# Theory and Practice of Near-Field Electromagnetic Ranging

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## BIOGRAPHY

Dr. Hans Schantz is CTO of the Q-Track Corporation, and a co-inventor of NFER® technology. His prior work experience includes stints with IBM, the Lawrence Livermore National Lab, The ElectroScience Lab of the Ohio State University, and Time Domain Corporation. Author of ***The Art and Science of Ultra-wideband Antennas*** (Artech House, 2005), his thirty-five U.S. patents include antennas, RF systems, RF-based location systems, and related inventions. He is a Senior Member of the IEEE, and an amateur radio operator [KC5VLD]. Schantz earned his Ph.D. in physics from the University of Texas at Austin. He also holds degrees in Industrial Engineering and Physics from Purdue.

## ABSTRACT

This paper illustrates the divergence of phase, signal, and energy velocities in the near field by employing space-time diagrams of the evolution of near-fields. In addition this paper describes near-field link and impedance relations a near-field phase diagram for electrically small quadrature transmitters. Near-field physics enables near-field electromagnetic ranging systems in a variety of modes for a diverse range of applications. This paper summarizes recent results applying near-field electromagnetic ranging to a Signal-of-Opportunity Location Device (SOLD) implementation. Q-Track tested this system in realistic environments including a multi-story building and underground. SOLD yielded an rms accuracy of 26cm when returning to a calibration point and 46cm rms between calibration points.

## INTRODUCTION

The fascinating physics of near-field signal phenomena supports a novel tracking system well suited for urban and indoor tracking applications. "Near-field electromagnetic ranging" exploits the superior penetration, diffraction, and all-around propagation properties of low-frequency signals. By applying near-field physics to the problem of precision location, this approach offers a potential alternative to conventional RF-based navigation techniques. Typically operating at FCC Part 15 power levels in the AM broadcast band at frequencies around 1MHz and with wavelengths around 300m, near-field electromagnetic ranging is available in a variety of modes for a diverse range of applications. This paper explains some of the physics underlying Near-Field Electromagnetic Ranging or NFER® technology and summarizes recent results applying NFER® to a path-finding first responder guidance system, as well as a signal-of-opportunity location device implementation.

## NEAR-FIELD ELECTROMAGNETIC VELOCITY

In far-field electromagnetics, “velocity” is a simple concept because signals, phase, and energy all propagate at the speed of light. In the near-field however, within about one-quarter wavelength or so of an electrically small transmitter, these relationships become much more complicated. This section explains the various velocities and explores their near-field behavior.

The signal velocity is that universal constant, the speed of light ($c$ = 299,792,458m/s). The rectangular components of the E and H fields satisfy the scalar wave or Helmholtz equation:[1,2]

$$\nabla^2\psi - \frac{1}{c^2}\frac{\partial}{\partial t}\psi = 0. \tag{1}$$

In the limit of a 1-D wave propagating in the z direction, we define advanced and retarded time variables $u = z - ct$ and $v = z + ct$ whereupon the Helmholtz equation may be rewritten:

$$\frac{\partial^2\psi}{\partial u \partial v} = 0 \tag{2}$$

with solutions of the form $\psi(z,t) = F(u) + G(v)$. The more general case is necessarily much more complicated. Nevertheless, all time-dependent solutions of Maxwell’s equations in free space end up being advanced or retarded functions of time in which changes of state propagate at the speed of light.[3] This physical principle holds true in both near-field and far-field zones. However, the near-field is a supposition of radiation, inductive, and static fields that interfere with each other in complicated ways to yield phase and energy velocities that diverge from the speed of light.

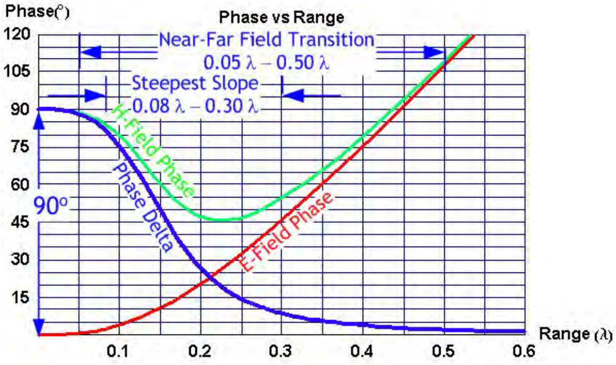


**Fig. 1** Near-field phase relations for an electric dipole.

Phase propagation for a steady-state system can appear to operate at superluminal speeds, in a fashion first identified by Heinrich Hertz in the 1880s.[4] Initially, the electric field phase propagates superluminally, gradually slowing down to the speed of light within a few wavelengths. The magnetic field phase is "antichronous," propagating backwards in time for the first quarter wavelength. Then, magnetic phase propagates forwards, at superluminal speeds. Gradually slowing down to the speed of light within a few wavelengths, the magnetic phase eventually converges with the electric field phase. Figure 1 shows these relations.

