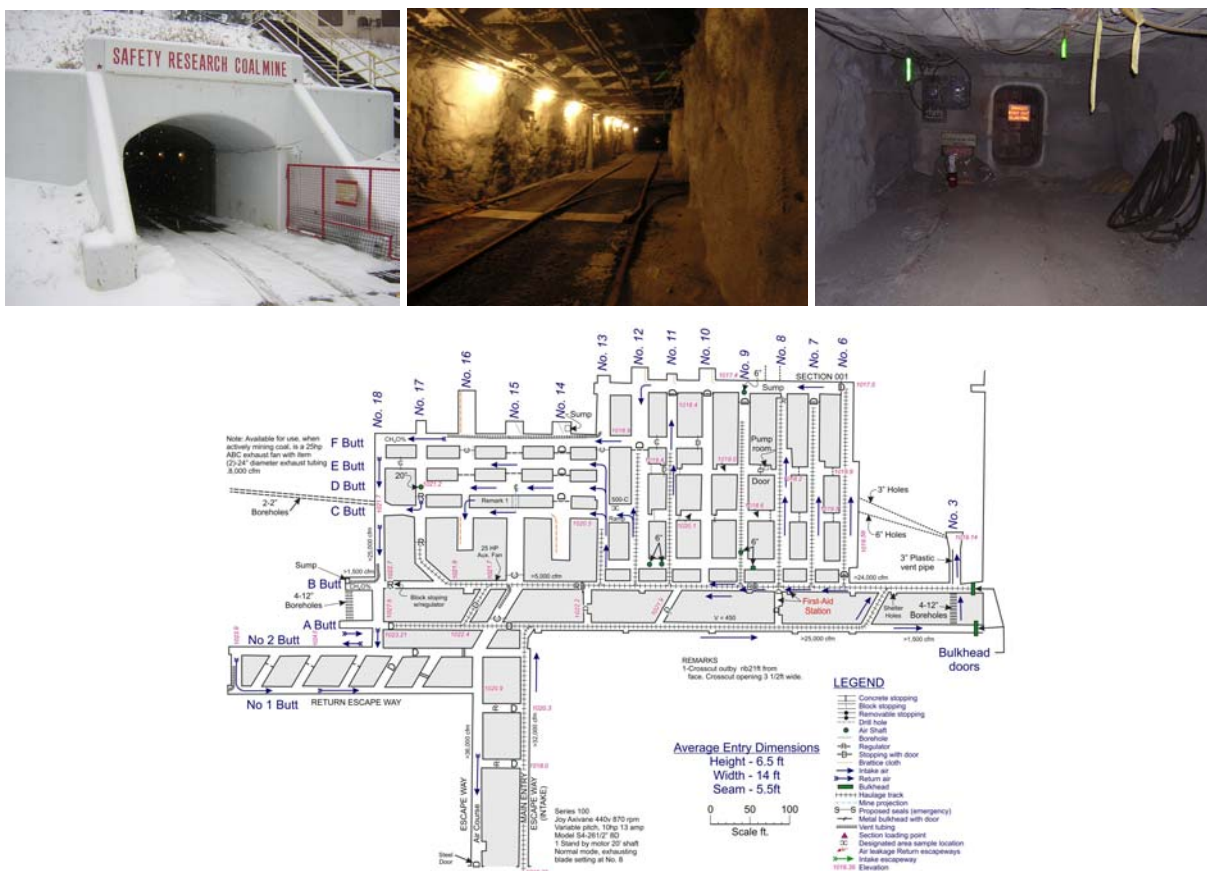


Figure 34a (top): Main entry of the Safety Research Coal Mine (left), view along B-Butt (center), and bulkhead door at the end of B-butt (right).

Figure 34b (bottom): Map of the Safety Research Coal Mine.

5.2 Experimental Set-Up

With the assistance of NIOSH personnel, we deployed and set-up receivers on February 10 and took data on February 11. Figure 35a shows the general arrangement. We set up our “Base Camp” and WiFi node in the vicinity of the First Aid Station at the intersection of the No. 8 Entry and the B-Butt. We were able to tap into 120VAC power at this location.

We deployed Receiver 101 along No. 8 Entry at the intersection of the E Butt. This area had a relatively high clearance, but also dense metal netting in the ceiling. The entry had a haulage track with cars immediately beyond the receiver on the side away from the Base Camp. The magnetic antennas were aligned 45 degrees relative to the Entry center line. Figure 35b shows the deployment of Receiver 101.

We deployed Receiver 102 at the intersection of B Butt and the No. 13 Entry. Here again we aligned the magnetic antennas were aligned 45 degrees relative to the center line of B Butt. We attempted moving Receiver 102 further away along B Butt, however the WiFi link became unreliable at greater distances. Figure 35c shows the placement of Receiver 102.

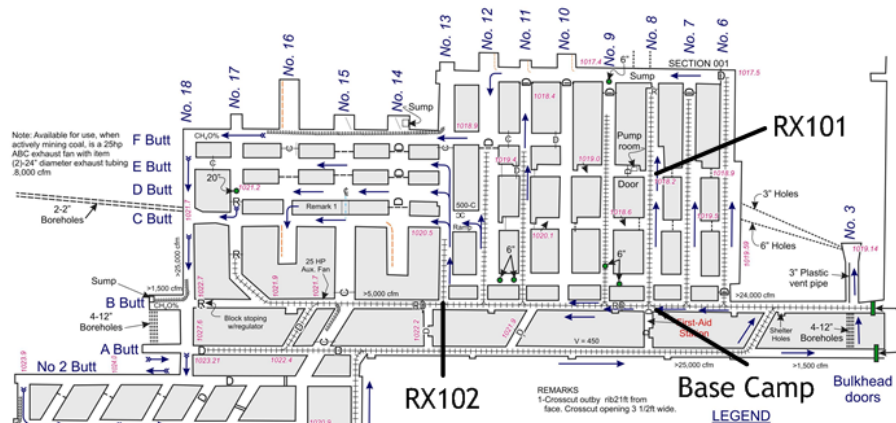


Figure 35a (top): Deployment of receivers in the Safety Research Coal Mine.

Figure 35b (bottom left): Receiver 101 was deployed in a particularly high clearance area at the intersection of Entry No. 8 and E Butt.

Figure 35c (bottom right): Receiver 102 was deployed at the intersection of Entry No. 13 and B Butt.

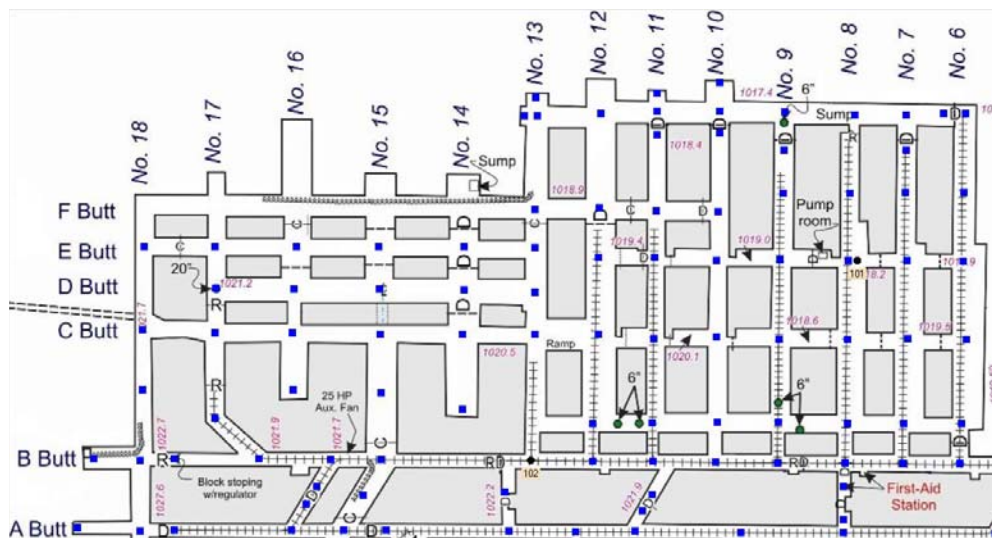


Figure 36a (top left): Base camp at the intersection of B Butt and Entry No. 8. WiFi node in foreground.

Figure 36b (top right): Drew wearing the transmitter vest.

Figure 36c (bottom): Field measurement points.

From our base camp position (shown in Figure 36a) we used handheld UHF radios provided by NIOSH to guide Drew wearing the transmitter vest (shown in Figure 36b) to each of about 100 field measurement points (shown in Figure 36c). We missed a few points in the vicinity of receiver 102.

5.3 Experimental Results

Figure 37 shows the signal maps for receiver 101. The magnetic signal propagation extended throughout most of the test area with a maximum range of about 350-450ft (120m). Electric field propagation was limited to only 200-300ft (80m). In part, this may have been to the particularly conductive environment where we placed the receiver. Signal contours showed significant anisotropies due to coupling. For instance, coupling was particularly strong along the No.8 entry, and along B-Butt relative to C-F-Butts. This is probably due to the greater infrastructure running along B-Butt. In general, haulage track, compressed air, and electrical utilities tend to branch off B-Butt to service each entry.

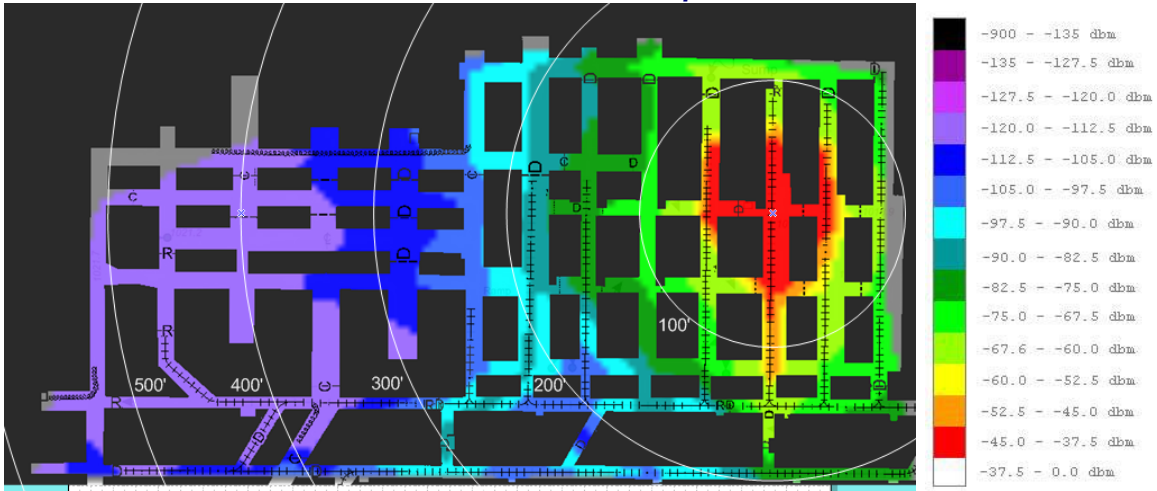


Figure 37a: Receiver 101 Magnetic (A) Channel Received Power.

