Towards Estimation of Soil Moisture Using RF Polarimetric Responses with Topographical Data and Electromagnetic Scattering Models

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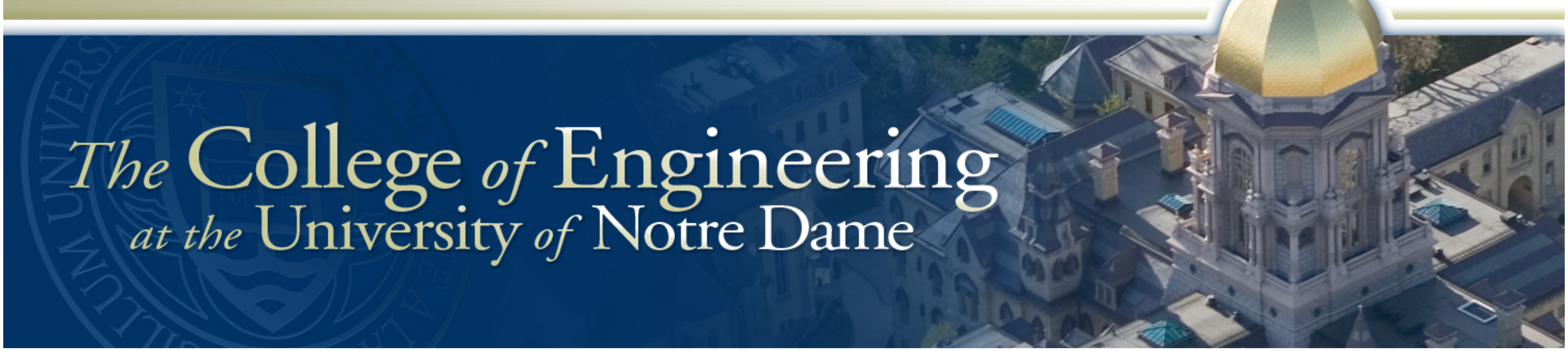
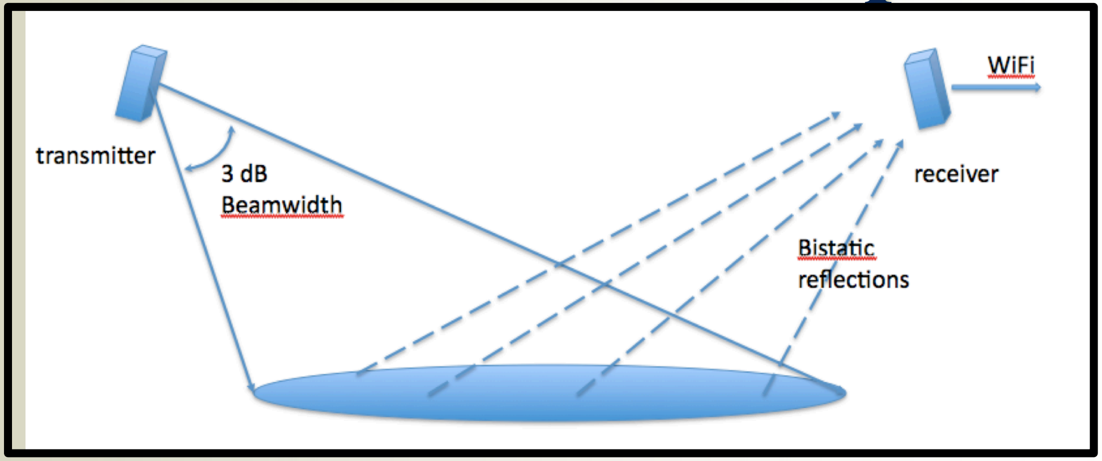


Remote Detection Concept



Remote detection of soil moisture at field scales of ~ 1 km.