Figure 1 also demonstrates why conventional Time-of-Flight (ToF) and Time-Difference-of-Arrival (TDoA) location techniques are problematic in the near-field zone (i.e. with low frequency signals at ranges less than a wavelength). Because the electric field phase propagates superluminally, it changes much more slowly with range than would be expected under far-field assumptions. This makes an inference of range challenging. Using magnetic field phase is even more problematic, because it is double-valued and therefore ambiguous. But, note one interesting feature of the near-field phases.

The E- and H-fields are in quadrature close to the dipole source and converge to be synchronous about a half wavelength away. This quadrature is consistent with "imaginary," stored, or reactive energy close to the dipole source, while synchronous fields are consistent with "real" or radiative energy expected in the far-field zone.[5] Although near-field phase anomalies complicate near-field RF ranging, exploiting the common-mode difference between these phases, yields a good metric for range. The range may be readily inferred from the phase delta between the electric and magnetic fields ($\Delta\phi = \phi_H - \phi_E$): [6]

$$r = \frac{\lambda}{2\pi}\sqrt[3]{\cot\Delta\phi} \qquad (3)$$

This near-field property, the blue curve in Figure 1, has proven useful for determining location.[7]

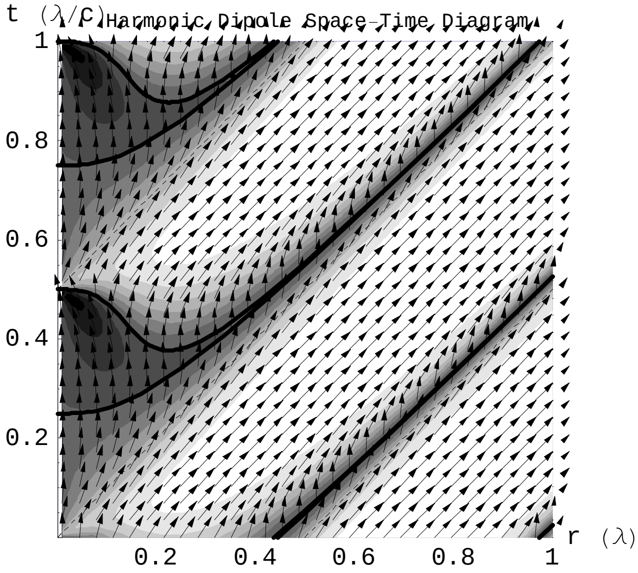


**Fig. 2** Space-time diagram for radial energy flow around an elemental dipole.

The final near-field velocity is the energy velocity, first identified by Heaviside:[8]

$$v_u = \frac{\mathbf{S}}{u} = \frac{\mathbf{E}\times\mathbf{H}}{\frac{1}{2}\varepsilon_0|\mathbf{E}|^2 + \frac{1}{2}\mu_0|\mathbf{H}|^2} \qquad (4)$$

where $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ is the Poynting vector and the energy density is $u = \frac{1}{2}\varepsilon_0|\mathbf{E}|^2 + \frac{1}{2}\mu_0|\mathbf{H}|^2$.[9] Elsewhere, the author has demonstrated how an effective radial energy velocity can be obtained by averaging over the spherical shell at a particular radial distance.[10] This energy velocity can be depicted on a "space-time" diagram as in Figure 2. The vertical axis depicts time, and the horizontal axis represents distance. The axes are scaled one wavelength in radial distance and one period in time so that energy propagating away at the speed of light travels at a 45 degree angle to the right. The dark lines trace the phase behavior depicted in Figure 1. These are the space-time surfaces on which the electric or magnetic fields go to zero. When this happens, the energy velocity instantaneously goes to zero as well. The shading denotes the magnitude of the energy velocity, with white denoting radiation and darker colors denoting absorption. The phase relations of Figure 1 track this transition from the reactive ebb and flow of energy to the far-field propagation of radiation energy.

The near-field exhibits additional complexities. The field impedance is $Z_S$ = E/H = 376.7 Ω for far-field signals. For near-field signals the impedance diverges depending on whether the source is magnetic or electric.[11] For a magnetic dipole source, magnetic fields dominate so the impedance is lower than for far-field signals. For an electric dipole source, electric fields dominate so the field impedance is higher than for far-field signals. Figure 3 shows this behavior.

