Short-Range Ultra-Wideband Systems

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A MURI Team Effort between

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University of California, Berkeley
University of Massachusetts, Amherst

UltRa Lab

An Introduction
to
Ultra-Wideband Radio

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Ultrawideband Radio

$$\frac{\text{Bandwidth}}{\text{Center Frequency}}$$

0 ← NB → .01 ← WB → .25 ← UWB →

$$\frac{\text{Bandwidth}}{\text{Center Frequency}} \sim \text{UWB}$$

→ Coexistence with other radio systems

Interference Mitigation

- spread spectrum
- NB signal excision

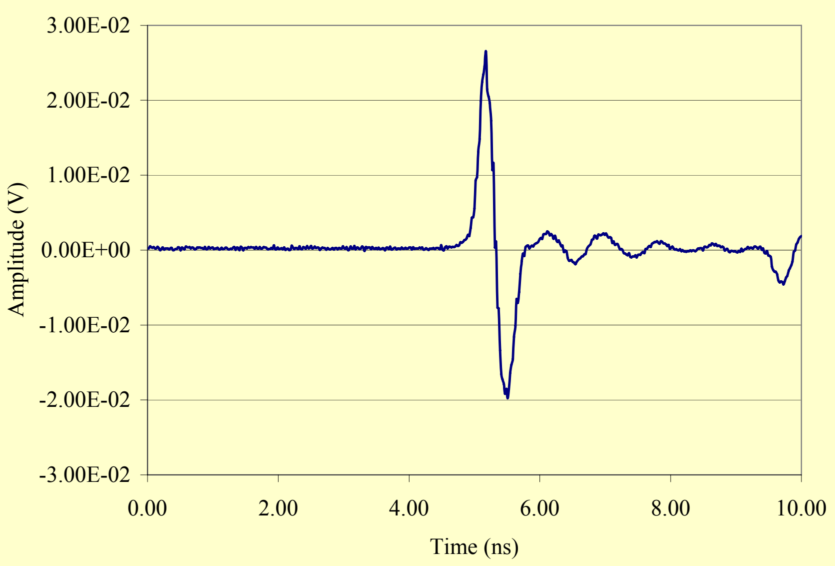
Noninterference to Other Systems

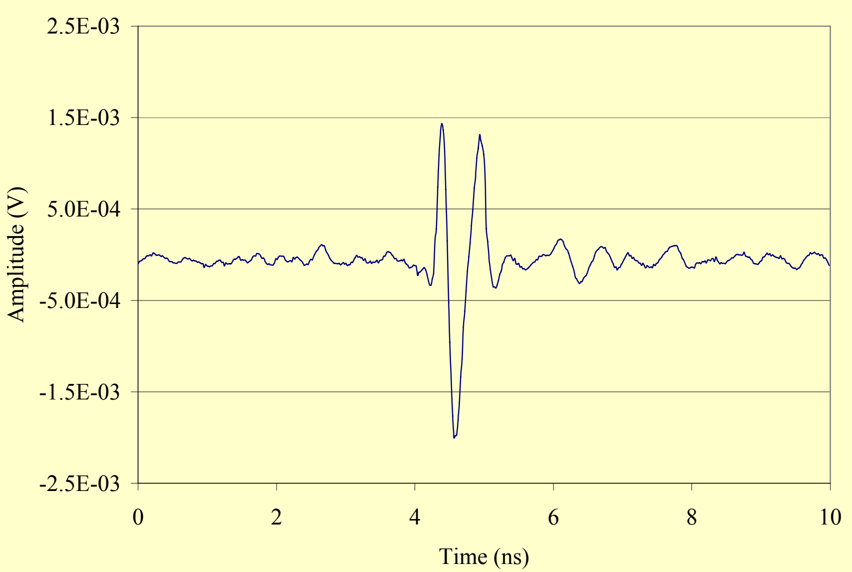
- low power density
- short range
- careful signal design

UWB Impulse Radio (simplified)

Radio Frequency Power Spectra

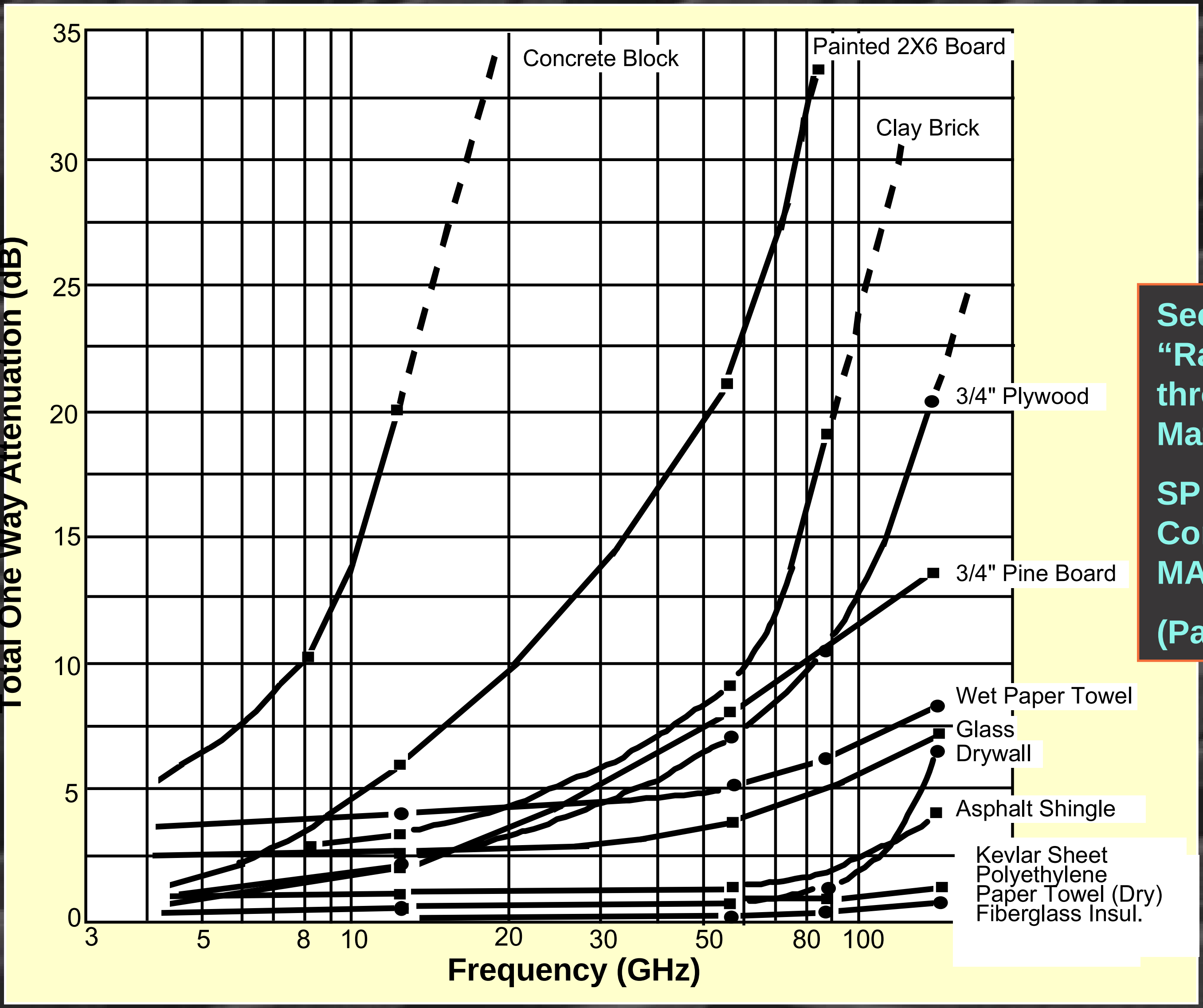
Transmitted and Received Pulses





- **Transmitted voltage waveform measured at coax input to the horn**
- **Received waveform shows a single time differentiation.**

Materials Penetration

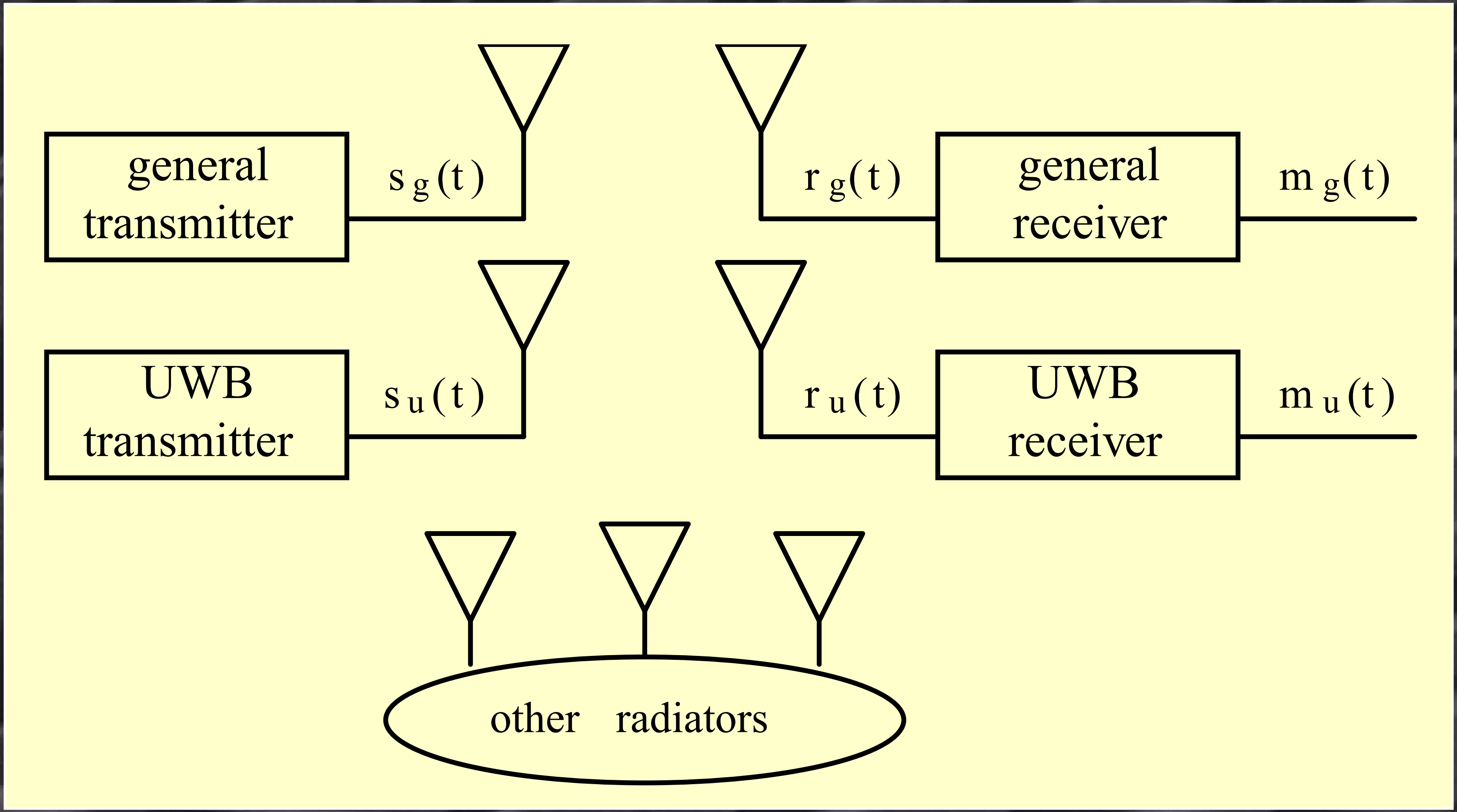


See: L. M. Frazier, "Radar Surveillance through Solid Materials,"

SPIE Photonics East Conference, Boston, MA, November, 1996.

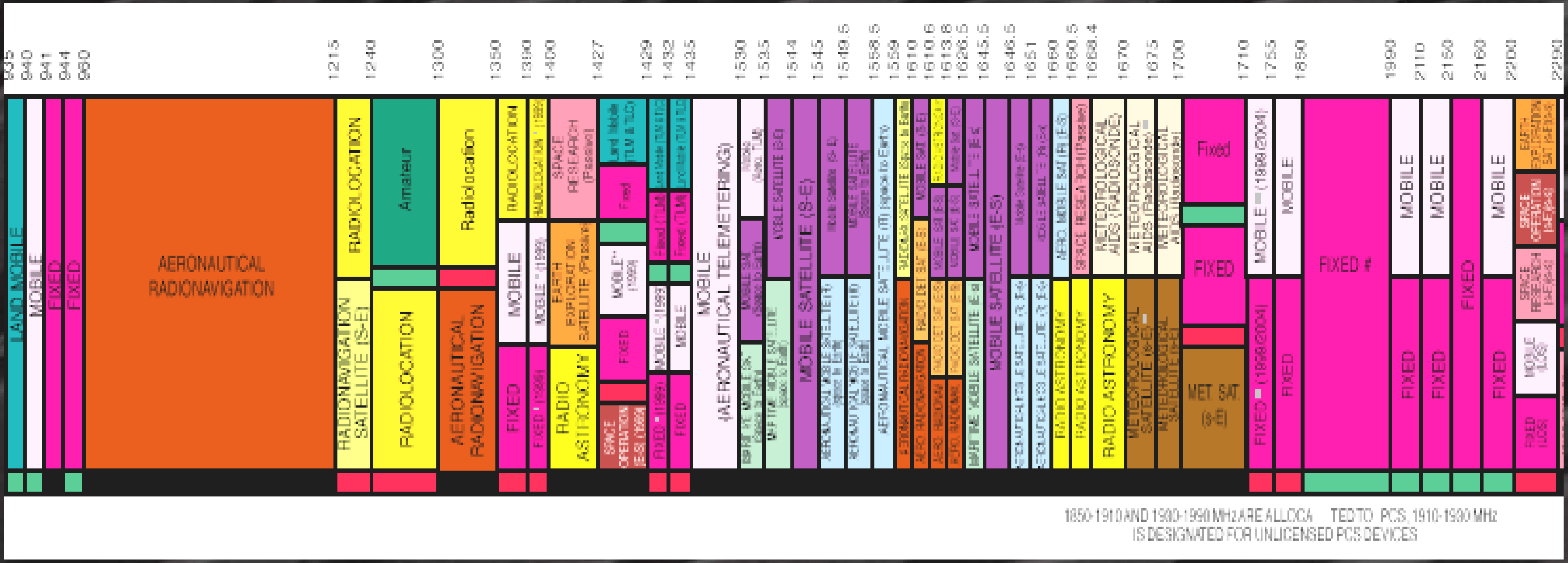
(Paper 2938-20)