Concept: Illuminate area to be characterized with radio frequency energy using multiple frequency bands. At the receiver, measure specific polarimetric features of the bistatic reflections to detect changes in the soil moisture

- Average reading over illuminated area
- Scalable coverage
- Potential for moisture vs. depth profiling using multiple frequencies

- Sensitive to changes in the soil moisture (e.g., dielectric properties)
- Conversion to absolute soil moisture measurements would require either some form of site-specific calibration or possibly could be achieved using time-series over long periods of time; we are investigating an approach that leverages topology and electromagnetic scattering modeling

This was our first data collection application at km-scales

Polarization-Based Channel Behavior

- RF signals in multipath channels will exhibit polarization mode dispersion (PMD) if channel exhibits
  - Polarization coupling
  - Delay spread between components
- PMD is characterized by a spread in polarization versus frequency on the Poincare sphere
- Channel also exhibits polarization dependent loss (PDL)

Poincare Sphere Representations

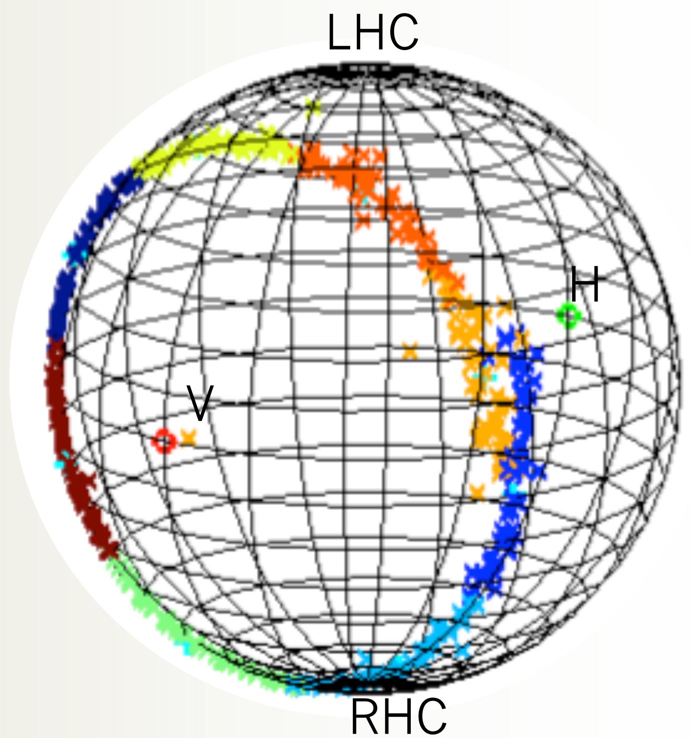
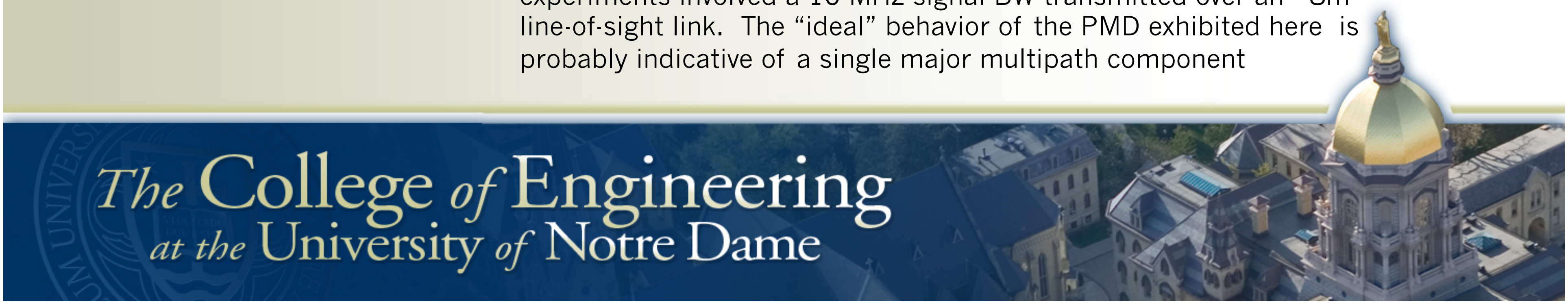