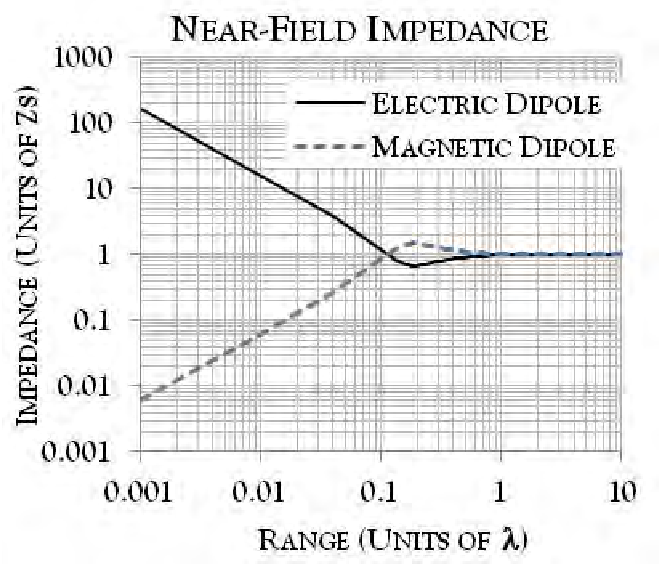


**Fig. 3** Near-field impedance relative to $Z_S = 376.7\ \Omega$

In summary, phase, signal, and radiation energy propagation all occur at the speed of light in far-field signals. Although near-field signals propagate at the speed-of-light, reactive electromagnetic energy itself propagates at much lower velocities. This remarkable divergence of signal, energy, and phase velocities complicates low-frequency RF-based location systems. Conventional time-of-flight (ToF) or time-difference-of-arrival (TDoA) techniques that assume far-field phase propagation in the near-field zone are unlikely to succeed. Instead, a comparison of the electric-magnetic phase delta has shown considerable promise. In addition, near-field RF location systems benefit from more trackable parameters than comparable far-field systems. Figure 4 summarizes this difference between the available near-field and far-field parameters.

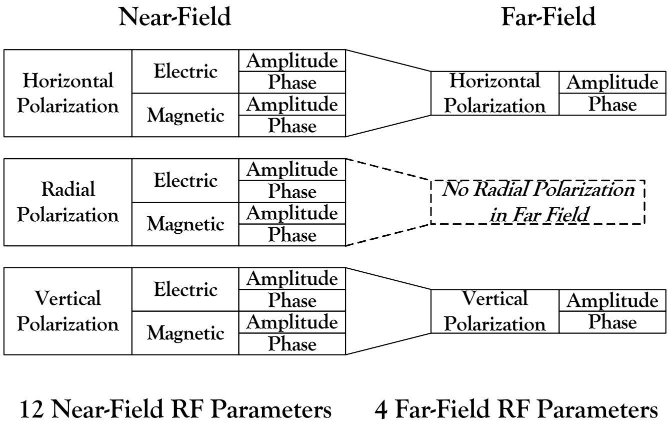


**Fig. 4** Near-field links offer more trackable parameters than far-field links.

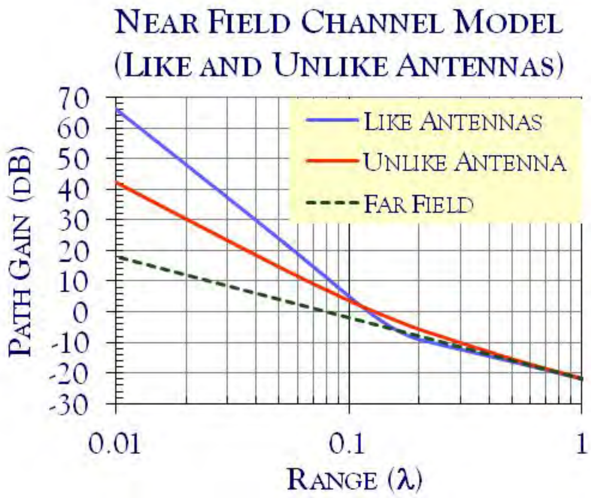


**Fig. 5** Near-field channel for like and unlike antennas.

## NEAR-FIELD PROPAGATION

Near-field propagation also exhibits idiosyncrasies. The Friis Law diverges in the near-field region depending upon whether the link comprises "like" antennas (i.e. both electric or both magnetic) or "unlike" antennas (i.e. one electric and one magnetic). In general, the gain of electrically small antennas tends to be quite low, so as to balance out the path gain of the near-field link.[12] For "like" antenna links, the link law is:

$$P_{like}(kr)=\frac{P_{RX}}{P_{TX}}=\frac{G_{TX}G_{RX}}{4}\left(\frac{1}{(kr)^2}-\frac{1}{(kr)^4}+\frac{1}{(kr)^6}\right) \tag{5}$$

where $k = 2\pi/\lambda$. The near-field path gain for like antennas goes as as $kr^{-6}$, so the path gain increases as 60dB per decade with decreasing range. For "unlike" antenna links, the link law is:

$$P_{unlike}(kr)=\frac{P_{RX}}{P_{TX}}=\frac{G_{TX}G_{RX}}{4}\left(\frac{1}{(kr)^2}+\frac{1}{(kr)^4}\right) \tag{6}$$

The near-field path gain for unlike antennas goes as $kr^{-4}$, so the path gain increases as 40dB per decade with decreasing range. Figure 5 shows this behavior.

