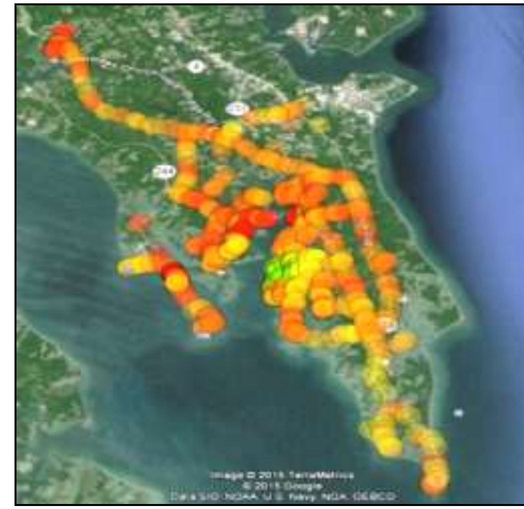
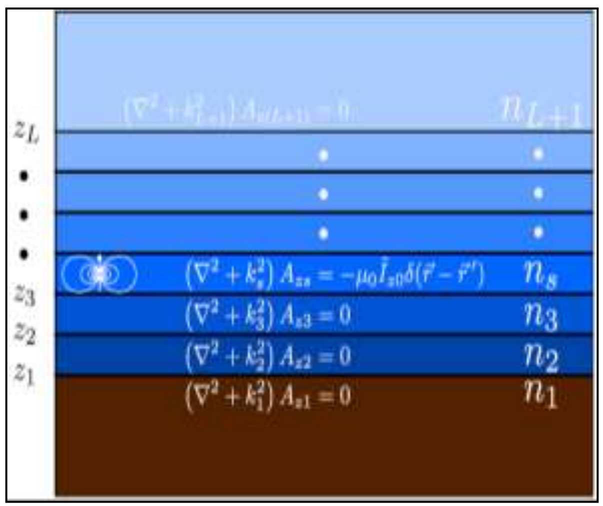
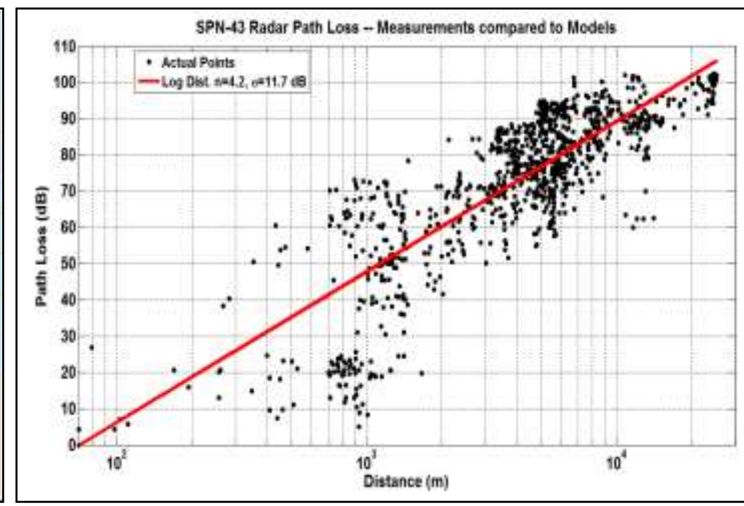
Propagation Measurements & Modeling: A Philosophical Approach







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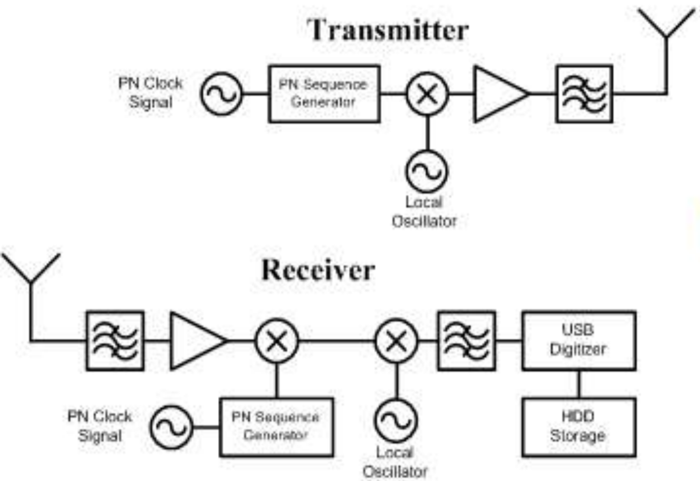
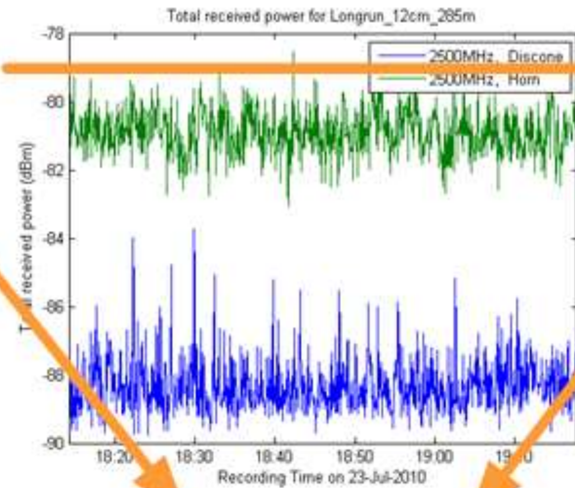
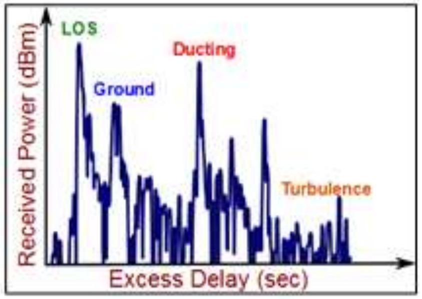
USNA WMG Philosophy of Propagation