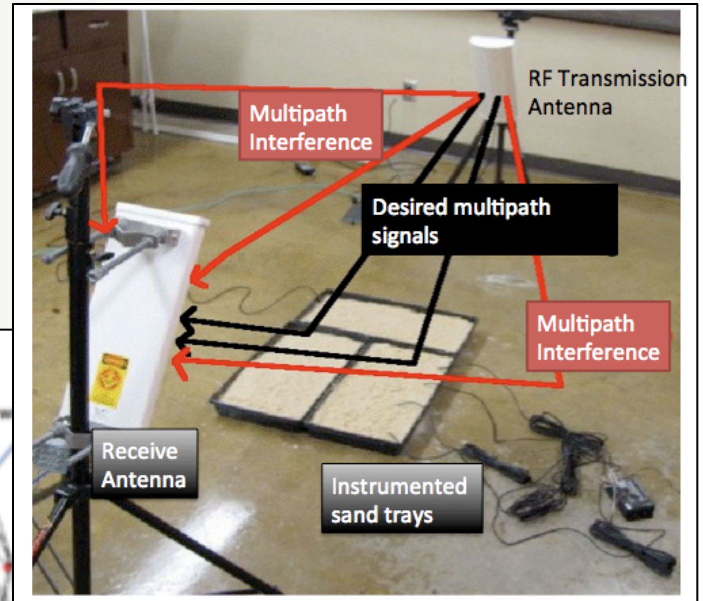
Illustration of PMD exhibited in indoor wireless experiments. The experiments involved a 10 MHz signal BW transmitted over an ~8m line-of-sight link. The "ideal" behavior of the PMD exhibited here is probably indicative of a single major multipath component

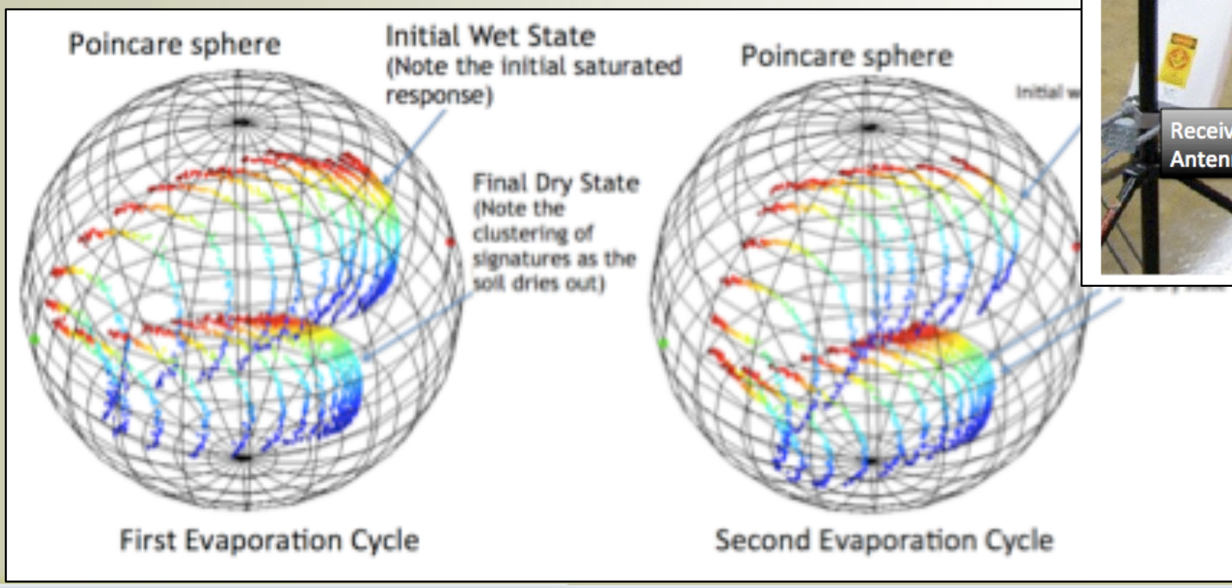


Experimental Illustration

- Technology is based on exploitation of propagation phenomenon known as polarization mode dispersion (PMD)
  - Identified for wireless in ~2006 in experimental results
- Lab-based soil experiments illustrated potential of the technique
  - Repeatable responses that changes as a function of the soil moisture level
  - Saturation and dry states are also distinctive

