DISTRIBUTED COHERENT RF OPERATIONS

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Abstract

The concept of "distributed coherent RF operations" is presented as a driver of requirements for growth in PTTI capabilities, and selected related disciplines such as navigation. The term "distributed coherent RF operations" is defined and classes of military operations are identified. The precision required for various parameters and basic phenomenology of different types of errors are discussed by way of simple examples. The capabilities widely available today via GPS are contrasted with those required for "distributed coherent RF operations" in a fully Network-Centric military paradigm.

1. INTRODUCTION

Among the contributing factors to transformation of the U.S. military are information operations (IO) and network-centric warfare (NCW). IO gives emphasis to the criticality of information in conflict: there is obvious advantage to knowing the enemy's capabilities, disposition, and intentions while denying him any such knowledge of your own forces. IO may be either offensive or defensive in nature, and includes aspects such as electronics support (ES, intelligence gathering, and threat warning) and electronic attack (EA, jamming, spoofing, deception). NCW gives emphasis to the synergistic operation of multiple entities distributed across the battle-space. In NCW, the whole is much greater than the sum of the parts. Here, we consider potential NCW approaches to IO in the context of RF signals, which leads to the concept of "Distributed Coherent RF Operations."

2. BASIC DEFINITION

In order to fully explore the concepts involved, and to capture the several linkages to other disciplines, it is helpful to fully expand a proposed definition of "Distributed Coherent RF Operations:"

> Distributed – divided among two or more **[1]**
>
> Coherent – united by some relation in form or order **[1]**
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> RF – of or using a radio frequency **[1]**
>
> Operations – a process or action that is part of a series in some work **[1]**

Here, we consider "RF Operations" as being *any* over-the-air *transmission* of an RF signal, or *any reception* of an over-the-air RF transmission. Thus, we consider communications, radar, and jamming in the family of transmission operations, and add signal intercept and radio location to the family of reception functions. The term “distributed” makes explicit that either the transmission or the reception function is divided among two or more separate and distinct sets of transmitter/receiver hardware. Simple examples would include bi-static and multi-static radar, and radio direction-finding nets; however, the concept as proposed here extends to all nature of RF systems, many of which are traditionally employed as independent, stand-alone nodes.

Finally, but perhaps most importantly in defining “Distributed Coherent RF Operations,” is the term “coherent.” In the RF community, this term would normally denote a specified or controlled carrier phase. However, in the definition considered here, the term in intended to mean much more. For example, in transmit operations, we consider that multiple transmitters are used to generate RF signals whose properties are controlled to such a degree as to permit the precise generation of a desired electromagnetic field at a particular location in space and at a specified instant in time. Similarly, for receive operations, we consider multiple receivers whose properties are controlled to such a degree that the received outputs for an arbitrary RF signal may be processed using coherent array processing techniques. These examples illustrate the much broader use of the term “coherent” than traditional: the RF transmitter/receiver must provide precise control of amplitude, frequency, and carrier-phase offsets, and must also take into account propagation delays. However, digging deeper still, we find that objectives further require precision location, precision timing, *and precise knowledge of axial orientation*. While there certainly exist today a variety of systems that embody some or all of these characteristics, the defining difference for NCW is simple: provide these capabilities to *every* piece of RF hardware within the battlespace.

3. SIMPLE ILLUSTRATIONS OF “COHERENCE”

In order to reinforce these concepts, we can consider some deliberately simplified examples of amplitude, frequency, time-delay offset, and carrier phase effects. The RF signals s_n are of the general form