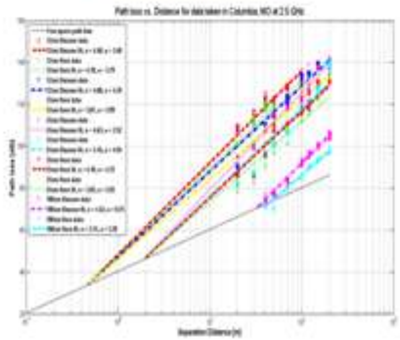
Measurements





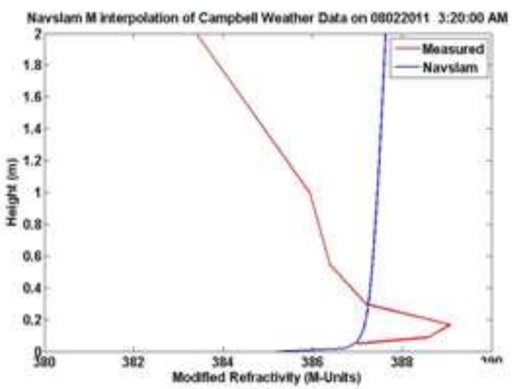
Analysis

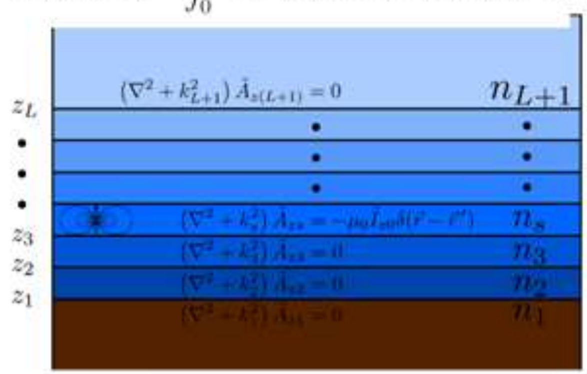


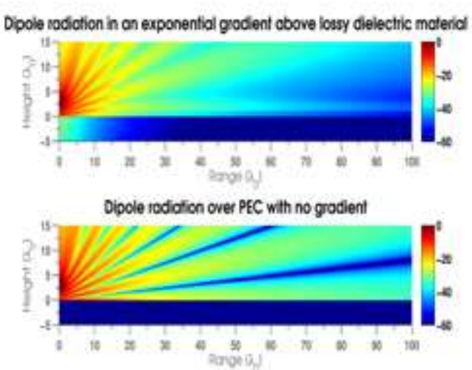


Modeling

$$A_z(\rho, z, z') = \int_0^\infty \tilde{A}_z\left(k_\rho, z, z'\right) J_0(k_\rho \rho) k_\rho \, dk_\rho$$