Interference Scenario



Coexistence and the FCC

Typical frequency bands spanned by a UWB transmitter



From United States Frequency Allocations (Wall Chart)
Office of Spectrum Management
National Telecommunications and Information Administration
US Department of Commerce

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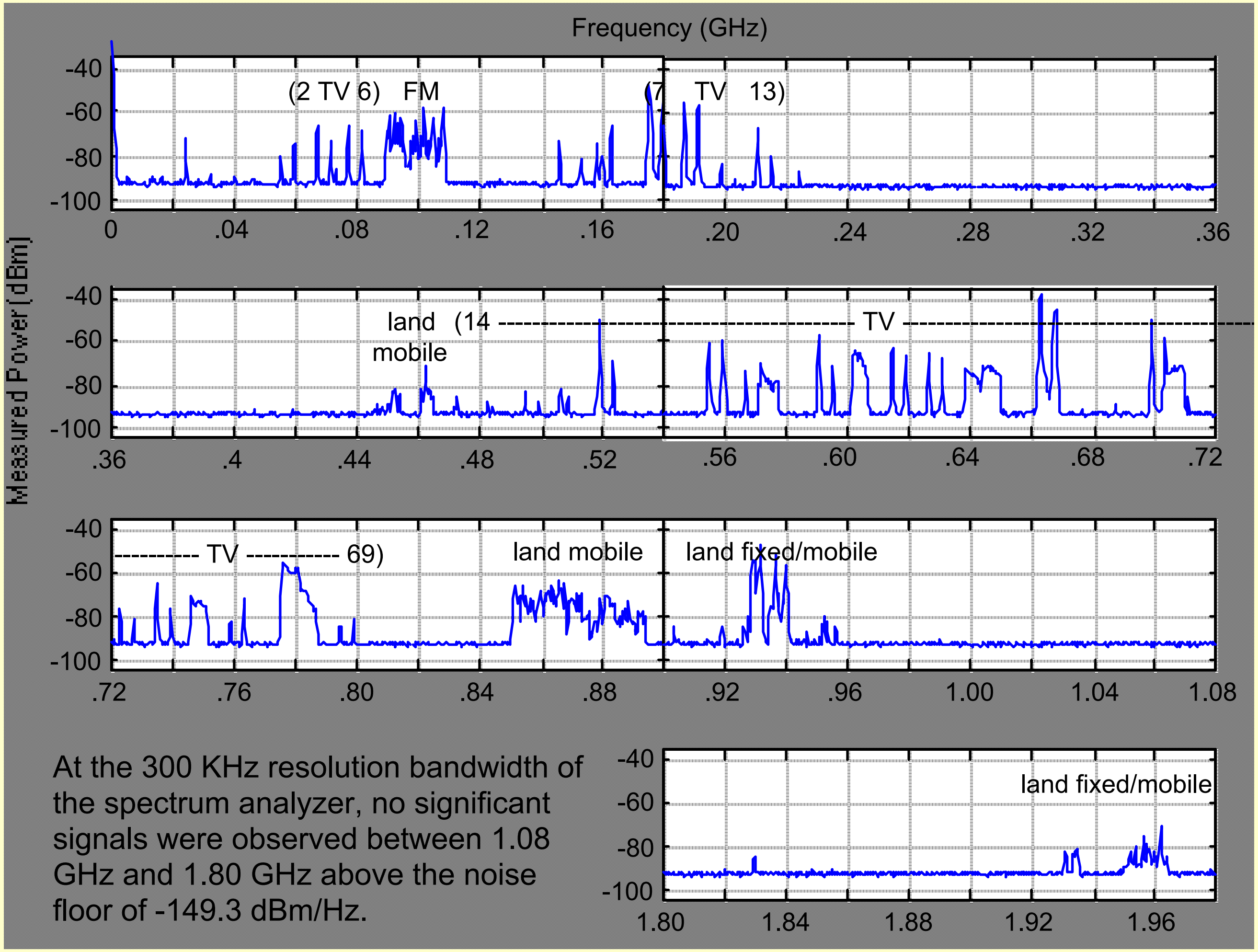
Interference in UWB Receiver



At the 300 KHz resolution bandwidth of the spectrum analyzer, no significant signals were observed between 1.08 GHz and 1.80 GHz above the noise floor of -149.3 dBm/Hz.

A Fabricated Regulatory Example

A UWB radiator must create an electric field strength that is at most 500 microvolts/meter at 3 meters from the radiator in every 1 MHz band.

Part 15 of Section 47 of the Code of Federal Regulations states that for signals above 960 MHz, the unintentional radiated emission limit for all but Class A devices is 500 microvolts/meter at 3 meters.

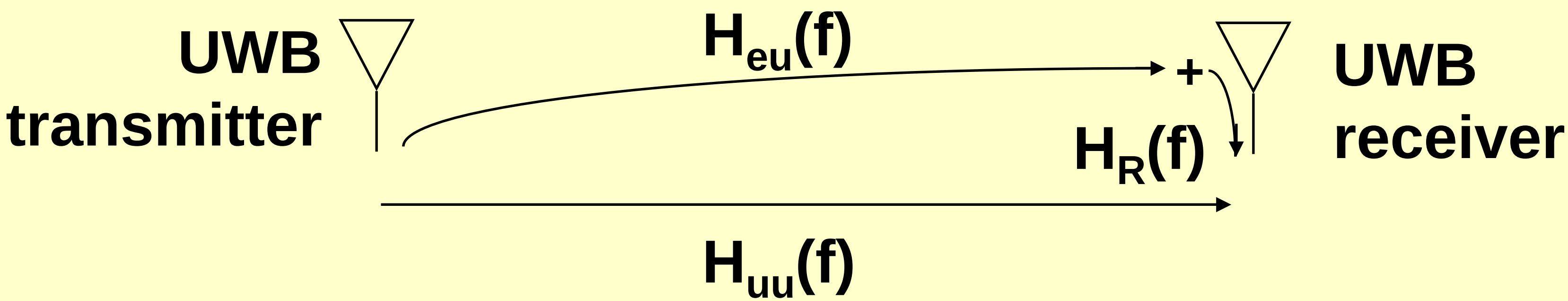
The above example differs from current regulation in three significant ways:

(1) the emission is intentional,

(2) the level of emission is per megahertz,

(3) the field strength is not limited to frequencies above 960 MHz.

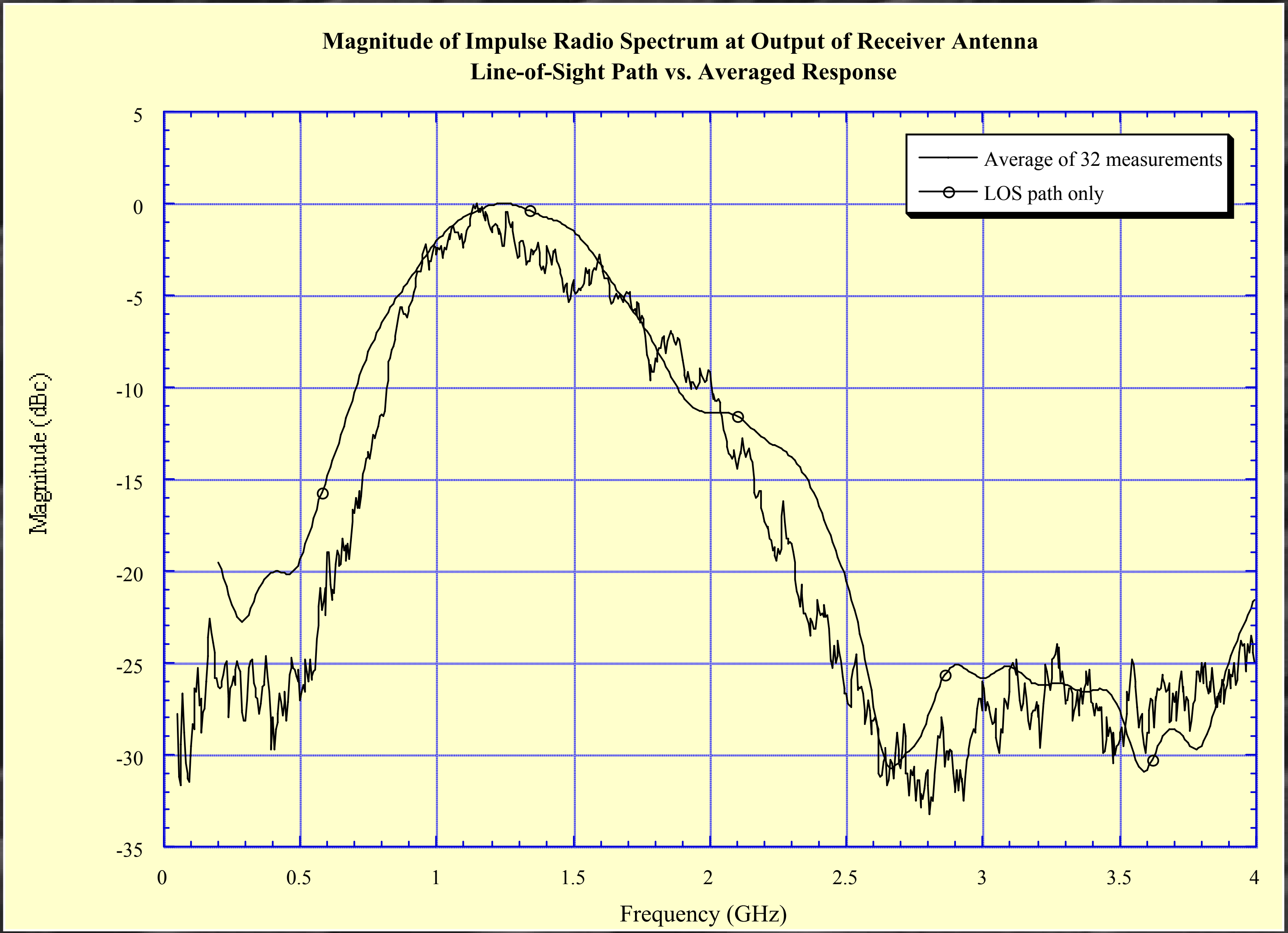
Transfer Function to a Point in Space



$$H_{Eu}(f) = \frac{H_{uu}(f)}{H_R(f)}$$

$$H_{uu}(f) = \frac{(j\,2\pi f)\mu_0}{2\pi c R Z_0} e^{-j\,2\pi f R/c} [H_R(f)]^2$$