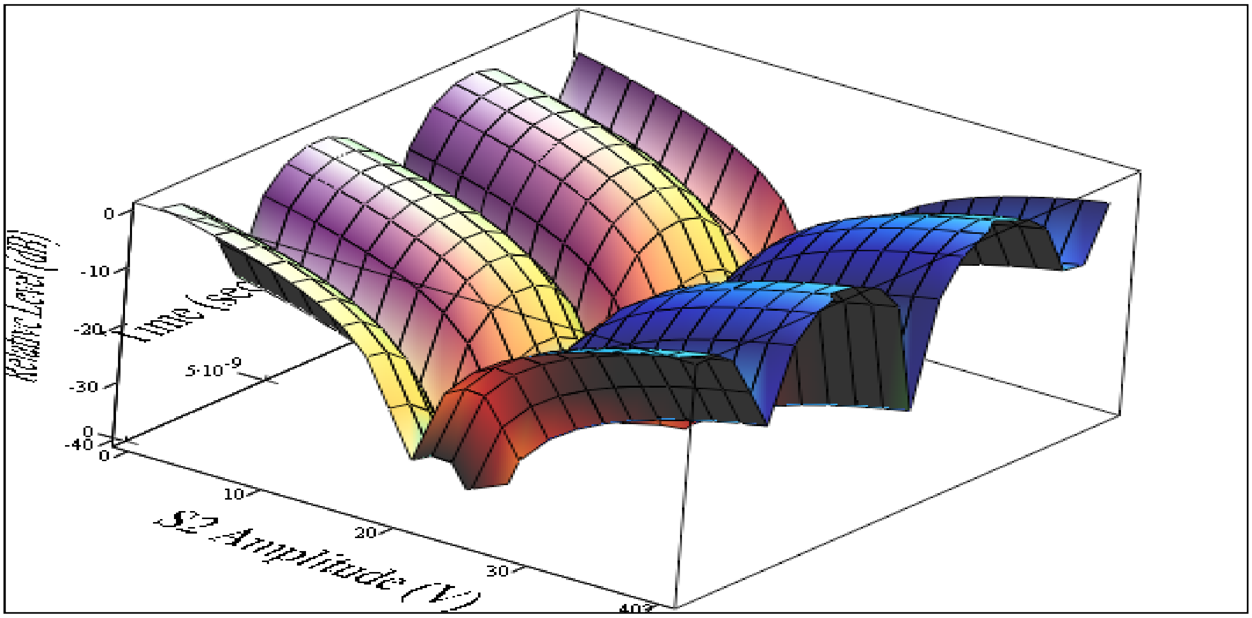
$$s_n(A_n, f_n, \tau_n, \theta_n, t) = A_n \cos(2\pi f_n(t-\tau_n)-\theta_n) \tag{1}$$

and are specified by amplitude A_n, carrier frequency f_n, time-delay offset τ_n, and carrier phase θ_n. Consider the simple case where we desire to achieve a null or signal cancellation at a particular point in space and at a particular instant in time. Such might occur, for example, where we desire to broadcast an RF communications signal, but have knowledge that an eavesdropper is listening and know his or her location. We might employ two transmitters to generate the signal, but under the constraint that $s_1(t)-s_2(t)=0$ for all time t. In practice, of course, there will be some degree of amplitude, frequency, time-delay offset, and carrier phase mismatch such that the signal null is less than perfect.

To examine some of the basic phenomenology, consider two signals at 90 MHz. First, consider the requirements for amplitude control by examining the case where both frequencies are identical, both delay-time offsets are zero, and the two signals have carrier phase of exactly zero and pi radians (perfectly out-of-phase) respectively. We consider the first signal as exactly 1 W, and allow power in the second signal to vary. Taking the impedance of free-space as 377 Ω leads to the results as listed in Table 1. Very little amplitude precision is required to generate a 3 dB null. In contrast, a null of 30 dB requires better than 1 dB precision in signal amplitudes. As shown in Figure 1, for the case where there are only amplitude errors, the main null behavior is stable and does not vary with time.

Table 1. Amplitude and power control precision required for varying degrees of signal cancellation.