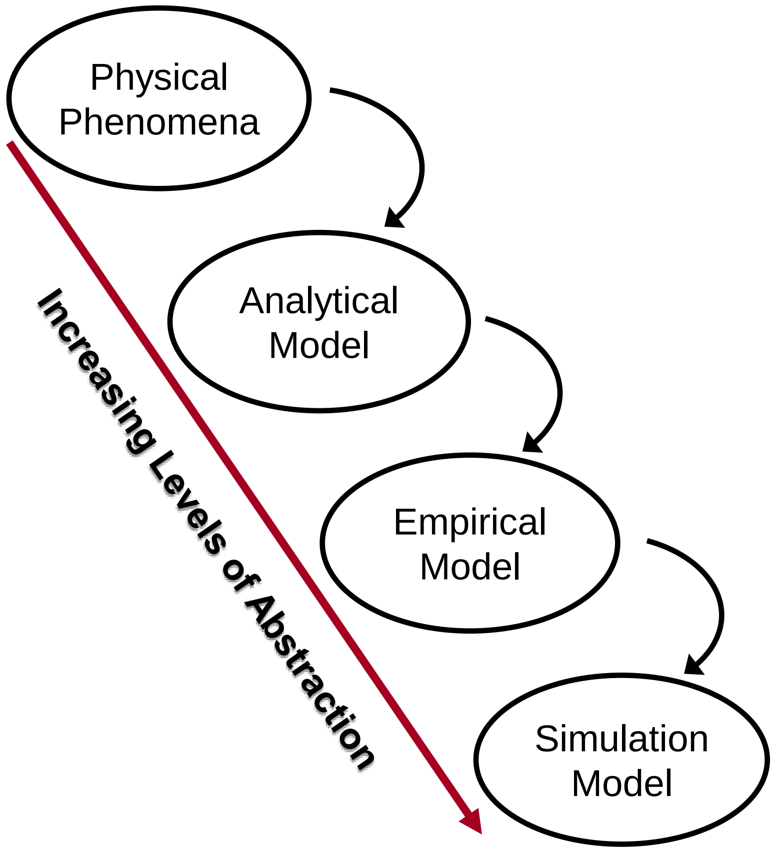


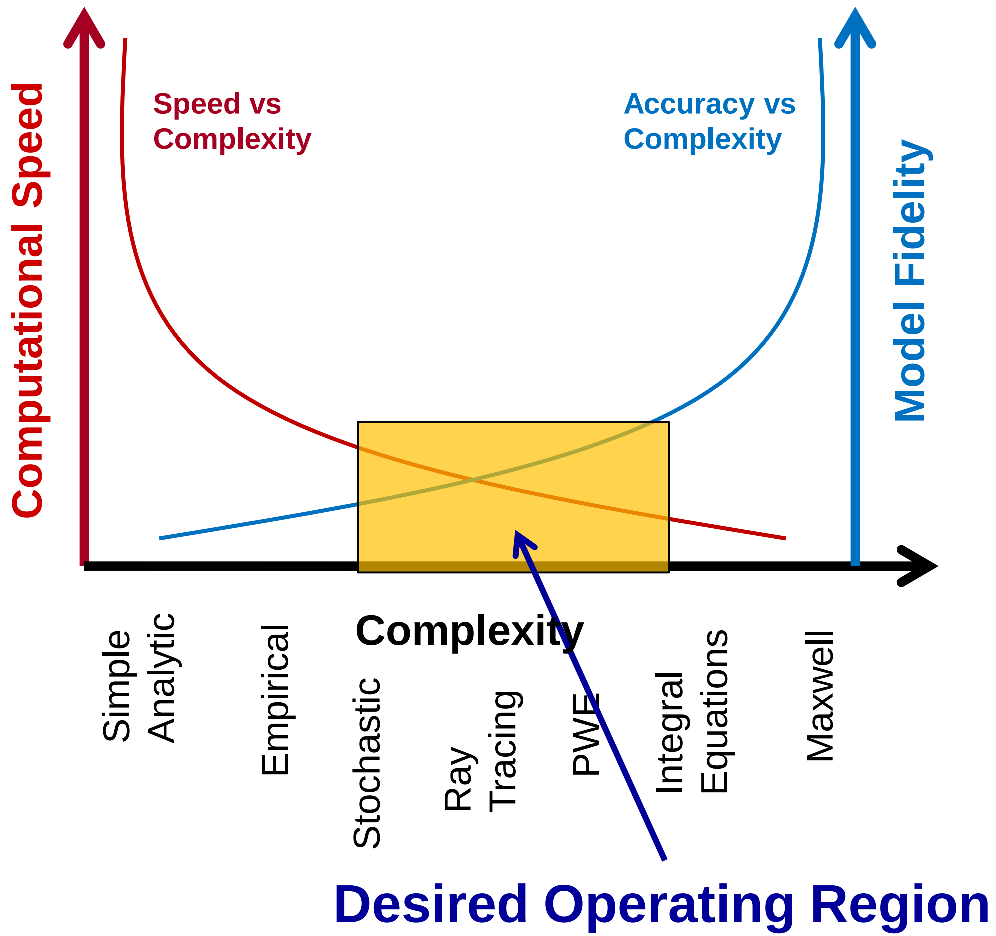




$$\tilde{A}_{z\ell} = j\frac{\mu_0 \tilde{I}_{z0}}{8\pi^2} \times \begin{cases} \frac{e^{jk_{z\ell}|z-z'|}}{k_{z\ell}} + R_\ell^+ e^{jk_{z\ell}(z-z_{\ell-1})} + R_\ell^- e^{-jk_{z\ell}(z-z_\ell)}, & \text{in source layer} \\ R_\ell^+ e^{jk_{z\ell}(z-z_{\ell-1})} + R_\ell^- e^{-jk_{z\ell}(z-z_\ell)}, & \text{in other layers.} \end{cases}$$

Model Fidelity vs. Model Complexity



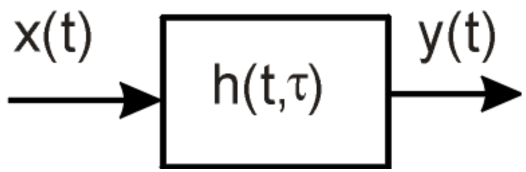


Higher level of abstraction: Reduced complexity / Reduced Accuracy

Lower level of abstraction: Increased runtime / Improved Accuracy

Shamelessly borrowed from William H. Tranter

Left side of the curve: In many cases we are concerned with the statistics of the channel.



$$y(t) = \int_{-\infty}^{\infty} h(t,\lambda)x(\lambda)d\lambda$$

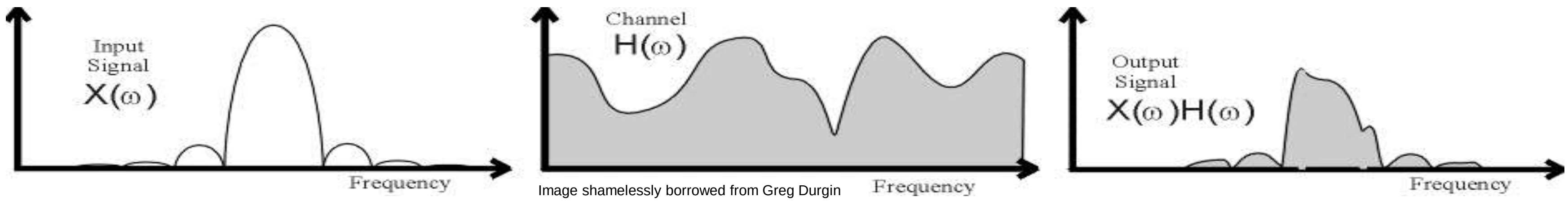
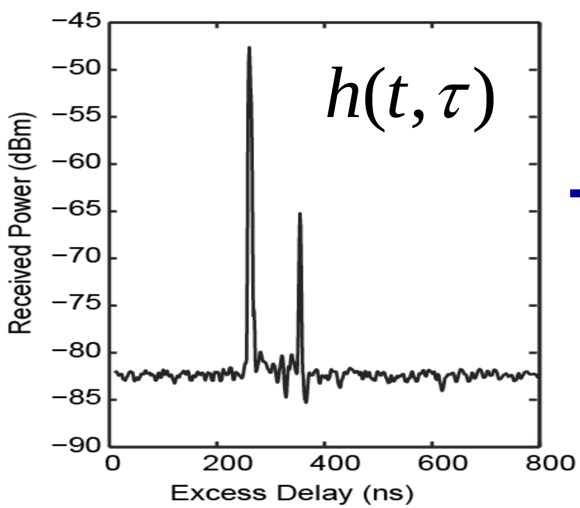
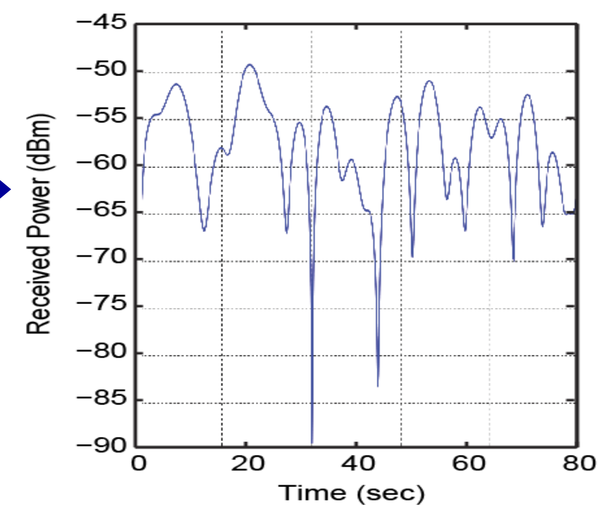


Image shamelessly borrowed from Greg Durgin



Time-Varying CIR:

Reflection, Refraction, Diffraction from objects in the environment.



Primary Assumptions

Channels can be modeled as Linear Time-Variant Filters.

Individual multipath signals arrive uncorrelated.**

Channel is static (or Wide Sense Stationary) over interval Δt.**

** Tends to be overly pessimistic for SISO or overly optimistic for MIMO

Right side of the curve: Concerned with the interaction of the signal with its environment.

Maxwells Equations

Set of partial differential equations EM fields obey.