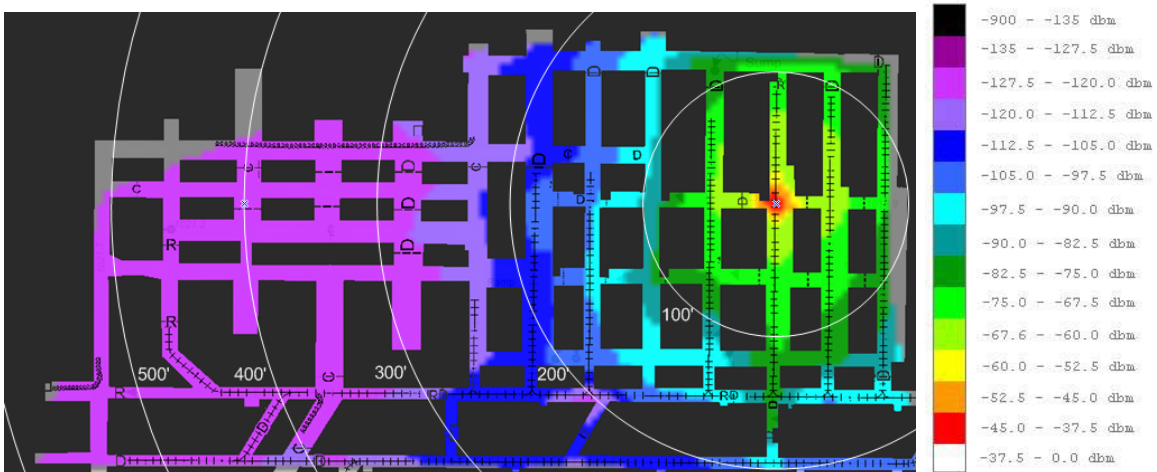


Figure 37b: Receiver 101 Electric (B) Channel Received Power.

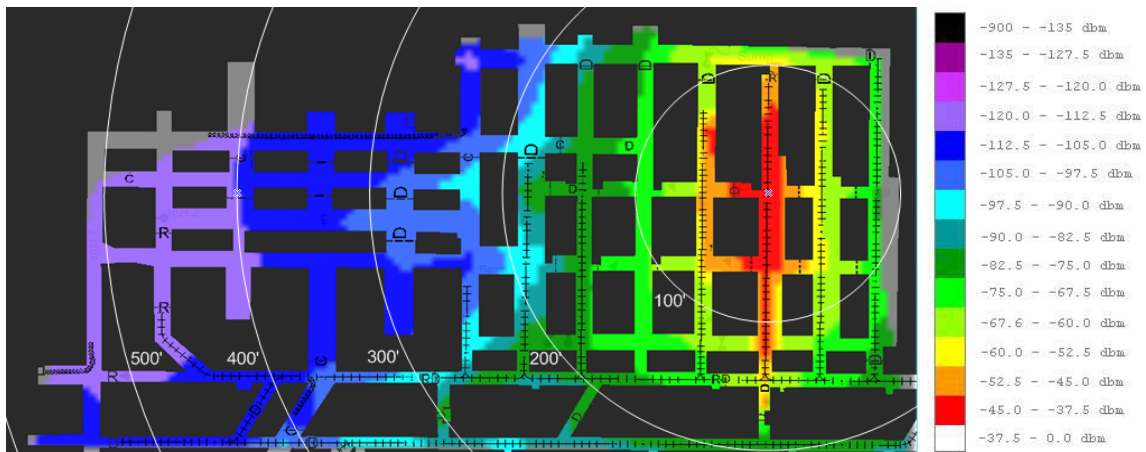


Figure 37c: Receiver 101 Magnetic (C) Channel Received Power.

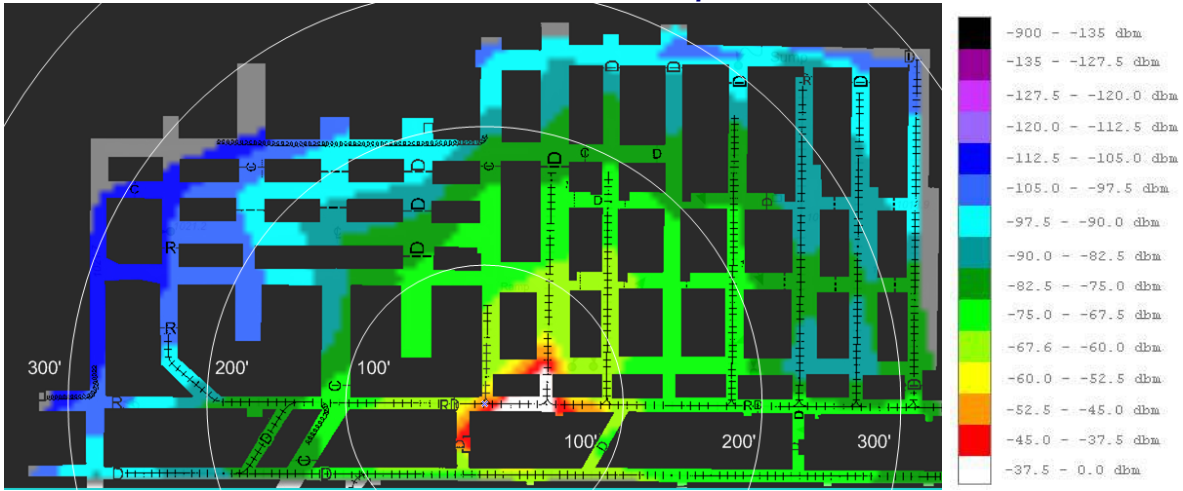


Figure 38a: Receiver 102 Magnetic (A) Channel Received Power.

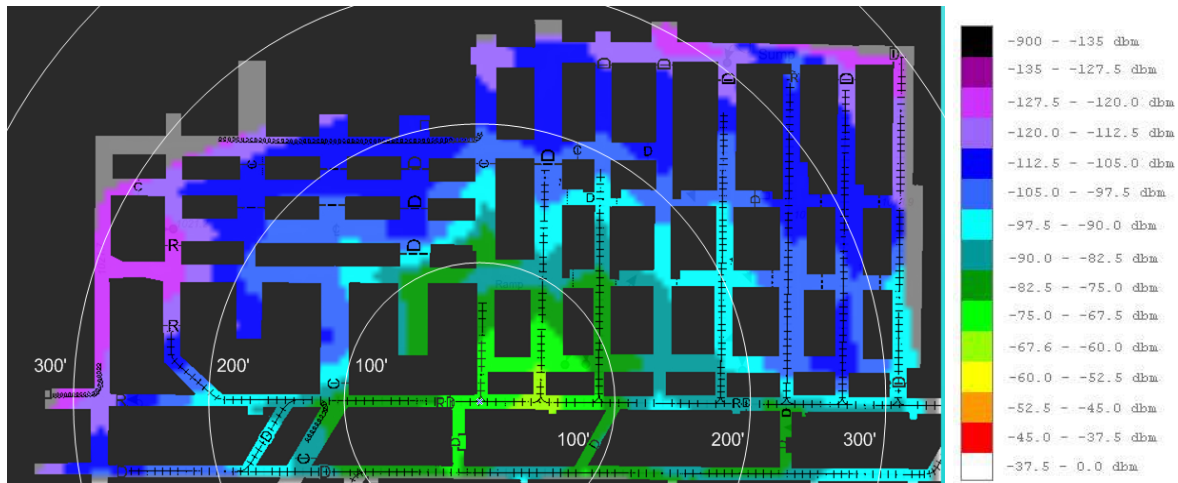


Figure 38b: Receiver 102 Electric (B) Channel Received Power.

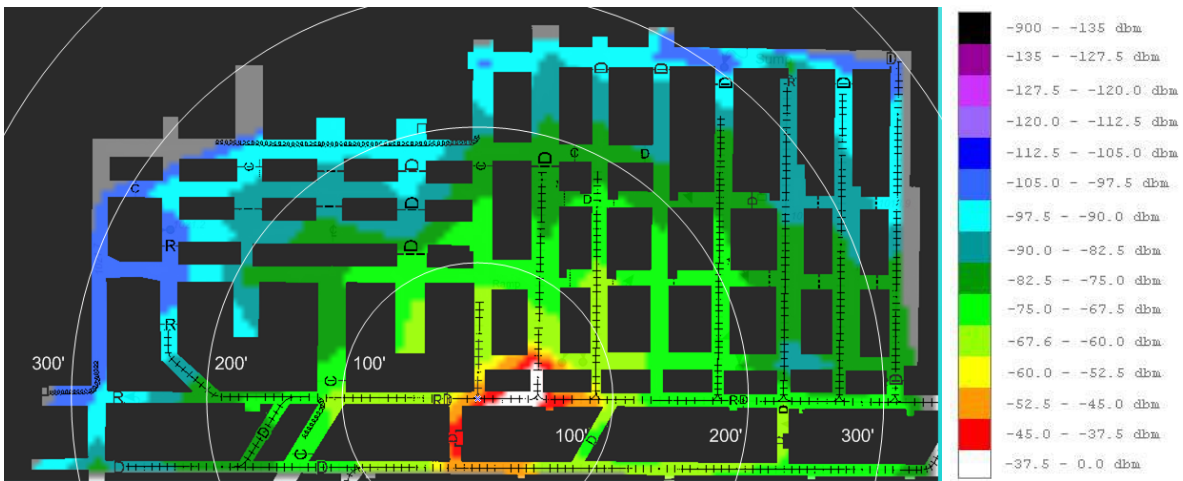


Figure 38c: Receiver 102 Magnetic (C) Channel Received Power.

Figure 38 shows the signal maps for receiver 102. The magnetic propagation extended 300-400ft, possibly further. The central location of receiver 102 made it difficult to determine the maximum range since in general we ran out of mine before running out of signal. The electric signal propagated successfully 250-300ft. The apparent “hot spot” in the signal strength is not co-located with the receiver because we accidentally omitted the field measurement points immediately adjacent to receiver 102.

The dead end in the No. 14 entry below C Butt can be compared to the signal strength at the intersection of No. 14 and C Butt to assess the extent to which signals might propagate through rock as opposed to along the passageways. One of the magnetic channels (C) showed stronger signals at the dead-end than at the intersection, suggesting the propagation mechanism might be through the ~50ft of rock instead of the ~180ft distance along the passageway. Figure 39 highlights this area.

