**Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANS)**

**Submission Title: [A Tutorial on Ultrawideband Technology]**

**Date Submitted:** [March 6, 2000]

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**Re:** [Tutorial Presentation on UWB for 802]

**Abstract:** [Material on ultrawideband (UWB)]

**Purpose:** [For tutorial #1 March 6, 2000]

# A Tutorial on Ultrawideband Technology

***XtremeSpectrum, Inc.***

**An Ultrawideband Technology Company**

**Presented by: John McCorkle (CTO)**
**(301) 614-1325**
**john@xtremespectrum.com**

# *Tutorial Outline*

- **Introduction**
- **Brief history of UWB**
- **Phenomenology**
    - Radar: study of scattering
    - Communications: channel model, path loss
- **Information theory**
- **Modulation**
- **Fit between UWB and wireless PAN, LAN and RG**

# *John McCorkle's Background*

- **PI for the Army's UWB radar Programs -- industry, DARPA university, tri-service, efforts**
- **Designed highest resolution LF SAR in the world**
  **< 1/2 sq. ft. pixels**
  **Over 1 GHz bandwidth**
- **John's 15 patents Include**
  - **Antennas**
  - **Baluns**
  - **RFI extraction**
  - **Adaptive background subtraction**
  - **T/R switch**
  - **Image formation**
  - **Optimal interleaver**
  - **Jitter code & hardware**
- **Co-Founder of XtremeSpectrum Inc. To commercialize high performance in-building communications**

# *Where UWB Comes From*

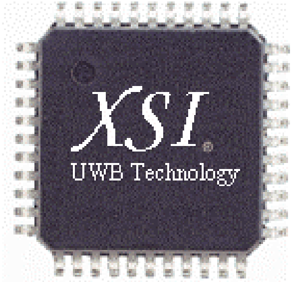
- **Gerry Ross** at Anro, Tunnel Diodes.
- **Carl Baum** at Kirkland Air Force base, Singularity Expansion method, EMP.
- **Leo Felson and Larry Carin** at Brooklyn Polytechnic, digital signal processing and EM modeling.
- **Paul Van Etton and Michael Wicks** at Rome Air Force Lab, antennas, pulse and chirp systems.
- **Larry Fullerton** at Time Domain Systems, avalanche transistor based systems, antennas, etc.
- **Tom McEwan** at Lawrence Livermore, avalanche based systems, receivers, samplers, etc.
- **Rex Morey** at Geophysical Survey Systems Inc., avalanche based commercial GPR systems
- **John Young, Leon Peters et al.** at OSU, GPR systems, Big Ear, antennas, signal processing K-pulse, E-pulse.
- **Fred Beckner & Steve Davis** at Power Spectra, Radscat, BASS – Bulk GaAs semiconductor switch.

# *Companies Specializing in UWB Communications*

- Aether Wire & Location, Inc.
- ANRO Engineering, Inc.
- Fantasma Networks, Inc. (Interval Corp.)
- Lawrence Livermore Labs
- Multispectral Solutions, Inc.
- Time Domain Corporation
- XtremeSpectrum, Inc.

# *XtremeSpectrum, Inc.*

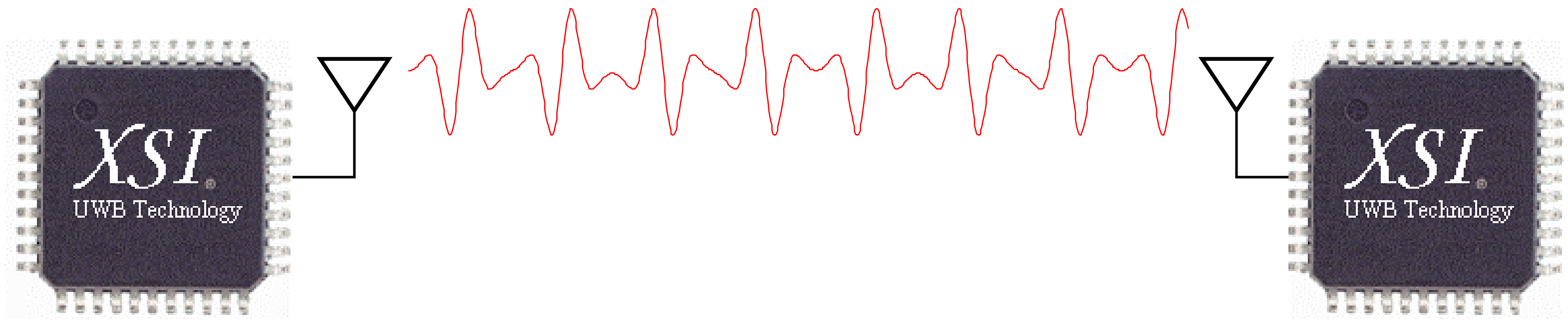
- **XtremeSpectrum formed to commercialize UWB technology for enabling high performance in-building wireless communications**
- **Developer of UWB communications technology for wireless PAN, LAN & RG**




- **OEM supplier to computer, networking and consumer electronics companies**
- **Products are embedded radio modem integrated circuits**

# *What Does an XSI Radio Look Like*

## Same low voltage CMOS as the chips in your computer




**Computer Chip**

**Pins toggle to send bits**

**Antenna is PC board traces**

**Unintentional UWB radiates**

**XSI Radio Chip**

**Pins toggle to send bits**

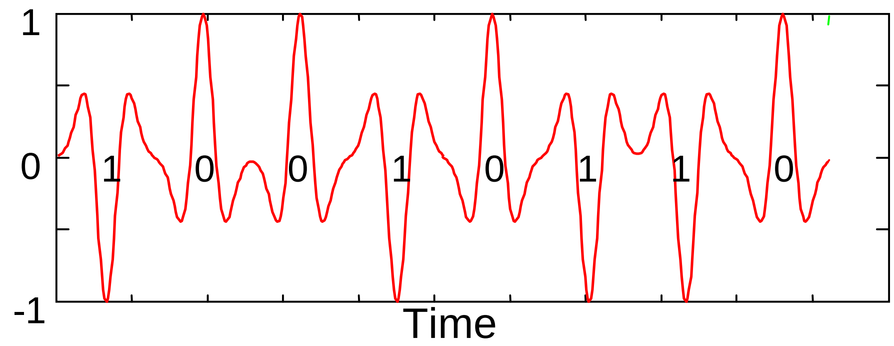
**Antenna is etched on PC board**

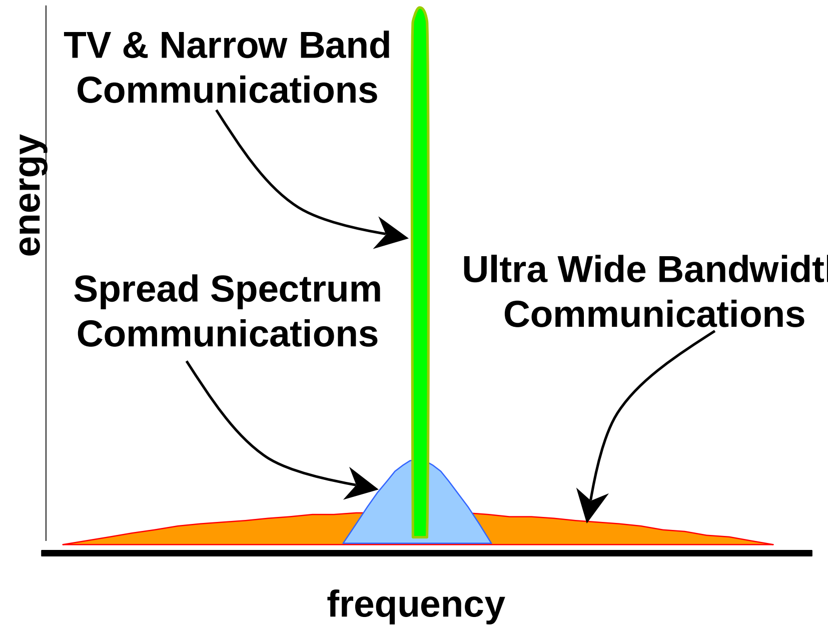
**Intentional UWB radiates**

**UWB signals are received**

# *UWB Concept*

- **Coded short duration pulses spread the signal energy over frequency and time**
- **Can overlay existing FCC frequency assignments**
  - Spread is so broad, little energy gets in a narrowband
  - Short range WPAN systems can operate below the detection threshold of conventional receivers
- **Low probability of intercept (LPI) Bi-Phase not spikey in time or frequency domains**