Cancellation	Net Power	Net Amplitude	Allowed Amplitude	Allowed Power	Required Precision
3 dB	0.5 W	0.61 V	5.69 V – 33.1 V	0.09 W – 2.91 W	10.7 dB
10 dB	100 mW	1.94 V	13.3 V – 25.6 V	0.47 W – 1.73 W	3.3 dB
20 dB	10 mW	6.14 V	17.5 V – 21.4 V	0.81 W – 1.21 W	0.9 dB
30 dB	1 mW	13.73 V	18.8 V – 20.0 V	0.94 W – 1.06 W	0.3 dB



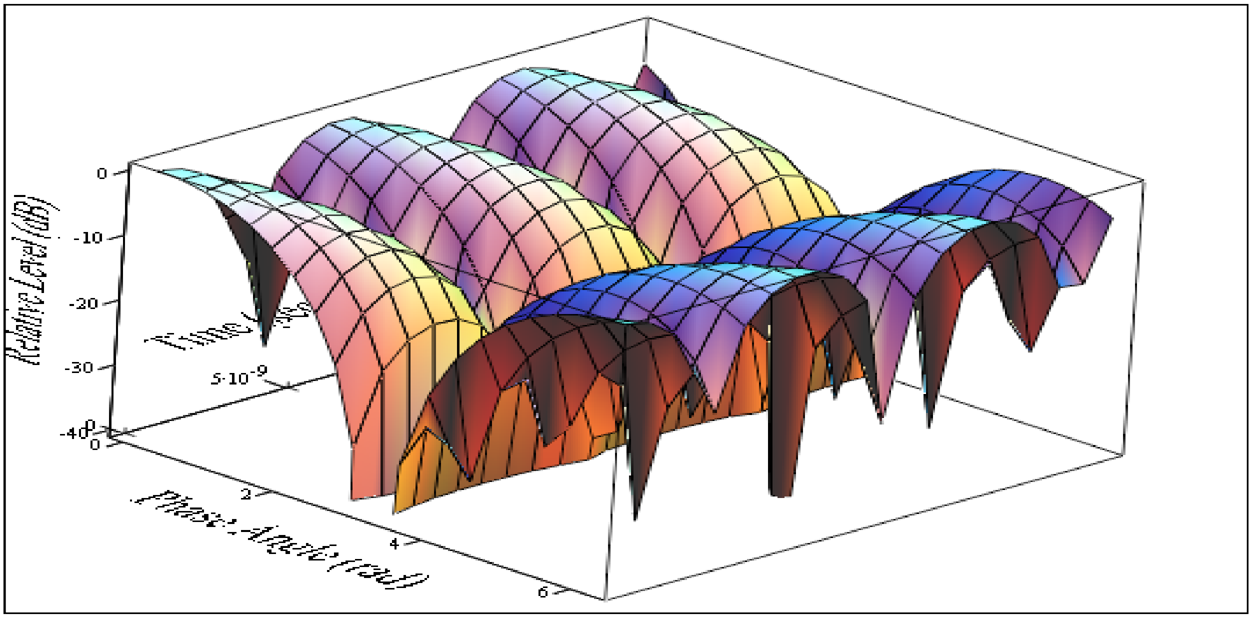
A

Figure 1. Time evolution of the relative signal level for amplitude-only errors versus amplitude of the second signal for two 90 MHz signals. The time scale runs for 15 ns.

Consider next the effects of differing carrier phase. For this case, we take both signals as having identical amplitudes, frequencies, and delay-time offsets. We take the first signal as having carrier phase of exactly zero and consider variations in the carrier phase of the second signal within the unambiguous range of zero to two pi radians. The phase angle variations yielding the various degrees of cancellation are listed in Table 2. As with amplitude only errors, for the case where there are only carrier-phase errors, the achieved main null behavior is stable and does not vary with time. However, there is a more complicated time evolution of the degree of cancellation away from the main null, as shown in Figure 2.

Table 2. Carrier-phase precision required for varying degrees of signal cancellation.