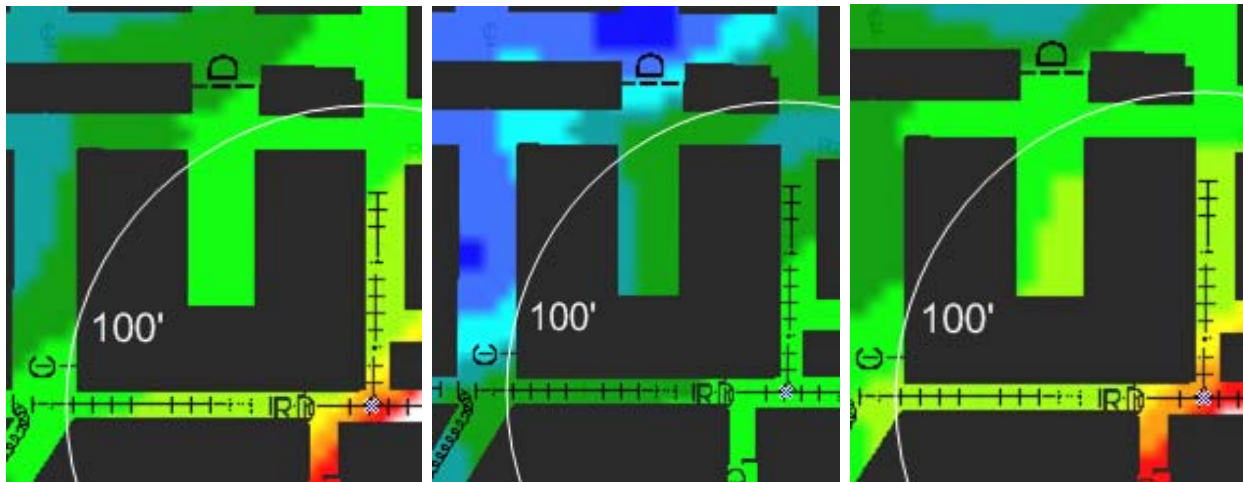


Figure 39: Signal strength measurements at the dead end of No. 14 Entry suggests propagation through rock in one measurement (Magnetic Channel C, right). The other two (Magnetic Channel A, left, and Electric Channel B, center) are inconclusive.

In a free space environment, within $\lambda/2\pi$ (273ft or 83m) we expect the magnetic signal to fall off as r^{-6} and the electric signal to fall off as r^{-4} . Past $\lambda/2\pi$, both signals should fall off as r^{-2} . In the complicated environment of the Safety Research Coal Mine, however, signal propagation will depend critically upon the idiosyncrasies of the mine infrastructure. We subjected the data collected from Receiver 101 to additional analysis to assess the power law behavior in the mine. Since Receiver 101 was off to the edge of the test environment, we have propagation data for this receiver at the greatest range. We performed a variety of regression analyses on the signal power versus range to determine the best fit to a power law of the form r^n . We fit the entire data set for each of three channel. Figure 40 shows signal power versus range for Receiver 101. There appeared to be a change in inclination of the roll-off so additionally, we compared a regression fit inside $\lambda/2\pi$ to a regression fit outside $\lambda/2\pi$.

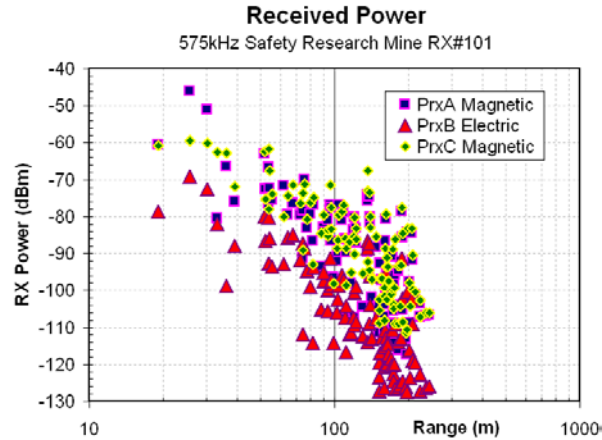


Figure 40: Received signal power versus range for Receiver 101.

Figure 40 clearly illustrates that the variations in signal strength versus range make signal strength only an approximate guide to range. Table 1 presents the results of the regression analysis for each of the three channels.

	Overall	r^2	Inside $\lambda/2\pi$	r^2	Outside $\lambda/2\pi$	r^2
A-Magnetic	-4.895 ± 0.407	0.596	-4.348 ± 0.904	0.524	-5.231 ± 0.975	0.275
B-Electric	-4.952 ± 0.380	0.634	-3.858 ± 1.020	0.405	-5.615 ± 0.884	0.347
C-Magnetic	-4.682 ± 0.359	0.634	-3.801 ± 0.752	0.549	-5.407 ± 0.868	0.338

Table 1: Regression analysis of received signal power versus range for Receiver 101.

The power law (r^{-n}) exponents for the three channels were identical to within the margin of error of the regression analysis. Fitting the entire data set yielded an estimate that propagation went approximately as $r^{-4.8 \pm 0.4}$. This suggests considerable mixing between the field components, either due to cross coupling in the antennas or cross-coupling due to the propagation environment. Correlation was somewhat weak with the regression model accounting for only 60% of the observed variation.

Looking at the correlations for inside $\lambda/2\pi$ versus outside $\lambda/2\pi$, deviation from linear increases markedly for increased distance. Inside $\lambda/2\pi$ the best fit was about $r^{-4.0 \pm 0.9}$ and outside $\lambda/2\pi$ the best fit was about $r^{-5.4 \pm 0.9}$. Correlations were weaker for the r^{-n} fits in this case, with the regression model accounting for only 50% of the observed variation inside $\lambda/2\pi$ and 32% outside $\lambda/2\pi$.

Since signal strength is not a terribly reliable measure of range, perhaps phase differences can help. Unfortunately, the phase response observed in the Safety Research Coal Mine was highly distorted by signal coupling to the mine infrastructure. Nevertheless, because the wavelength is so long, 1711ft (521m), the phase perturbations tend to be relatively gradual. Thus, a calibration or fingerprinting scheme can readily record the phase response at different locations and use the information as part of an overall tracking system. Appendix 4 presents the phase differences observed in the Safety Research Coal Mine study.

6.0 Conclusions

The Q-Track Corporation has assessed the feasibility of applying Near-Field Electromagnetic Ranging to the difficult problem of location awareness within coal mines. Our work established several key principles:

- 🔑 Vertical polarization performs better than horizontal polarization in underground environments.
- 🔑 A power law roll-off of about r^{-5} is a reasonable estimate for mine propagation.
- 🔑 Phase response is distorted by mine infrastructure but in a gradual, slowly varying fashion that lends itself well to an RF mapping or fingerprinting approach to tracking.
- 🔑 Current NFER prototypes could be the basis of a tracking system with a range of about 150-200m (450-600ft). Reasonably foreseeable improvements could substantially extend the range.

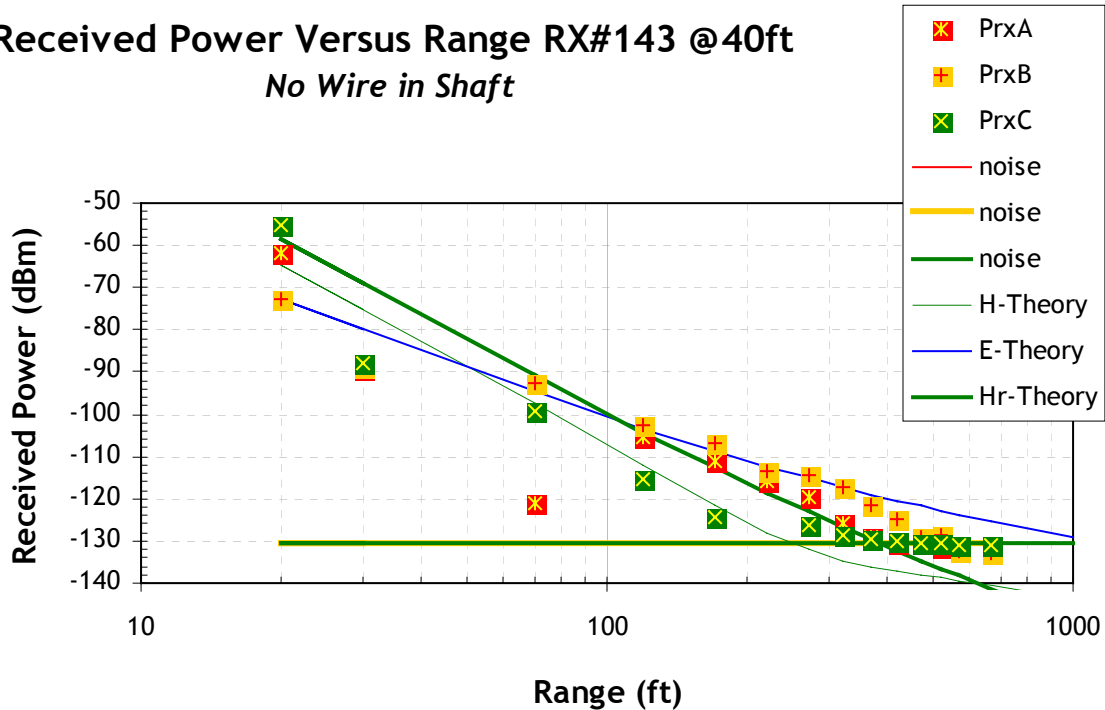
Our experience at the Safety Research Coal Mine suggests that existing NFER prototypes could be the basis of a tracking system with a range of about 150-200m (450-600ft). Q-Track's prototype transmitter used a $NIA = 0.0016\text{Am}^2$ signal source. Typical high performance mine transmit systems achieve $NIA = 2.5\text{Am}^2$, about 32dB stronger. With a r^{-5} propagation characteristic, 30dB in system improvements would extend range by a factor of about four (i.e. $30\text{dB}/5 = 6\text{dB}$, or to about 600-800m or 1800-2400 feet). With this kind of range, we can envision deploying a relatively limited number of receivers and obtaining accurate location information throughout mines of substantial size.

Q-Track is far from the first organization to attempt to use medium frequency signals within coal mines. As detailed in the introduction, typical MF communications systems have demonstrated reliable links at ranges of 120m in conductor free areas to 600m in the presence of conductors. But NFER location equipment has a substantial advantage. Typical communications gear might require a bandwidth of 10kHz to carry a voice channel or adequate data for a digital voice channel. NFER location equipment can operate on an unmodulated or slowly modulating carrier. At present, NFER receivers use a 500Hz filter to improve noise immunity. This bandwidth advantage results in $10\text{kHz}/500\text{Hz} = 20$ times less noise or a 13dB improvement in SNR relative to communications systems. This should enable NFER systems optimized for mine applications to ultimately achieve at least twice the range of comparable communications systems (i.e. $13\text{dB}/5 = 2.6$). With more narrow filtering, even greater range advantages relative to communications systems should be forthcoming.