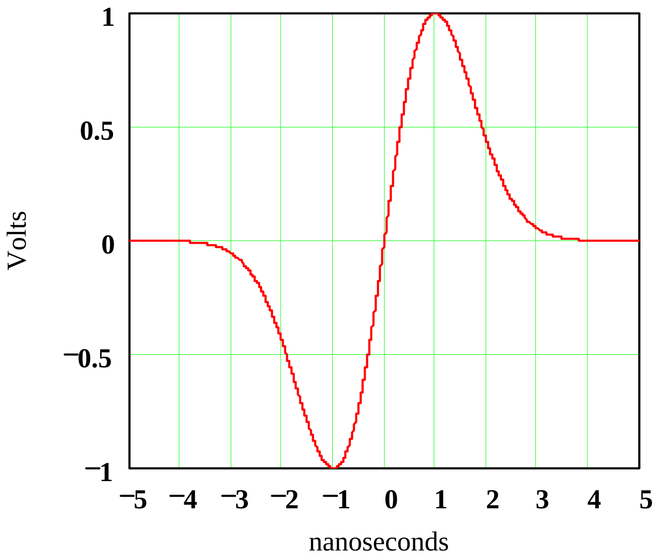


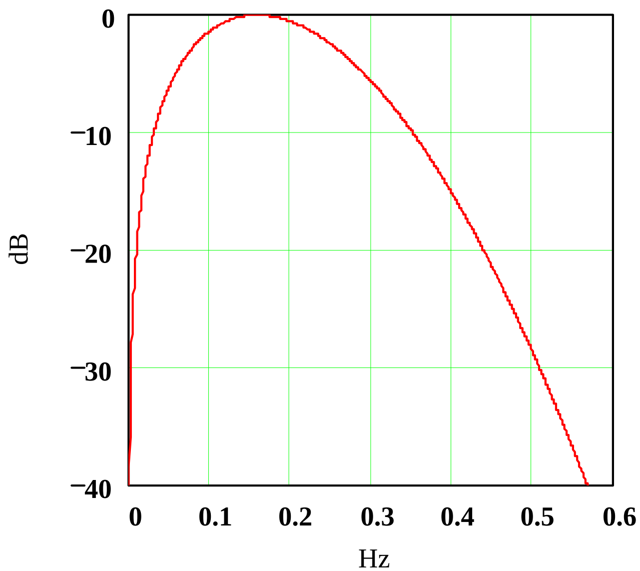



# *Useful Analytic Waveforms: Derivatives of a Gaussian*

$$s(t) = \frac{A\sqrt{e}}{t_p} t e^{-\frac{1}{2}\left(\frac{t}{t_p}\right)^2}$$

$$S(\omega) = A\sqrt{2\pi e}\, t_p \omega e^{\frac{-1}{2}(t_p \omega)^2}$$




$$f_{\max} = \pm \frac{1}{2\pi t_p}$$

$$f_c = \frac{f_{lo} + f_{hi}}{2} = 1.12 f_{\max}$$

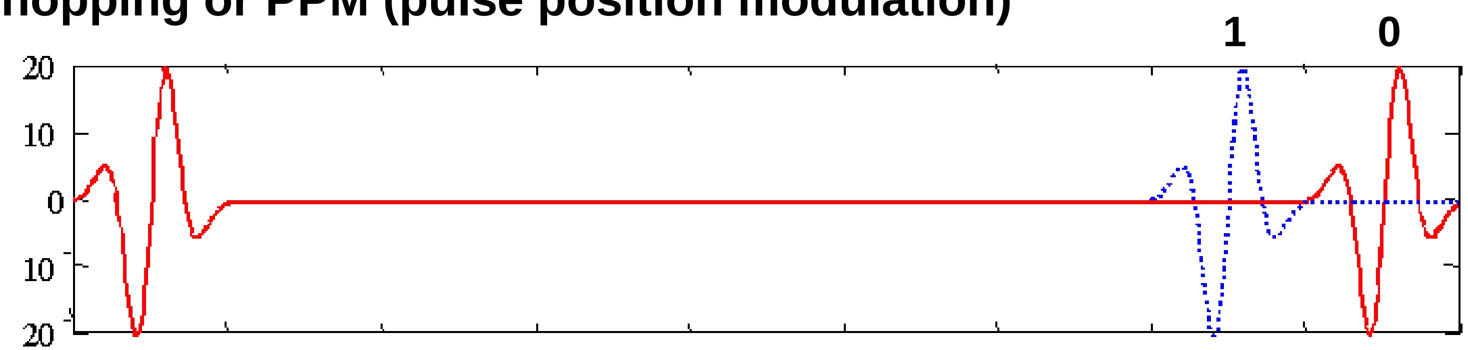
$$f_{lo} = 0.3191057 f_{\max}$$

$$f_{hi} = 1.9216229 f_{\max}$$

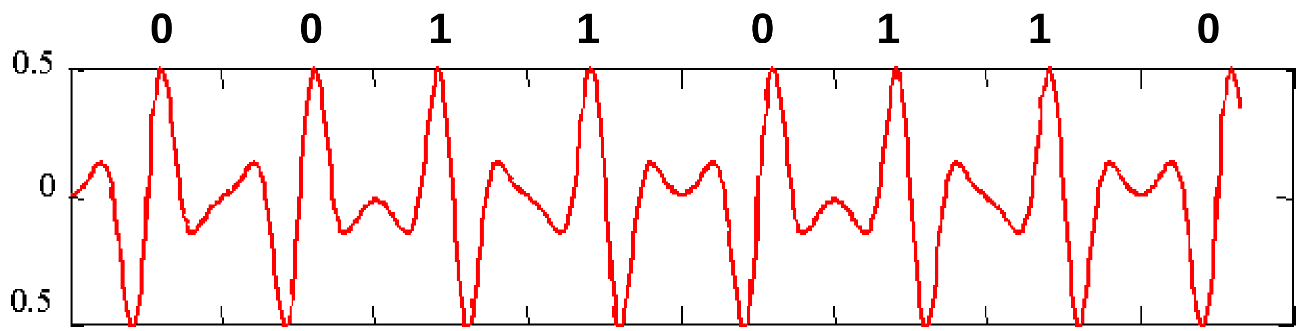
$$p = A^2 t_p \frac{e\sqrt{\pi}}{2}$$

# *What Do UWB Signals Look Like?*

- Time-hopping or PPM (pulse position modulation)

