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

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Abstract: [Material on Ultra Wide Band]

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, 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 Corp. (Avalanche transistor based systems, antennas, etc.)
- Tom McEwan at Lawrence Livermore (avalanche based systems, receivers, samplers, etc.)
- Rex Morey at Geophysical Survey Systems Inc. (GSSI) (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 and Steve Davis, at Power Spectra (Radscat, BASS – Bulk GaAs semiconductor switch)

Companies Specializing in UWB Communications

- Aether Wire and Location
- ANRO Engineering, Inc.
- Fantasma Networks (Interval Corp.)
- Lawrence Livermore Labs
- Multispectral Systems, Inc.
- Time Domain System, Inc.
- 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**

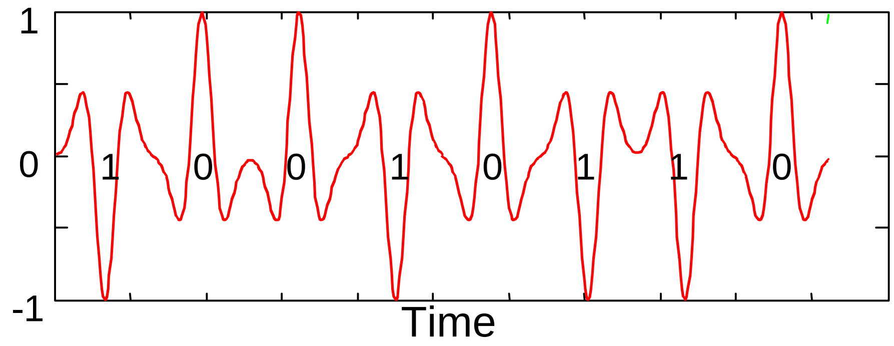
What Does an XSI Radio Look Like

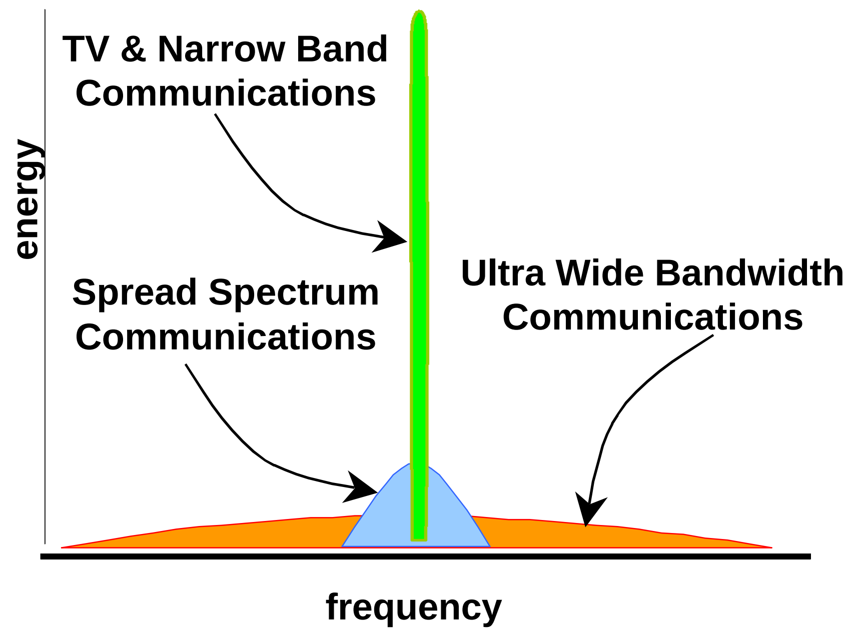
Same low voltage CMOS as the chips in your computer

Computer Chip	XSI Radio Chip
Pins toggle to send bits	Pins toggle to send bits
Antenna is PC board traces	Antenna is etched on PC board
Unintentional UWB radiates	Intentional UWB radiates
	UWB signals are received

UWB Concept

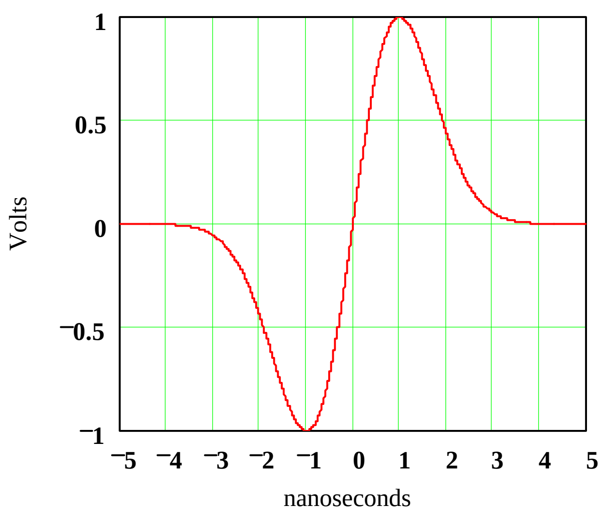
- **Coded short duration pulses spread the signal energy over frequency and time**
- **Can overlay existing FCC frequency assignments**
  - Spread is so broad, little energy gets in a narrowband
  - Short range WPAN systems can operate below the detection threshold of conventional receivers
- **Low probability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