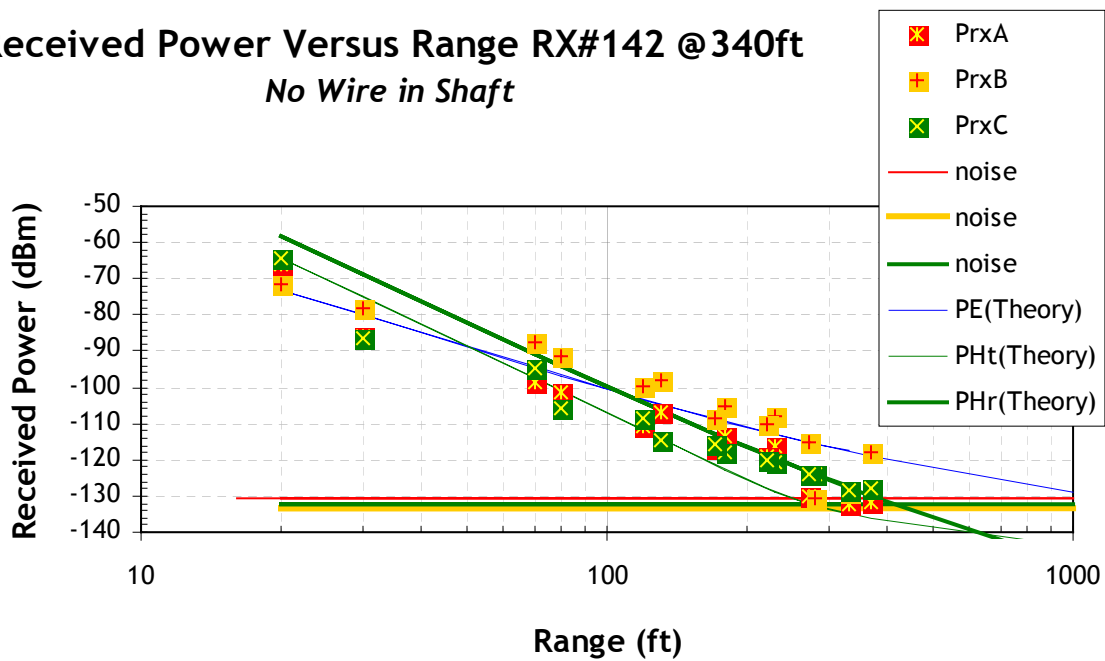
The Q-Track team believes that our Phase I experience demonstrates the feasibility of NFER tracking in coal mines. We will soon be submitting a proposal for a Phase II effort to implement a prototype system for tracking in a mine environment.

Appendix 1: Cave Mountain Results

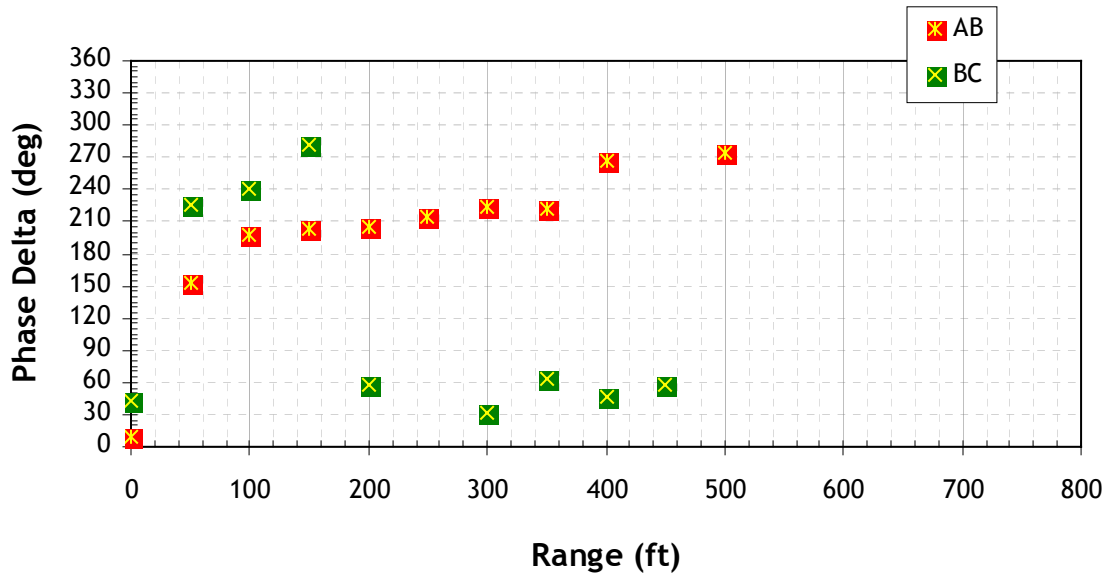
Received Power Versus Range RX#143 @40ft
No Wire in Shaft



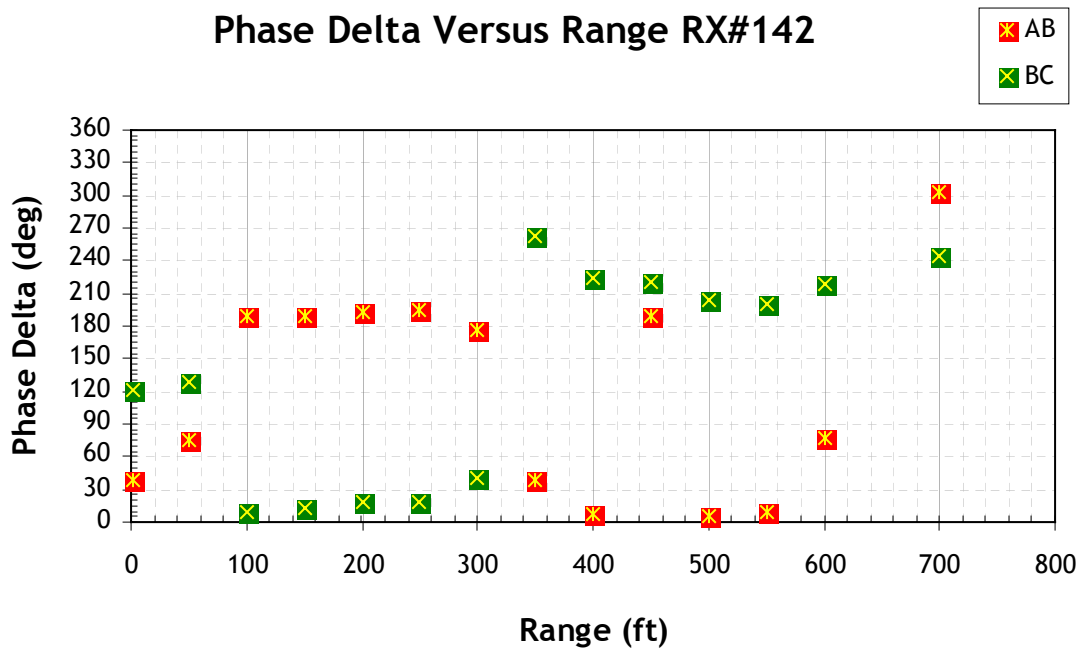
Received Power Versus Range RX#142 @340ft
No Wire in Shaft

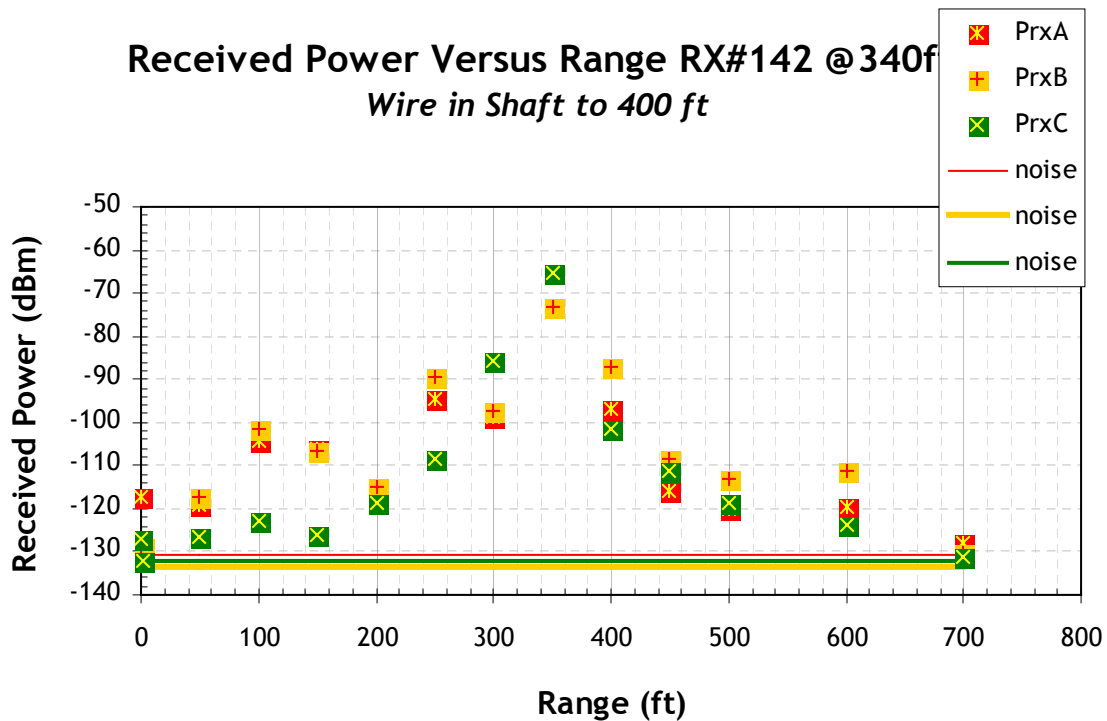
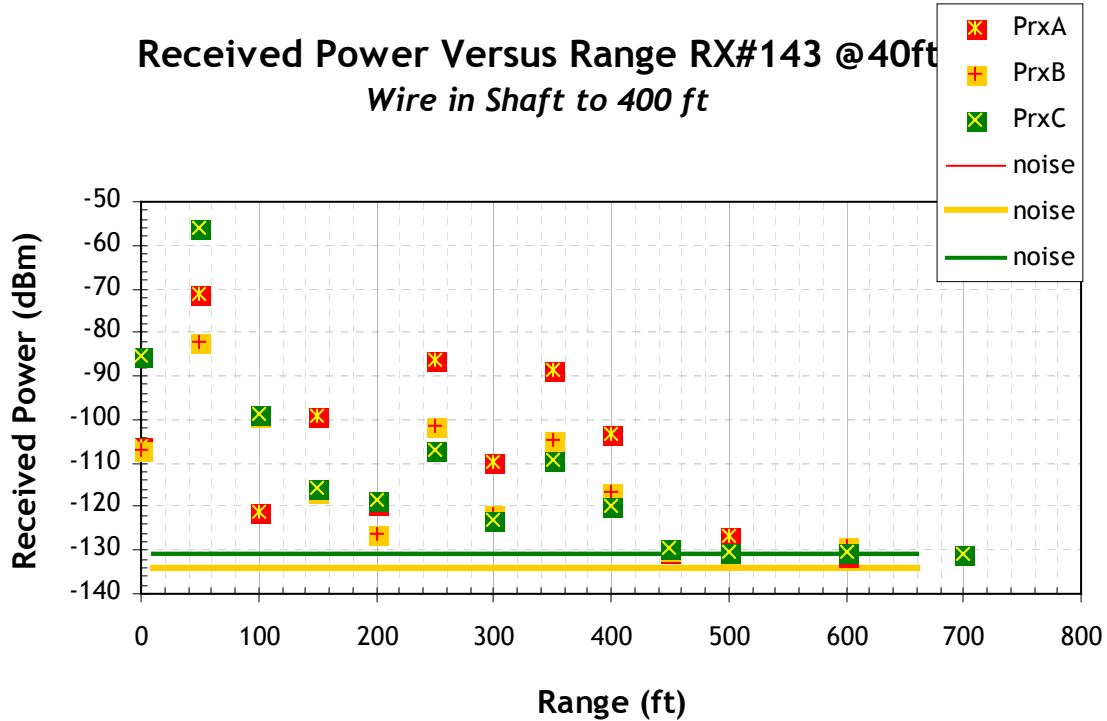