## ELECTRICALLY SMALL ANTENNAS

Electrically small antennas pose particular challenges to the RF designer. An electric antenna provides an omnidirectional vertically polarized signal, and a magnetic antenna provides an omnidirectional horizontally polarized signal as seen in Figure 6.

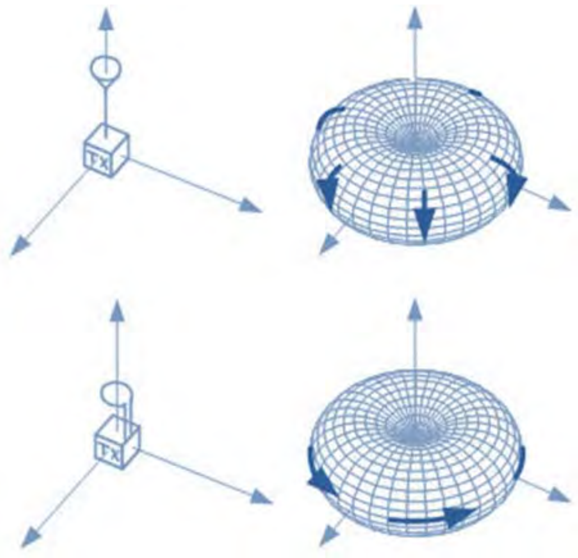
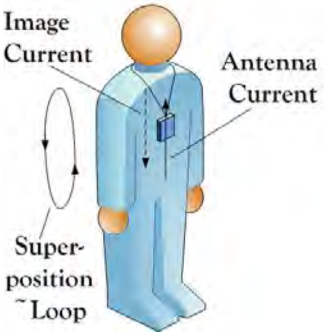
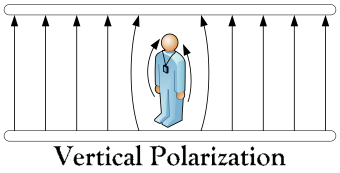


**Fig. 6** An electric antenna provides an omnidirectional vertically polarized signal. A magnetic antenna provides an omnidirectional horizontally polarized signal.

Electric antennas (like whips) are prone to coupling to the human body, as shown in Figure 7a. An electric antenna current creates an equal and opposite image current. The superposition of these currents yields a loop-like current distribution that destroys the desired electric antenna pattern. Magnetic antennas (like loops) are better behaved in close proximity to the human body. But the horizontally polarized signals from small loop antennas tend to propagate more poorly than vertically polarized signals, as shown in Figure 7b and 7c.





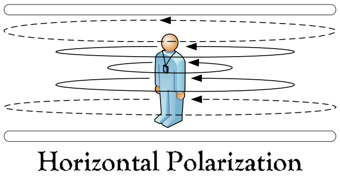


**Fig. 7a (left)** An electric antenna couples with the human body generating an opposing image current that confounds the desired pattern.

**Fig. 7b (top-right)** Vertically polarized signals propagate well in indoor environments where floor and ceiling resemble ground planes.

**Fig. 7c (bottom-right)** Horizontally polarized signals propagate poorly in indoor environments where they tend to be shorted out by the floor and ceiling ground planes.

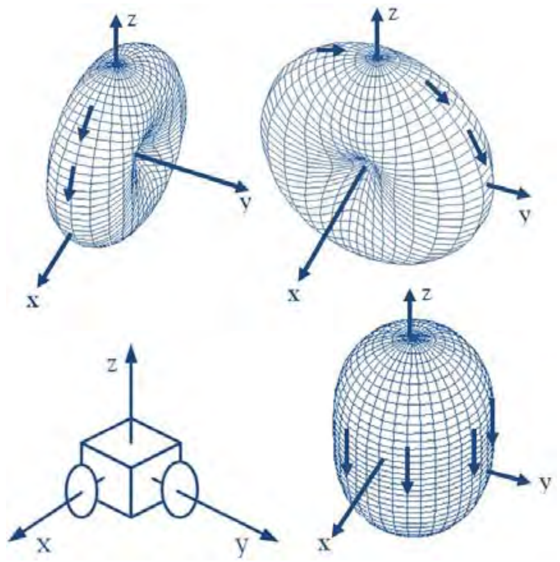


**Fig. 8** A quadrature fed orthogonal magnetic antenna system.

The solution is to employ a transmitter with orthogonal magnetic loop antennas driven in quadrature. This system generates a quasi-isotropic pattern with unusual phase characteristics. The angular momentum imparted to the transmitted signals by the rotating fields causes the energy flow to curve approximately ninety degrees during the transition from the source to the far-field zone. The resulting energy trajectory lies on a line tangent to a circle of radius λ/π from the quadrature source. For instance, conventional direction finding techniques will yield an angle-of-arrival along a tangent line λ/π away from the source. The rotating fields mix the longitudinal and transverse polarization components to yield an angle and range dependent electric-magnetic phase response that "spirals" in the near-field zone around a transmitter, as shown in Figure 9.[13]