Single-frequency system



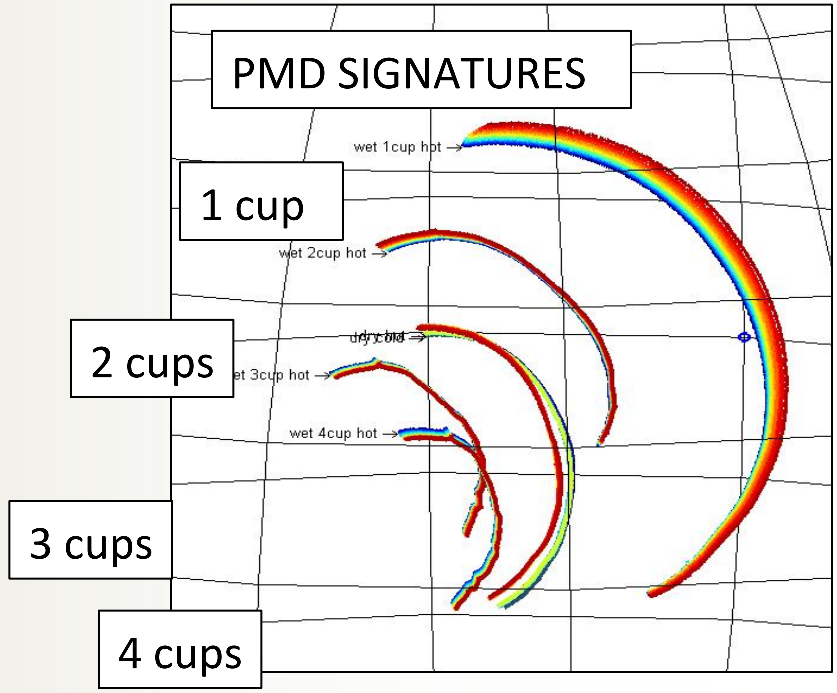


Experiments validated the ability to calibrate the PMD responses

Temperature Sensitivity Tests (Lab-based)

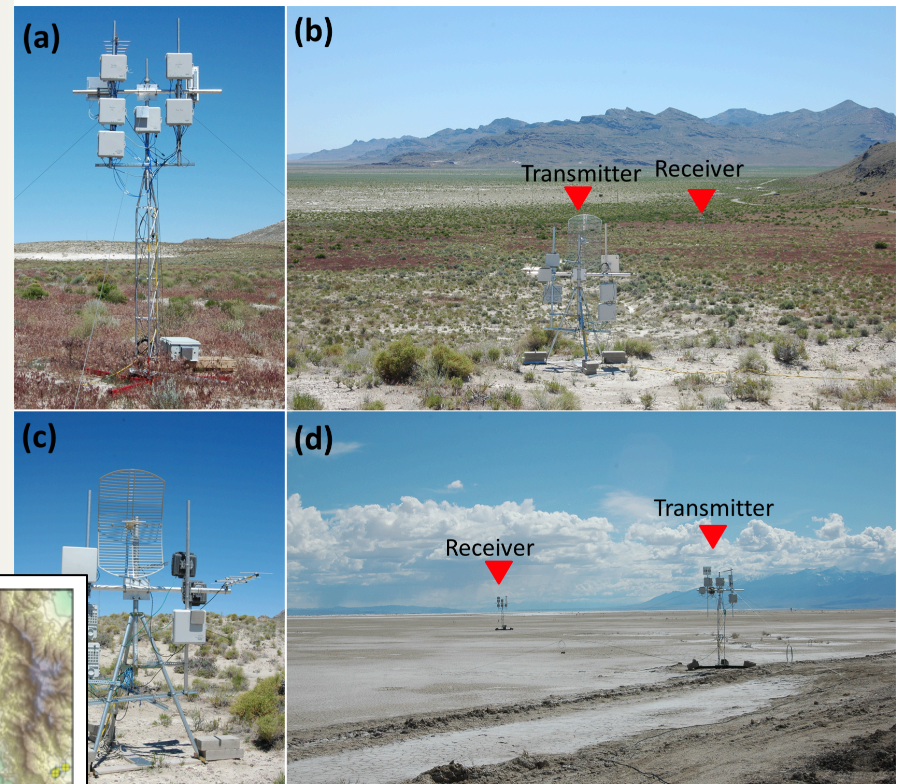
- Five heating and cooling cycles between 24C and 41C, at different moisture levels, RF = 2.4 GHz