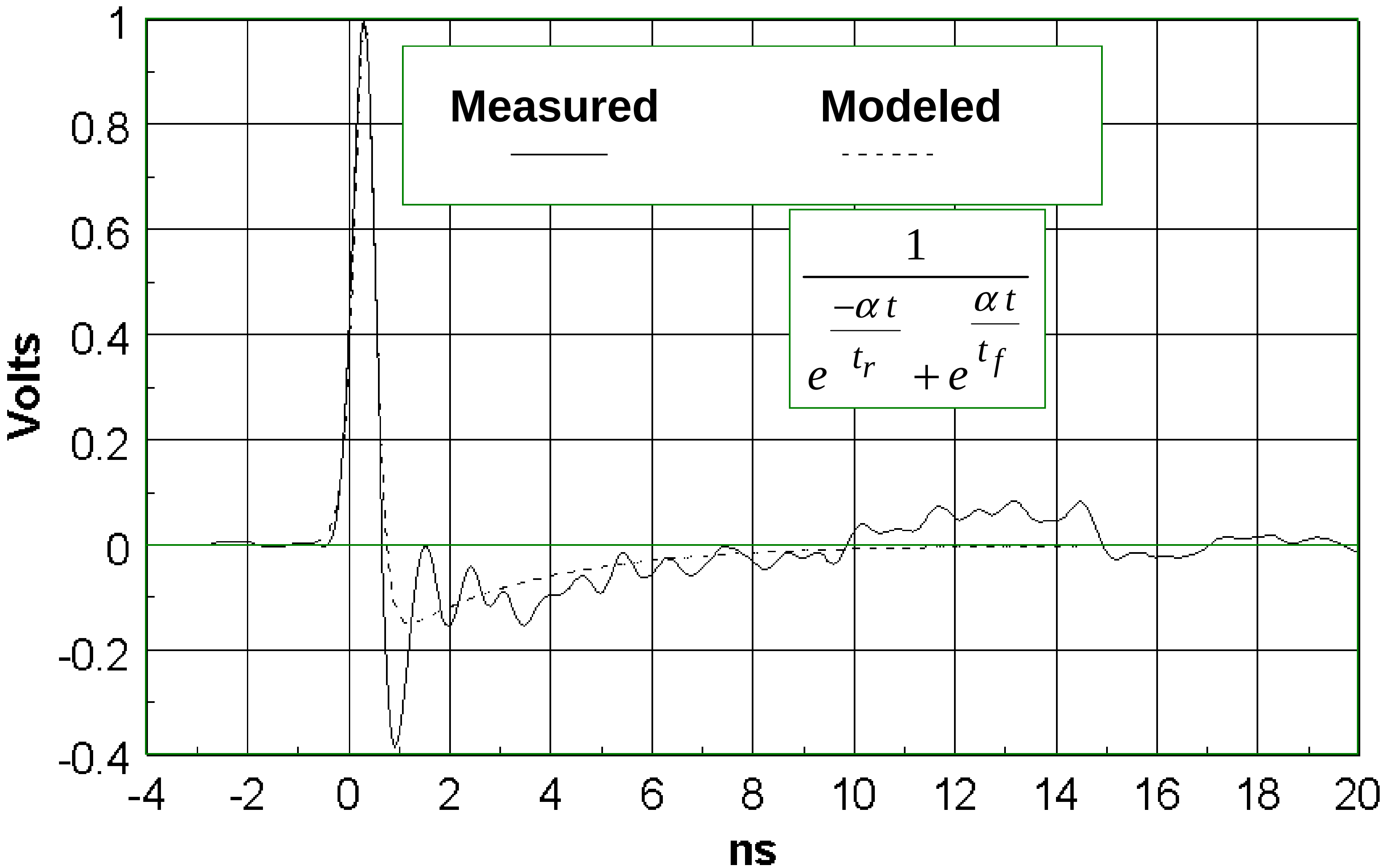



- Bi-phase monocycles




- Positive and negative video pulses (no DC)
- Chirp and step frequency
- Noise

# *Antenna-to-Antenna System Response (i.e. ~Radiated Waveform)*



## *Definition of UWB - Phenomenology Based*

- **UWB is a term of art implying wide relative coherent bandwidth**

$$B_f = \frac{B}{f_c} = \frac{(f_h - f_l)}{(f_h + f_l)/2} \approx 1$$

- **Definition is based on physics of wave interaction (i.e. scattering and loss phenomenology)**
- **The interaction of UWB emissions with the environment enables utility that cannot be obtained with** $B_f < 0.25$
  - **Elimination of ambiguous multipath, scintillation, fading**
  - **Capability to penetrate at high data rates and high resolution**
  - **Minimizing reflections from clutter**
- **John was on the DARPA panel that produced the report,** "Assessment of Ultra-Wideband (UWB) Technology", OSD/DARPA Ultra-Wideband Radar Review Panel, R-6280, Defense Advanced Research Projects Agency (July 13, 1990) that originally coined the term UWB and defined it to be >25%

# *Phenomenology from Foliage Penetration Radar Sensor Testbeds*

**U.S. NAVY P-3 UWB SAR**

UHF; Polarimetric;
0.3 x 0.7 m Resolution
(X-, C-, L-Bands; Polarimetric;
1.5 x 1.5 m Resolution)

**SRI FOLPEN III**

100 - 300 MHz, 200 - 400 MHz,
or 300 - 500 MHz;
HH, VV, or HV Polarization;
0.5 x 0.5 m Resolution

**FOA CARABAS II**

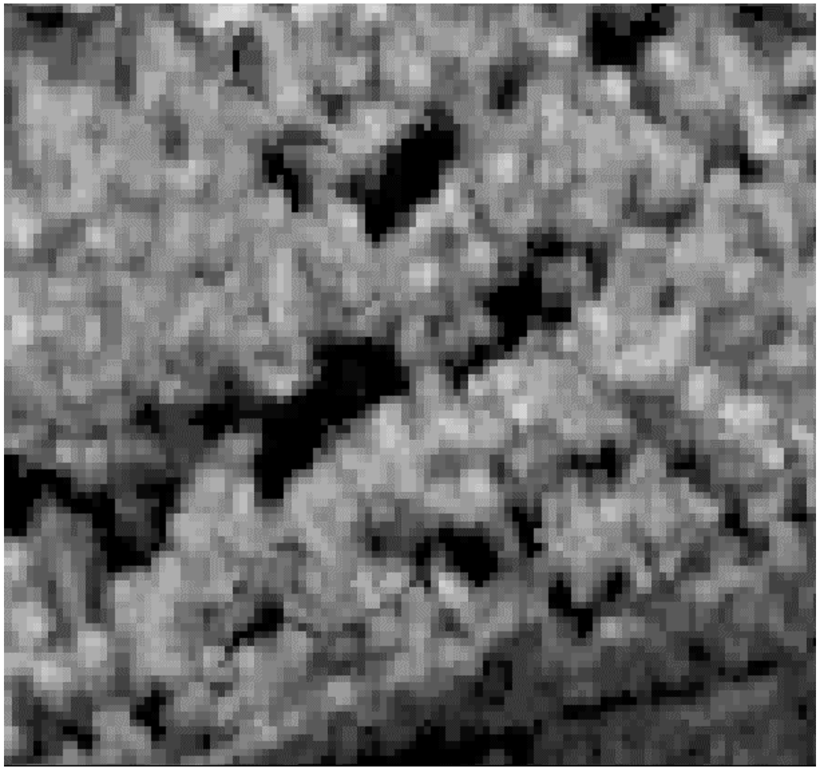
20 - 90 MHz;
HH Polarization;
2 x 2 m Resolution