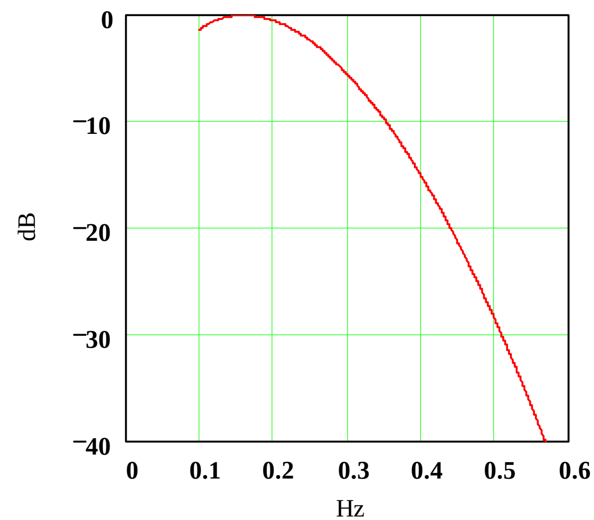




Useful Analytic Waveforms
Derivatives of a Gaussian

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



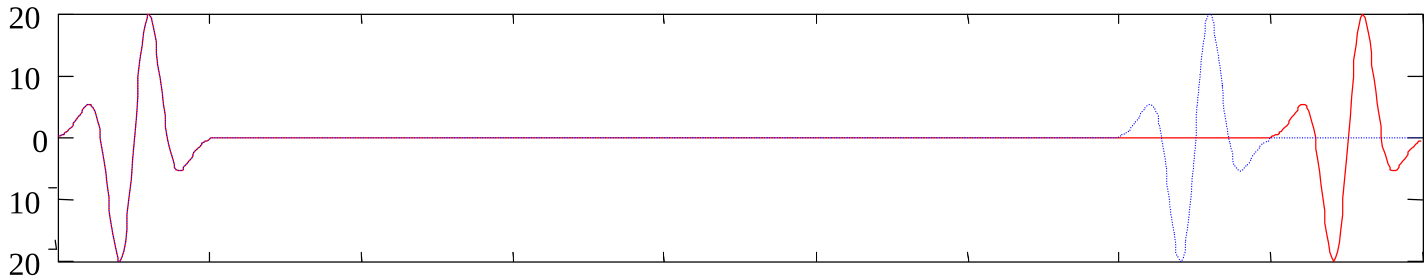


$$f_{max} = \pm\frac{1}{2p\ t_p} \qquad f_c = \frac{f_{lo} + f_{hi}}{2} = 1.12\, f_{max} \qquad \begin{aligned} f_{lo} &= 0.3191057\, f_{max} \\ f_{hi} &= 1.9216229\, f_{max}, \end{aligned}$$

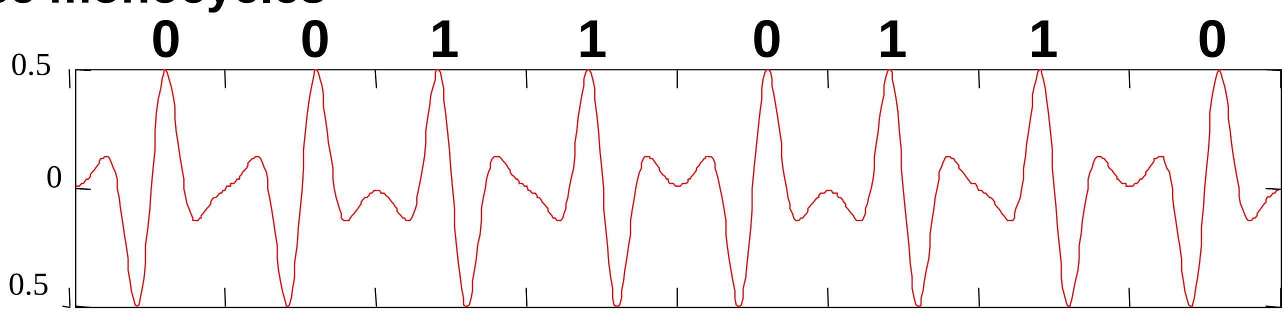
$$p = A^2 t_p \frac{e\sqrt{p}}{2}$$

What Do UWB Signals Look Like?

- Time-hopping or PPM (pulse position modulation)