Cancellation	Allowed Carrier Phase Error
3 dB	± 73°
10 dB	± 47°
20 dB	± 26°
30 dB	± 14°



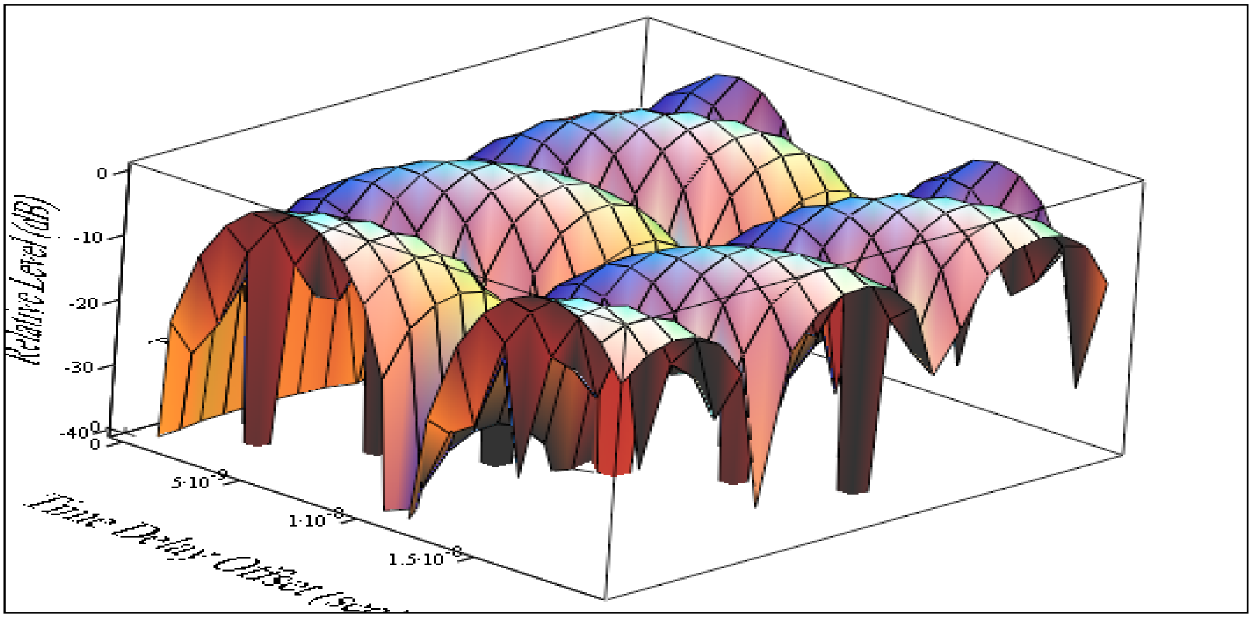
B

Figure 2. Time evolution of the relative signal level for carrier-phase-only errors versus carrier- phase angle for two 90 MHz signals. The time scale runs for 15 ns.

Now consider the effects of time-delay offset. For this case, we take both signals as having identical amplitudes and frequencies, and the two signals have carrier phase of exactly zero and pi radians (perfectly out-of-phase) respectively. We take the first signal as having a delay time of exactly zero and consider variations in the delay time of the second signal. The behavior in this case has both a similarity to the carrier phase case as well as a distinct difference. The two cases are similar in that the degree of cancellation can be related to an allowed phase error, in one case arising from an unsupervised local oscillator and in the other case arising from delay variations inherent in over-the-air RF propagation. However, they are distinctly different in that the phase errors arising from delay-time errors are not limited to two pi radians and are, thus, periodic with the carrier period across the range of delay times. Further, the allowable range of delay times to achieve a degree of cancellation is inversely proportional to the RF frequency. Finally, as with carrier-phase errors, for time-delay offsets there is a more complicated time evolution of the degree of cancellation away from the main null, as shown in Figure 3.

Table 3. Time-delay offset precision required for varying degrees of signal cancellation.