**SANDIA LF SAR TESTBED**

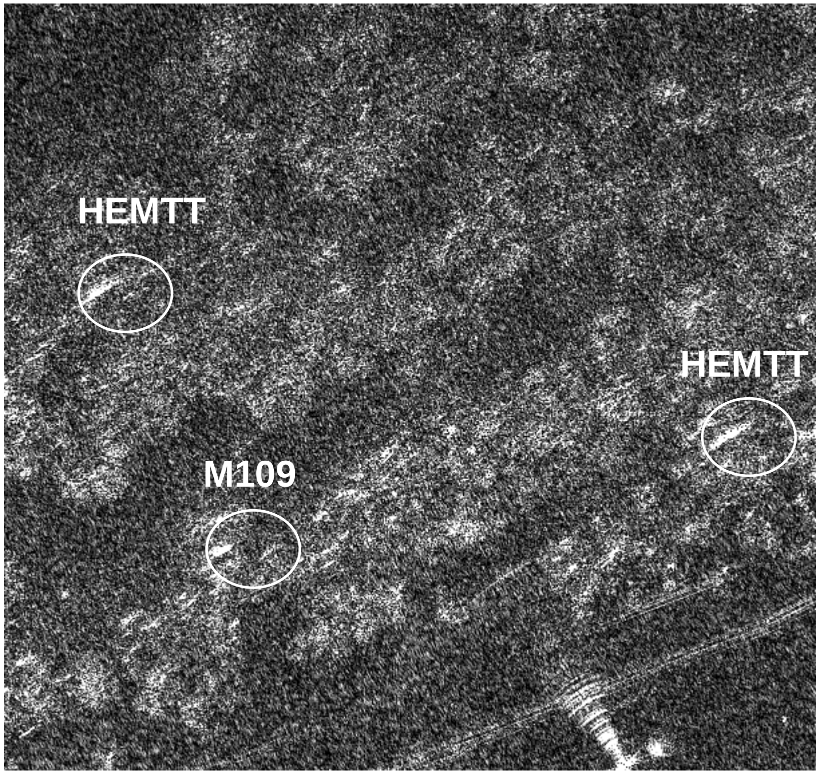
125 - 950 MHz; Polarimetric
Resolution: UHR