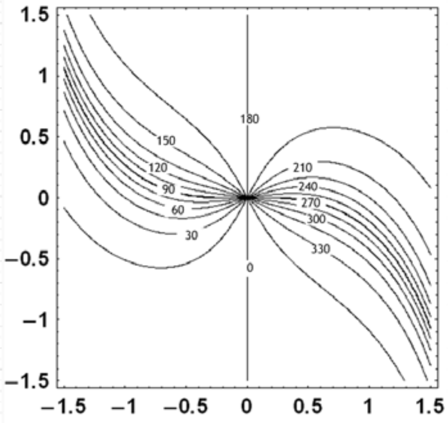


**Fig. 9** Electric-magnetic phase difference for a quadrature fed orthogonal magnetic antenna system (scale in units of $kr = 0.16\lambda$).

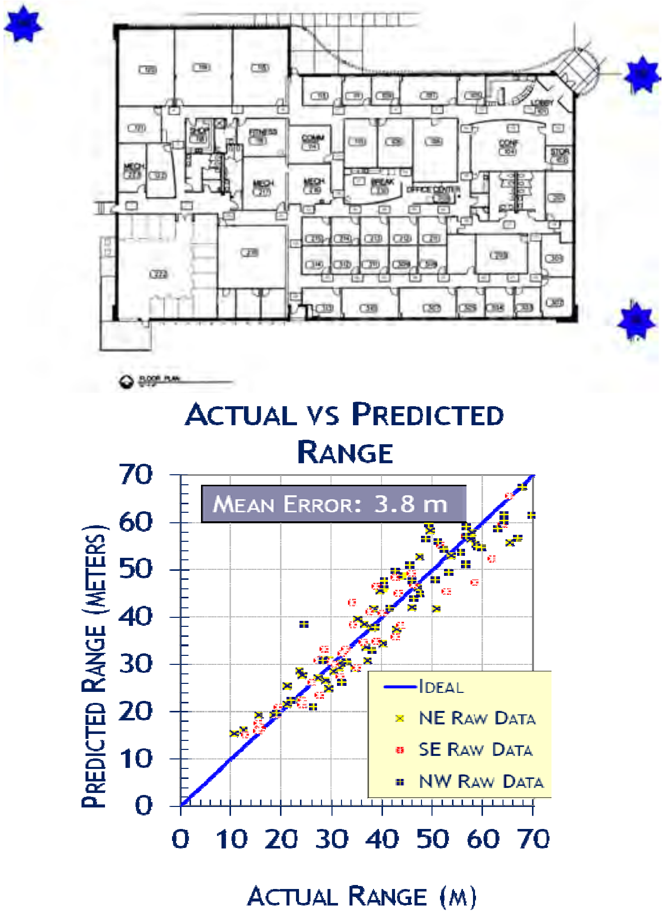
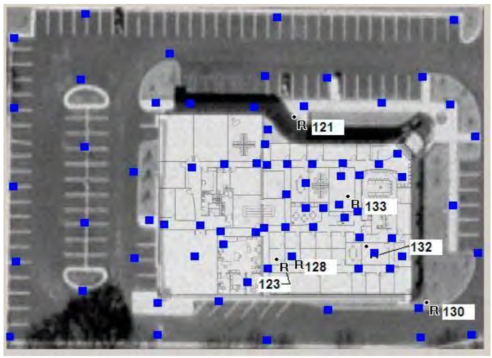


**Fig. 10** In an indoor-to-outdoor tracking test, mean error increased from about 10cm open field to 3.8m in a building.

## NFER RTLS INDOORS

In an open-field environment, a 1.3MHz NFER accuracy is on the order of 15cm (6in) for a 1.3MHz system operating out to 60m (200ft) range.[5] However, large scale conductors like electric lines and building structures tend to distort these phase responses. Fig. 10 shows data for a ranging test at three locations around an office building. The mean error was 3.8m.

A usual office environment has a multipath delay spread of about 4-25ns.[14] This corresponds to 1.2m - 7.5m error for time-of-flight location systems. Also, for typical microwave signals (assume $f$ = 2.4GHz and $\lambda$ = 12.5cm), even the most modest delay spread means phase is essentially uncorrelated. For a low frequency, long-wavelength signal (assume $f$ = 1MHz and $\lambda$ = 300m) however, the typical indoor delay spread yields modest phase perturbations of about 1-9 deg. These perturbations tend to be relatively gradual and monotonic as shown in the electric-magnetic phase delta measurements of Fig. 11. Thus, a near-field RF-fingerprinting approach yields precise geolocation indoors.