Antenna System Characteristics



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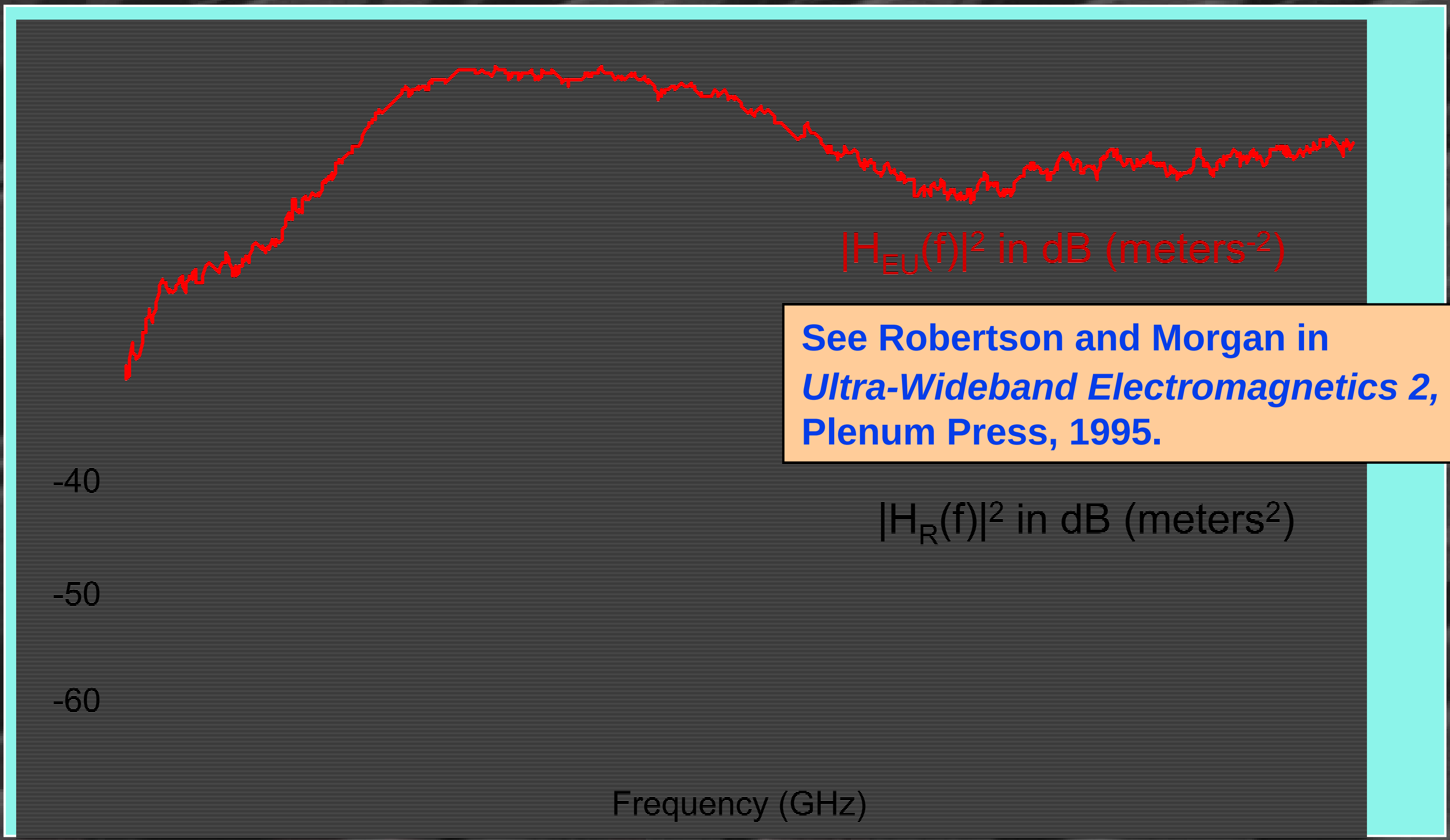
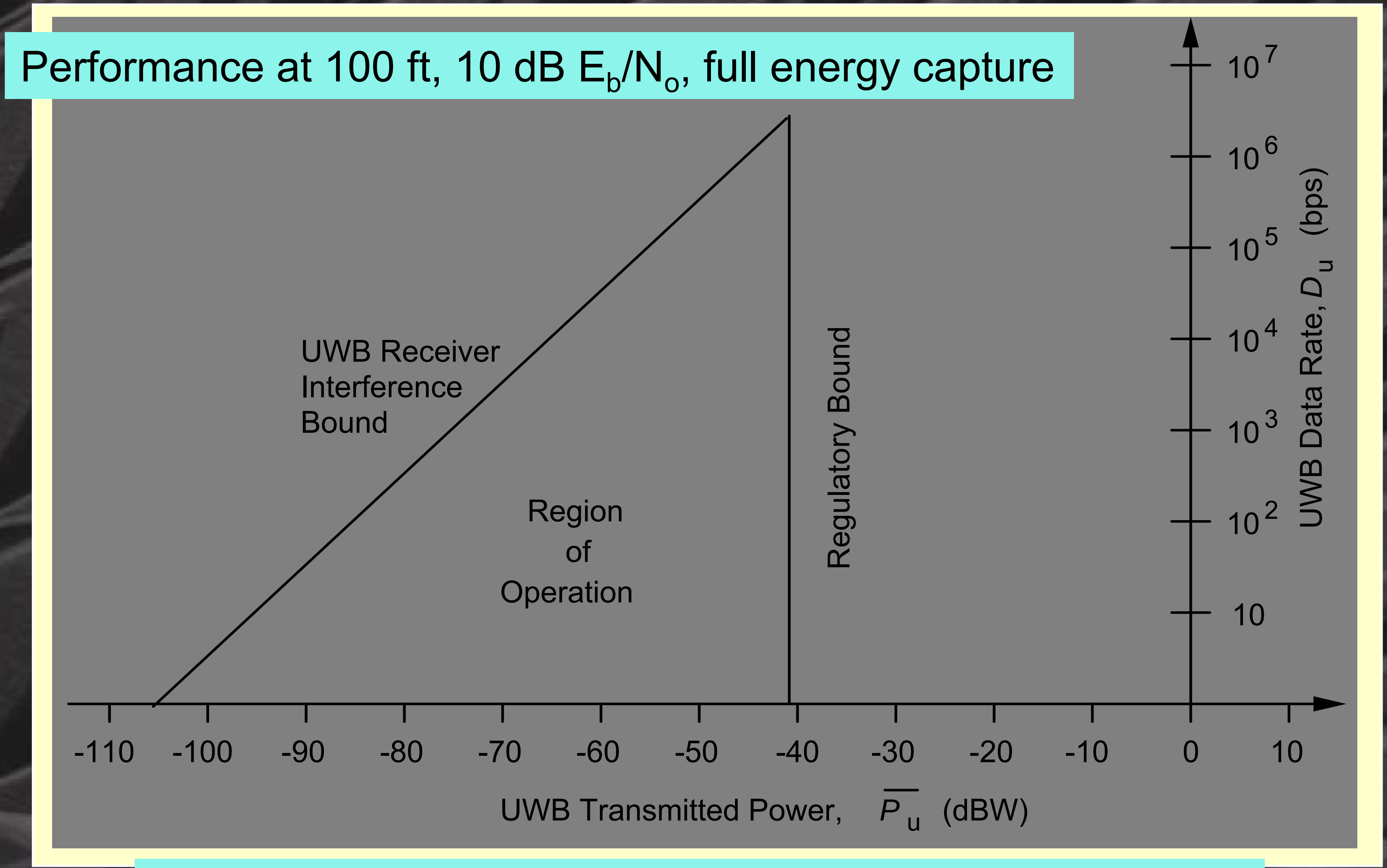
Antenna Transfer Functions



See Robertson and Morgan in *Ultra-Wideband Electromagnetics 2*, Plenum Press, 1995.

Operating Region Example



From Scholtz, et al., “UWB RadioDeployment Challenges,” PIMRC 2001.

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Features of a Rationale

FCC Compliance → Low Power Applications
→ Short-Range and/or Low Data Rate Applications

For a Given Center Frequency:
"Ultra-Wide Bandwidth" → Very Large Bandwidth
→ Fine Time Resolution
→ Ranging is a Killer Application

For a Given Bandwidth:
"Ultra-Wide Bandwidth" → Very Low Center Frequency
→ Good Propagation through Materials

These are comparative/relative statements.

More Consequences of UWB Constraints

Fine Time Resolution → T_{unc}/T_{res} Large
→ Long Acquisition Times

"Ultra-Wide Bandwidth" → Channel Distortions
→ Matched Filter Design Problems
→ Receiver Design for Efficient Energy Capture

Very Large Bandwidth → Large Frequency Diversity
→ Multipath Mitigation

FCC Compliance → Power Optimization Requirements
→ Design for Spectral Flatness/Shaping

Questions We Often Hear

- Propagation Characterization?
- Link Budgets?
- Battery Budgets?
- Diversity Receiver Design?
- Covertness?
- Antenna Characterization?

The devils are in the details

High-Level Questions

Are answers for UWB questions simply bandwidth-scaled from narrowband designs, or is there a paradigm shift in approach/viewpoint?

Is UWB radio the best choice for a given application?

Is asynchronous UWB radio an effective use of the RF spectrum?

Overview of the Proposal

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The Team of Enthusiastic Skeptics

University of Southern California
Bob Scholtz, Keith Chugg, Won Namgoong
(propagation, systems, circuits)
UltRa Lab

University of California, Berkeley
Bob Brodersen, David Tse
(circuits, information theory)
Berkeley Wireless Research Center

University of Massachusetts, Amherst
Dave Pozar, Dan Schaubert, Dennis Goeckel
(antennas, systems)
Antennas Laboratory

Goals

- Channel Characterization: UWB propagation and interference models for short-range propagation scenarios
- Antenna Design: basic limits on radiation and reception of UWB signals; time-domain characterization; practical antennas for integrated UWB tagging systems
- System Design: issues uniquely affected by large bandwidth, fine time resolution, large frequency diversity, e.g., rapid sync acquisition, designs and architectures for efficient recovery of signal energy, low power-density modulation, ranging in dense and resolvable multipath
- Implementation: UWB architectures and topologies for single-chip implementation in CMOS; simultaneous optimization of antennas, algorithms, and circuits for performance and power consumption
- Test Beds: hardware and simulation test beds for UWB systems and components; cooperate with government agencies in testing efforts.

Focus

- The study of UWB systems that require both position location and communication as operational requirements.
- To ground research in reality, environments in which we can perform measurements and experiments will be pursued.
- Parameters for design related to RF tags, e.g., IFF systems, shipping and logistic systems, status monitoring, battlefield asset tracking, traffic monitoring, medical tagging.

Research Applicability

Table 2: UWB Research Applicability and Impact Assessment
(H = high, L = low)

	Autonomous manifesting	covert comm	IFF systems	sensor arrays	intrusion detectors
Channel measurement & modeling	H	H	H	H	L
Antennas & EM characterization	H	H	H	H	H
Design for energy capture	H	H	H	H	H
Multiple access design	H	H	H	H	L
Sync acquisition techniques	H	H	H	H	L
Ranging techniques	H	L	H	H	H
Asymmetric tagging systems	H	L	L	H	L
Low Power Implementation	H	H	H	H	H
Possible testbeds	H	H	H	L	L

Impact on Universities and Education

- New Relationships between Team Members
- New Relationships with Industry
- Improved Infrastructure and Capabilities of Labs
- Training of Graduate Students in UWB Technology
- Annual Workshops on UWB Technology
- Student Exchange

Where We Want To Be In Three Years

Understand the issues, answer the questions posed today.

(basic research and cross-fertilization)

Characterize, optimize, construct, and test critical/novel parts of a UWB radio

(fabrication feasibility)

Have the ability to do reasonable sanity checks on a design:

- Develop good performance prediction techniques
- Produce believable link budgets
- Produce reasonable battery power budgets

(system feasibility)

UWB Propagation and its Implications

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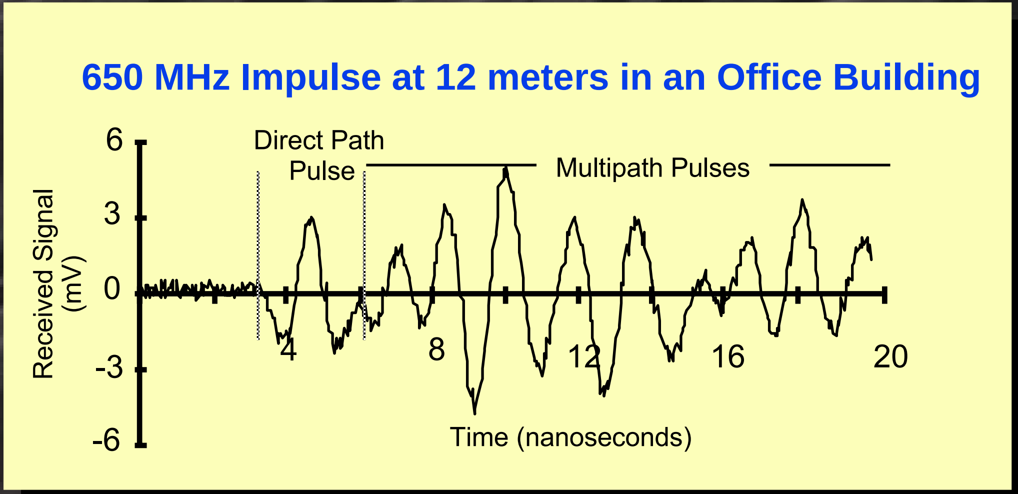
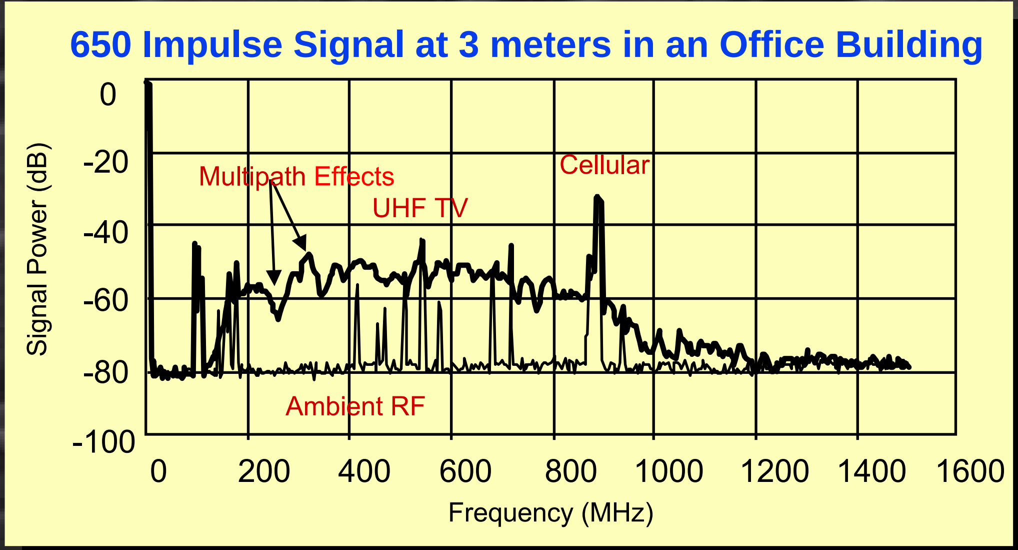
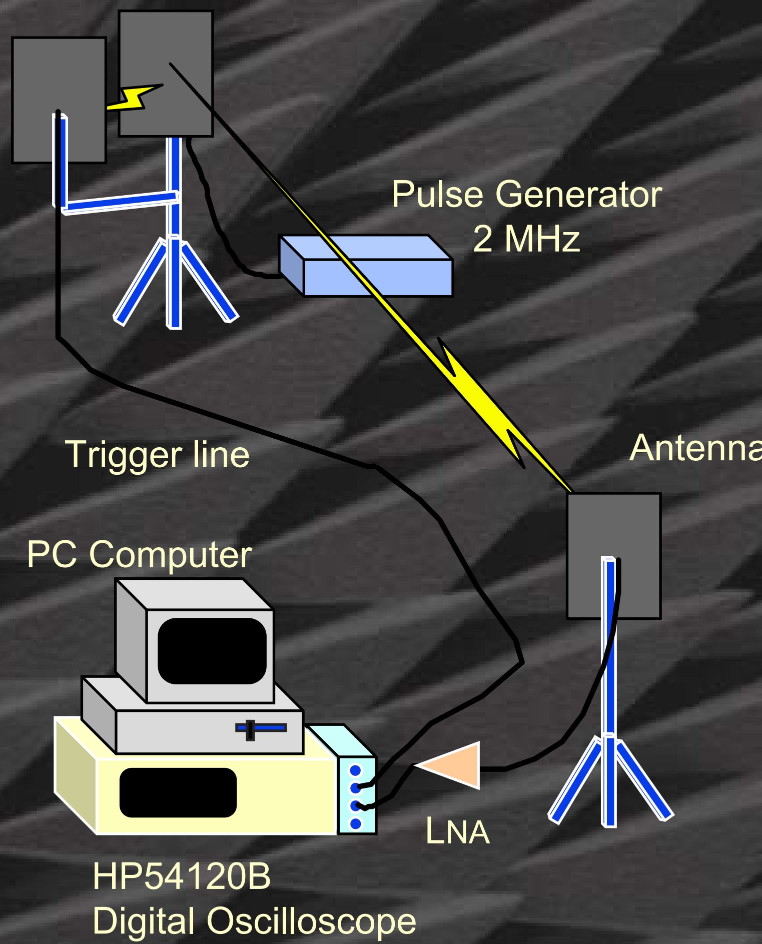
Propagation Measurement







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CLEAN Analysis

QuickTime™ and a
Animation decompressor
are needed to see this picture.