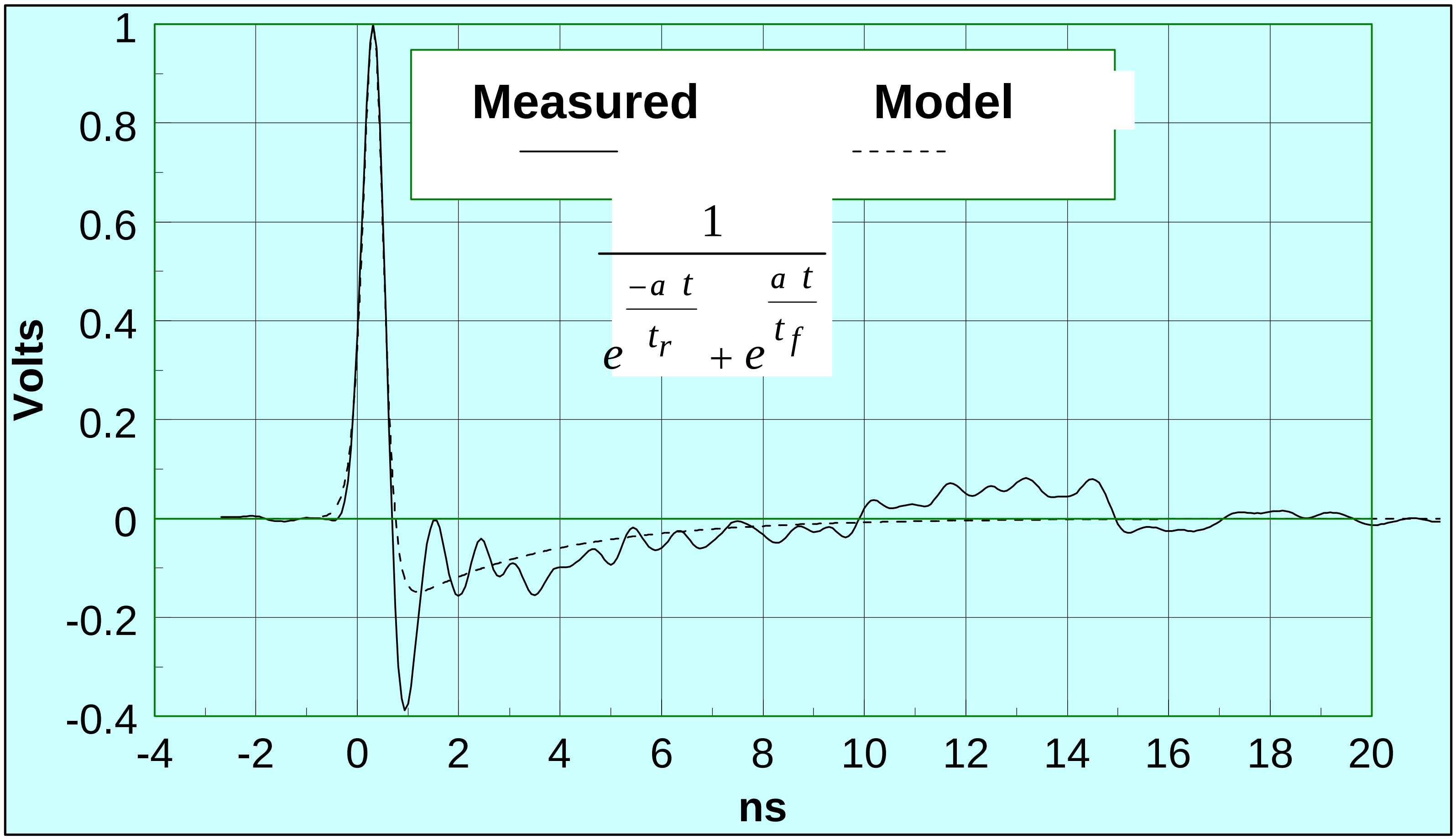


- Bi-phase monocycles



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

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



$$\frac{1}{e^{\frac{-a\,t}{t_r}} + e^{\frac{a\,t}{t_f}}}$$

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

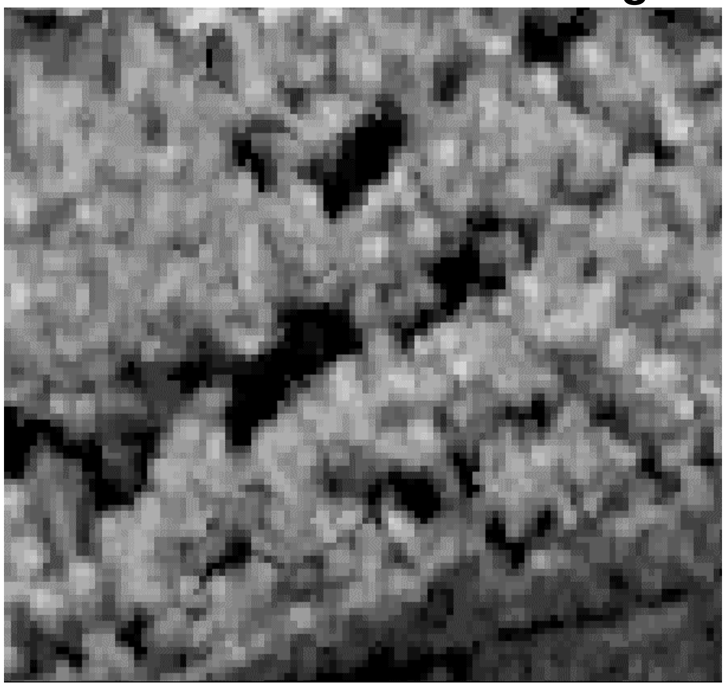
SANDIA LF SAR TESTBED

125 - 950 MHz; Polarimetric
Resolution: UHR

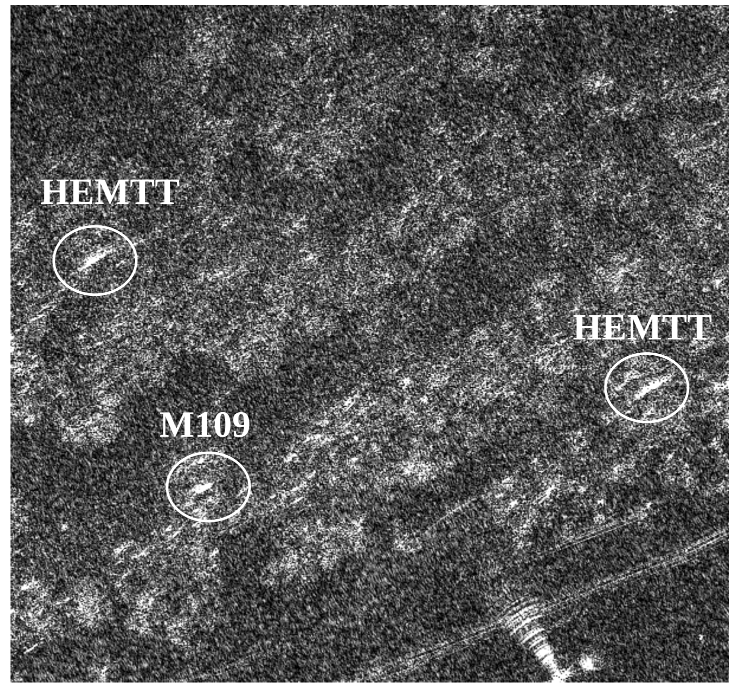
X-BAND / UHF Comparison From DARPA Field Tests