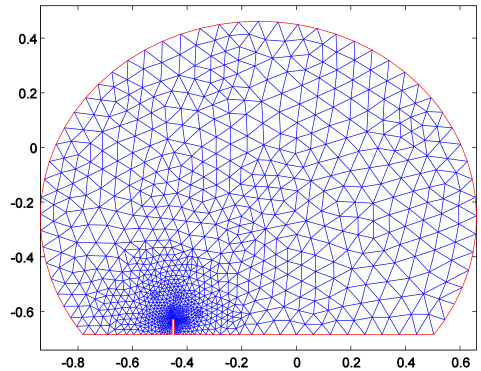
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = -\frac{n^2}{c_0^2}\frac{\partial \vec{E}}{\partial t}$$

$$\nabla \cdot \vec{B} = \nabla \cdot \vec{E} = 0$$

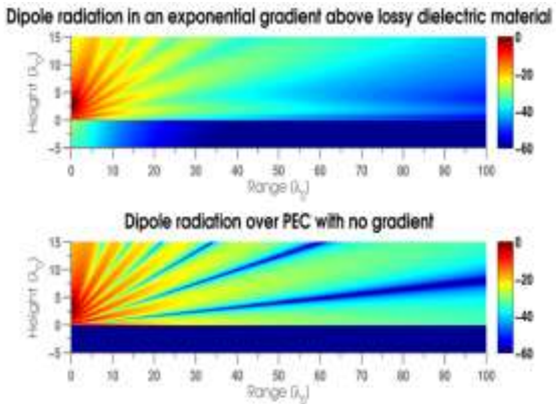
Computed Numerically

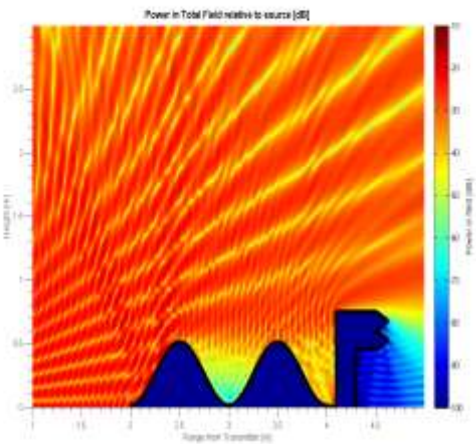
FEM/FDTD typically used.



Achieves Exact Solution

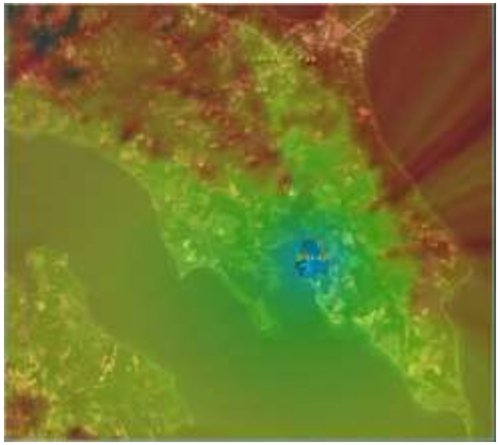
Matches every classical EM experiment.





Plane Wave Propagation:

Atmospherics, soil dielectric, terrain, foliage, building databases.



Primary Assumptions

Generally use MANY simplifications or approximations.

Models may not account for all environmental features.

Note: All empirical/statistical models are not created the same!

First Principles Based

Free Space / Two-Ray / Diffraction

Benefits

- Underlying physical principles.
- No large structures or calcs.
- Extremely simple and fast.

Issues

- Does not account for real propagation environments (terrain, clutter, etc.).
- Rarely matches reality.

Curve Fit

Log Distance / Hata / COST-231

Benefits

- Simple to implement, even under complex environmental conditions.
- Can account for scattering/shadowing in a statistical sense.

Issues

- Relevant to a specific environment.
- Accuracy and connection to physical reality can be suspect.

Hybrid Methods

Longley-Rice / ITM / ITU-R

Benefits

- Can provide greater accuracy.
- Can include various levels of terrain/building/etc effects.

Issues

- Computational complexity and run-time.
- Requires accurate knowledge of propagation environment.

All EM models are not created the same either!

Helmholtz Method

Benefits

NO PDE APPROXIMATIONS!

Full-wave solution at one freq.

Broadband wave solutions.

Complex boundary conditions.

Issues

Fine meshing required.

Long run times for large (1000λ) propagation environs.

Geometric Optics Method

Benefits

Simple to implement, even under complex environmental conditions.

No large matrix calcs. or data structs.

Can account for backscatter.

Issues

High frequency approximation.

No diffractive or forward scatter effects.

Large Number of rays to trace.

Parabolic Wave Equation Method

Benefits

FFT method can be very fast.

Can be meshed in large steps (>1000λ).

No matrix inversion.

Accounts for diffraction.

Issues

Doesn't always account for backscatter

MANY APPROXIMATIONS AND ASSUMPTIONS

Example: Comparing 3.5 GHz Radar propagation to several model predictions.

Measured RSS

Comparison Parameters

Measurements collected July/Oct. by USNA WMG.

ITM/TIREM simulations in NRL Builder.

Ext. Hata was Matlab implementation of Paul McKenna's Oct. 2014 code.

Assumptions contained in each modeling code.