# *X-BAND / UHF Comparison From DARPA Field Tests*

## "Sherwood Forest," Camp Roberts, CA
## Tactical Targets Parked Under Oak Trees



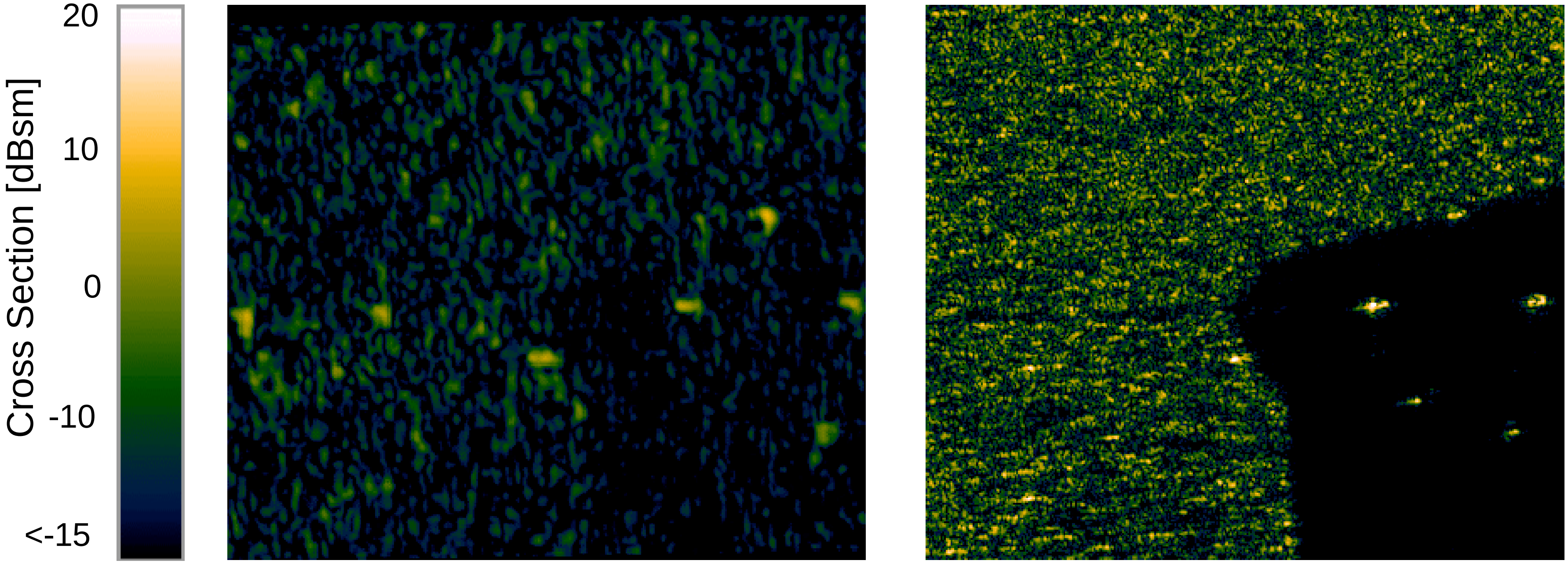
**2.5 m X-band IFSARE**




**P3 0.4 m UHF FOPEN**

**Ultra Wideband Radar Enables Target Visualization Below Foliage That Was Intractable Without UWB**

# *VHF / UHF Comparison From DARPA Field Tests*

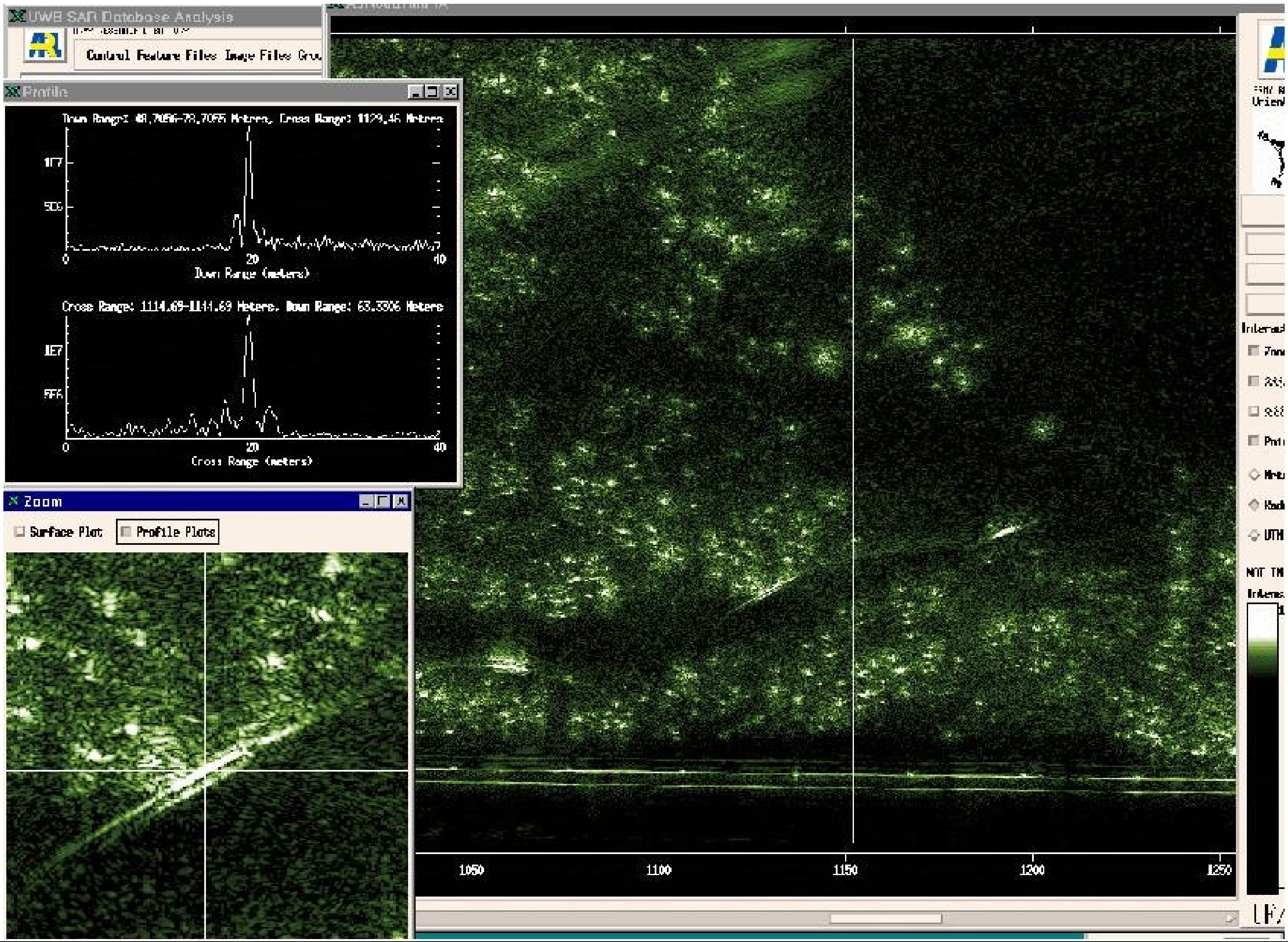



**CARABAS VHF RADAR**
**Frequency 20 - 83 MHz**
**Resolution: 3 m x 3 m**
**Polarization: HH**

**SRI UHF FOLPEN II**
**Frequency 200 - 400 MHz**
**Resolution: 1 m x 1 m**
**Polarization: HH**

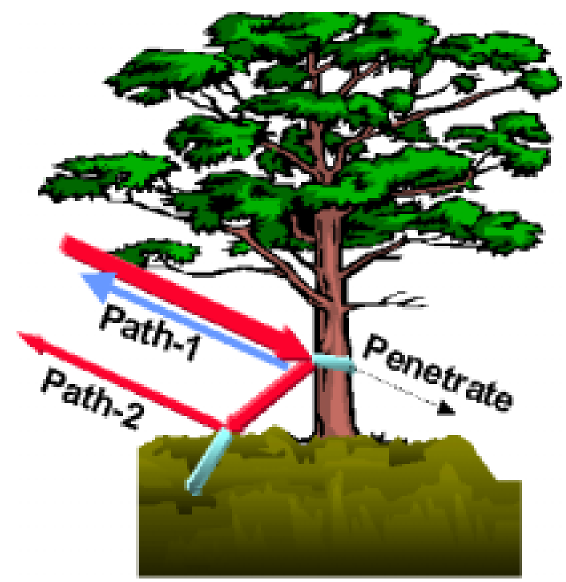
**Lower Frequencies Drop Both Clutter and Smaller Targets**

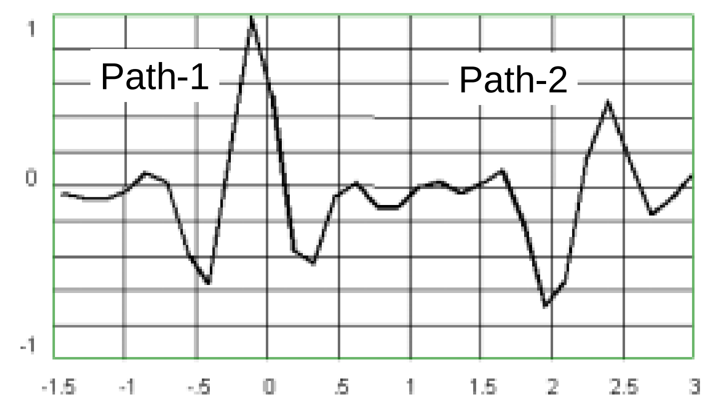
# *Rich Phenomenology Image From ARL*



# *How UWB Works -- Multipath, Clutter & Penetration Phenomenology*

- **Radio waves reflect and penetrate Reflections are multipath**
- **Key is resolving multipath and penetrating**
- **Only way to do this is UWB**
  - Lower frequencies in UWB penetrate
    - submarine⇒VLF; Walls/trees ⇒VHF/UHF
    - millimeter wave ⇒stopped by rain/fog
    - Concrete is 10F dB/m, F in GHz
  - Lower frequencies interact with fewer (only larger) objects
  - Bandwidth in UWB resolves multipath
- **Multipath is a critical issue for RF**
  - causes scintillation in radar
  - causes fading in communications
- **FOPEN radar phenomenology same as in-building communication phenomenology**



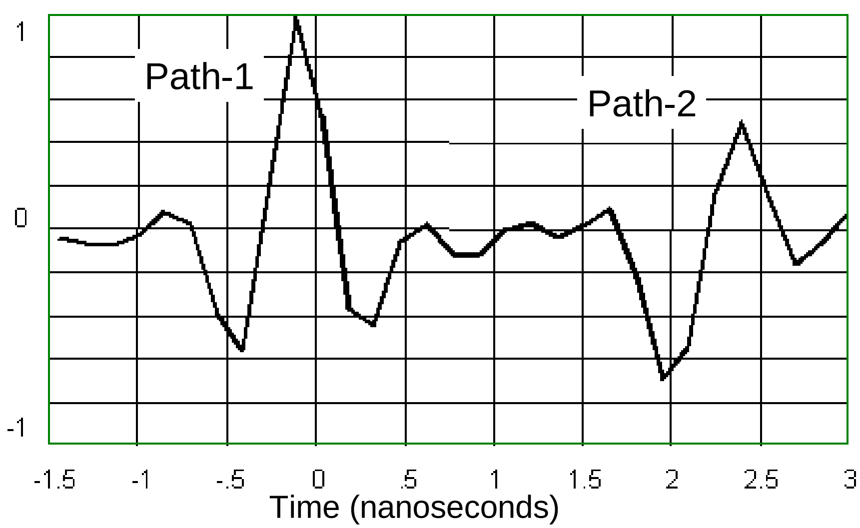



# *View From ARL Rooftop SAR*

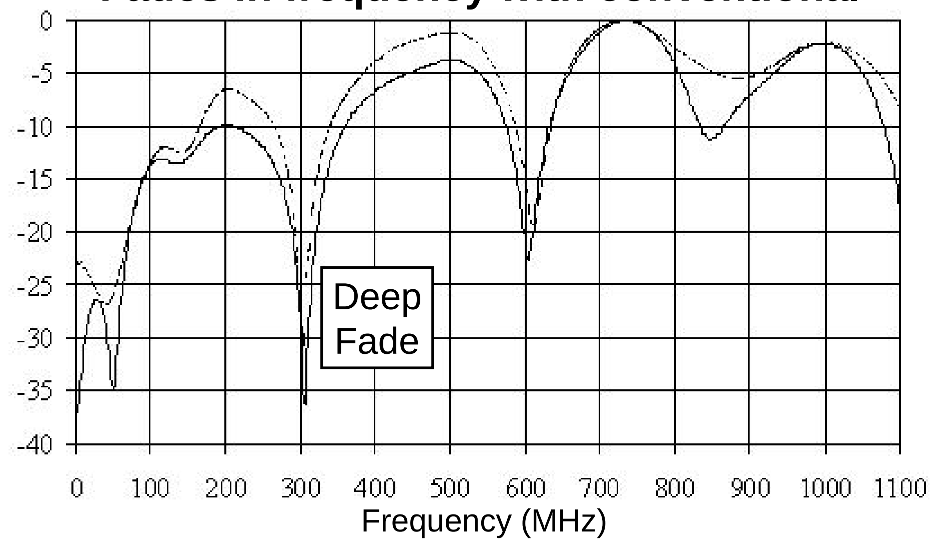
# *Difference With Conventional RF*
# *UWB Is Highly Immune To Multipath Fading*

- NB measurements can confuse multipath fading for attenuation
- UWB is immune to multipath fading because it resolves reflections
- UWB can use multipath components to increase performance
- Spatial diversity provided by multipath allows UWB signals to propagate around obstacles that would otherwise attenuate them