"Sherwood Forest," Camp Roberts, CA

Tactical Targets Parked Under Oak Trees



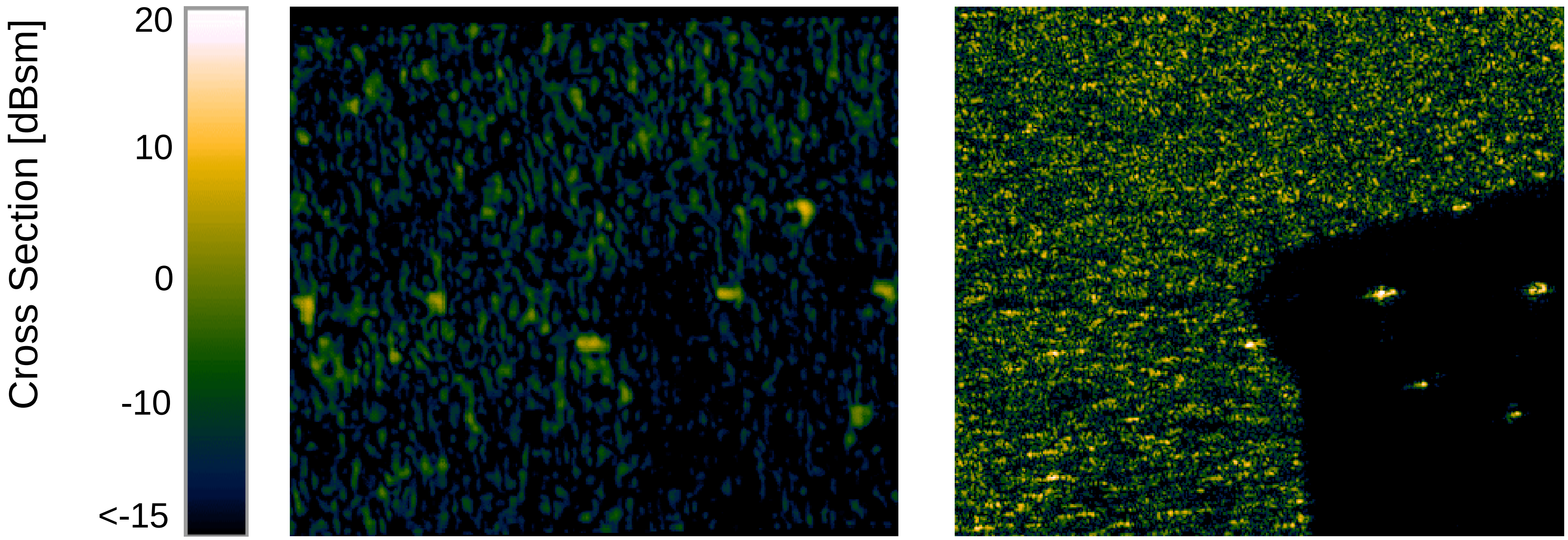
2.5 m X-band IFSARE



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

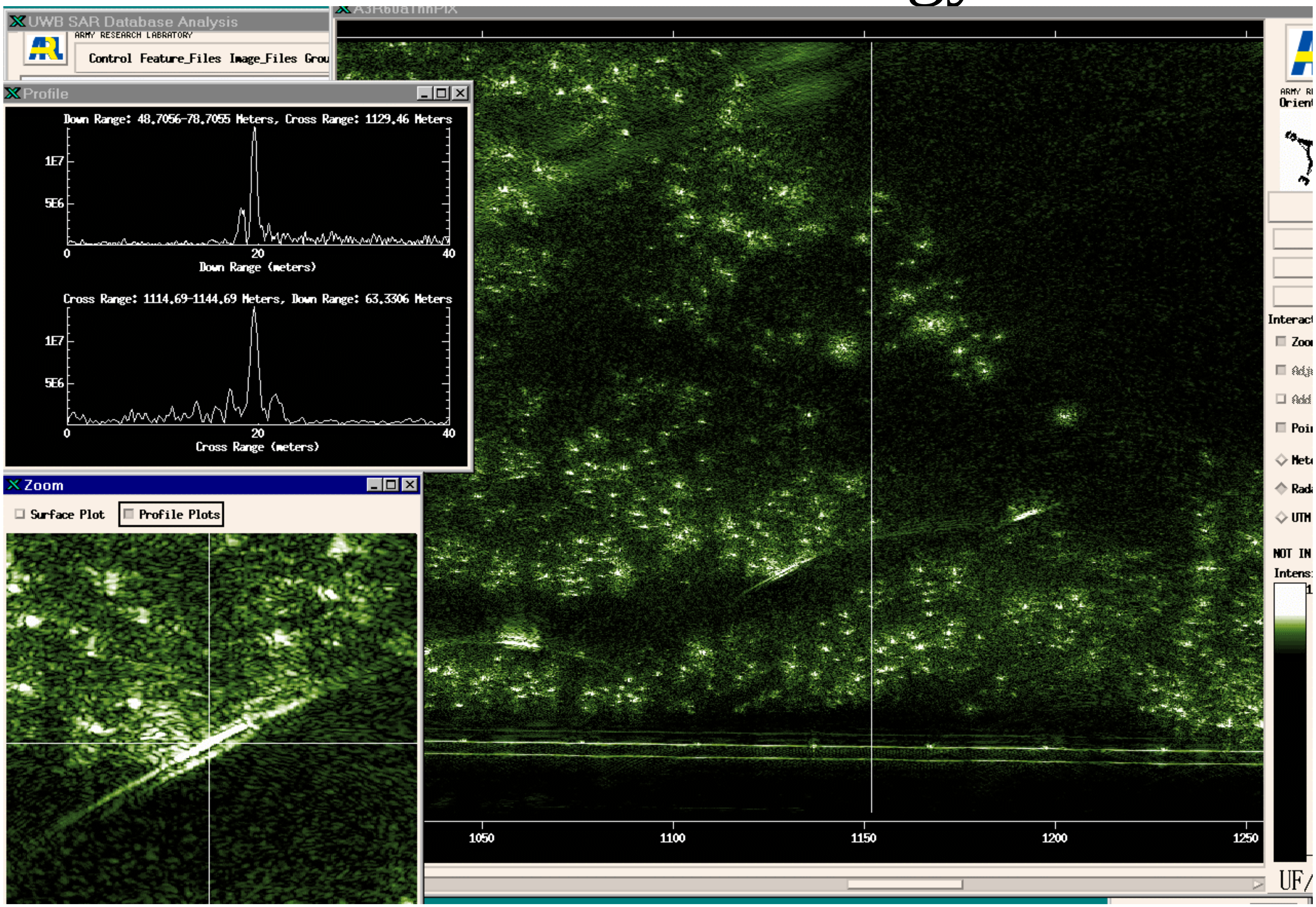


<u>CARABAS VHF RADAR</u>
Frequency 20 - 83 MHz
Resolution: 3 m x 3 m
Polarization: HH

<u>SRI UHF FOLPEN II</u>
Frequency 200 - 400 MHz
Resolution: 1 m x 1 m
Polarization: HH