Note: Heatmap $\Delta = \left| Meas - Model \right|$

Δ is truncated to 30 dB

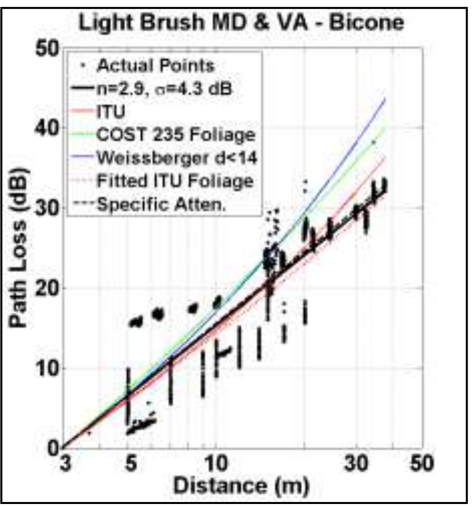
ITM Δ

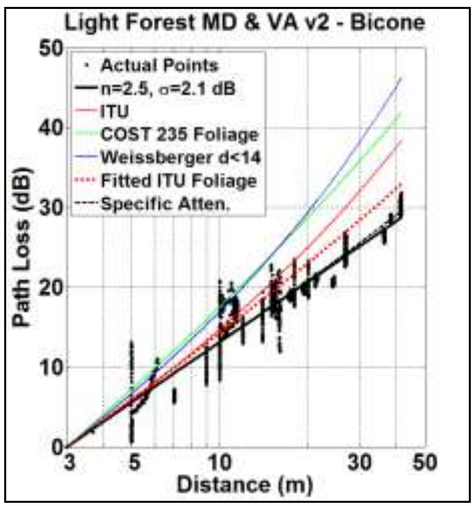
TIREM Δ

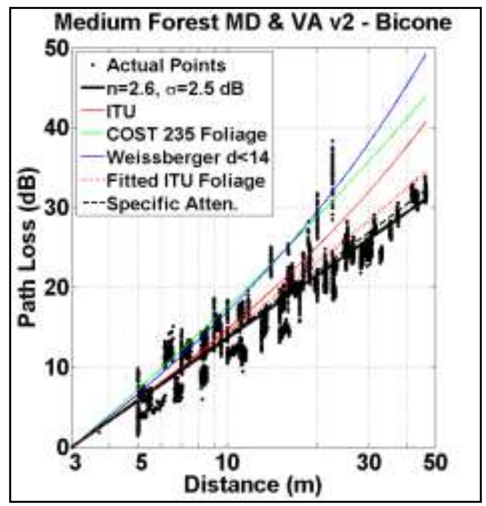
Ext. Hata Δ

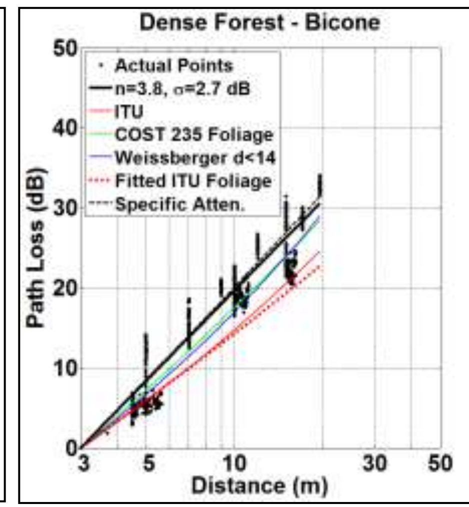
Clutter is not necessarily a Loss!
CW models do not always apply to Broadband

Light Brush | Light Forest | Medium Forest | Heavy Forest









Note:

"Clutter" does not always produce loss → Improvement from Brush to Med. Forest.

Models developed for CW do not always apply to UWB/broadband.

Conclusions

Propagation modeling is a severely complex endeavor, part science and part creative art.

All propagation models are not created equal: one must understand the assumptions and limitations.

All propagation model applications are not created equal: anathema to one engineer is performance enhancement to another.

Backup Slides

Path Loss Model Comparison

ITM (Longley-Rice)

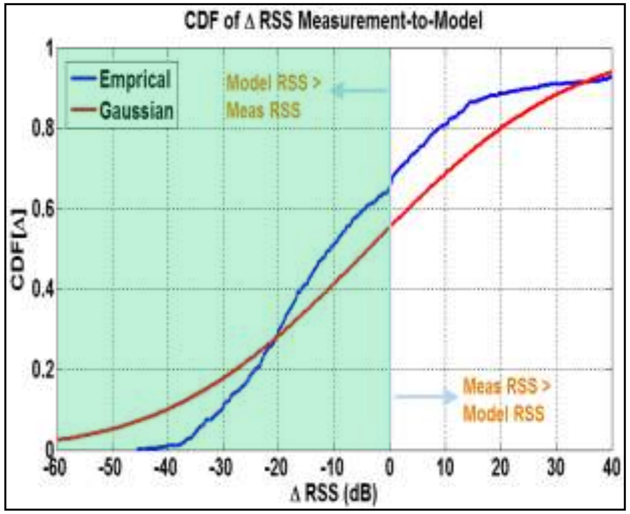
Meas-to-Model Error Analysis	
Mean Error	-3.8 dB
RMS Error	28.5 dB
Mean Error *d* > 5km	-4.3 dB
RMS Error *d* > 5km	15.4 dB

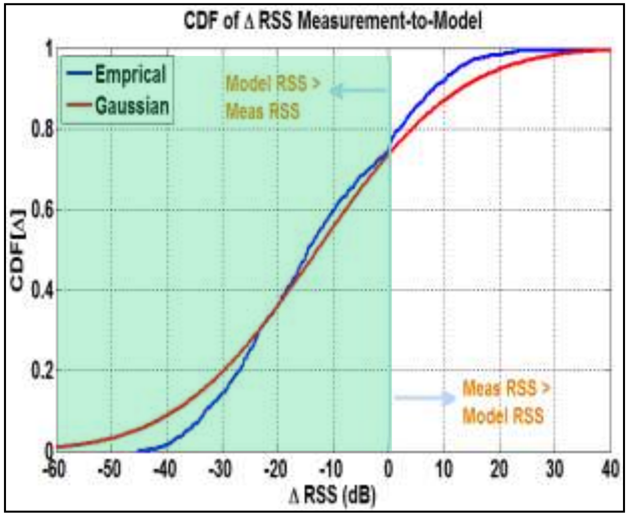
TIREM

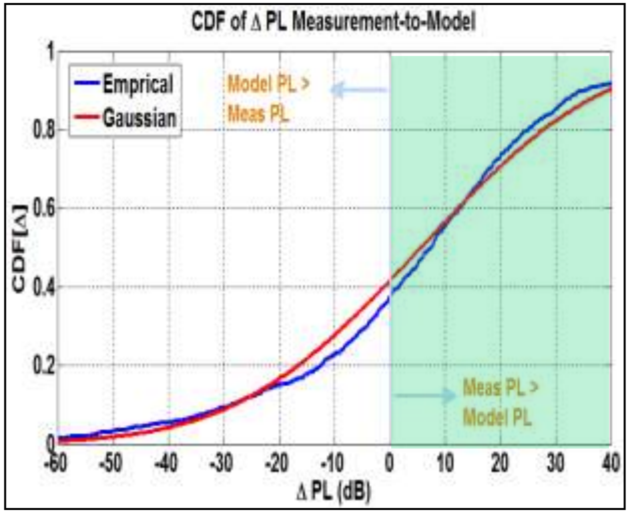
Meas-to-Model Error Analysis	
Mean Error	-12.8 dB
RMS Error	20.2 dB
Mean Error *d* > 5km	-9.1 dB
RMS Error *d* > 5km	16.5 dB