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Animation decompressor
are needed to see this picture.

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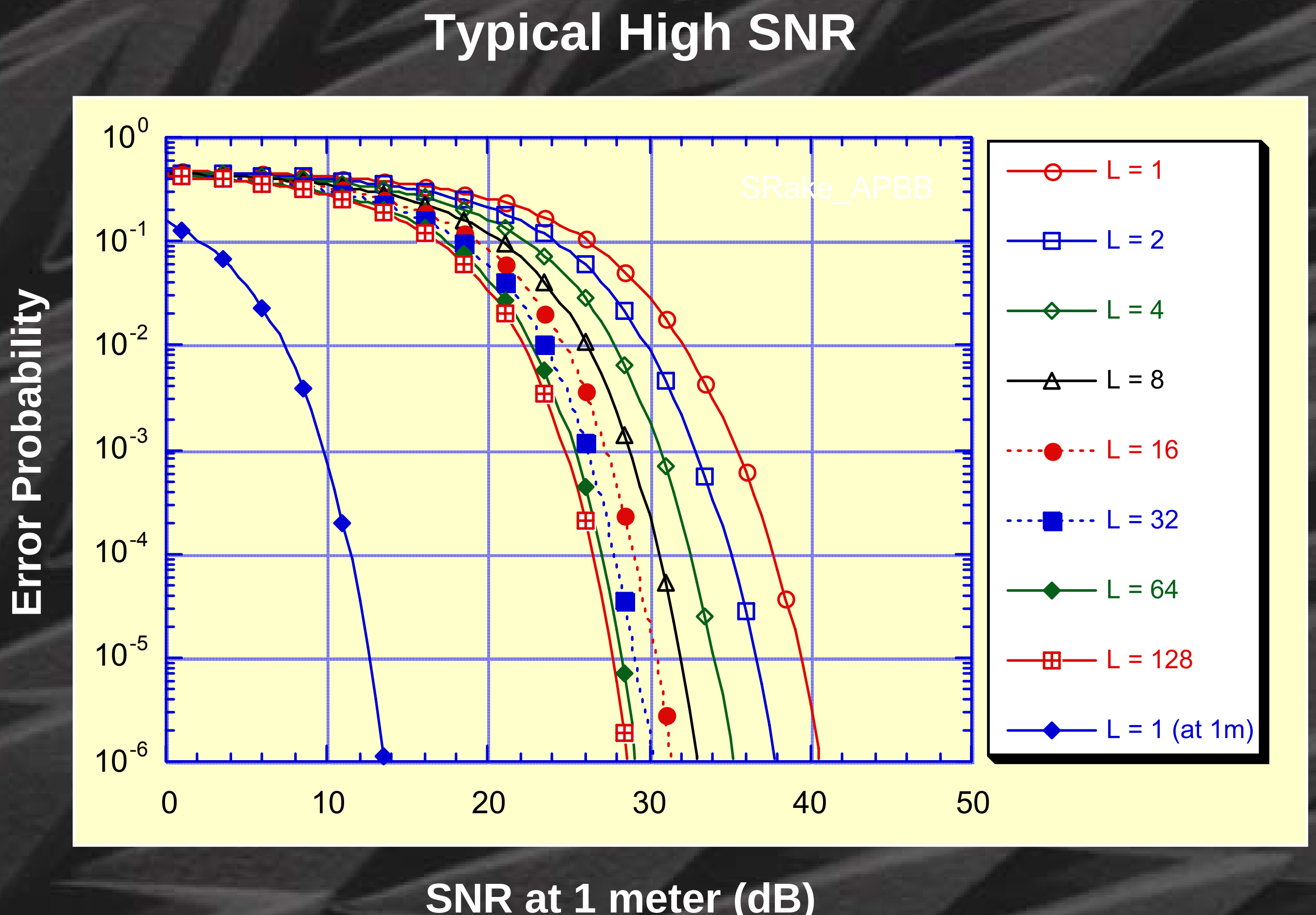
Selective Rake Performance



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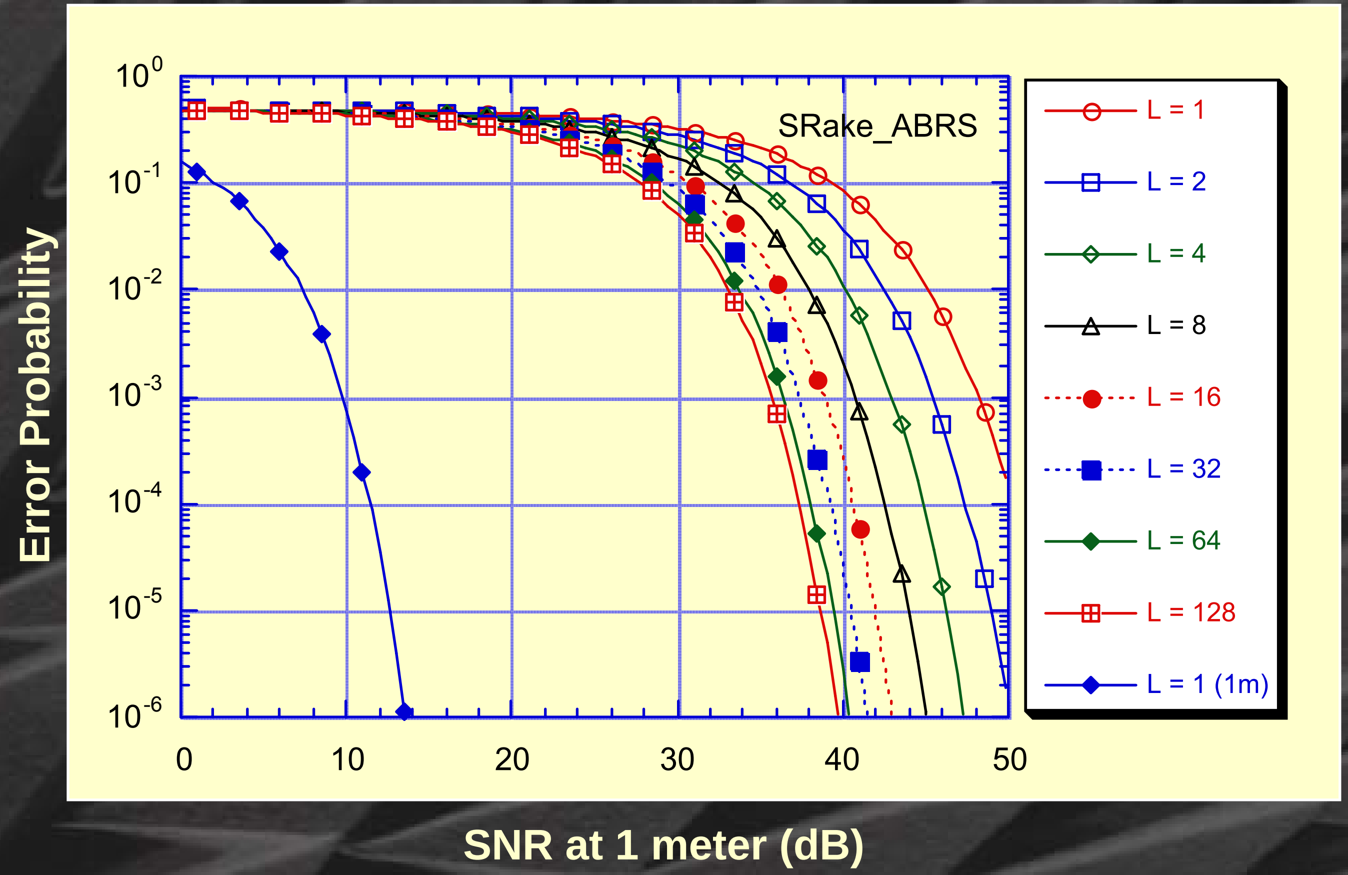
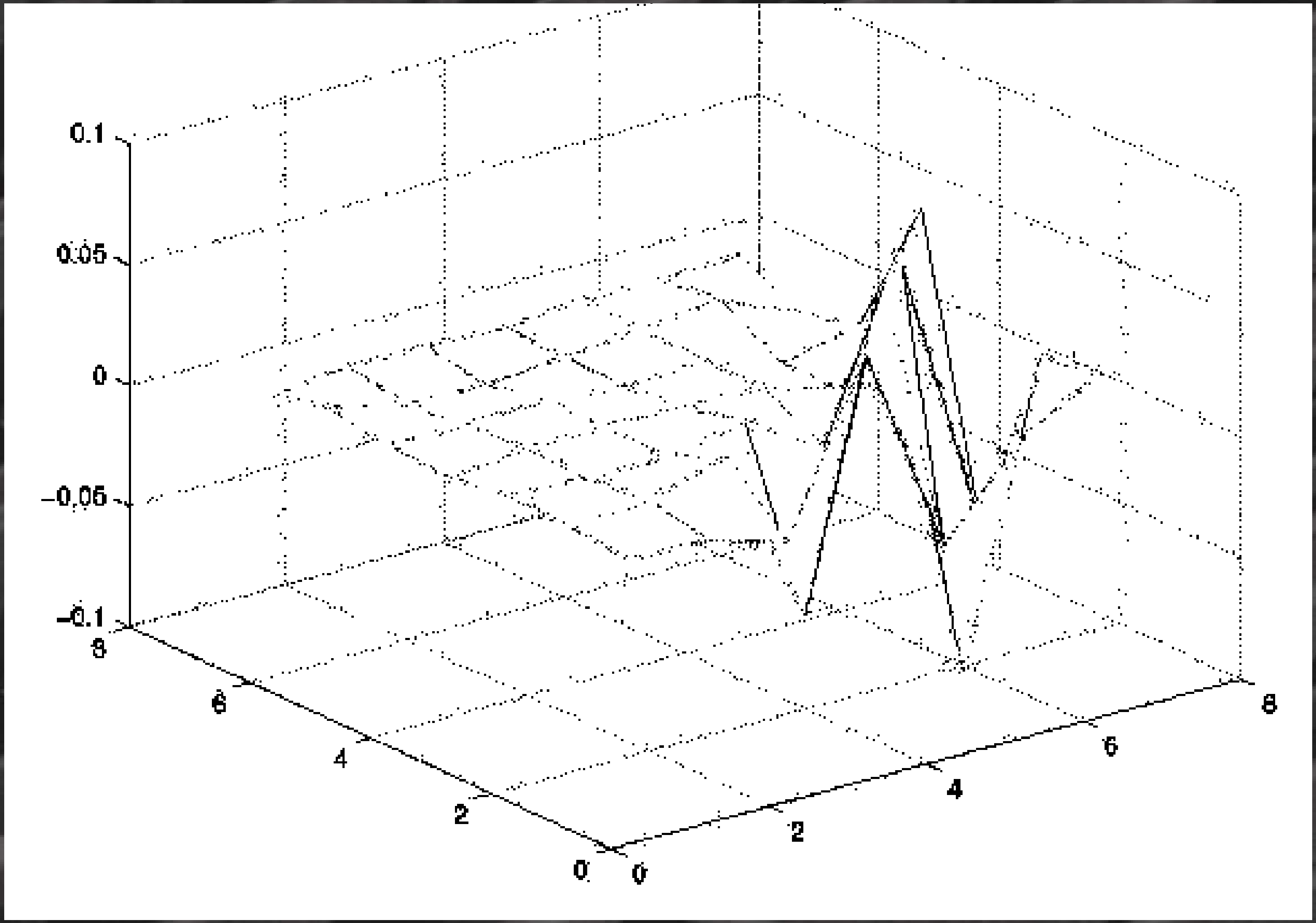
Selective Rake Performance