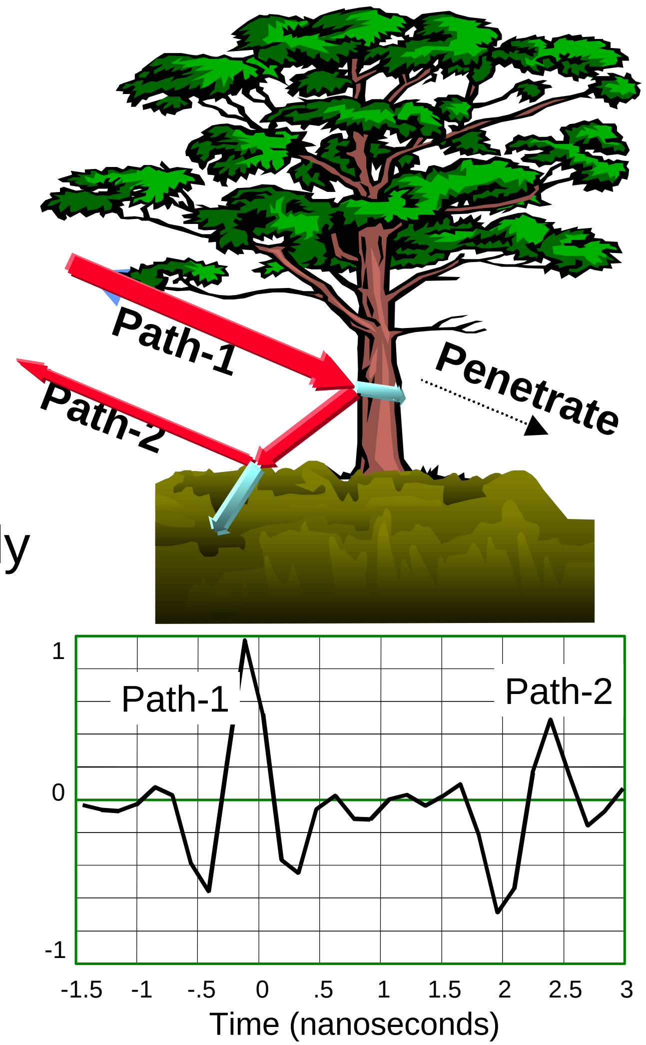
Lower Frequencies Drop both Clutter and Smaller Targets

Rich Phenomenology



How Come 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=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**

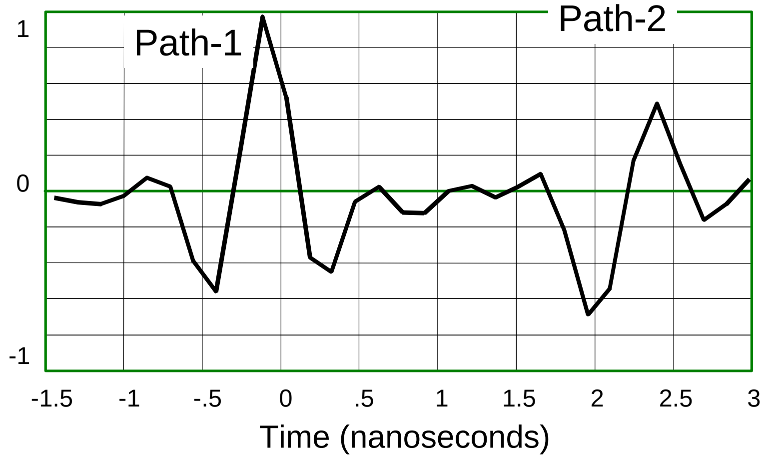


View From ARL Rooftop SAR

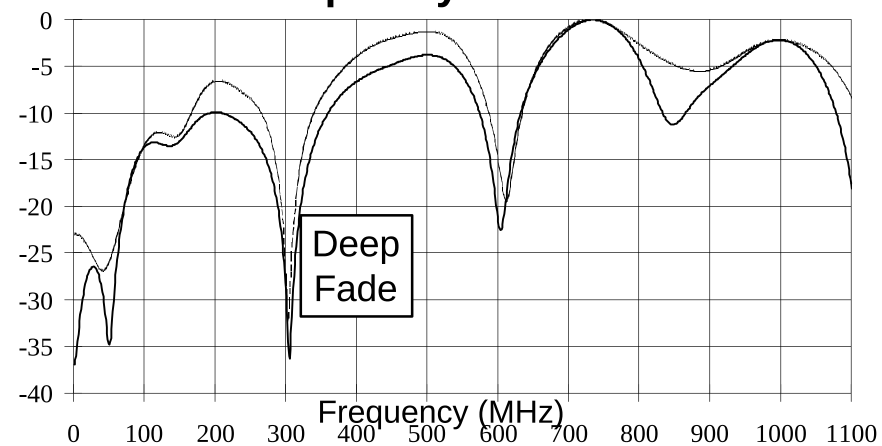
Difference With Conventional RF, UWB Is Highly Immune To Multipath Fading