Ext. Hata

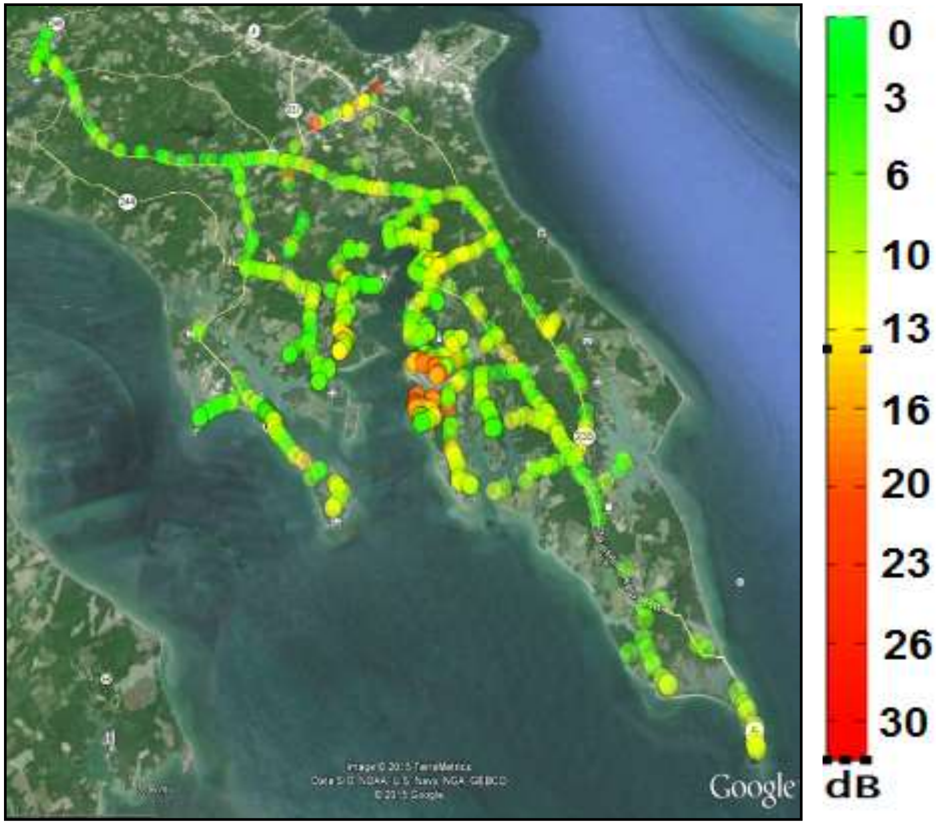
Meas-to-Model Error Analysis	
Mean Error	5.6 dB
RMS Error	26.4 dB
Mean Error *d* > 5km	7.6 dB
RMS Error *d* > 5km	13.1 dB







Clutter is not necessarily a loss: 3.5 GHz "partition" based analysis [Preliminary]

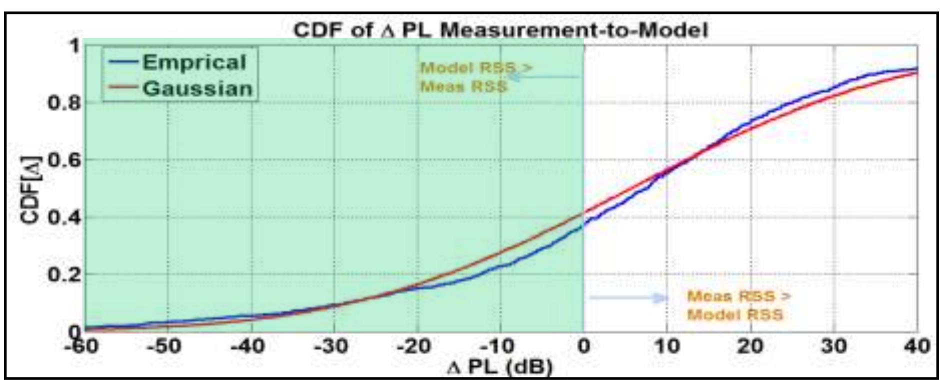


PBPL: Fully empirical, used in many indoor scenarios.

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + \sum_{i=1}^{P} a_i x_i$$

- n is the Path Loss Exponent
- a_i is the number of partition type i
- x_i is the attenuation associated with partition type i
- P is the number of different types of partitions

Calculated Partition Losses for *n = 4.0*	
Open Land	2.93 dB/km
Over Water	0.41 dB/km
Forest	-1.27 dB/km



Meas-to-Model Error Analysis	
Mean Error	-1.1 dB
RMS Error	11.3 dB
Mean Error *d* > 5km	-0.5 dB
RMS Error *d* > 5km	8.1 dB

Example of the 2010 measurement setup

Transmitter

Receiver

Cattle Farm Hay Field

Modeling the wireless channel: Time-Varying Impulse Response (CIR)

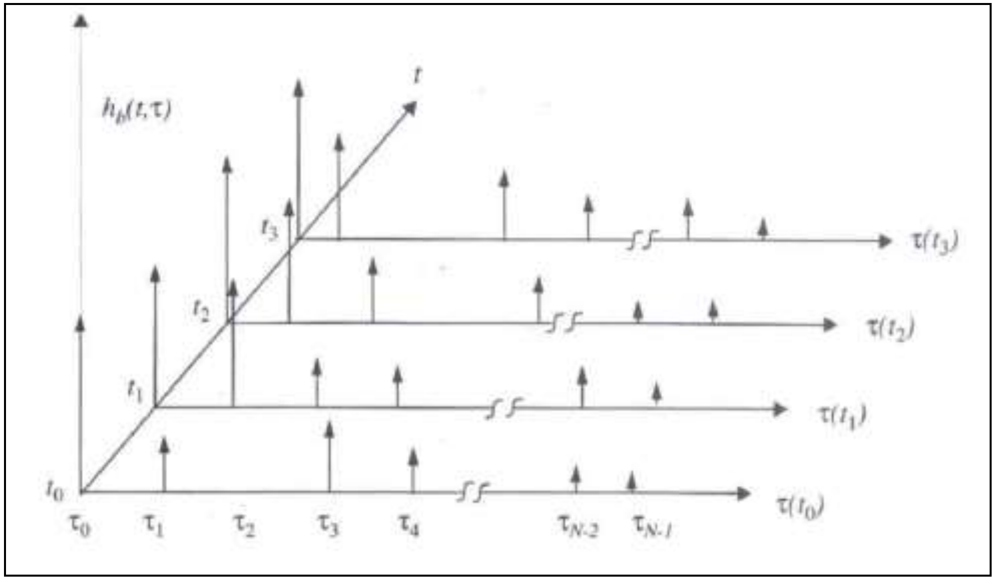


Image shamelessly borrowed from T. S. Rappaport

$$h(t,\tau) \approx \sum_{i=1}^{N} a_i(t) e^{-j\theta_i(t)} \delta(\tau - \tau_i(t))$$