Extremely Low SNR



Ultrawideband Propagation

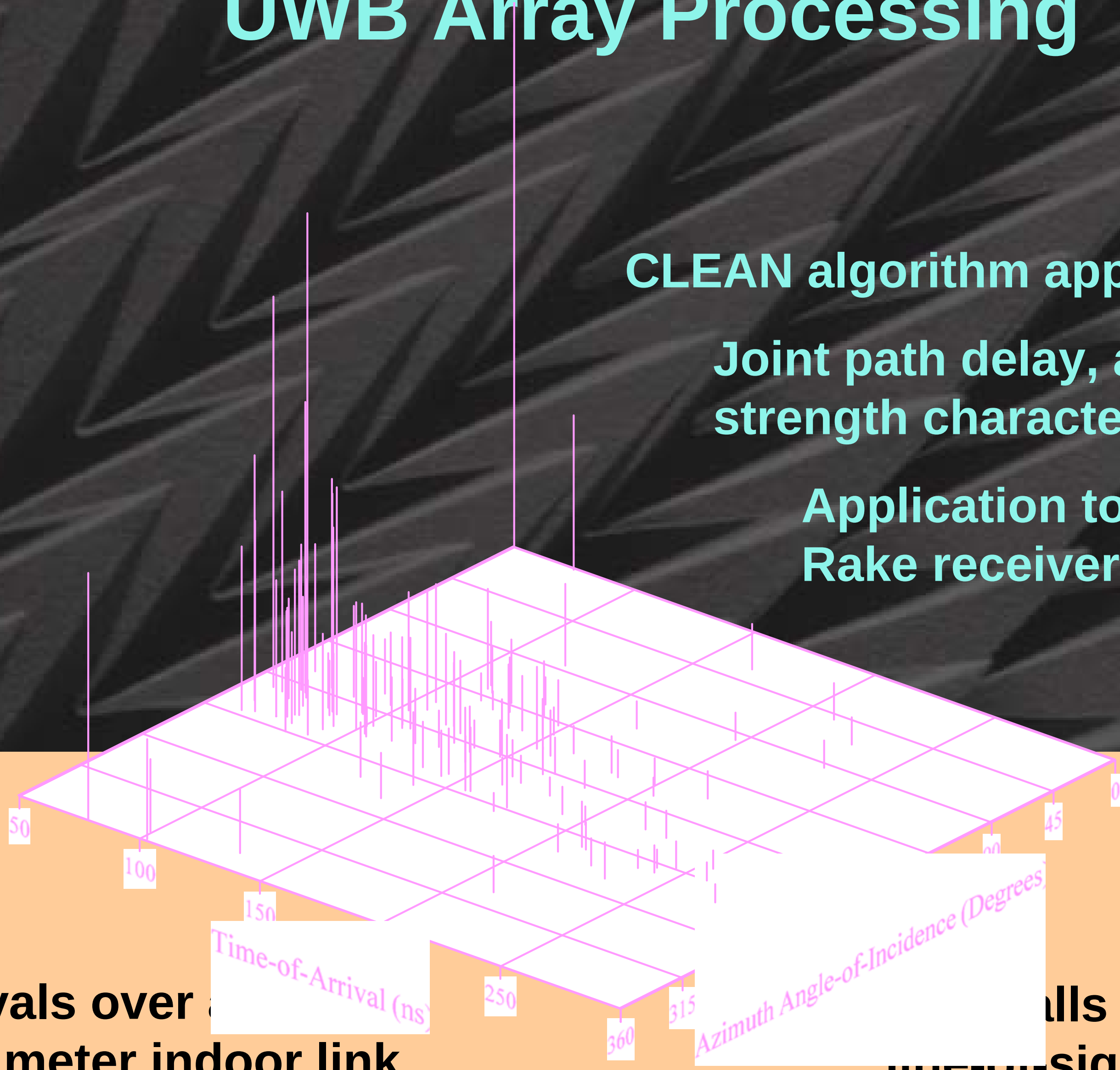


UWB Array Processing

CLEAN algorithm application

Joint path delay, angle, and strength characteristics

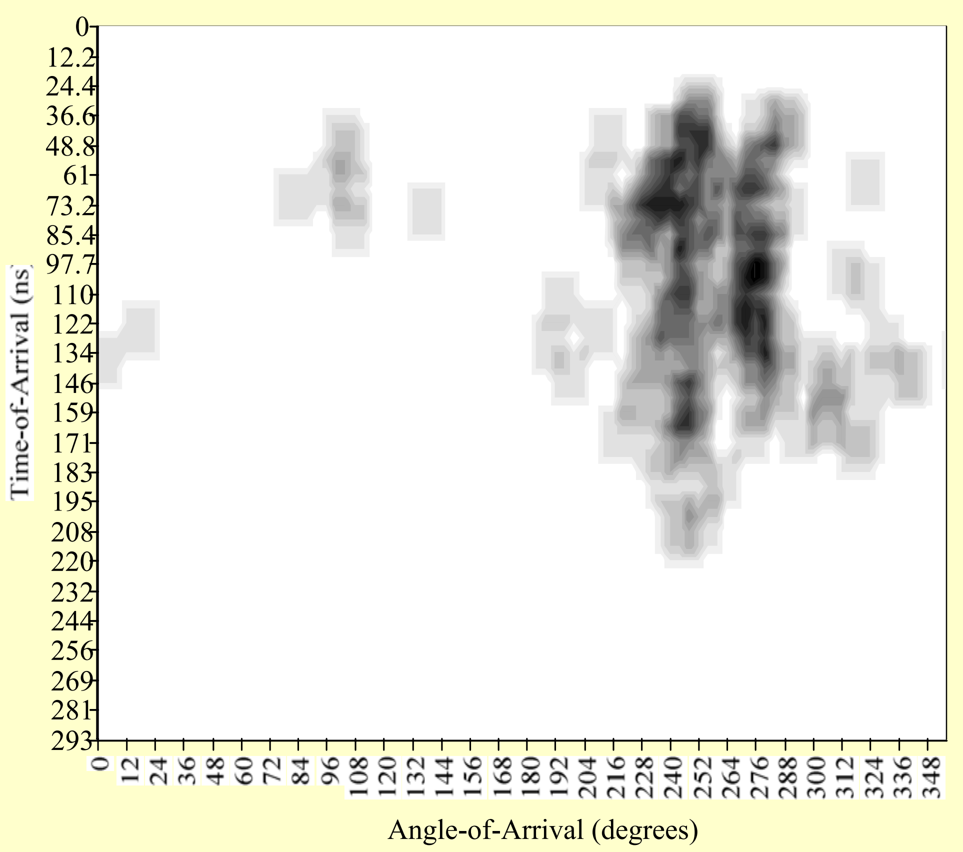
Application to selective Rake receiver design