- **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 of UWB signals allows signals to propagate around obstacles that would otherwise attenuate them.**

Resolved in time with UWB



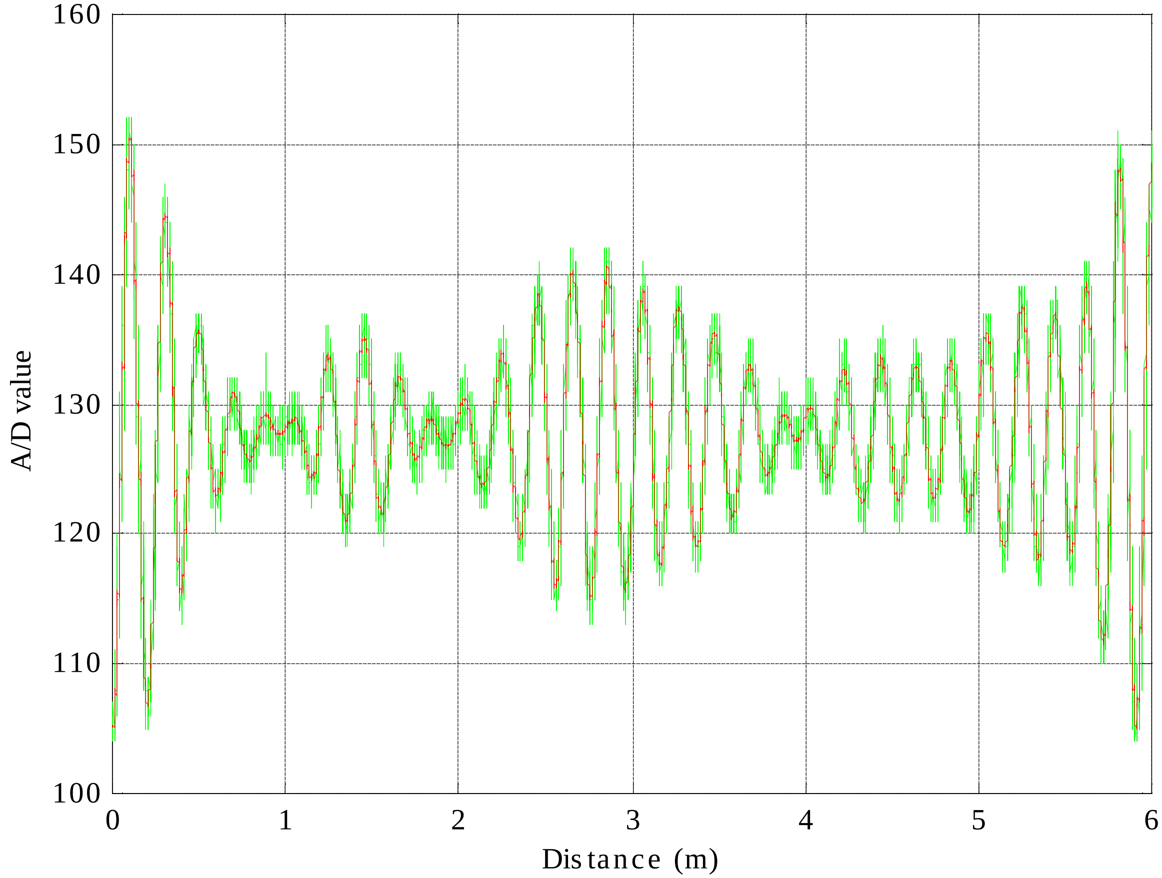
Fades in frequency with Conventional



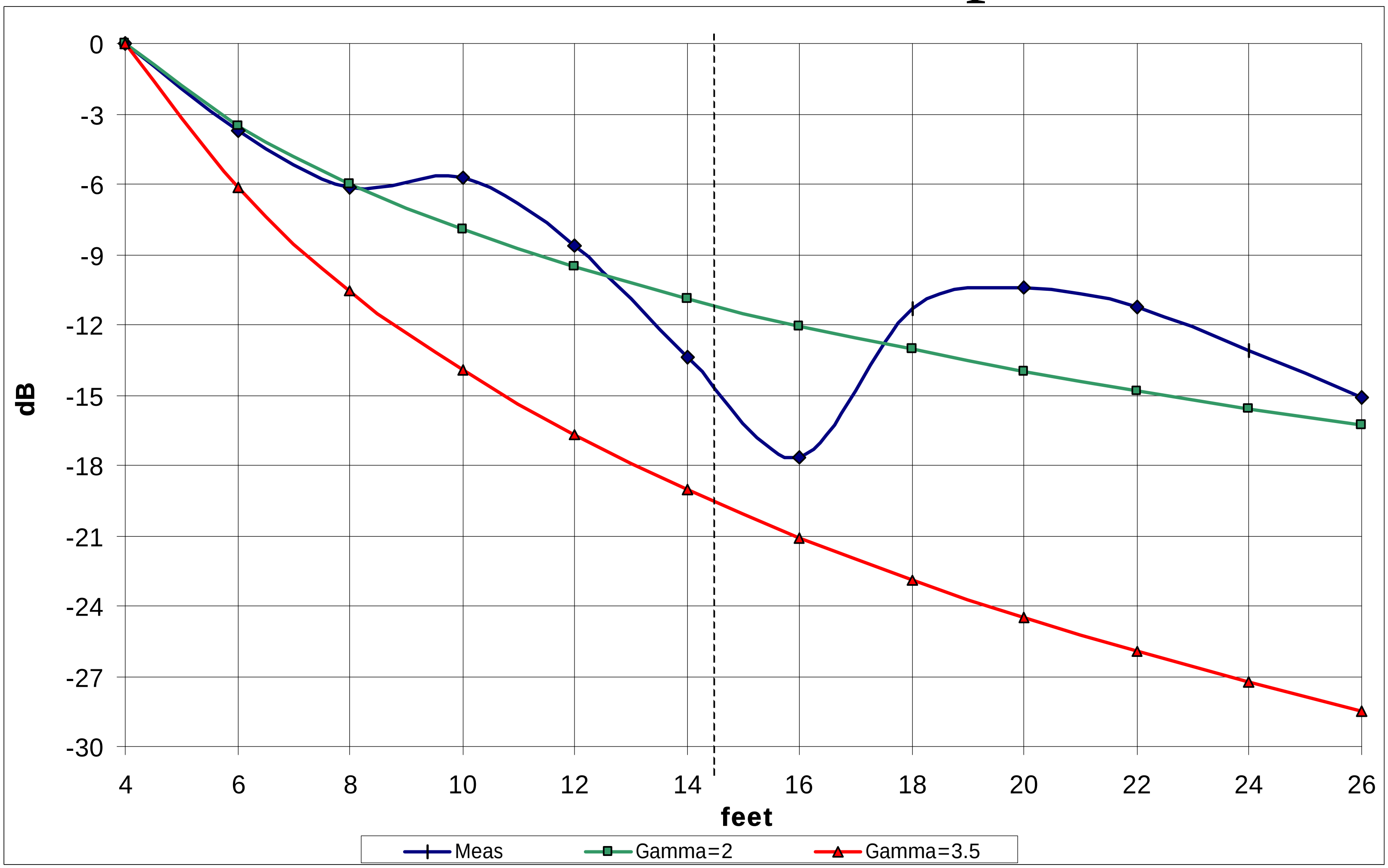
UWB Channel Physics

- **Phenomena includes**