$h(t,\tau)$	time-varying impulse response
$a_i(t)$	magnitude of the ith signal
$\theta_i(t)$	phase of the ith signal
$\tau_i(t)$	excess delay of the ith signal

Primary Assumptions

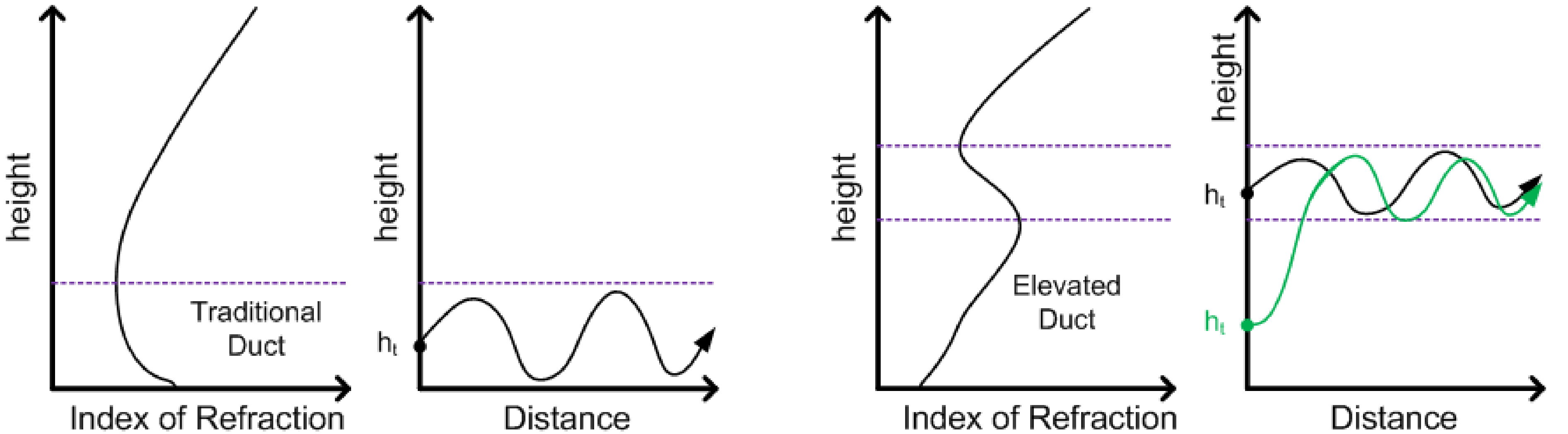
Channels can be modeled as Linear Time-Variant Filters.

Individual multipath signals arrive uncorrelated.**

Channel is static (or Wide Sense Stationary) over interval Δt.**

** Tends to be overly pessimistic for SISO or overly optimistic for MIMO

Tropospheric Refractivity and Ducts



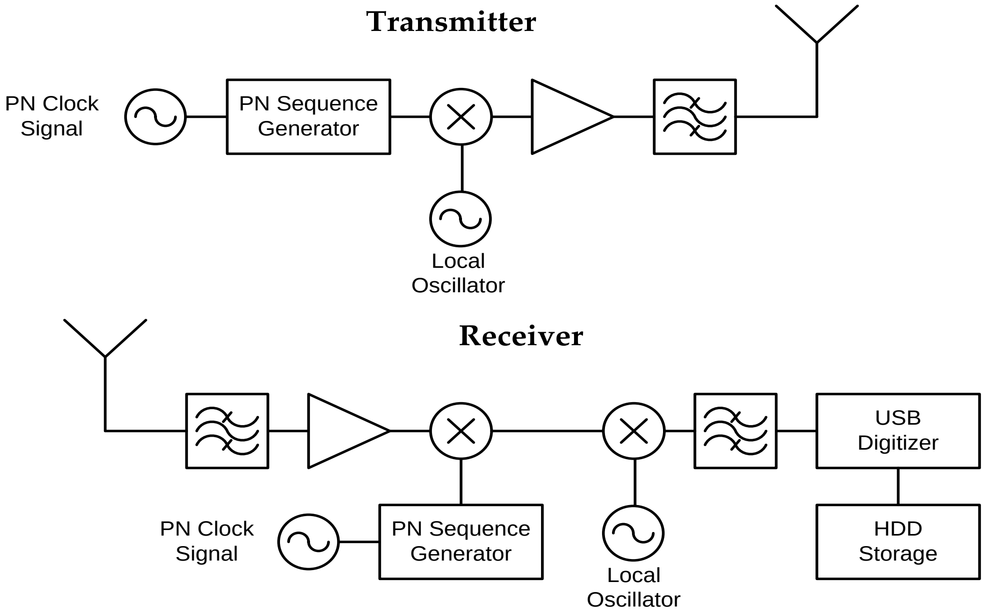
Duct -- Region of the atmosphere where electromagnetic energy bends towards (parallel to) the Earth's surface.

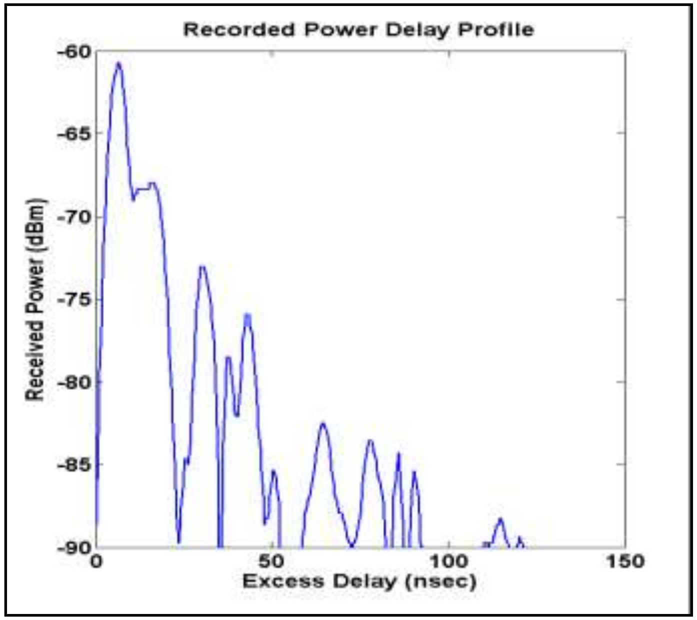
$$N(h) = 77.6\frac{P}{T} - 5.6\frac{e}{T} + \left(3.73\times10^{5}\right)\left(\frac{e}{T^{2}}\right)$$