Phase Delta Versus Range RX#143

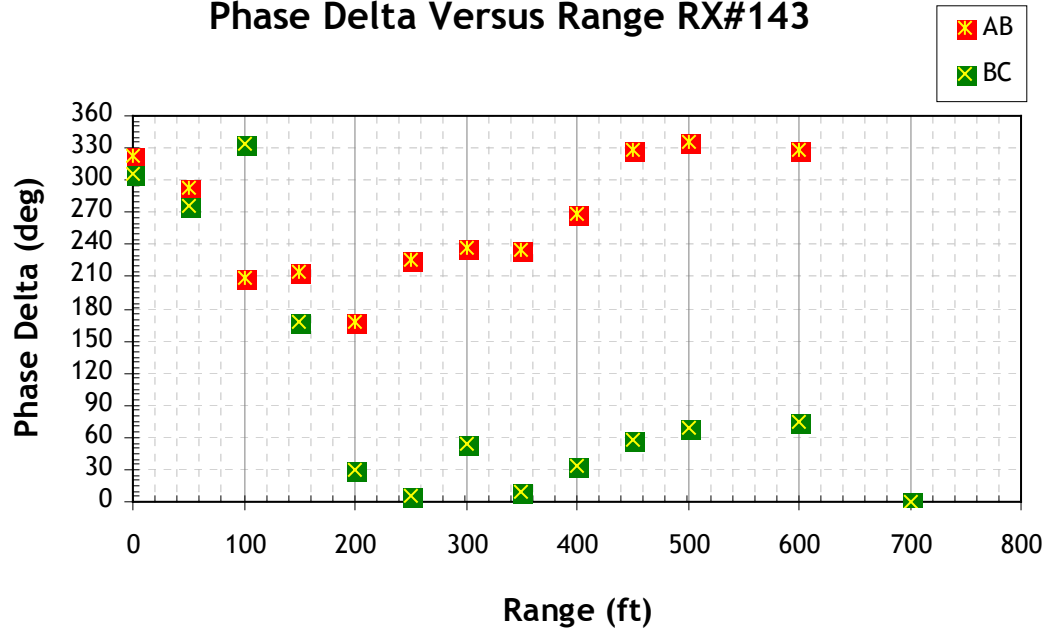


Phase Delta Versus Range RX#142

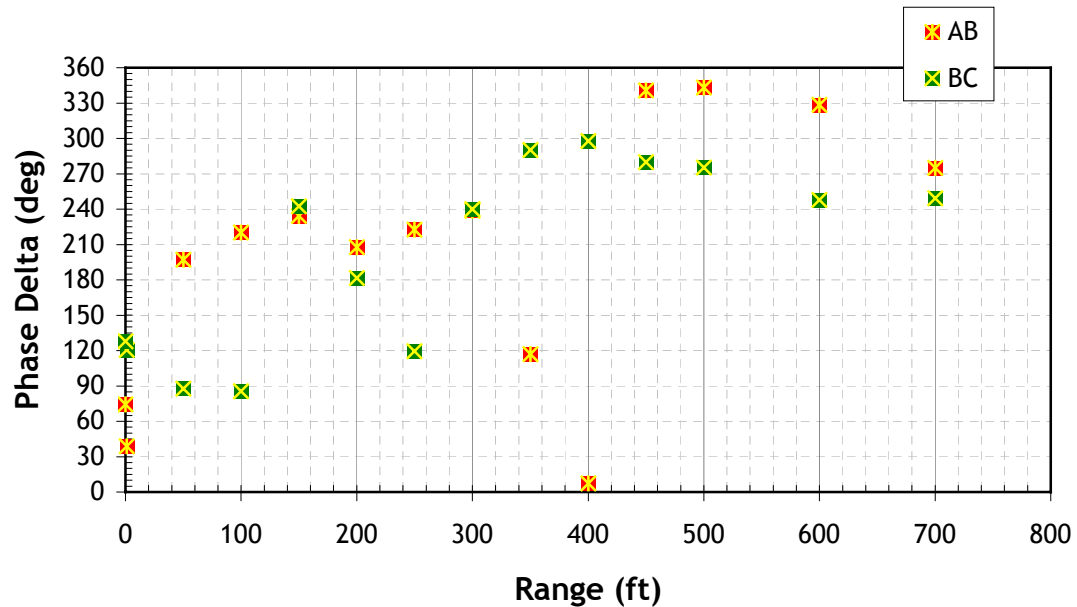




Phase Delta Versus Range RX#143

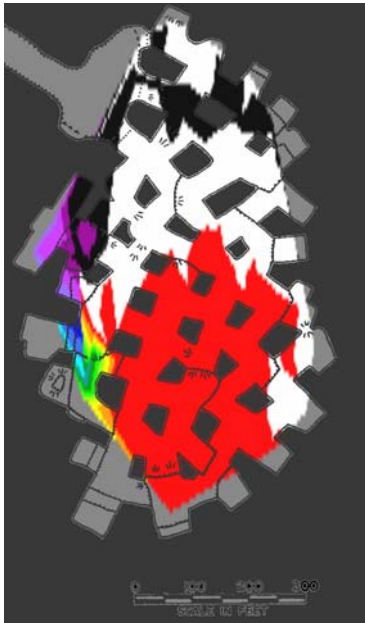


Phase Delta Versus Range RX#142

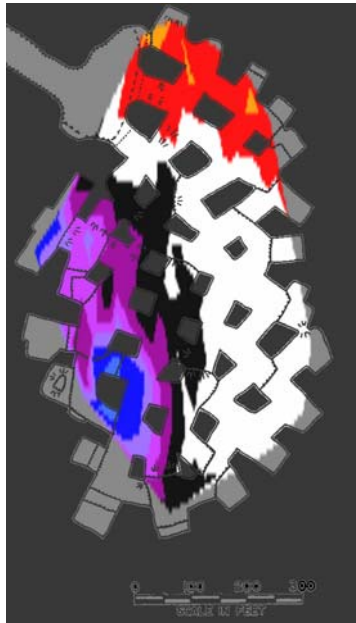


Appendix 2: Three Caves V-Pol Results

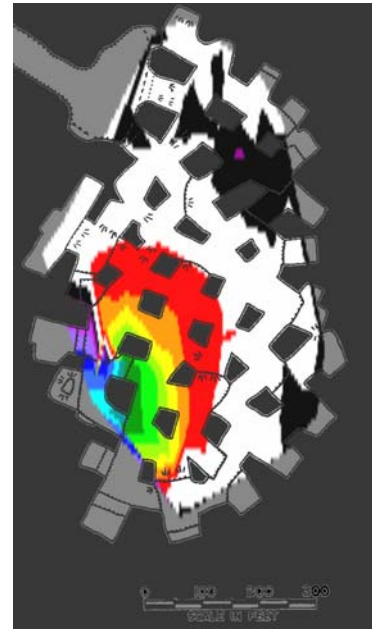
3 Caves V-Pol System Unit 123



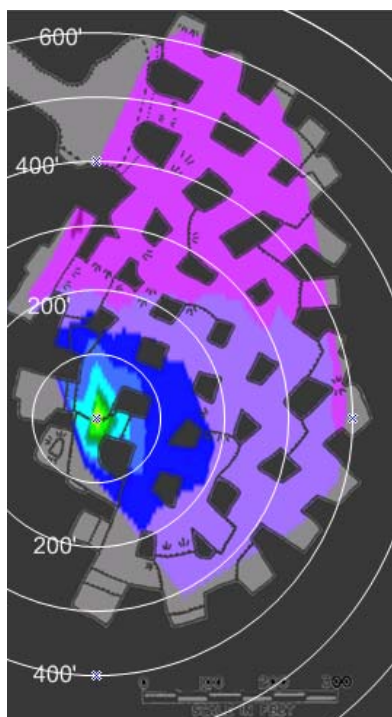
Phase AB



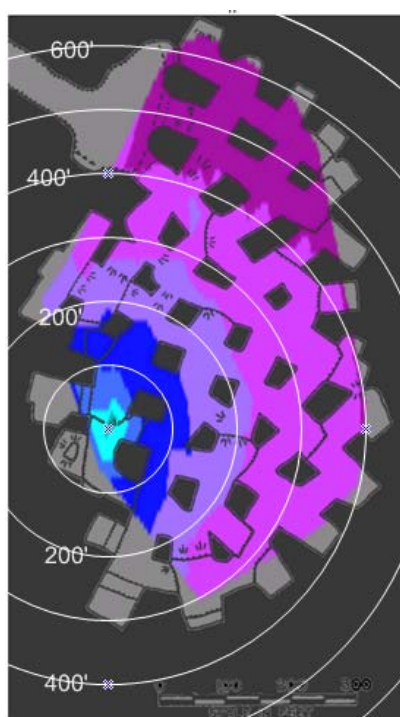
Phase AC



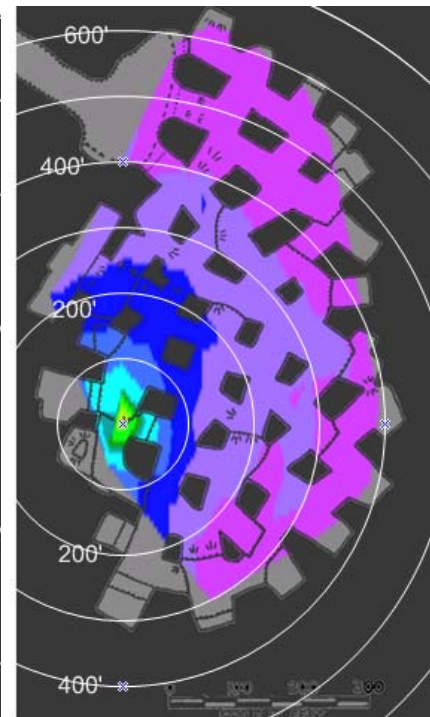
Phase BC



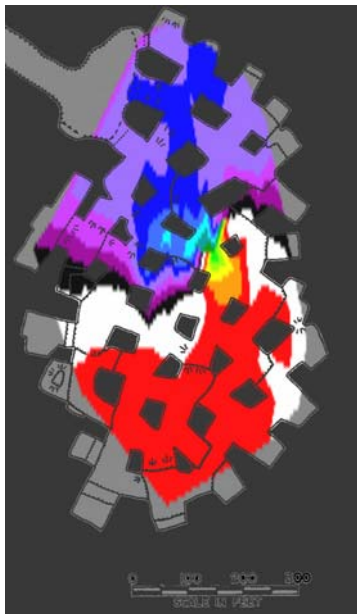
RSSI A



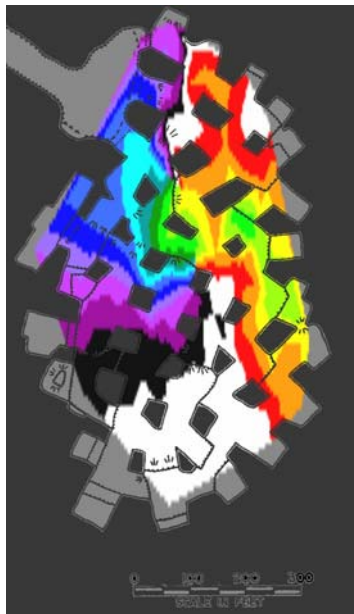
RSSI B



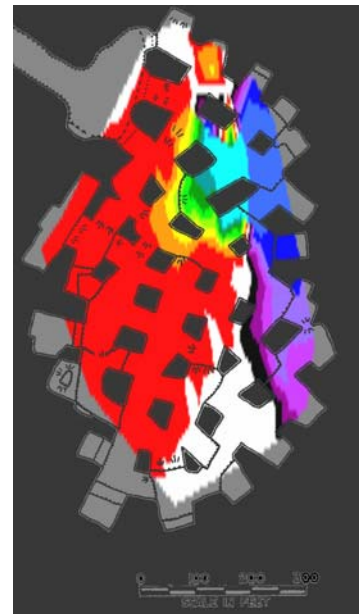