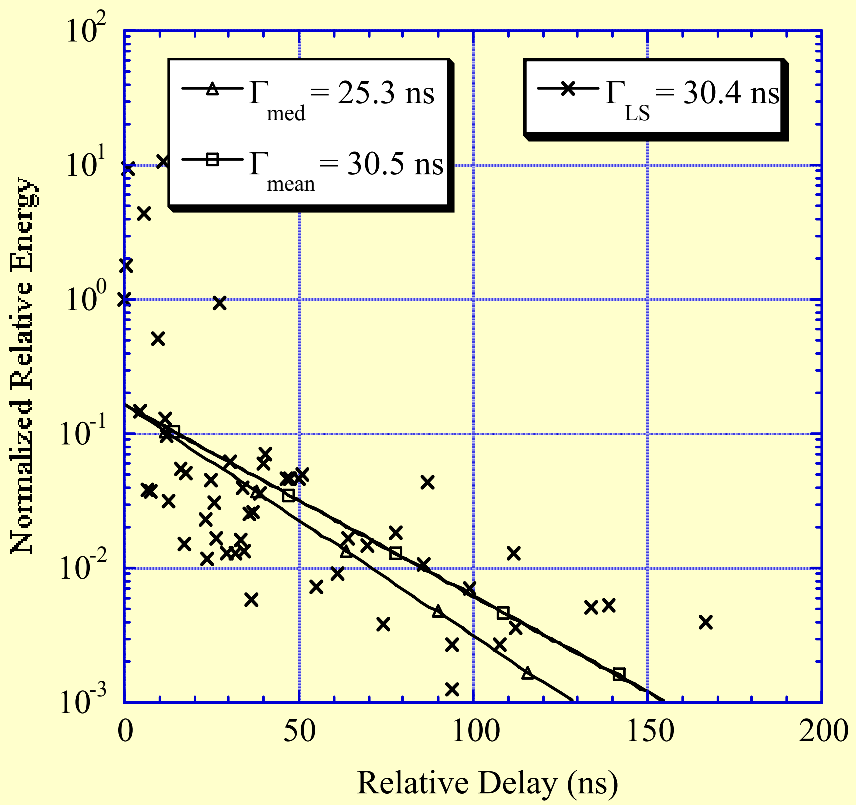


Arrivals over a
16.9 meter indoor link

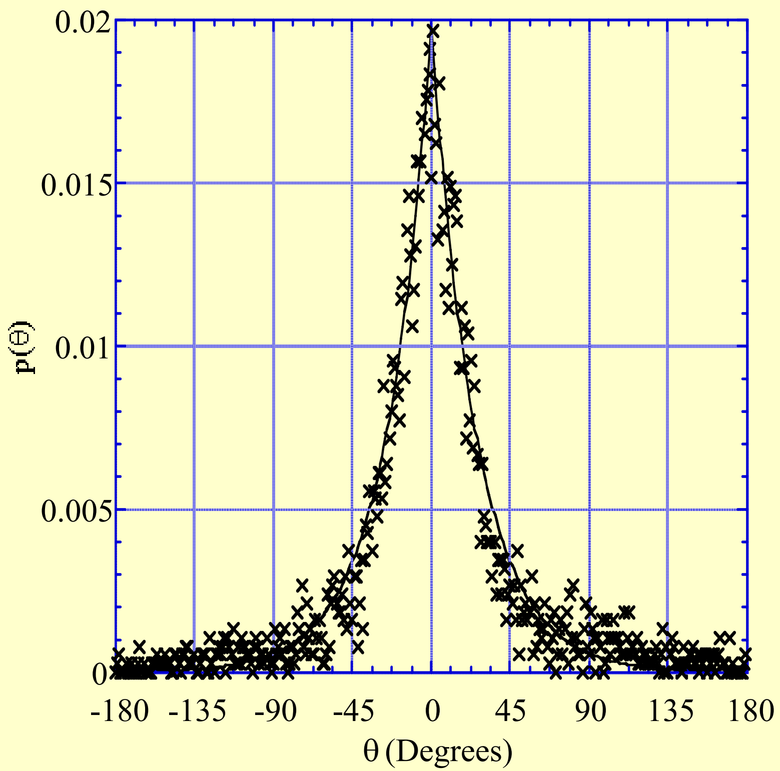
alls in
line-of-sight

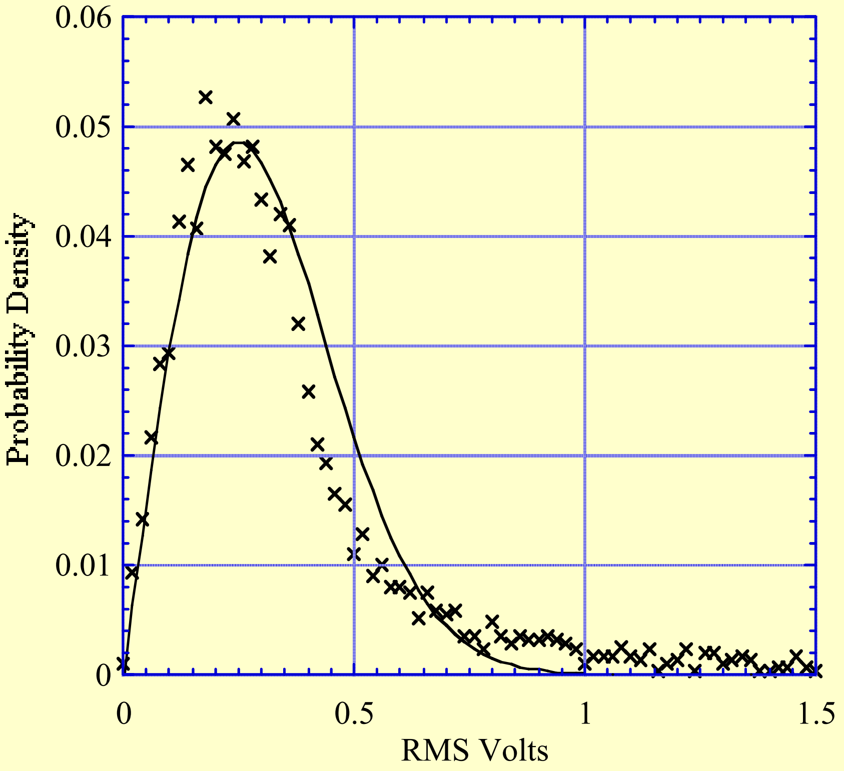
Cluster Models





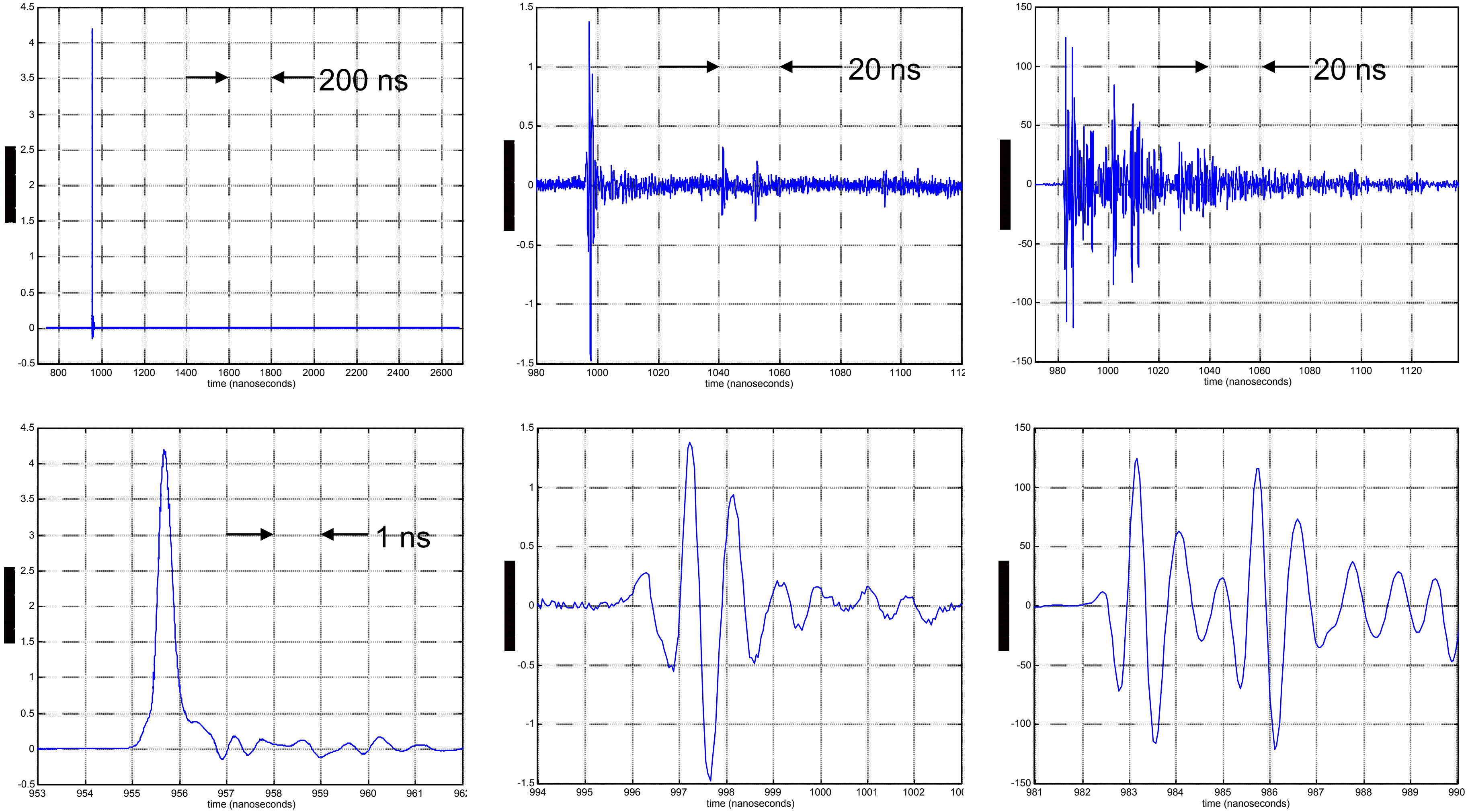
Intra-Cluster Path Statistics





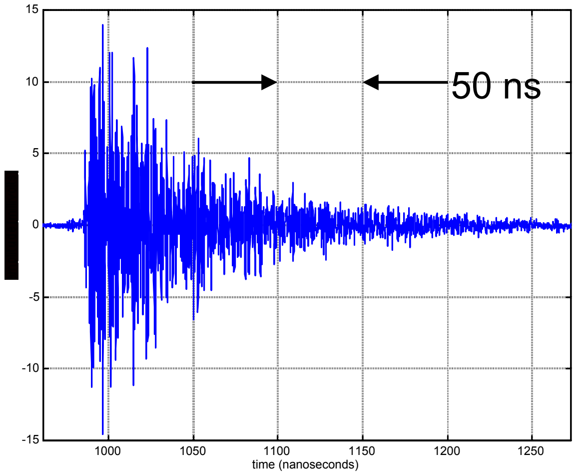
Representative Measurements I

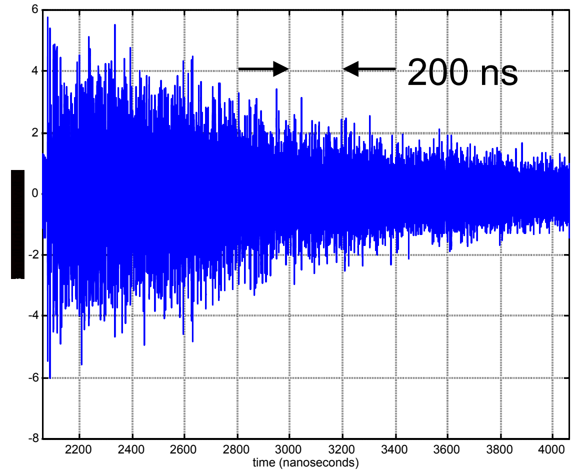
Transmitted Signal	Outdoor Rcvd Clear LoS	Office Rcvd Clear LoS

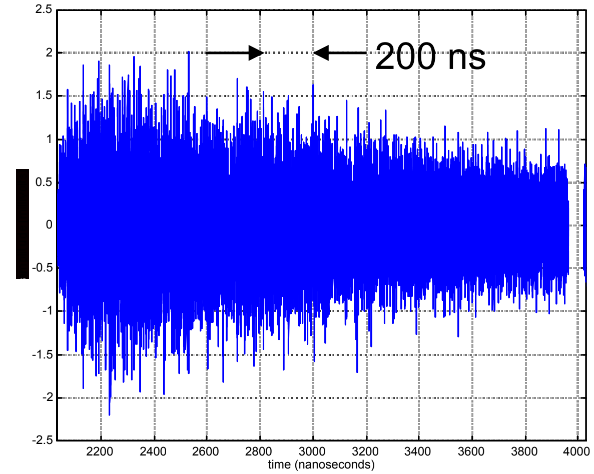


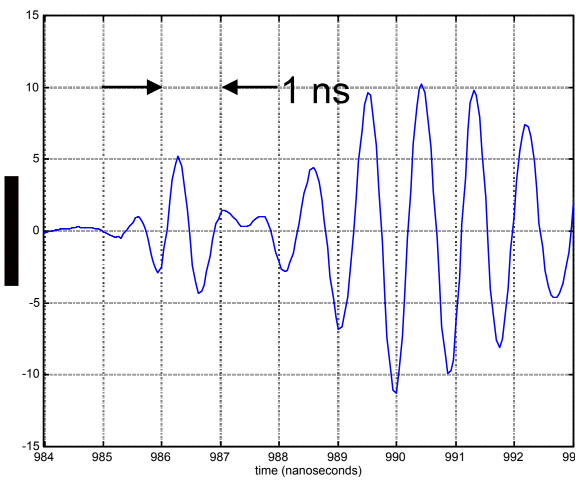
Representative Measurements II

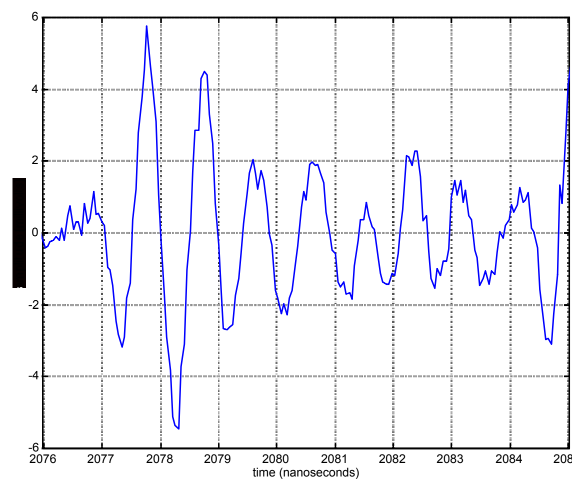
Office Rcvd Blkd LoS	Hold Rcvd Clear LoS	Hold Rcvd Blkd LoS

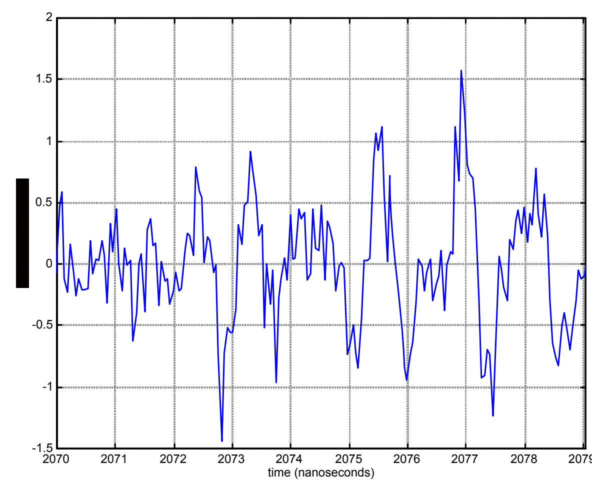












USS Curtiss Measurements

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Ring Decay Rates

Ringing → Interpulse Interference
→ Degraded Receiver Performance

Can traditional ISI techniques be scaled to handle this?

Does ring time limit pulse rate for simple receivers?

Can ringing be used to speed up sync acquisition?

For possible ring-time estimation techniques, see D. Hill et al., "Aperture Excitation of Electrically Large, Lossy Cavities," *IEEE Trans. on Electromagnetic Compatibility*, 1994.

USS Curtiss Measurements

Four experiments:

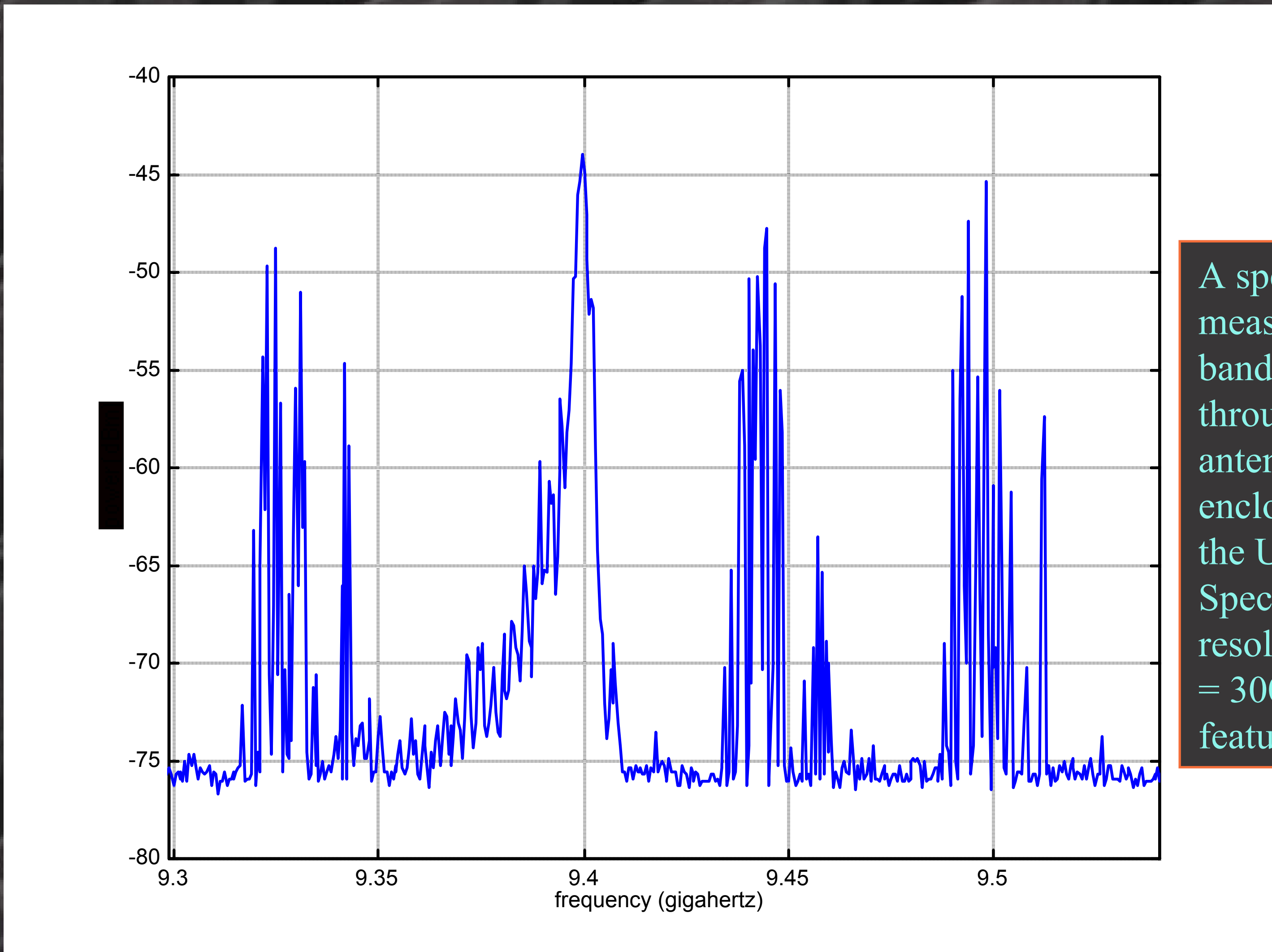
•Pulse response with sampling oscilloscope

•Transfer function with network analyzer

•Pulse response with a UWB test radio

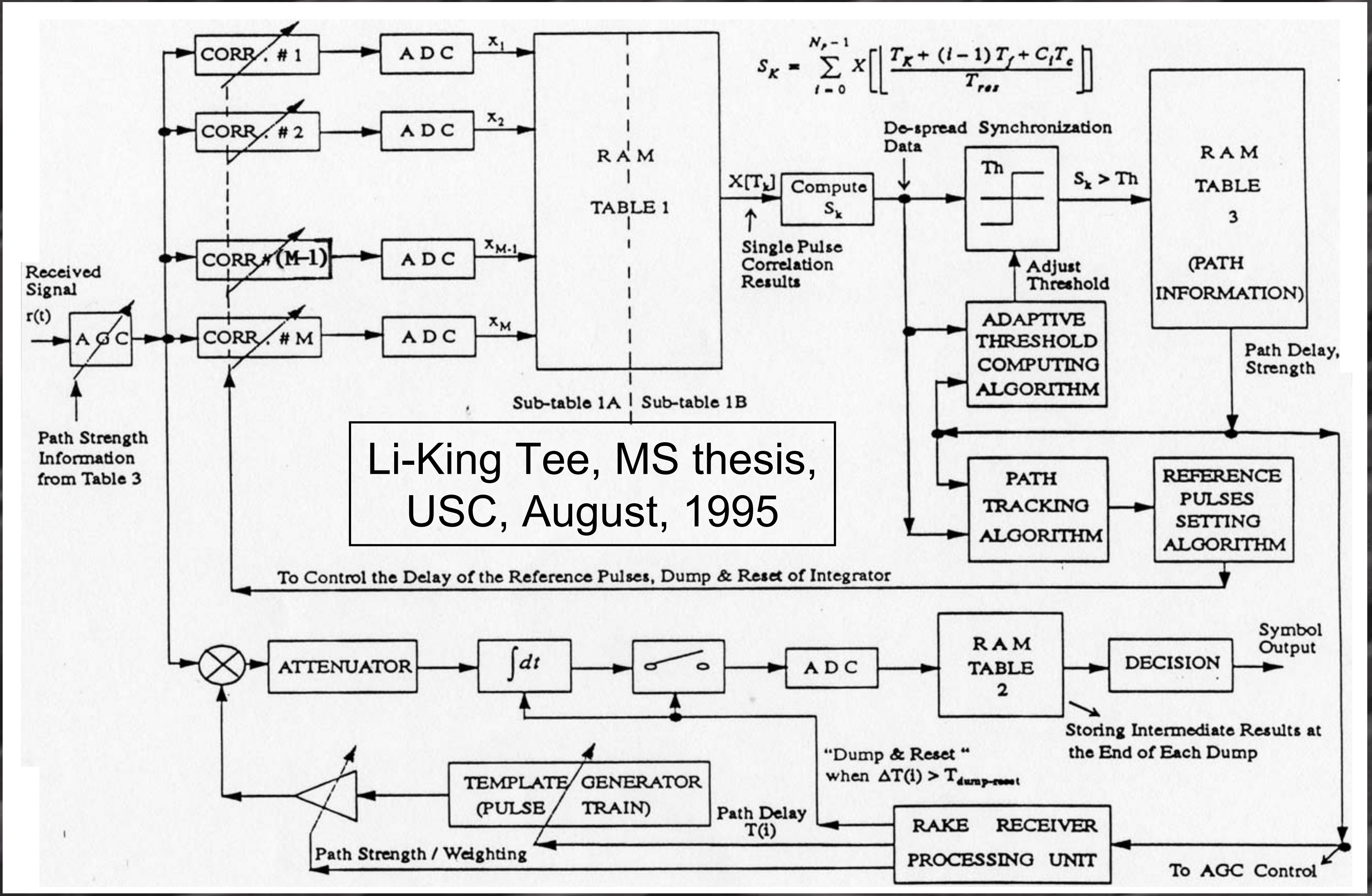
•Interference check with spectrum analyzer

Shipboard Interference



A spectral measurement of an X-band radar signal through a UWB antenna, made in the enclosed cargo bay of the USS Curtiss. Spectrum analyzer resolution bandwidth = 300 kHz, *max hold* feature ON.