  - **Material Properties** s,e,m
  - **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.** l**/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** $a = +2 \ldots -2$ **(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)**

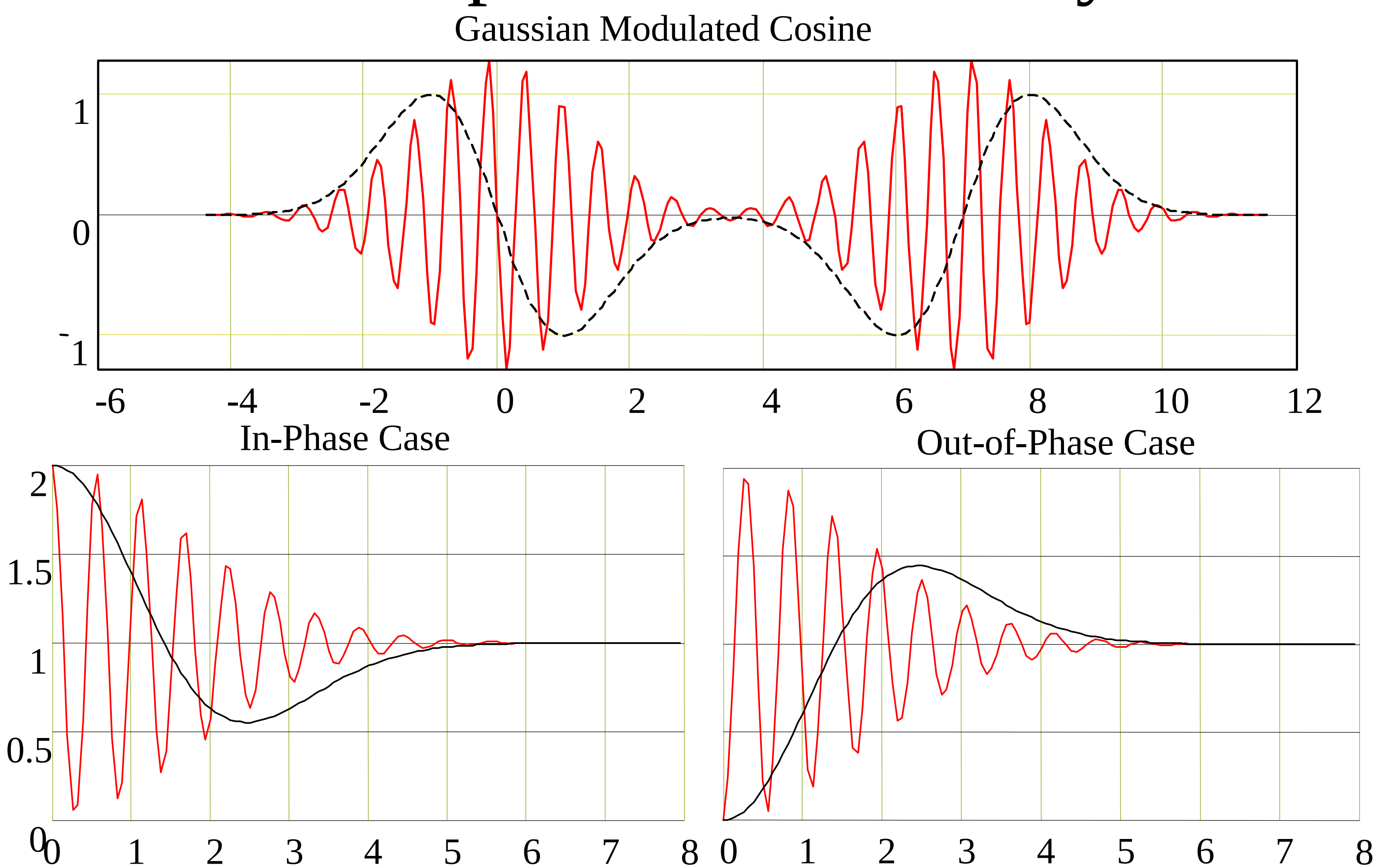
Communications Channel Sounding with 15 ft. Separation