Cancellation	Allowed Phase Error	Fraction of RF Period	Allowed Error at 90 MHz
3 dB	± 73°	20%	± 2.25 ns
10 dB	± 47°	13%	± 1.44 ns
20 dB	± 26°	7%	± 0.80 ns
30 dB	± 14°	4%	± 0.44 ns



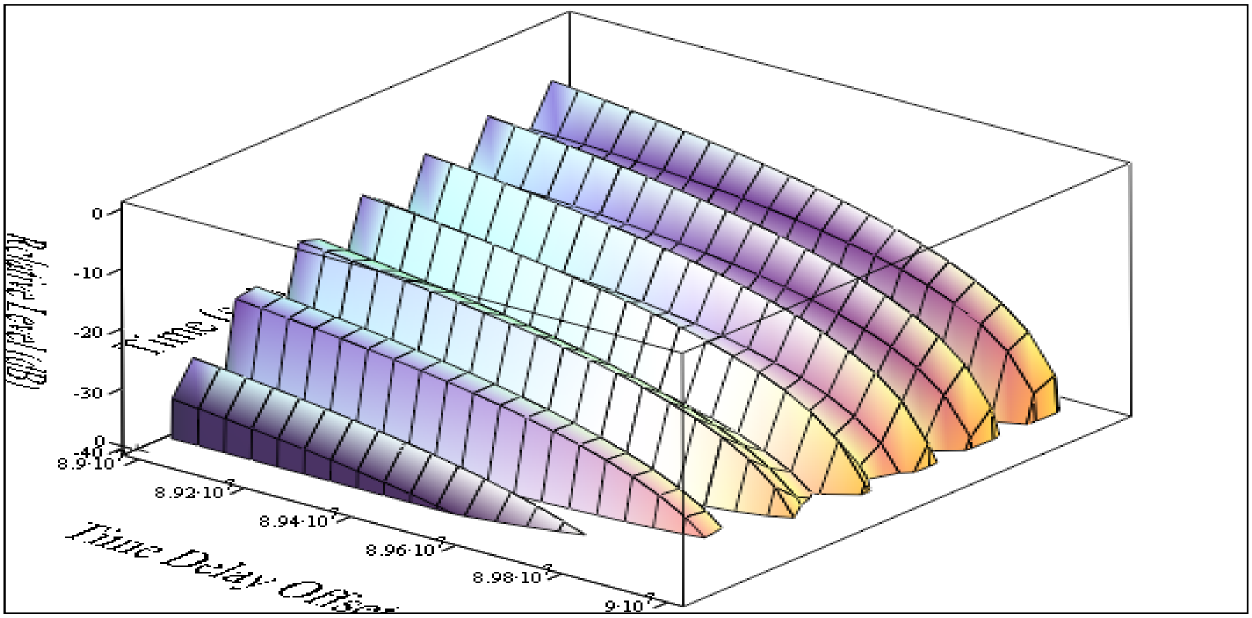
C

Figure 3. Time evolution of the relative signal level for time-delay-offset-only errors versus time-delay offset for two 90 MHz signals. The time scale runs for 15 ns.

Lastly, consider the effects of carrier-frequency errors. For this case, we take both signals as having identical amplitudes, identical zero delay-time offsets, and carrier phase of exactly zero and pi radians (perfectly out-of-phase) respectively. We consider the carrier of the second signal to be 10 ppm greater than the first, i.e. 90 Hz above 90 MHz. For this simple analysis, we consider the evolution of the signals from time t = 0. The behavior in this case is somewhat complicated, as shown in Figure 4. The null comes and goes with a period determined by the frequency difference between the two signals.

Thus, for the simple example considered, in order to achieve a 30 dB null, we require power level control to a few tenths of a dB, carrier phase to 4% of a cycle, time delay to a few nanoseconds, and perhaps frequency within a few ppm. While these specifications are certainly achievable in the laboratory using a cable connected single system, they may be substantially more difficult to achieve on a distributed basis in a field environment.