RSSI C



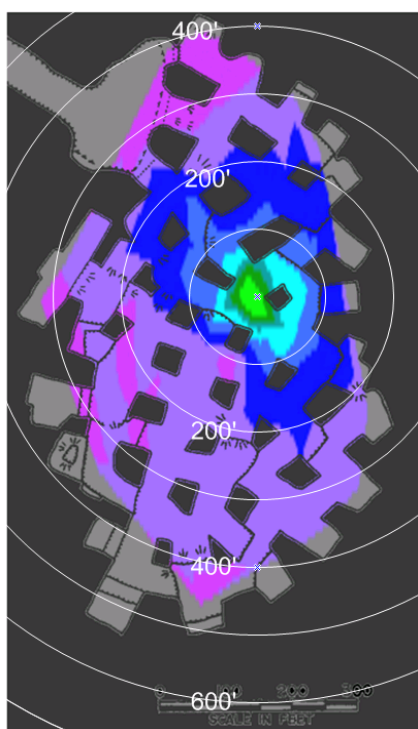
Phase AB



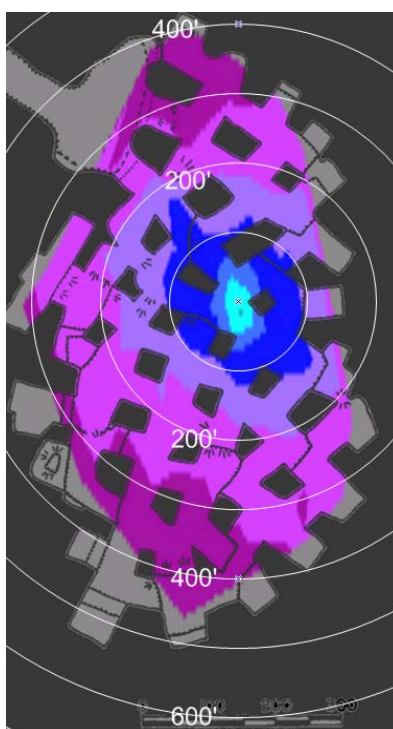
Phase AC



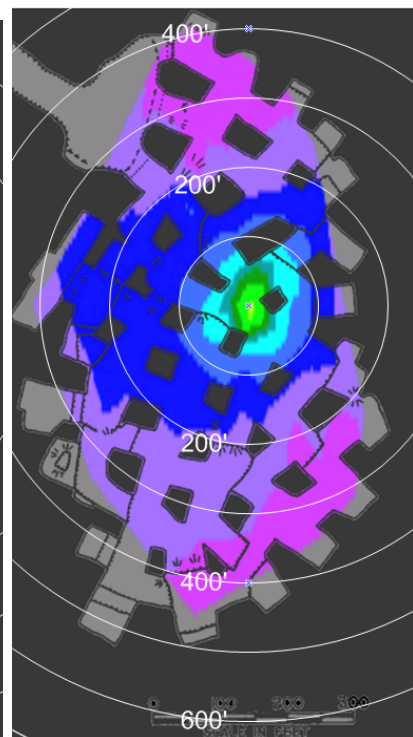
Phase BC



RSSI A

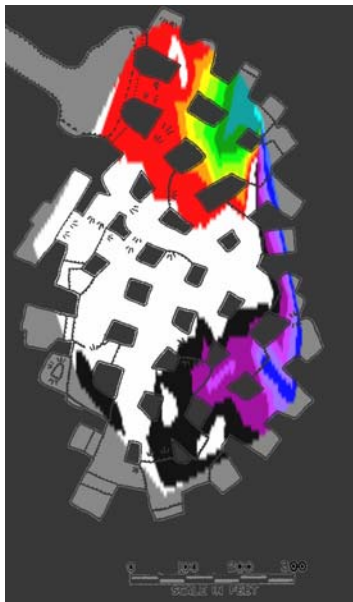


RSSI B

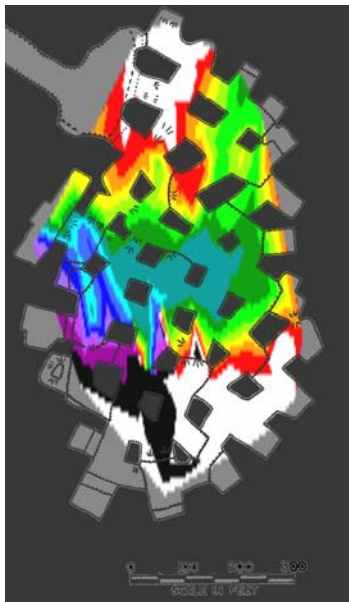


RSSI C

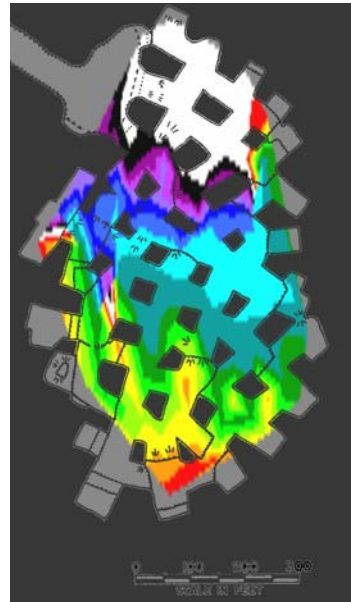
3 Caves V-Pol System Unit 141



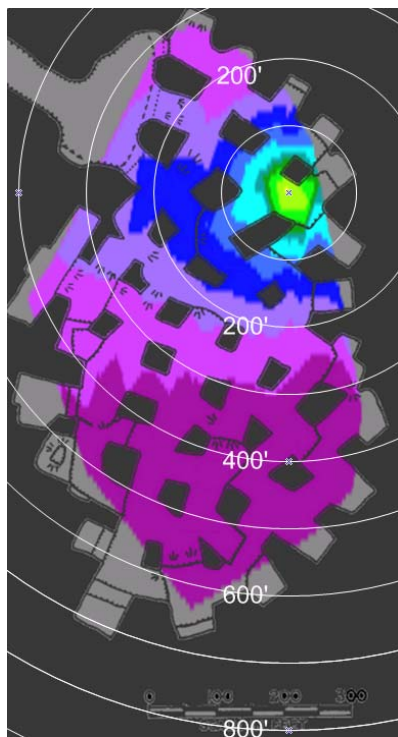
Phase AB



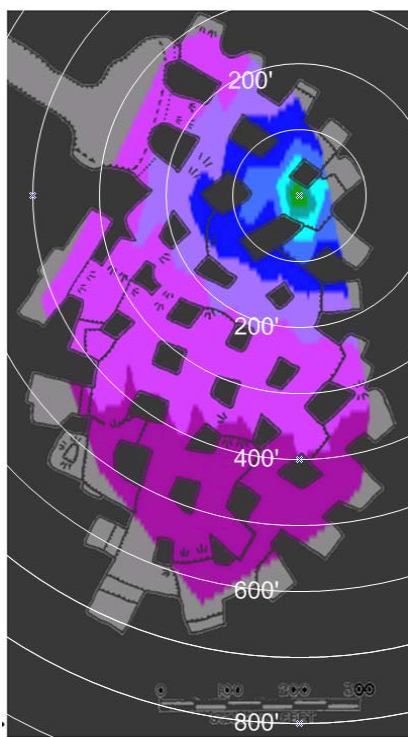
Phase AC



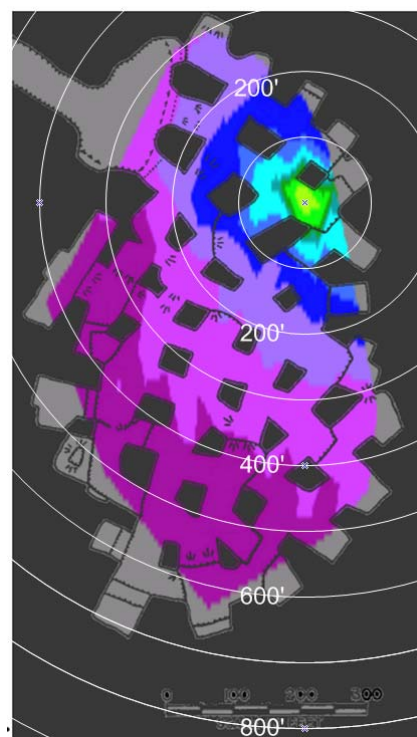
Phase BC



RSSI A

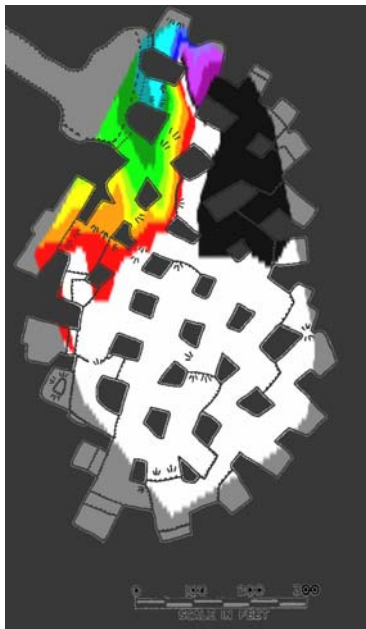


RSSI B

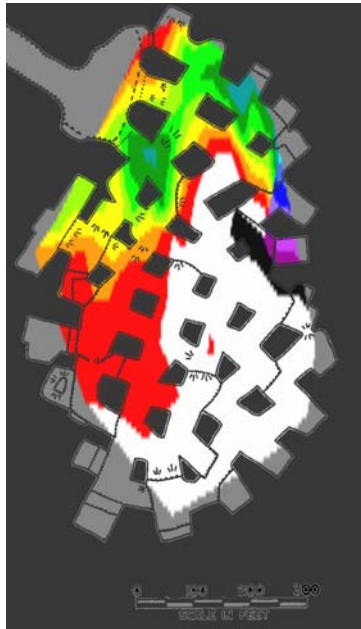


RSSI C

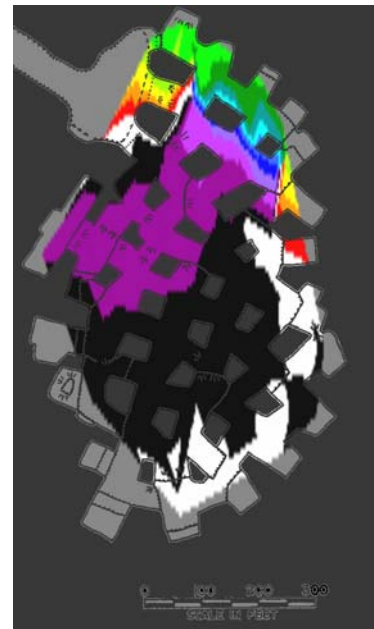
3 Caves V-Pole System Unit 143