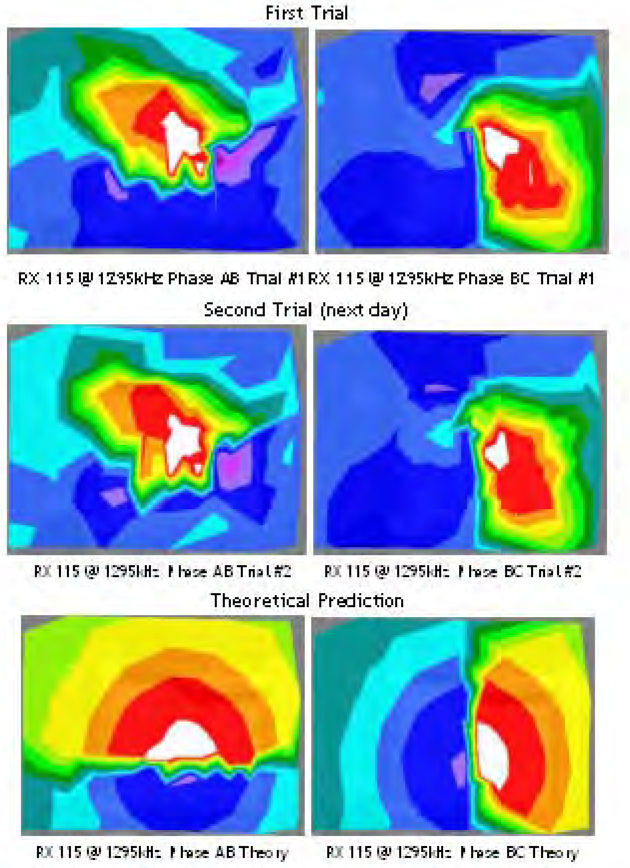


**Fig. 11** Buildings perturb near-field signals in a gradual, monotonic fashion as shown in this comparison of near-field phase delta to a free-space theoretical prediction.

A reasonably coarse calibration set can capture the perturbations and restore highly accurate tracking. Calibrated near-field electromagnetic ranging is the basis of the near-field electromagnetic ranging real-time location systems (RTLS) Q-Track sells and deploys in nuclear power, manufacturing, and other industrial settings. Typical location accuracy is 55cm rms with error less than 1m 85% of the time. Fig. 12 shows cumulative location error for several receivers in a recent test.[15] Local noise and propagation conditions impact performance and accuracy of particular receivers.

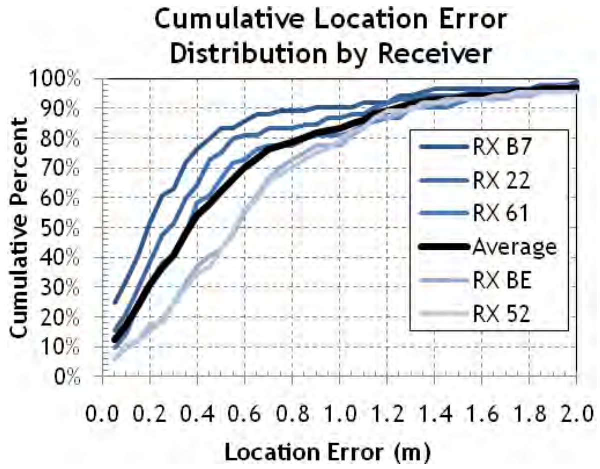


**Fig. 12** Cumulative location error for five NFER RTLS receivers in an eighty point test.[15]

## FIREFIGHTER LOCATION AND RESCUE EQUIPMENT

Many applications of interest, such as first-responder tracking, cannot tolerate a pre-calibration process. In such settings, a path calibration is feasible. The Firefighter Location And Rescue Equipment or "FLARE" system employs a unique RF signature breadcrumb approach to calibrate specific paths or routes within an emergency incident scene, thus guiding rescuers to the location of firefighters needing assistance. A proof-of-concept system delivered results comparable to or better than the best available inertial-based location systems in a real-world simulated rescue at Worcester Polytechnic Institute in 2010. This paper presents results of more recent trials of a FLARE system in multi-story buildings, underground, and other settings.

The organizers of Fifth Precision Personnel Locator (PPL) Workshop (held on the campus of Worcester Polytechnic Institute (WPI), 2-3 August, 2010) collaborated with the Worcester Fire Department to conduct realistic firefighter rescue exercises.[16] The quickest rescue of the day was performed with the assistance of Q-Track's NFER® FLARE prototype system.[17] Q-Track's FLARE system records near-field signal characteristics of firefighters' tracking tags to characterize and calibrate the system to their paths. Then a rescuer can be vectored along the same path, or firefighters may guide themselves back out along their entry path.[18] Another key feature is the ability to detect and bypass path "loops" or "dead ends" to follow the most direct path. Figure 13 shows a screenshot of the tracking GUI from a video of the simulated rescue exercise testing.[19] Figure 14 shows the graphic created by the *Boston Globe* to illustrate how the system works.