There is a direct linkage between control of these primary parameters (amplitude, frequency, time delay offset, and carrier phase) and at least two other significant parameters of each distributed component: position and axial orientation. The criticality of precise position is immediately obvious; it determines directly the propagation path length responsible for the propagation time delay. The criticality of axial orientation is perhaps less obvious, but no less important; in order to control the signal power to within a few tenths of a dB, we require very precise knowledge of the antenna gain pattern in the direction of propagation, which is directly dependent upon knowledge of the antenna axial orientation.



D

Figure 4. Time evolution of the relative signal level for frequency-only error of 10 ppm for two 90 MHz signals. The time scale runs for 150 ns.

4. REPRESENTATIVE MILITARY OPERATIONS

There are a number of military RF operations that could conceivably be executed using “Distributed Coherent RF Operations.” These include both communications and non-communications functions. The general rule of thumb is that the incoherent combination of data from N entities will enhance the signal-to-noise ratio (SNR) by a factor of $\sqrt{N}$, whereas truly coherent combination of data from N entities will enhance performance by a factor of N.

The potential advantages for RF communications using “Distributed Coherent RF Operations” relate to the use of multiple transceivers to form ad-hoc beam-forming arrays. As envisioned, this behavior would be available for both transmit and receive ends of the communications link. The implementation of beam-forming provides several distinct advantages over simple isotropic operation: 1) the beam-formed link can achieve a higher SNR and, hence, higher data rate operation, 2) the higher SNR can be used to enable more robust encryption, 3) the direction of the beam-formed link can be steered so as to minimize the potential for interception, 4) the beam-forming algorithm can be used to null jamming and interference inclusive of co-channel interference. Further, coherently received data can be processed using any number of known advantageous multi-channel signal processing techniques, such as multiple user detection (MUD) and multiple signal interference cancellation (MUSIC). Note that the basic concepts behind "Distributed Coherent RF Operations" apply to both simple antenna elements, such as dipole whips, as well as to advanced shaped beam antennas being considered for future military systems.

Non-communications operations would include bi-static and multi-static radar, along with electronic support measures such as radio direction-finding.

The potential advantages for non-communications operations similarly relate to the use of multiple transceivers to form ad-hoc beam-forming arrays and to provide fully coherent data for multi-channel signal processing. Additional nuanced advantages may be possible with regard to advanced jamming techniques. Again, we note that the basic concepts behind "Distributed Coherent RF Operations" apply to both low-cost systems with simple antenna elements as well as to substantially more advanced radar and electronic support measures systems.

Perhaps the clearest example of a developing military application of "Distributed Coherent RF Operations" is the DARPA Wolfpack program **[2]**. The stated goal of Wolfpack is to develop a "close-in distributed, autonomous, ground-based jamming system to selectively deny enemy use of the RF spectrum." The basic system concept is illustrated in Figure 5, wherein one can readily recognize the underlying concept as equivalent to "Distributed Coherent RF Operations."