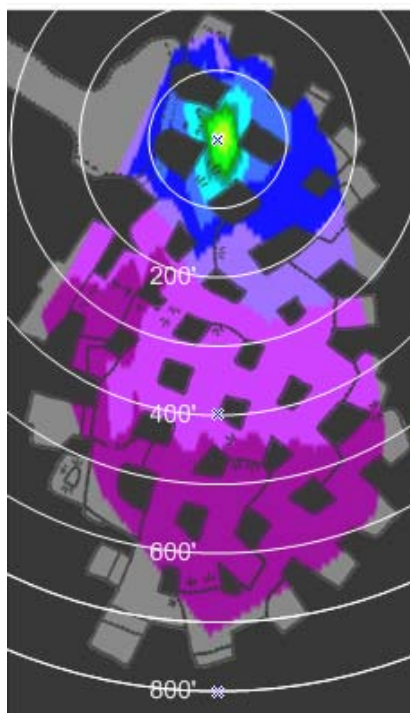
Phase AB



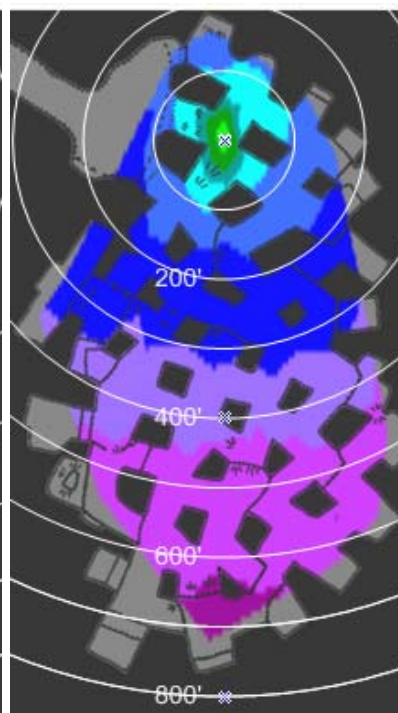
Phase AC



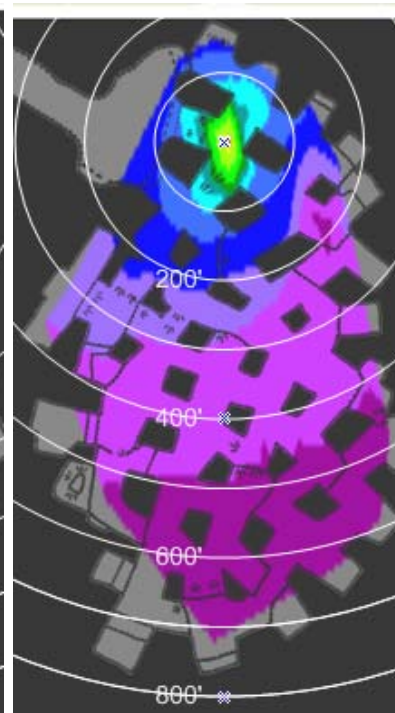
Phase BC



RSSI A



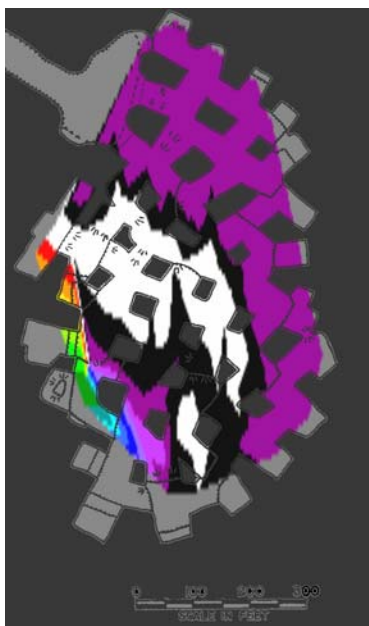
RSSI B



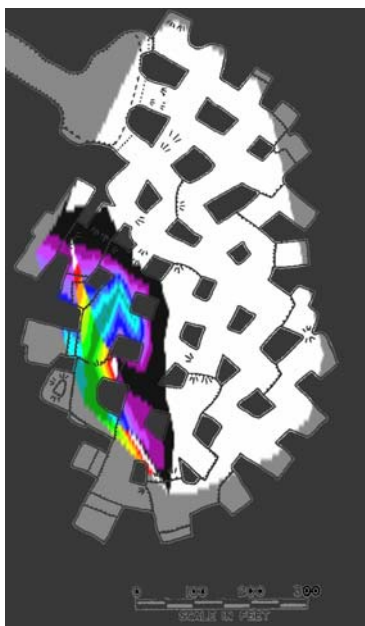
RSSI C

Appendix 3: Three Caves H-Pol Results

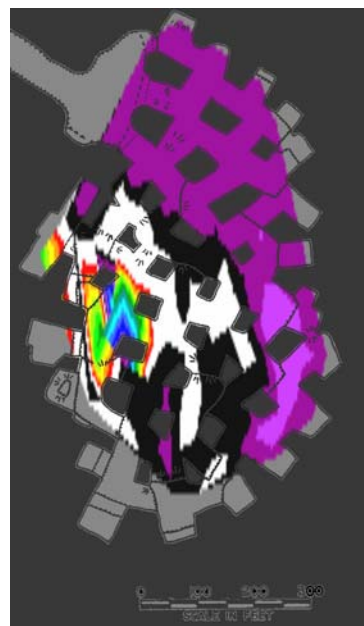
3 Caves H-Pol Unit 137



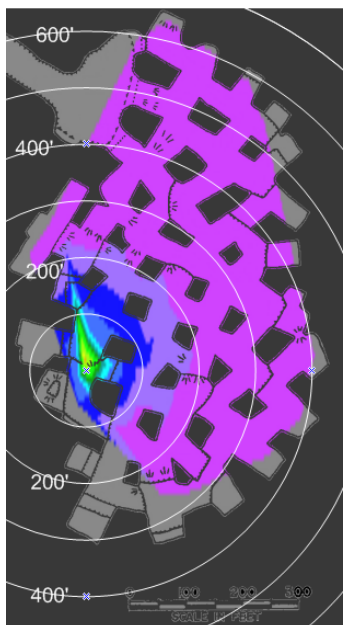
Phase AB



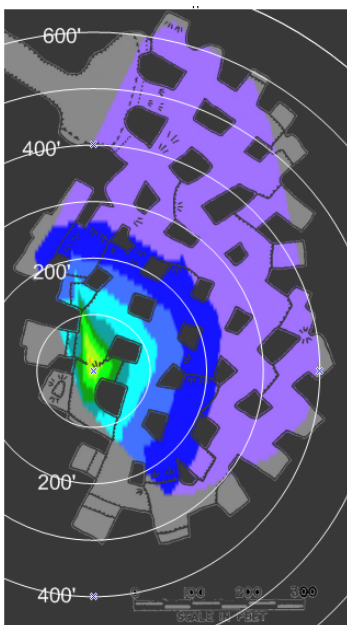
Phase AC



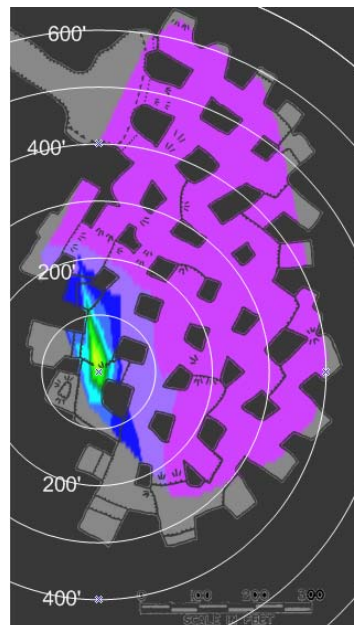
Phase BC



RSSI A

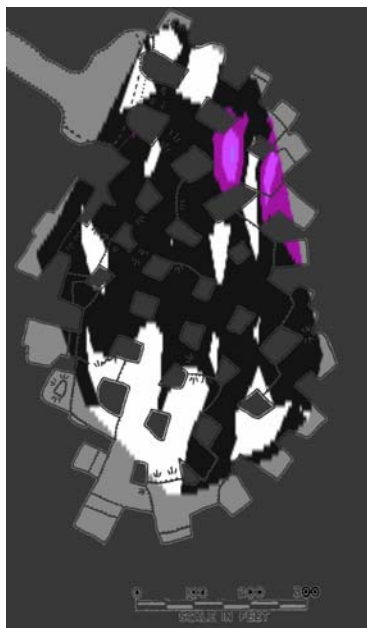


RSSI B

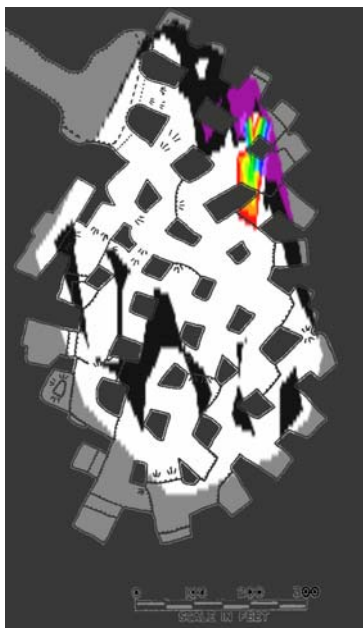


RSSI C

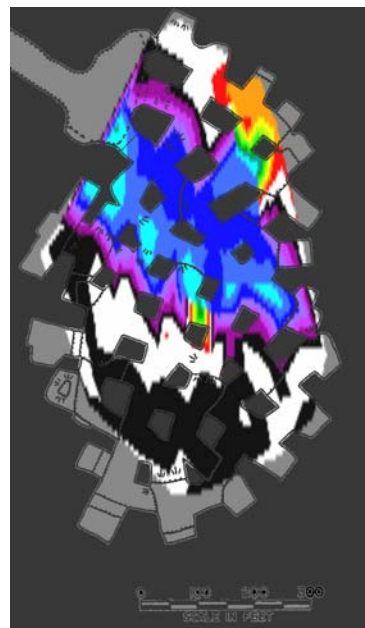
3 Caves H-Pol Unit 139