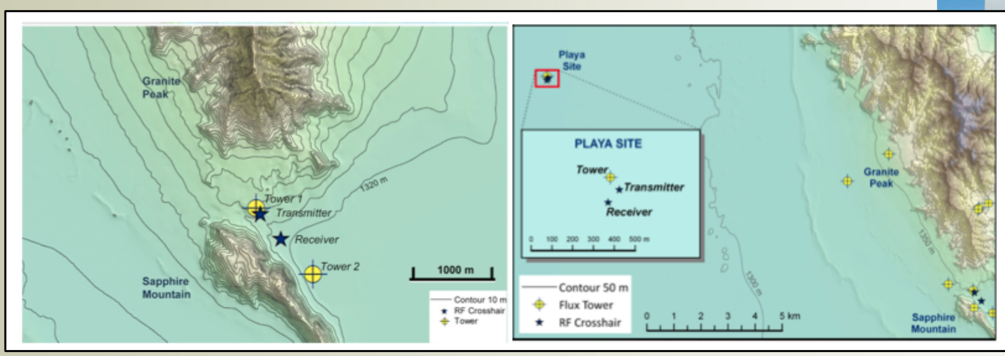
Temperature tests using heat lamps



Deployment at DPG

- System deployed in gap between Sapphire Mountain and Granite Peak.
- Transmitter situated on plateau,
- Receiver in valley floor
- Range was approximately 0.42 km