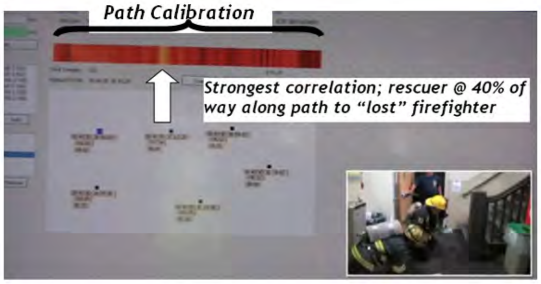
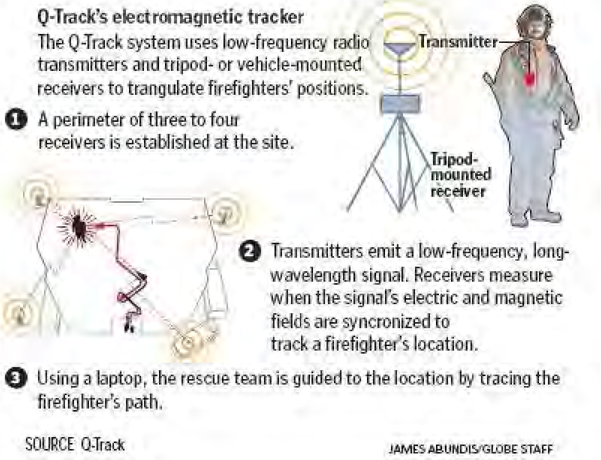


**Fig. 13** Screenshot showing the annotated FLARE GUI.



The Q-Track system uses low-frequency radio transmitters and tripod- or vehicle-mounted receivers to trangulate firefighters' positions.

❶ A perimeter of three to four receivers is established at the site.

❷ Transmitters emit a low-frequency, long-wavelength signal. Receivers measure when the signal's electric and magnetic fields are syncronized to track a firefighter's location.

❸ Using a laptop, the rescue team is guided to the location by tracing the firefighter's path.

**Fig. 14** Q-Track's FLARE system.

## AM BAND SIGNALS-OF-OPPORTUNITY

A final implementation of near-field electromagnetic ranging shows considerable promise. As AM broadcast band signals propagate through urban environments, they couple to power lines and buildings causing them to perturb signals. These perturbations introduce near-field components that are detectable by Q-Track's Locator-Receivers. Because these perturbations result from interactions with fixed objects like electrical lines, buildings, and geological features, a tracking system that maps these perturbations and uses them for geo-location has the potential to achieve remarkably good accuracy and repeatability.[20] The classic RTLS infrastructure architecture can be replaced by a Tag Receiver exploiting ambient signals as shown in Figure 15.

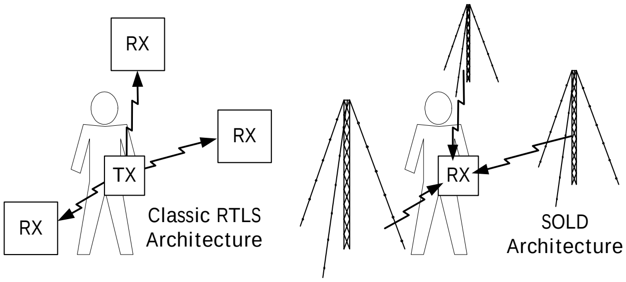


**Fig. 15** AM-band signals-of-opportunity enable an infrastructure-free RTLS architecture.

**Fig. 16** Testing accuracy of a SOLD proof-of-concept unit (gray box on cart).

| | Error (m) | | |
|---|---|---|---|
| **Freq.(kHz)** | **Mean** | **Std. Dev.** | **Max** |
| 730 | 1.28 | 1.22 | 5.22 |
| 770 | 3.64 | 1.97 | 7.95 |
| 1000 | 0.93 | 1.11 | 6.16 |
| 1140 | 1.80 | 1.66 | 6.16 |
| 1230 | 0.88 | 0.92 | 5.39 |
| 1450 | 1.05 | 1.31 | 7.39 |
| 1550 | 1.00 | 1.12 | 4.69 |
| 1600 | 0.72 | 0.97 | 6.41 |
| 1700 | 0.80 | 1.10 | 5.52 |
| **Composite** | 0.45 | 0.28 | 1.83 |

**Table 1:** SOLD system accuracy, off cal points.

| | Error (m) | | |
|---|---|---|---|
| **Freq.(kHz)** | **Mean** | **Std. Dev.** | **Max** |
| 730 | 0.78 | 1.02 | 5.67 |
| 770 | 2.80 | 1.50 | 5.48 |
| 1000 | 0.76 | 1.07 | 5.31 |
| 1140 | 1.98 | 1.58 | 6.18 |
| 1230 | 0.38 | 0.41 | 1.43 |
| 1450 | 0.73 | 0.92 | 4.31 |
| 1550 | 0.64 | 0.63 | 3.17 |
| 1600 | 0.57 | 1.09 | 6.37 |
| 1700 | 0.36 | 0.45 | 2.14 |
| **Composite** | 0.26 | 0.23 | 0.87 |