**Resolved in time with UWB**



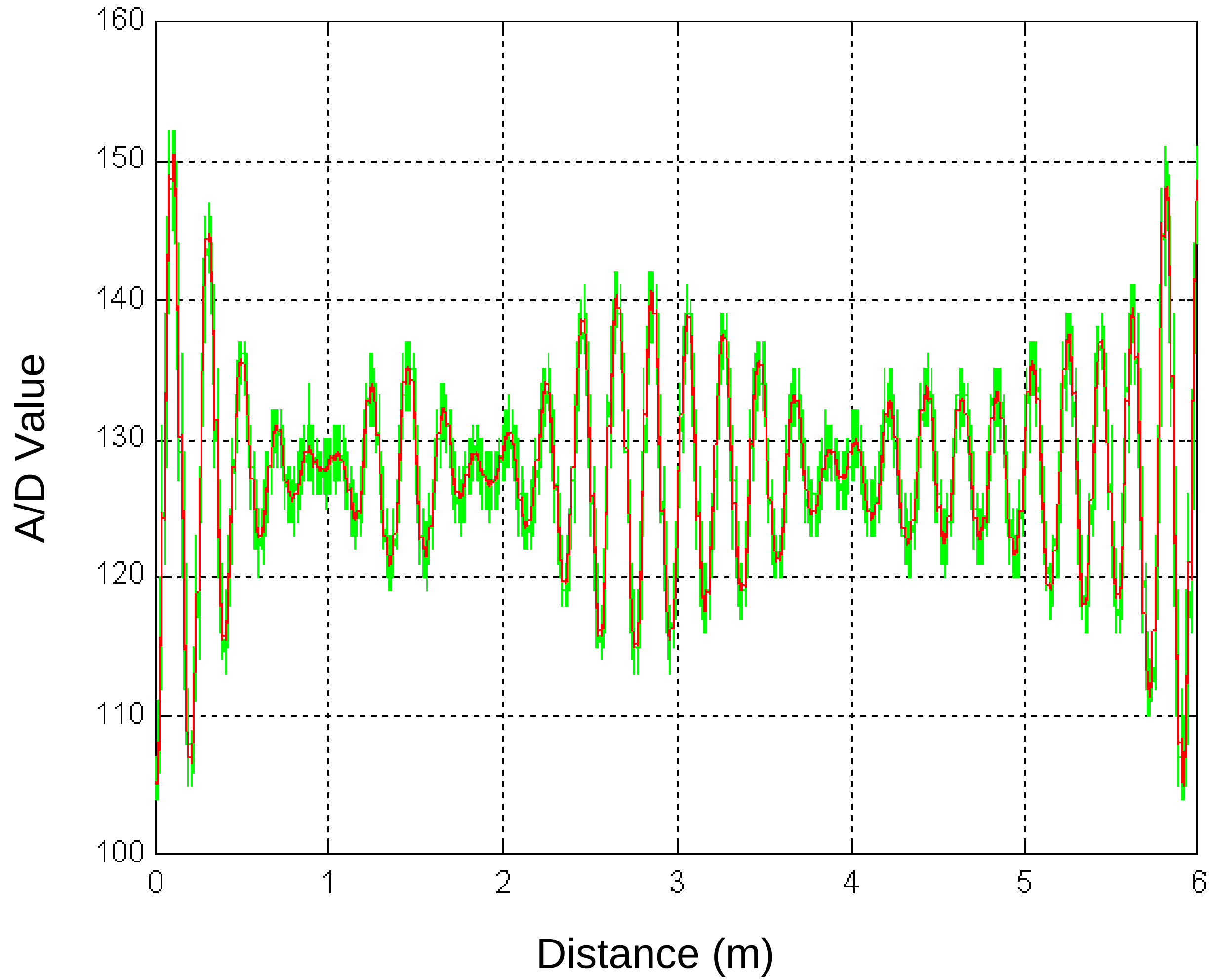

**Fades in frequency with conventional**



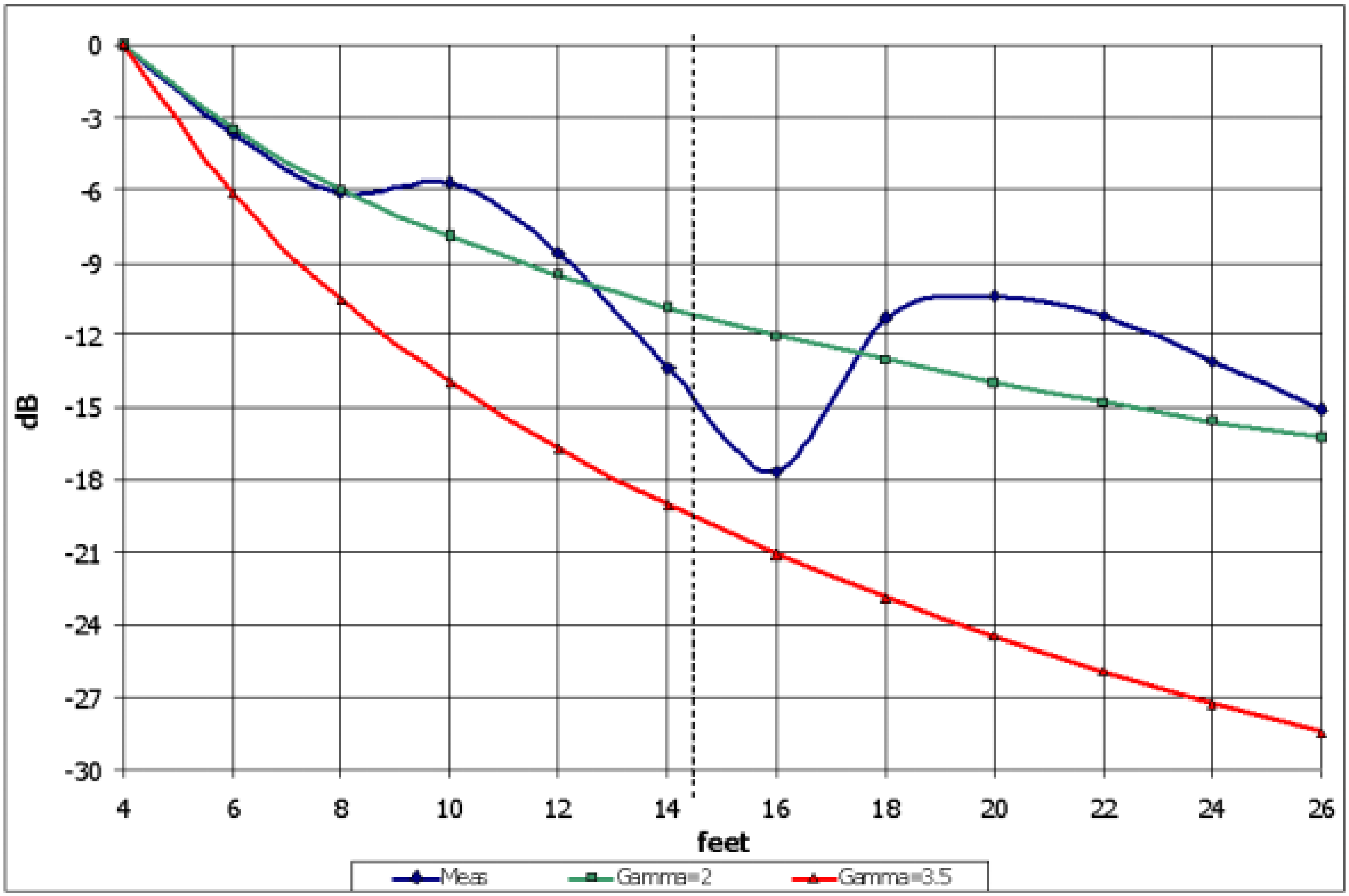
# *UWB Channel Physics*

- **Phenomena includes**
  - Material Properties $\sigma,\varepsilon,\mu$
  - Interface Properties (i.e. scattering from and coupling into a material at given polarization and incidence angle -- like the Brewster angle)
  - Multipath
    - Material homogeneity, density and graininess
    - Material thickness (e.g. $\lambda$/4 raydome)
    - Object-to-Object or Surface-to-Surface (classical "multipath")
    - Object size/shape scattering physics can include Rayleigh, resonant, and optical regions where the scattering amplitude is $\propto f^a$ where a = +2…-2 (e.g. tip, edge, plate, sphere, corner)
  - Ducting or waveguide modes
  - Diffraction -- bending around earth terrain and objects, also coupling through apertures (e.g. door in room with metal partitions)