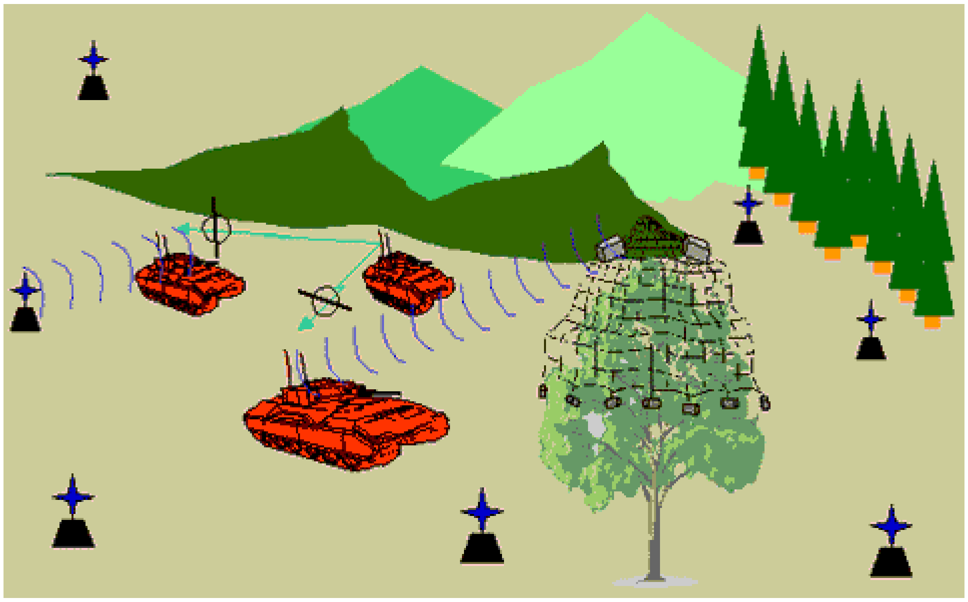


Figure 5. DARPA Wolfpack concept illustration **[2]**.

Other activities touching on aspects of "Distributed Coherent RF Operations" are being undertaken within the US Army. These include the Warfighter Electronic Collection and Mapping (WECM) Science and Electronic Sensors for the Objective Force (ESOF) Technology Objectives (STOs) **[3]** as well as Army Small Business Innovative Research efforts such as "Position and Orientation for Distributed Sensors (PODIS)" and "Digital Direction Finding" **[4]**.

5. THE PRESENT AS COMPARED TO THE FUTURE

At the present time, GPS is relied upon to provide ubiquitous position and timing to many DoD and civilian users. The military value of precise position and timing is reflected in the broader application GPS receivers to more and more military platforms and systems. However, these installations are not sufficient to enable "Distributed Coherent RF Operations:" 1) these installations do not provide axial orientation for most static or slow-moving ground-based systems, 2) these installations do not provide take advantage of GPS to provide a common frequency reference, and 3) these installations do not consider a common phase reference.

In order for the next generation of PTTI and position, navigation, and timing (PNT) systems to enable "Distributed Coherent RF Operations," several actions need to be taken. First, the PTTI and PNT implications of "Distributed Coherent RF Operations" and systems such as Wolfpack need to be considered fully. An appropriate set of amplitude, frequency, time, carrier phase, position, and axial orientation specifications needs to be developed as a guide for research and development of the next generation of PTTI and PNT systems such as the DARPA Precision Inertial Navigation Systems (PINS) program. These specifications will, of course, depend on expanded distribution of the requisite references. A subtle nuance here is that the references will need to be distributed more broadly than before to lower echelons than before, and using message sets and communications links not previously considered such as tactical combat net radios.

6. REFERENCES

[1] Webster's Deluxe Unabridged Dictionary (Simon and Schuster, New York), 1979.

[2] *http://www.darpa.mil/ato/programs/wolfpack.htm*

[3] 2003 Army Science and Technology Master Plan, Volume **II** Annexes, pp. A-20 and A-22.

[4] *http://www.aro.ncren.net/arowash/rt/sbir/022ph1to.htm*

QUESTIONS AND ANSWERS

JUDAH LEVINE (National Institute of Standards and Technology): The usual problem that most of us have to face is multi-path. At least where we live, that is not really under our control, especially when you are moving around. Could you say a word about that, because it sounds like you have the problem big time?

JOHN KOSINSKI: There are a variety of operational scenarios that we would like to do operations in. They are going to have different ranges that we need to be effective over. That is going to color whether or not the multi-path is a big problem to us. There are a variety of directional antenna initiatives ongoing, some of which are at Ft. Monmouth, smart antenna work. It remains to be seen how inexpensive that will be become. Those will be part of the multi-path mitigation problem.

I believe, also, my assessment is that the distributed coherent RF is another piece of solving multi-path issues. We are going to have enough people distributed in most of the areas that we are concerned with to deal with that now.

There are some other things that I cannot talk about here that, particularly for electronic attack, I think are going to be very effective.