**Table 2:** SOLD system accuracy, on cal points.

In a recent test, we employed an AM broadcast band Signal-of-Opportunity Location Device (SOLD) to calibrate a 7m x 7m area at 35 points in a 6 x 6 grid. Figure 16 shows the area and the SOLD unit. The system used nine local AM radio stations, determining a location from each of the nine stations. Then, we averaged solutions from the nine individual stations to yield a composite solution. We evaluated the tracking accuracy within the area at the 35 calibration points and found composite rms accuracy of 26cm with a maximum error of 87cm. Then, we checked accuracy at 59 points off the calibration grid and found rms accuracy of 47cm with a maximum error of 1.8m. Our daytime calibration did not track successfully after sunset, however, a night time calibration yielded good night time tracking accuracy.

**Fig. 17** The SOLD proof-of-concept tracked successfully underground in an abandoned limestone mine as well as in a twelve-story apartment building.

The current proof-of-concept system is orientation dependent. Ultimately, the system will be able to determine both location and orientation. For proof-of-concept testing, however, the orientation of the system must be maintained constant in order to assess location accuracy. This becomes more difficult outside the controlled environment of a lab. Nevertheless, we have begun preliminary testing of the system in underground and multi-story environments, as shown in Figure 17.

In an abandoned limestone mine, the SOLD proof-of-concept accurately tracked a user along a loop as far as 100m from the entrance of the cave. In a twelve story apartment building, the SOLD proof-of-concept correctly determined floor and location about 60-80% of the time. The principal error mode of the SOLD proof-of-concept is an occasional erroneous location solution far from the current location. These errors are amenable to relatively simple filtering algorithms. Work is ongoing to assess sources of location error and develop algorithms to determine orientation as well.

## SUMMARY AND CONCLUSIONS

This paper provides a brief summary of the theory and practice of near-field electromagnetic ranging. Phase, signal, and energy velocities diverge in the near-field zone. Near-field physics enables precise geo-location using techniques other than classical time-of-flight or time-difference-of arrival methods. Q-Track's commercially available NFER® RTLS offers 55cm rms tracking accuracy in typical deployments for customers in the nuclear, manufacturing, and other industries. The Firefighter Location and Rescue Equipment, or "FLARE," prototype (successfully demonstrated at the WPI PPL Workshop in 2010) is currently under development. This system guides rescuers to first responders needing assistance using an innovative near-field RF breadcrumb approach. Also under development is a Signal-of-Opportunity Location Device (SOLD) which employs AM broadcast signals to determine location to an rms accuracy of 26cm when calibrated in an indoor environment. The system shows promise for tracking underground and in multi-story buildings.

## ACKNOWLEDGMENTS

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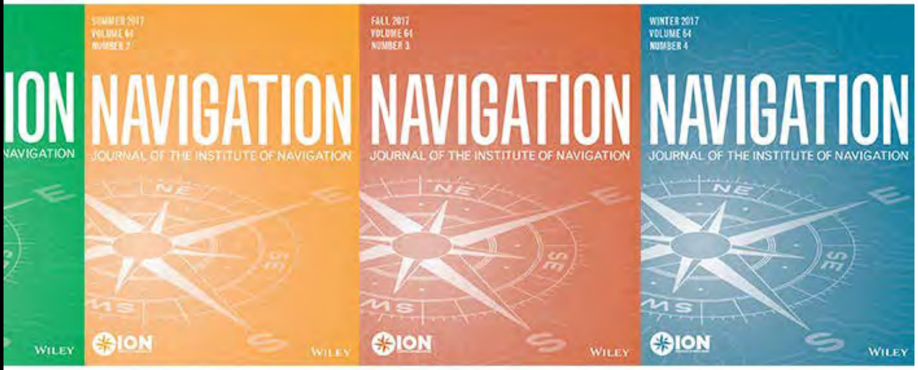

# Theory and Practice of Near-Field Electromagnetic Ranging

H.G. Schantz

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|---|---|
| Abstract: | This paper illustrates the divergence of phase, signal, and energy velocities in the near field by employing space-time diagrams of the evolution of near-fields. In addition this paper describes near-field link and impedance relations a near-field phase diagram for electrically small quadrature transmitters. Near-field physics enables near-field electromagnetic ranging systems in a variety of modes for a diverse range of applications. This paper summarizes recent results applying near-field electromagnetic ranging to a Signal-of-Opportunity Location Device (SOLD) implementation. Q-Track tested this system in realistic environments including a multi-story building and underground. SOLD yielded an rms accuracy of 26cm when returning to a calibration point and 46cm rms between calibration points. |
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