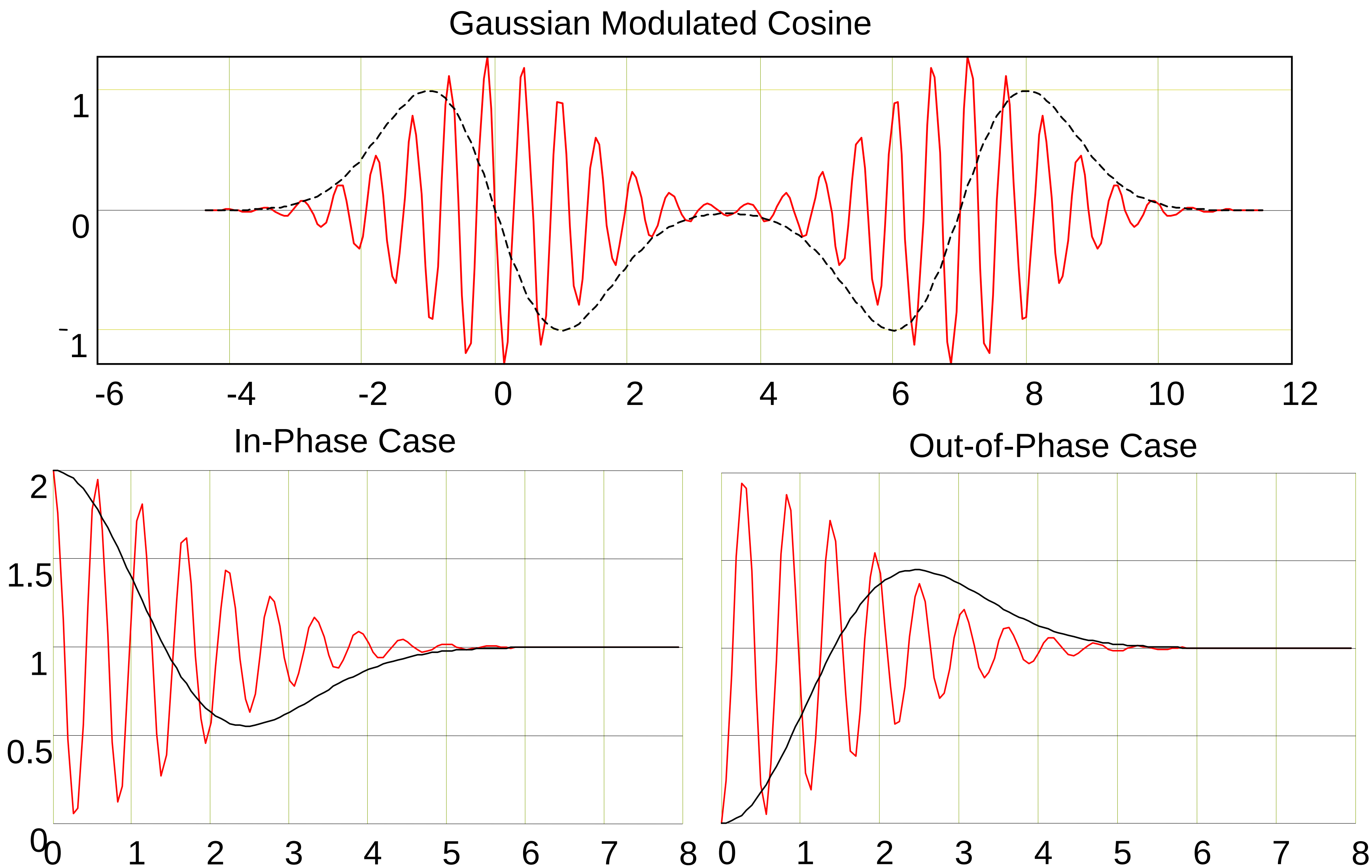
# *Communications Channel Sounding with 15 ft. Separation*



# *Received Power as a Function of Tx/Rx Separation*



# *UWB Versus Narrowband Multipath Interferometry*



## *Simplicity of UWB Implementation Follows from UWB Phenomenology*

- Free-space $1/R^2$ propagation losses and shallow multipath dips allow small worst-case link margin
- There exist many resolvable path-lengths between a transmitter and receiver. Each of these path lengths can be used to communicate.
- Because they are resolvable in time, they can be combined for better SNR.
- Since a bit is represented by a pulse that does not have multiple cycles for RF energy, nothing is required to derive the "phase" of any particular multipath term. Once the peak is found, the phase is also found.
- There is a low likelihood that multipath meets the unique conditions to cancel a UWB signal (or cause a fade) on all path lengths available between a transmitter and receiver simultaneously.
    - On the contrary, there is a high likelihood that there are multiple path-lengths that provide a strong signal.
- RAKE that is useless in short range applications with narrowband, can be applied with UWB.
- Implementing RAKE is simple - no deconvolution, no phase
- Result is the radio can work with a lower RF power than a narrowband radio.

## *Information Theory Benefits*

**Shannon's Equation** $C = B\log\left(1+\frac{S}{N}\right)$

**Data rate capacity (*C*) can only go above the channel bandwidth *B* at a unfavorable *log* function with power.**

**Regulatory limits provide** $P_0 = \text{Watts/Hz}$

$$C = B\log\left(1+\frac{S}{N}\right) = B\log\left(1+\frac{P_0 B}{KTB}\right) = B\log\left(1+\frac{P_0}{KT}\right)$$

**Data-rate is now proportional to channel bandwidth *B***
**Data-rate is linearly scaleable (use code gain to keep S/N low)**

# *Bi-Phase Optimal Modulation Properties*

- **Bi-phase modulation yields a 3dB to 6dB advantage over PPM (time-hopping) in multipath-free environments -- greater advantage in multipath since multipath appears as data modulation in PPM**
- **Bi-phase modulation exhibits a peak-power to average-power ratio of less than 3 (for reference, a sine wave is 2). This leads to efficient transmitters and a natural fit into low cost, low voltage CMOS.**

$b \in \{0,1\}$ Bit is either 1 or 0

$s(t,b)$ Energy Normalized Waveform,

$t = \text{time}, b = \text{bit}$

$n(t)$ AWGN, zero mean, standard deviation $\rho$

$r(t) = V_t s(t,b) + n(t)$ Received Signal

$\langle s(t,0), s(t,0) \rangle = 1$ Receive 0 and correlate to 0

$\langle s(t,1), s(t,1) \rangle = 1$ Receive 1 and correlate to 1

$\langle s(t,0), s(t,1) \rangle = \rho$ Receive 0 and correlate to 1

$$P_e = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right)$$ Probability of error

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} \partial y$$ Error Function, $Q(\cdot)$