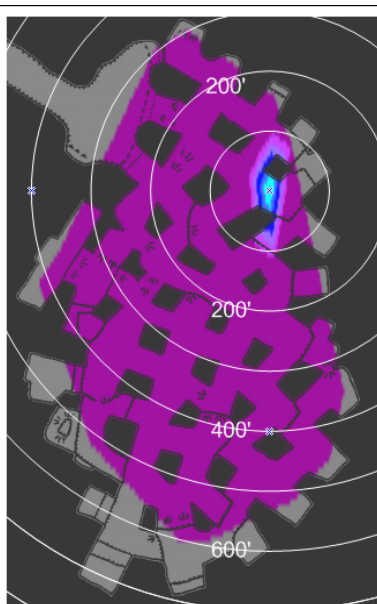
Phase AB



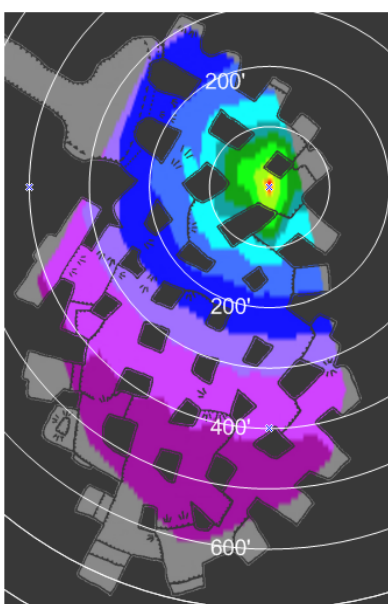
Phase AC



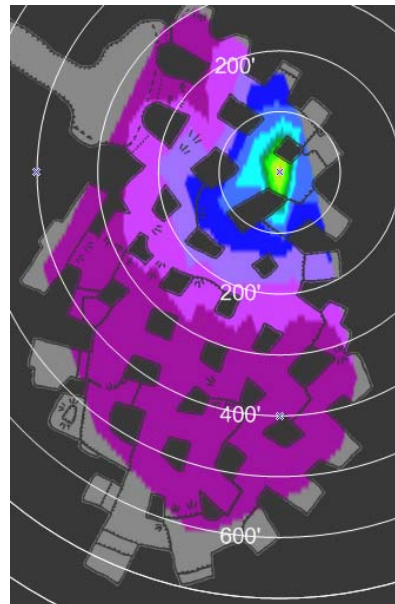
Phase BC



RSSI A



RSSI B

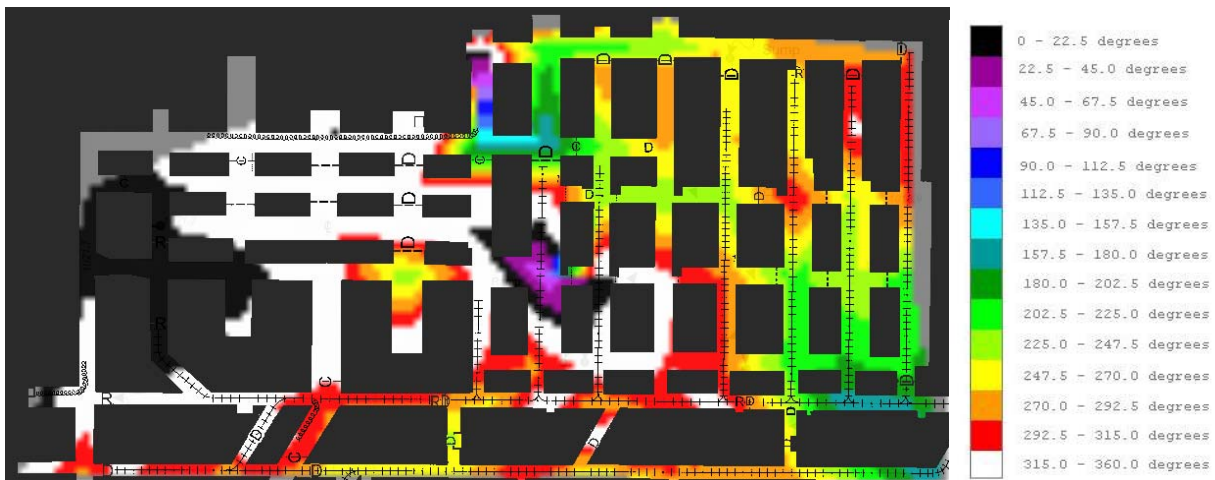


RSSI C

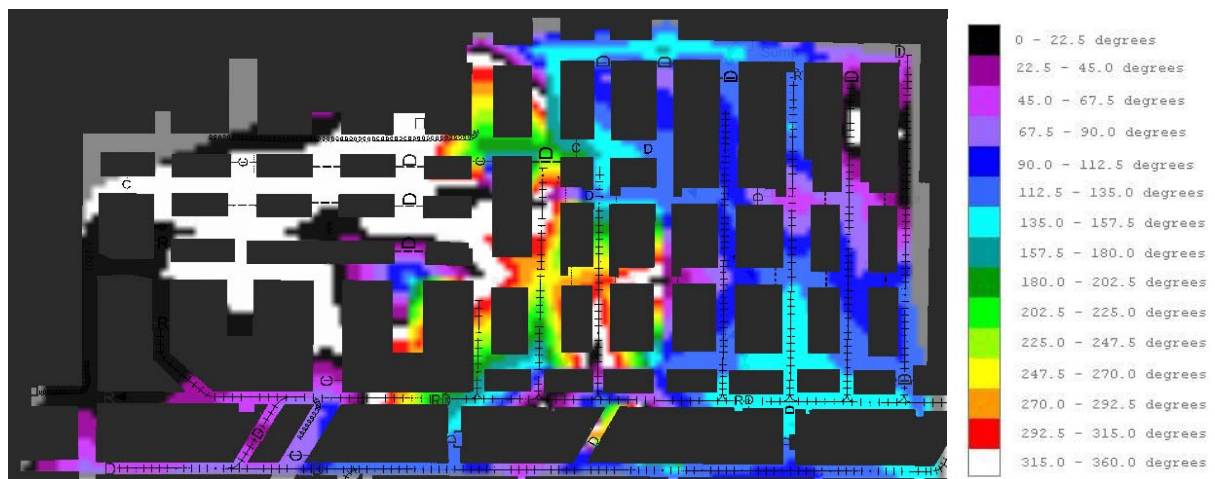
Appendix 4: Safety Research Coal Mine-Phase Delta Response



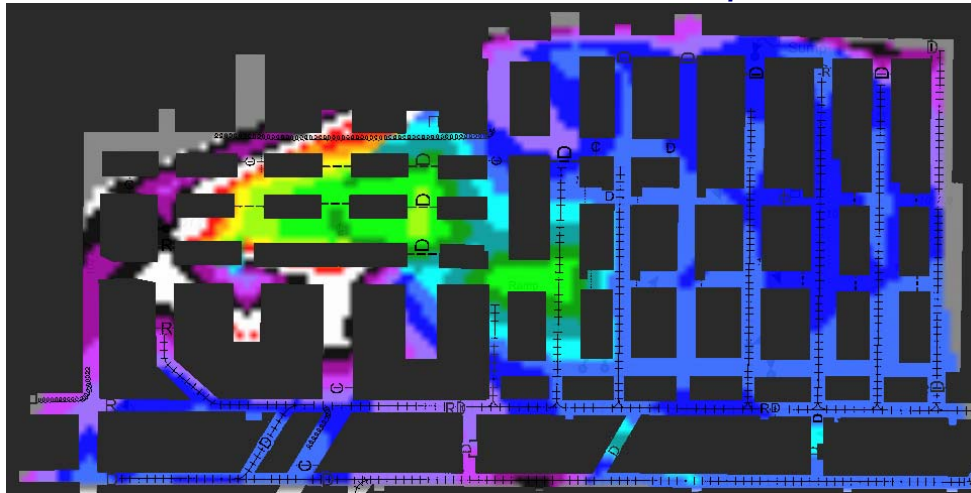
Receiver 101 Phase Difference Between A & B



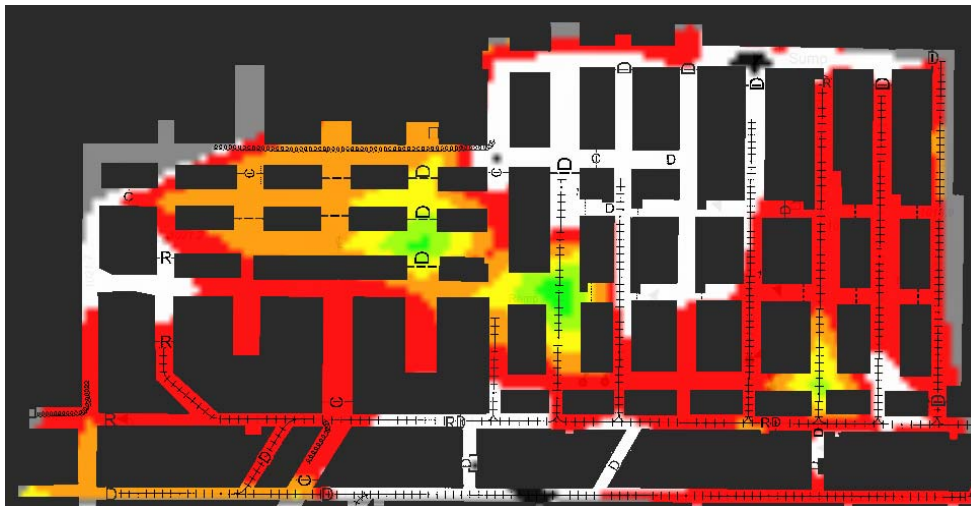
Receiver 101 Phase Difference Between B & C



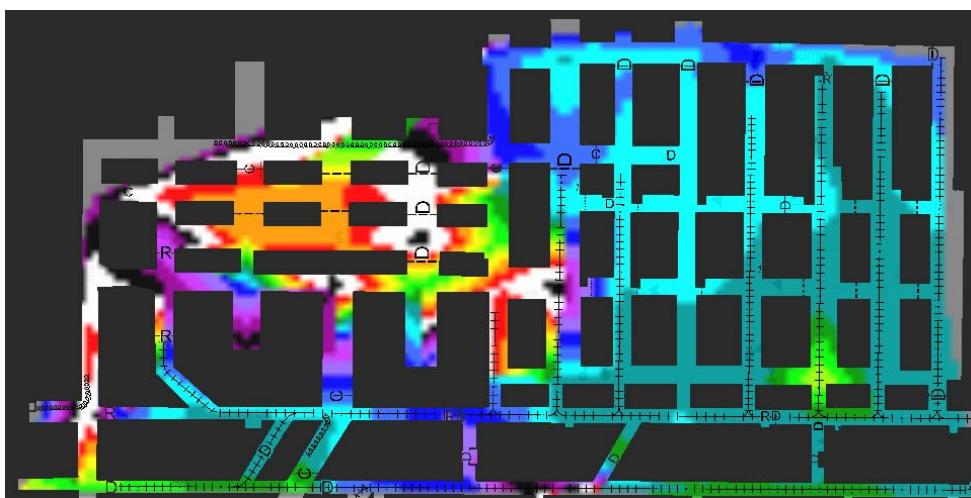
Receiver 101 Phase Difference Between A & C



Receiver 102 Phase Difference Between A & B



Receiver 102 Phase Difference Between B & C



Receiver 102 Phase Difference Between A & C