Where :
N = Refractivity
T = Temperature (K)
P = Pressure (mb)
e = Vapor pressure (mb)

Equation based on Smith and Weintraub

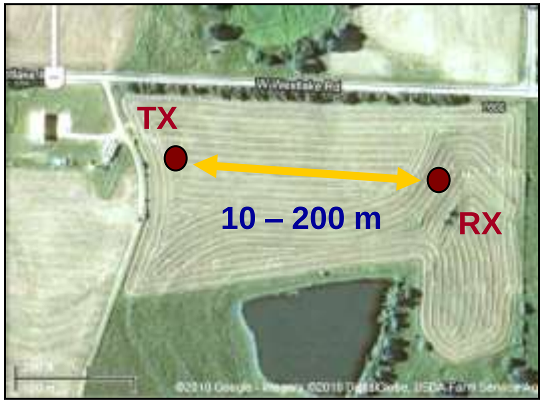
Vector Channel Sounder Overview



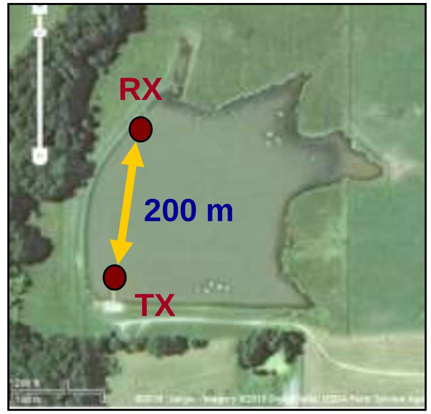


USNA "Big Box" Sliding Correlator Channel Sounder System Capabilities	
Parameter	**Value**
Center Frequency	2.5 GHz
M-Sequence Clock Rate	Variable 25 MHz – 450 MHz
RF Bandwidth	Variable 50 MHz – 900 MHz
Multipath Time Resolution	20 ns – 2.25 ns (based on bandwidth)
Multipath Spatial Resolution	20 ft – 2.25 ft (based on bandwidth)
M-Sequence Length	63, 2047, or 131,071 chips
Measurement Dynamic Range	selectable 18, 35, or 51 dB (set by m-sequence length)
Measurement Rate	40 per sec. max (set by m-sequence length and clock)
Transmit Power	+45 dBm maximum (+27 dBm nominal)
Receiver Noise Floor	-120 – -80 dBm (based on bandwidth)
Maximum Range	300m @ +40 dBm Transmit Power & 24cm TX height

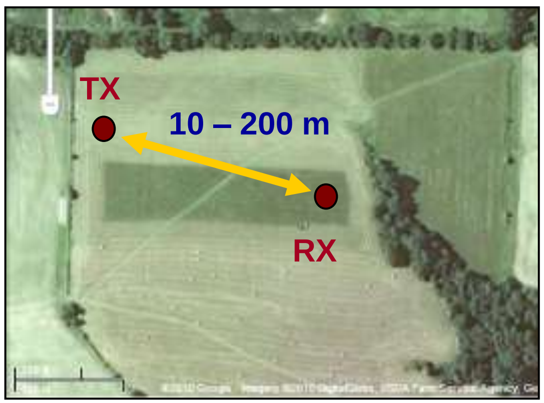
2010 Measurement Locations and Setup



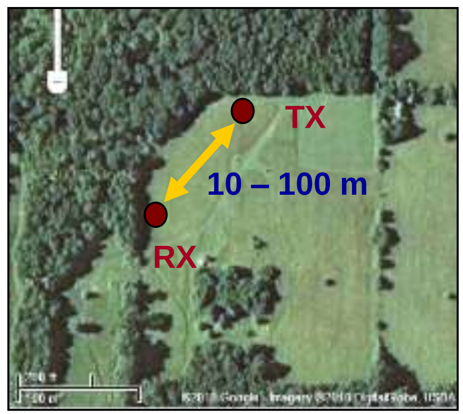
Dairy Farm – Brome Field



Private Lake



Cattle Farm – Hay Field



Gun Club – Tall Weeds

Baseline Data

TX, RX height 100 cm

Measurement Runs

TX & RX height 24 cm
TX & RX height 12 cm

Distances

Log spaced from 20 – 200m
Long day runs at 100 – 200m

Frequencies

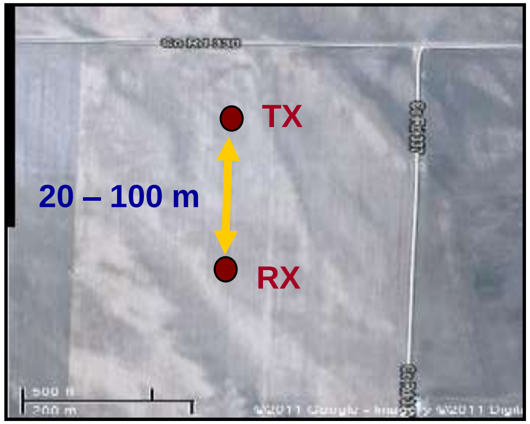
2.5 GHz Horiz./Vert.
5.8 GHz (partial) Horiz./Vert.

Location: Columbia, MO

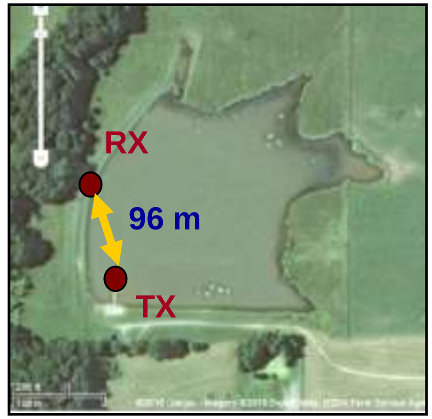
Ground: Rock, Clay, & Farm Soil

Atmosphere: Hot, humid, still air

2011 Measurement Locations and Setup



Clements Farm – Sugarsand



Private Lake

McBaine Bottoms – Clay Soil

Baseline Data

TX, RX height 100 cm

Measurement Runs

TX & RX height 24 cm
TX & RX height 12 cm

Distances

Log spaced from 20 – 100m
Long day runs at 100m

Frequencies

2.5 GHz Horiz./Vert.

Location: Columbia, MO

Ground: Sand, Clay, & Water

Atmosphere: Hot, humid, still air