Multi-Correlator Receiver



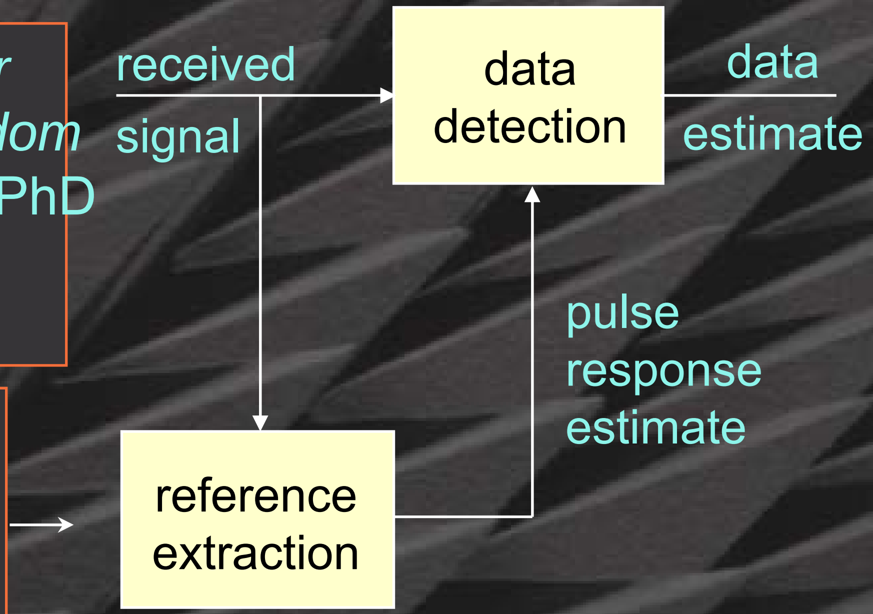
$$S_K = \sum_{i=0}^{N_p-1} X\left[\left[\frac{T_K + (i-1)T_f + C_i T_c}{T_{res}}\right]\right]$$

Li-King Tee, MS thesis, USC, August, 1995

Transmitted-Reference System

From R. Scholtz, *Coding for Adaptive Capability in Random Channel Communications*, PhD Thesis, Stanford University, 1963.

Contains averaging of measurements to eliminate noise on the reference



For more and earlier examples, see R. Scholtz, "The Origins of Spread Spectrum Communications," *IEEE Trans. on Communications*, May 1982.

Directional Effects - Large Antennas

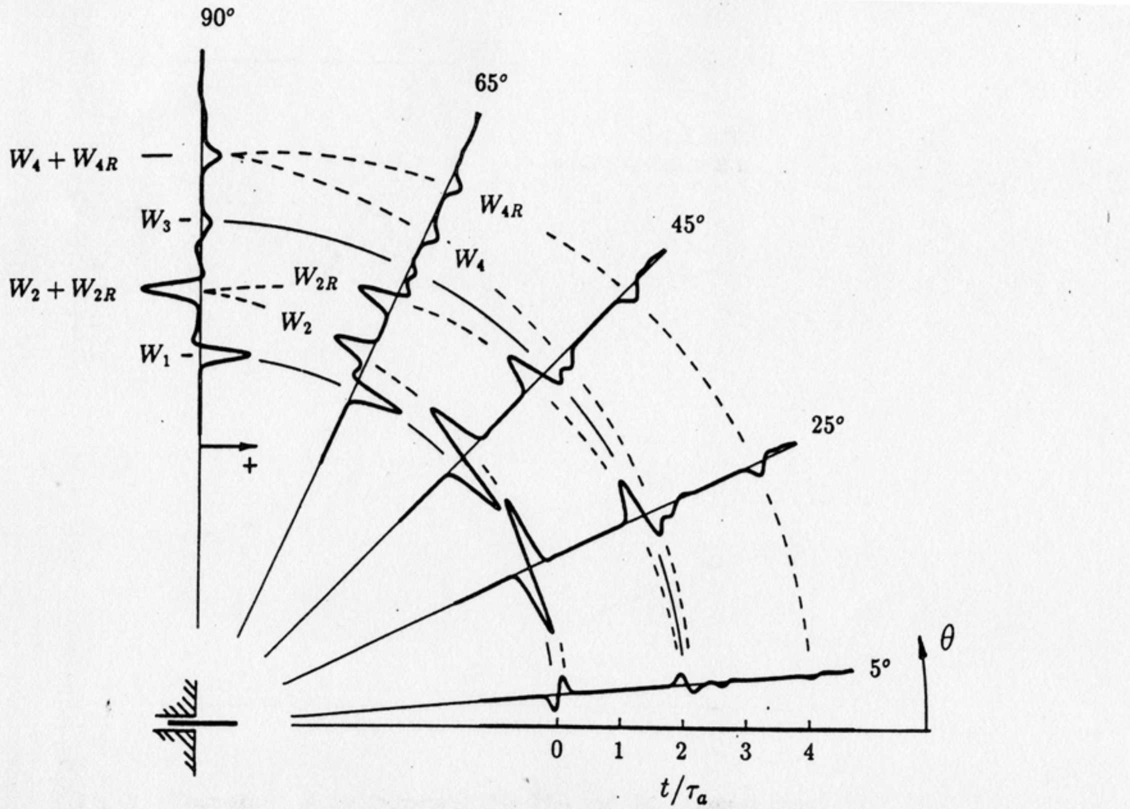


Fig. 7. Radiation of a Gaussian pulse from a cylindrical monopole antenna. Each trace shows the far-zone electric field $\mathcal{E}^r_\theta$ at a fixed polar angle θ as a function of the normalized time t/τ_a. $b/a = 2.30$, $h/a = 65.8$, and $\tau_p/\tau_a = 8.04 \times 10^{-2}$.

From: J. Maloney et al., "Accurate Computation of the Radiation from Simple Antennas Using the Finite-Difference Time-Domain Method," *IEEE Trans. On Antennas and Propagation*, July 1990.

Questions Related to Robust System Design

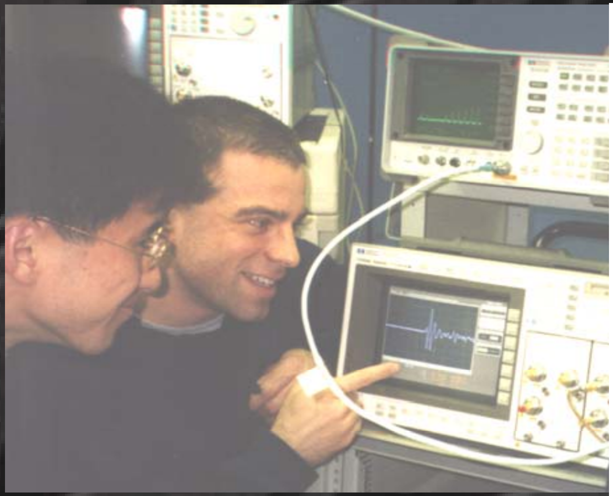
- What is the full channel characterization of UWB channels, including polarization effects, and how does this affect antenna/system design?

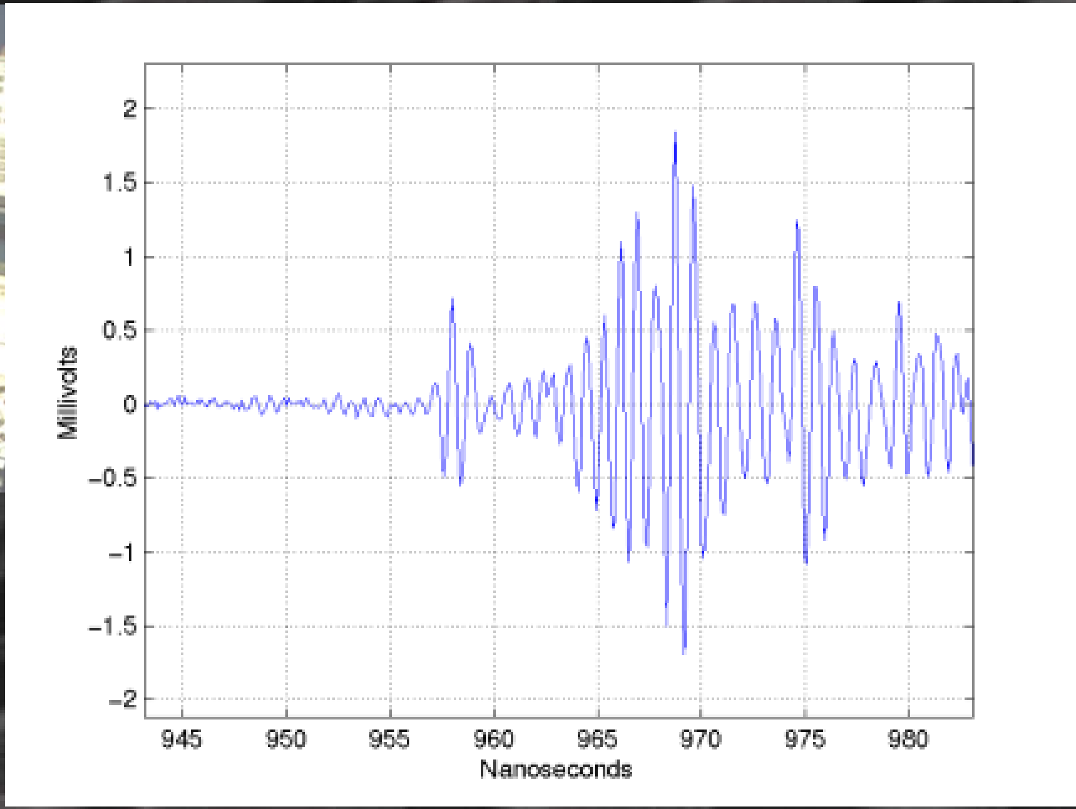
- What are the effects of large conducting bodies on UWB radiation from nearby antennas and how does this affect tag antenna design?

- Which channel is the design driver: indoor or outdoor? Which channel requires the most resources to communicate reliably?

- What is an effective architecture for a UWB receiver that efficiently collects signal energy?

Ranging Algorithms





Where is the beginning of the first return?

Is the line-of-sight blocked?

1 ns (time) → | | ← **1 foot (space)**

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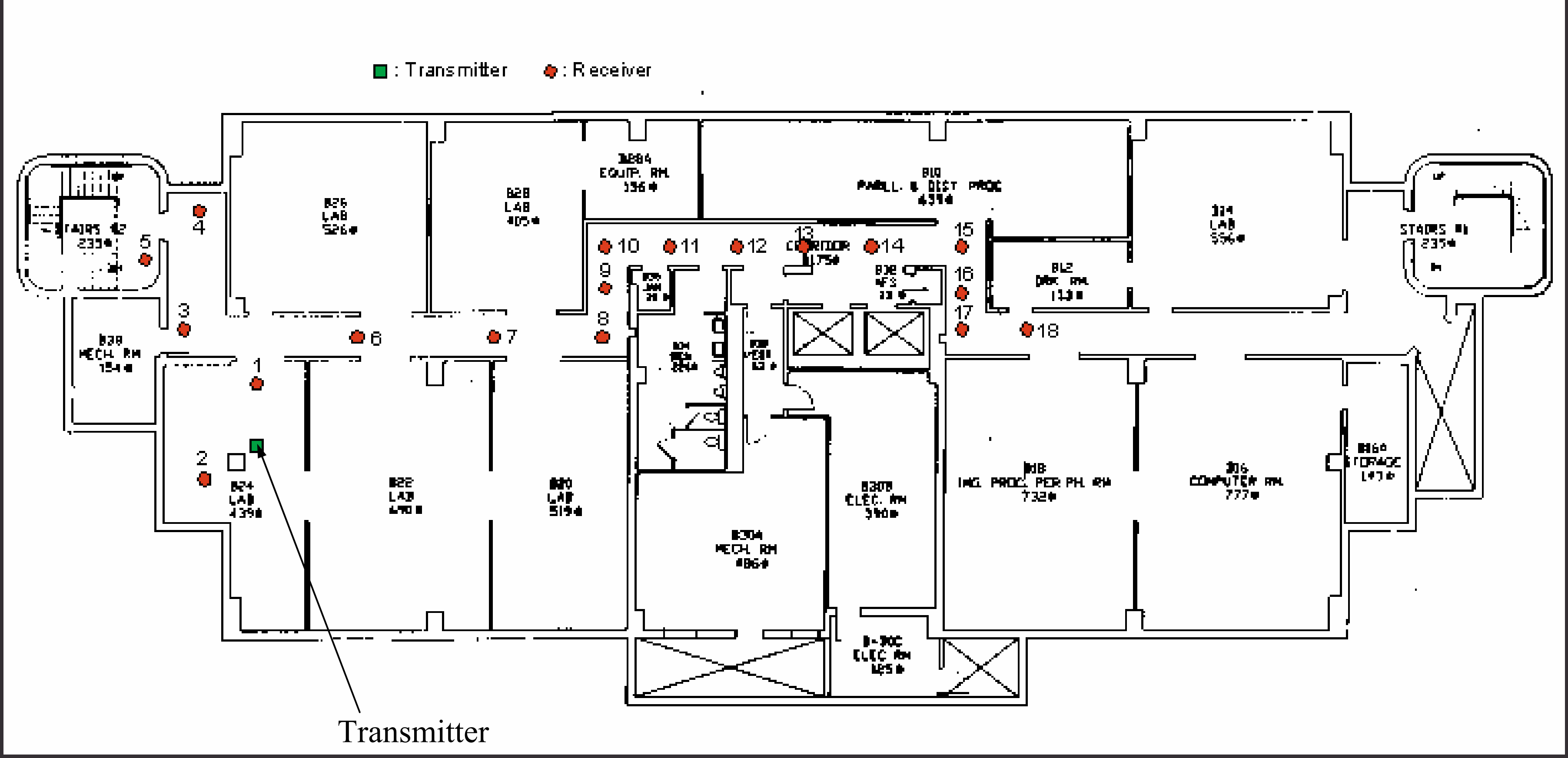
Test Site (Basement, EEB, USC)