For Bi-phase, $s(t,0) = -s(t,1)$, so $\rho = -1$

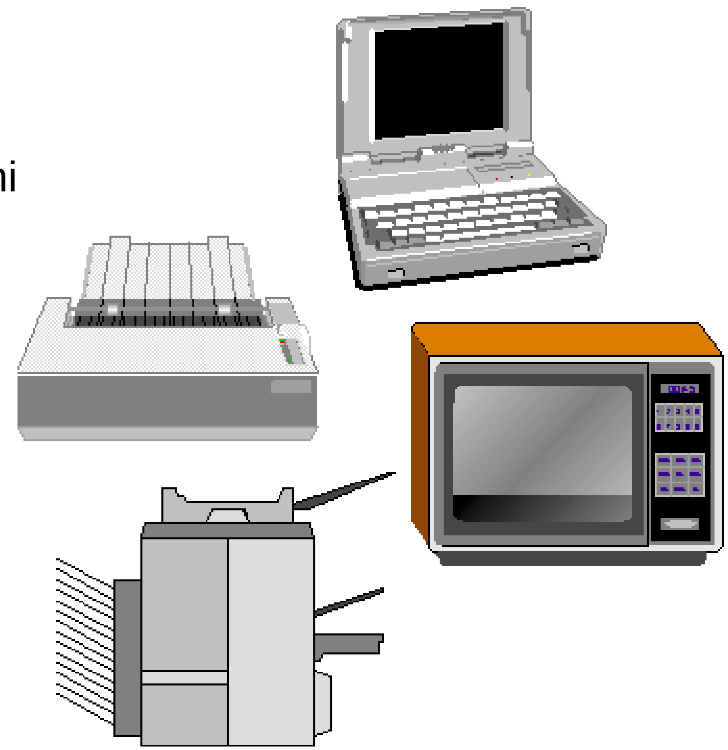
For PPM, $\rho = 0$

$$P_e^{biphase} = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right) = Q\left(\frac{V_t}{\sigma}\right)$$

$$P_e^{PPM} = Q\left(\frac{V_t}{\sigma}\sqrt{\frac{1-\rho}{2}}\right) = Q\left(\frac{V_t}{\sigma\sqrt{2}}\right)$$

# *Regulatory Implications*

- **Unintentional emissions**
  - From radio and TV transmitter spurs/harmoni
  - From Part 15 devices
    - Computers, printers, electric shavers, …
- **Cumulative impact has been benign**
- **Frequency re-use/overlay**
- **Rules that allow intentional UWB emissions**



# *Phenomenological Benefits Provide Capability Previously Unobtainable With Narrowband*

- **Communications**
  - Radios with a few dB fading margin & $1/R^2$
  - High speed radios with low SNR (Shannon) and low prime power
  - Radio's that are scaleable from kbps to 100 Mbps - under software control
  - Reuse of crowded frequency spectrum
  - Reliable in-building links at high data rates
- **Radar**
  - Imaging sensors with no speckle
  - Airborne radar that images targets hiding behind trees
  - High resolution imaging of objects under the ground, through walls, etc.
- **Safety**
  - Extremely low total RF power
  - Extremely low power in any band that resonates with an organ

# *Personal Area Networks (PAN) are a Natural Application for UWB Radios*

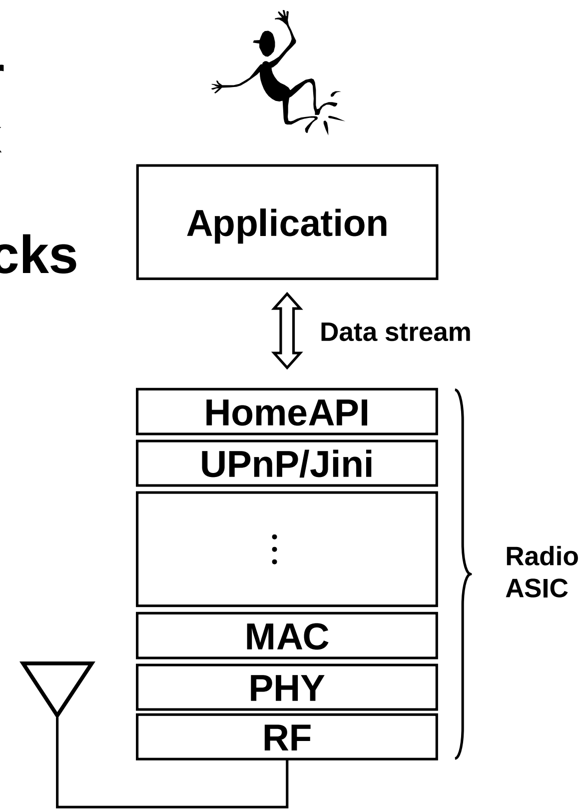
- **XtremeSpectrum PAN Radios**
  - High data rates allow multimedia
  - Low power enables handhelds
  - No line of sight or orientation problems
  - Software scaleable data rate 1-100 Mbps
- **Data driven PAN world view**
  - Purpose of radios is to connect devices nearby to each other and the net
  - Wired & wireless LANs are enhanced by high data rate wire replacement
  - Computers, peripherals, VCR, video camera, DVD, MP3, …
  - Requires low cost 10-100 Mbps
  - New radios must be found
- **XtremeSpectrum UWB PAN radios are ideal for a data driven future**
- **Products will be embedded radio modems with significant performance advantages**

  Support wireless 100BaseT, Firewire (1394), USB, …

# *UWB Communications In The Stack*

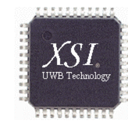
## Leverage knowledge base, form fit and function of existing standards into next generation high performance standards

- **UWB technology is the physical radio layer**
  - The radio is at the base of the technology stack
- **Can support industry defined protocol stacks**
  - Microsoft's Universal Plug and Play (UPnP)
  - SUN Jini
  - Wireless HAVI
- **Can add UWB physical layers to extend**
  - HomeRF SWAP
  - Bluetooth
  - 802.11x
  - HiperLAN

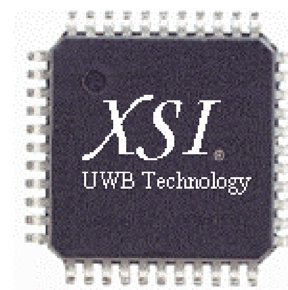


## *What Does UWB Provide the User Community*

- **Personal area network (PAN) radios**
  - Addresses short range wireless markets -- Personal Operating Space (POS)
  - 10 to 20m range
  - Data rates scaleable to 100 Mbps
  - Price target $5-8 per radio in >100K quantities




- **Local area network (LAN) radios (Residential Gateway, WLAN)**
  - Addresses residential gateway, WLAN
  - 50m range
  - Initial data rate 25Mbps scaling to 100 Mbps
  - Price target $12-15 per radio in >100K quantities



# *XtremeSpectrum's Current Radio Performance*

- **Measurement environment**
  - Seventh floor of a glass & rebar concrete office tower
  - System built from discrete analog and digital components
  - Results are for basic radio
    - Performance can be enhanced with FEC, DSP, RAKE
  - Many range, data rate, power, BER combos possible
    - Demonstration system scalable from 50Mbps down

- **Measured performance**
  - Transmit-Receive separation 45 feet

**Data rate 50 Mbps**
**BER $10^{-5}$**
**Transmit power 20 uW**

**Data rate 7 Mbps**
**BER $10^{-5}$**
**Transmit power 2.67 uW**

- **Headroom of over 30dB already defined**

# *Conclusion*

- **UWB solves problems that are otherwise intractable**
- **It provides a compelling new technology impacting both communications and remote sensing applications**
- **UWB can drastically impact the way people use and access information (e.g. WPAN, Residential Gateway)**
- **It uniquely enables high speed wireless communications in high clutter (in-building) areas at *wireline costs***
- **UWB chips CAN resemble the chips in Part 15 devices and generate similar emissions.**