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 = 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,
	$t =$ time, $b =$ bit
$n(t)$	AWGN, zero mean, standard deviation r
$r(t) = V_t s(t,b) + n(t)$	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
$\langle s(t,0), s(t,1) \rangle = r$	Receive 0 and correlate to 1
$P_e = Q\left(\frac{V_t}{s}\sqrt{\frac{1-r}{2}}\right)$	Probability of error
$Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2p}} e^{-\frac{y^2}{2}} \partial y$	Error Function, $Q(\cdot)$

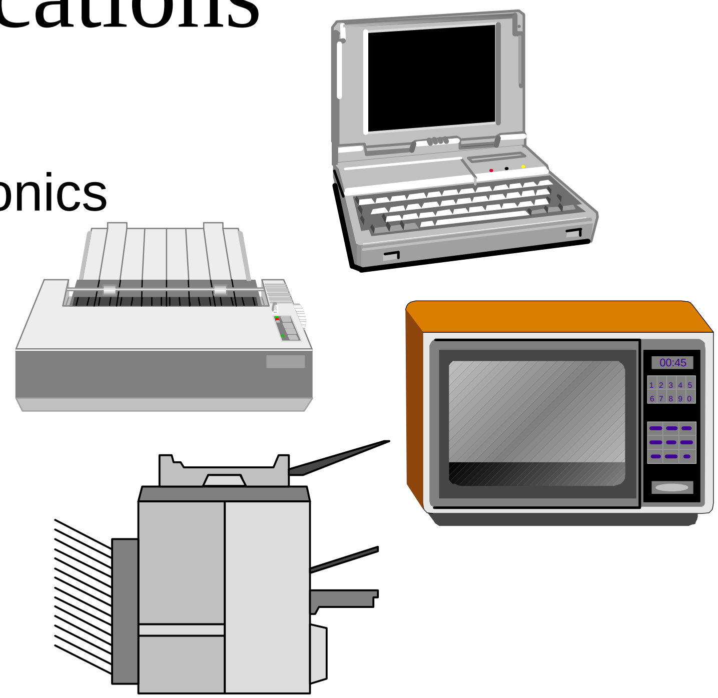
For Bi-phase, $s(t,0) = -s(t,1)$, so $r = -1$

For PPM, $r = 0$

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

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

Regulatory Implications



- **Unintentional emissions**
  - From radio and TV transmitter spurs/harmonics
  - 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

COMMUNICATIONS

- Radio's with a few dB fading margin & $1/R^2$
- High speed radio's with low SNR (Shannon) and low prime power
- Radio's that are scaleable from kbps to 100's 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.

Extremely low total RF power

- Extremely low power in any band that resonates with an organ

Natural Application for UWB Personal Area Network (PAN) Radios

- **XSI PAN radios**

  Low power enables handhelds Software scaleable data rate 1-100 Mbps

- **Data driven PAN world view**

  the net

  Wired & wireless LANs are enhanced by high data rate wire replacement

  -100 Mbps

  New radios must be found

- **XtremeSpectrum UWB PAN radios are ideal for a data driven**

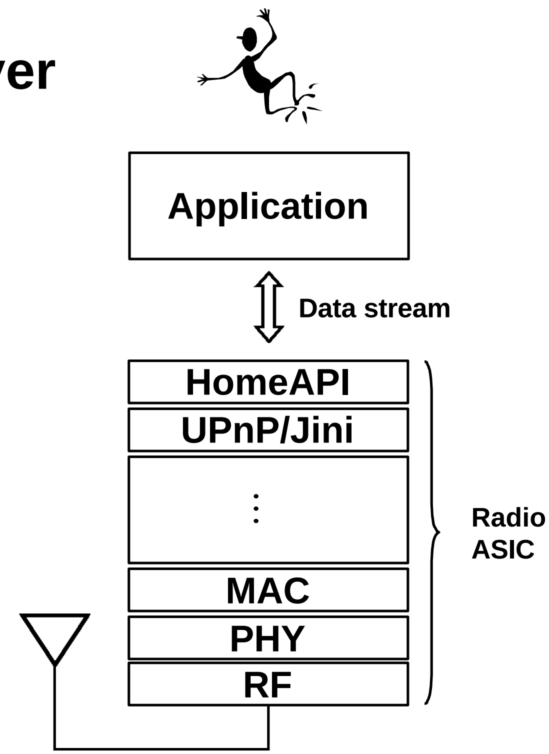
  performance advantages

  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

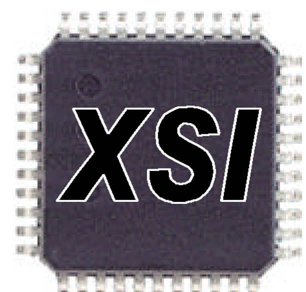
- **UWB technology is the physical radio layer**
  The radio is at the base of the technology stack
- **Can support industry defined protocol stacks**
  Microsoft's Universal Plug and Play (UPnP)
  SUN Jini
  Wireless HAVI
- **Can add UWB physical layers to extend**
  HomeRF SWAP
  Bluetooth
  802.11x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



XSI’s Current 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 (next slide)
  - 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	**Data rate 7 Mbps**
BER 10^{-5}	**BER 10^{-5}**
Transmit power 20 uW	**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.**