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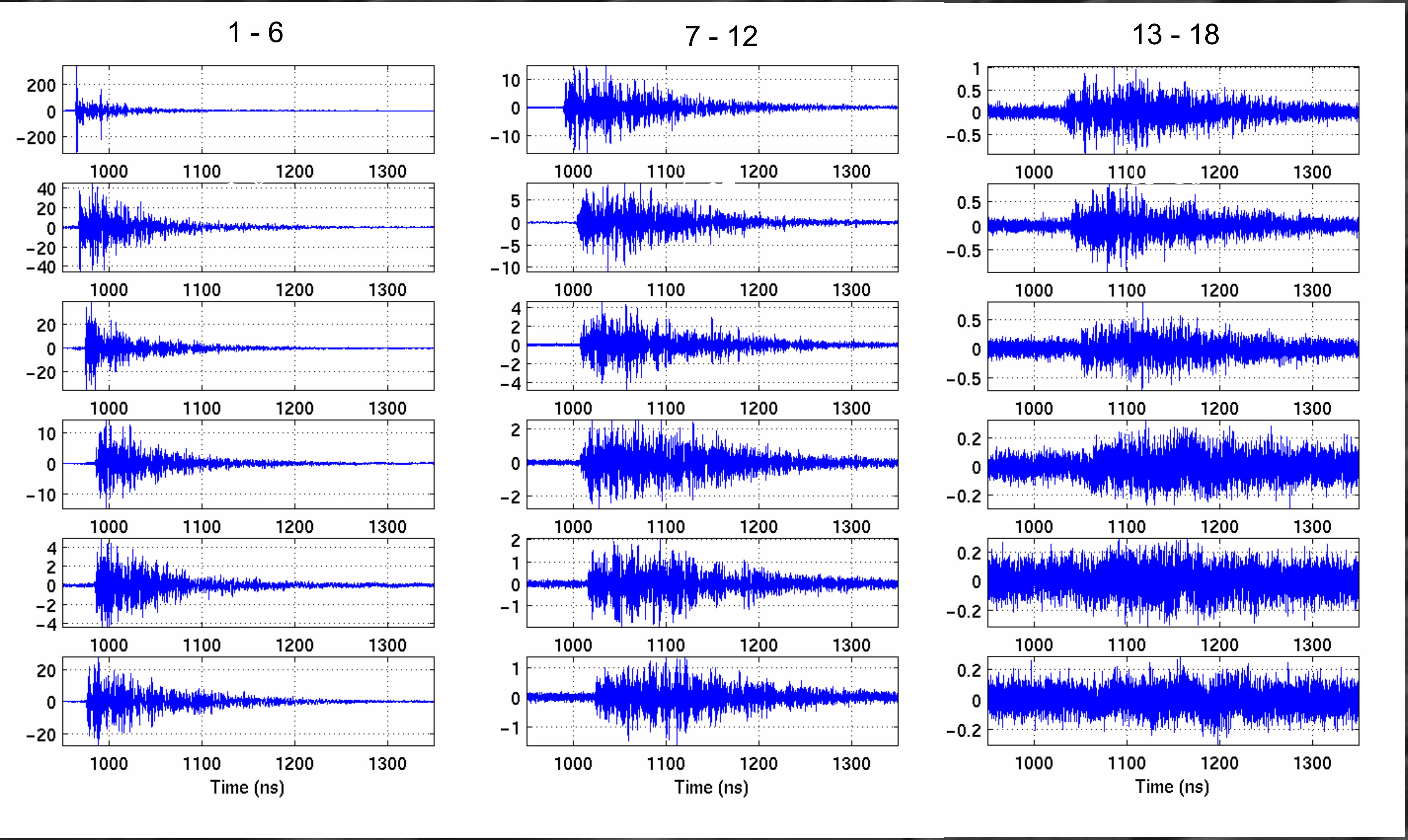
Measured Signals



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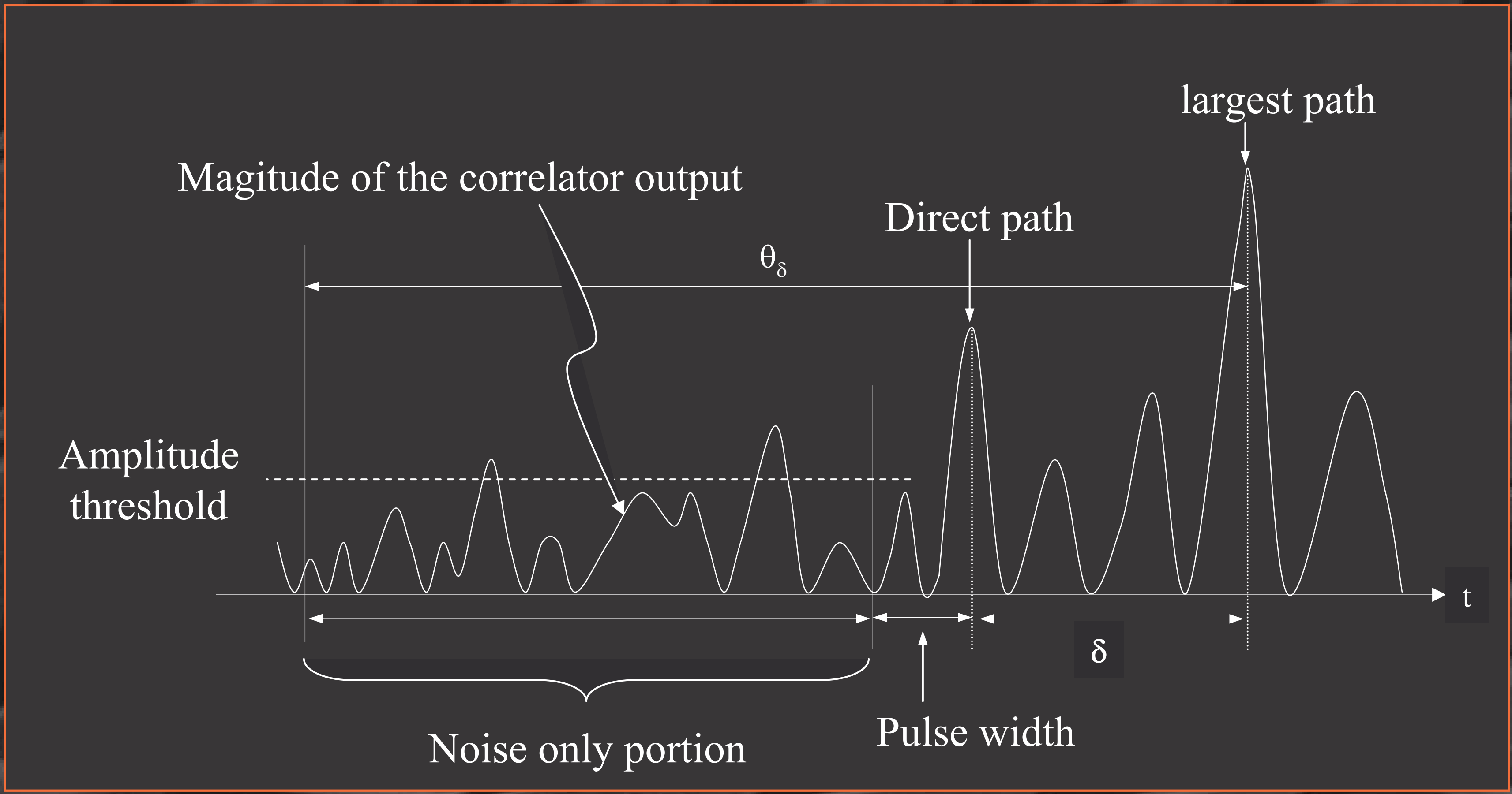
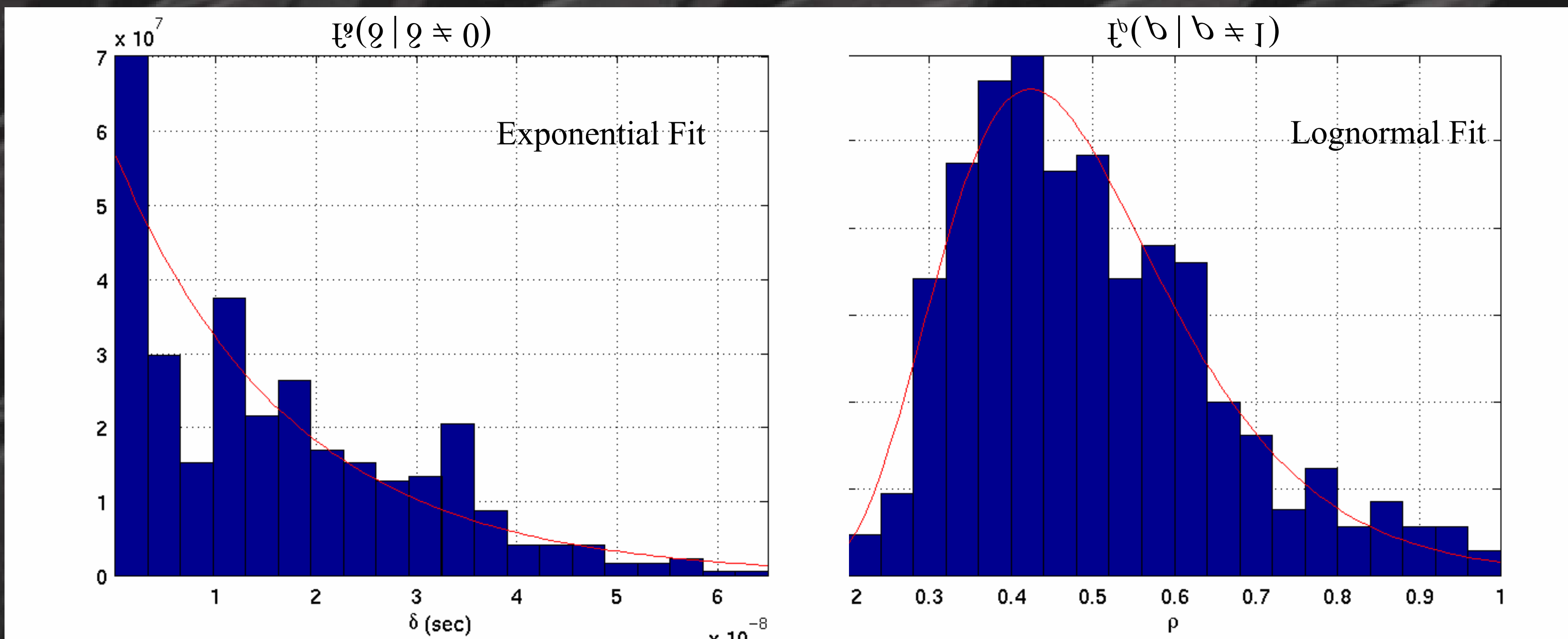
Probability of Early False Alarm



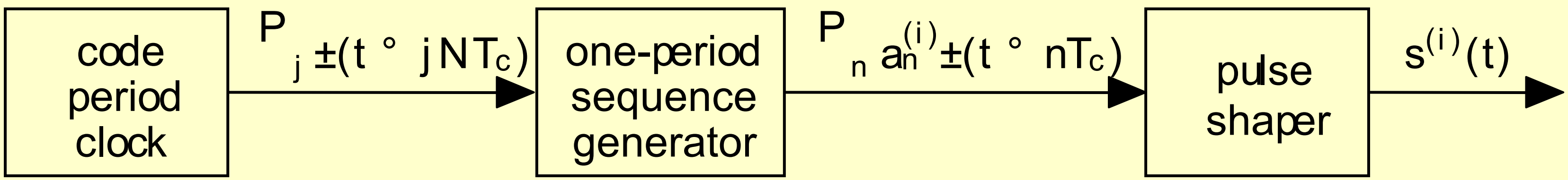
Statistics of δ_d and ρ_d



Ranging Issues

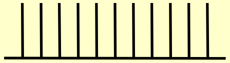
- Relevant statistics for tagging environments
- Complexity reduction of CLEAN LoS algorithm
- Embed CLEAN LoS in a returnable timing system
- System accommodation of LoS blockages
- End-to-end positioning performance prediction
- Generalizations to hyperbolic location systems

Power Spectral Density Calculations



power spectral density

$$\frac{1}{(NT_c)^2} \sum_k \delta\left(f - \frac{k}{NT_c}\right)$$

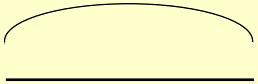


system function

$$\sum_{n=0}^{N-1} a_n^{(i)} e^{-j2\pi f n T_c}$$

system function

$$P(f)$$



output power spectral density

$$\frac{|P(f)|^2}{(NT_c)^2} \sum_k \left| \underbrace{\sum_{n=0}^{N-1} a_n^{(i)} e^{-j2\pi k n / N}}_{C_k^{(i)}} \right| \delta\left(f - \frac{k}{NT_c}\right)$$

Spectral Shaping Questions

- Difference sets provide flat spectral coefficients. Are there enough quasi-uncorrelated difference sets to provide a reasonable multiple access design?
- Can spread-spectrum code design be used to shape the power spectral density of the signal, e.g., to satisfy FCC constraints or to avoid interference?

UltRa Lab Time Line

USC Ultrawideband Radio Workshop, May 1998.

September 1996: NSF funds UWB instrumentation proposal
May 1998: FCC announces upcoming NoI at UWB Workshop
September 1998: NSF funds UWB radio studies
November 1999: UltRa Lab gets UWB Experimental License from FCC
December 1999: UWB Ranging study awarded by ONR
May 2000: FCC announces NPRM on UWB radiation
August 2000: UltRa Lab's Paul G. Allen Wireless Test Facility funded
January 2001: ARRL - UltRa Lab cooperative interference tests begin
February 2001: USC, UC Berkeley, UMass receive UWB MURI award

For more information, copies of papers, links to other sites, etc., visit the UltRa Lab's web site at

http://ultra.usc.edu/ulab/