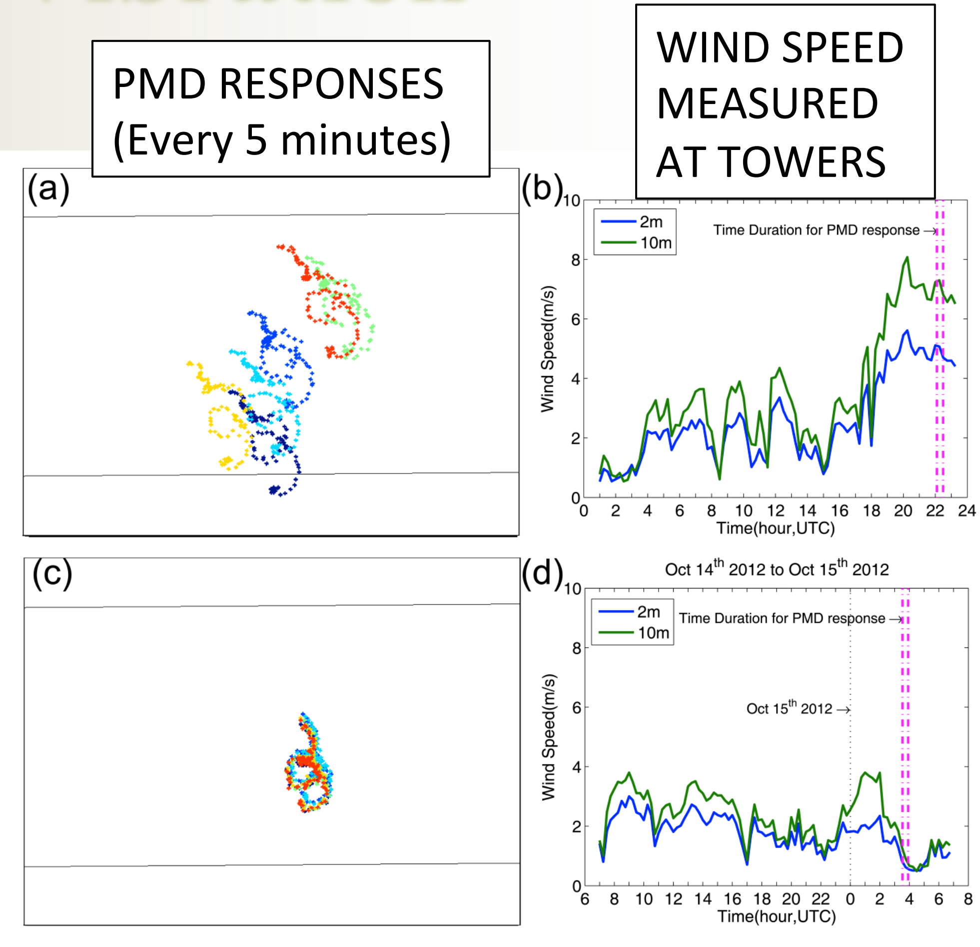


What We Anticipated…..

- PMD responses that vary slightly with temperature, but more substantially with soil moisture
- PMD responses that vary in position and/or shape as the soil moisture changes
- Capability to discriminate dry soil from moist soil
- Capability to discriminate saturated soil from moist soil
- Responses from 3 frequencies that could be used to study depth profiling

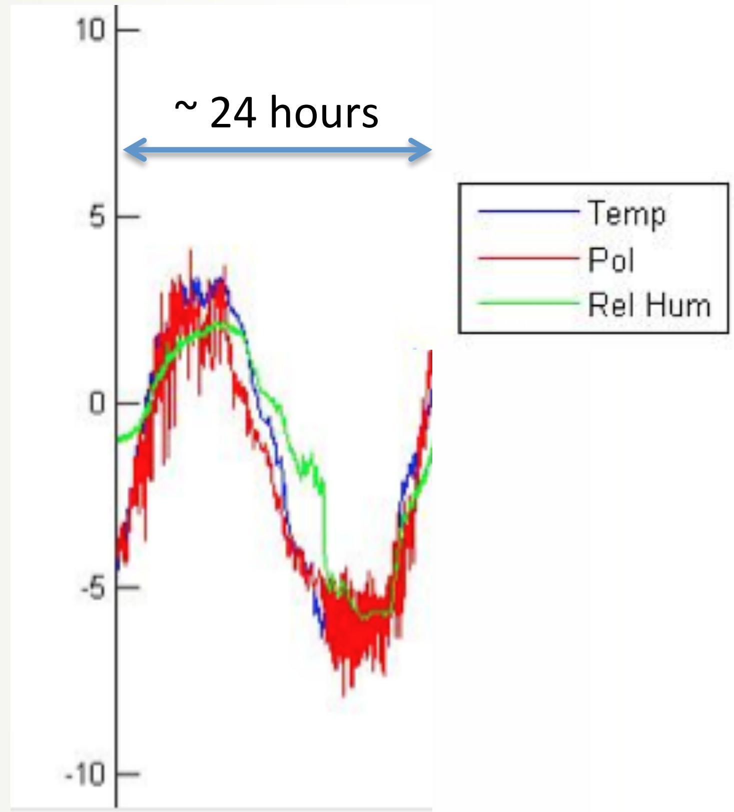
Antenna Mast Vibration

- Impact of antenna vibration due to high wind on the PMD response are shown.
- In the absence of wind-induced vibration of the antennas, the responses exhibit nearly identical responses.
- Better antenna/mast system would have benefitted the ability to draw more significant conclusions



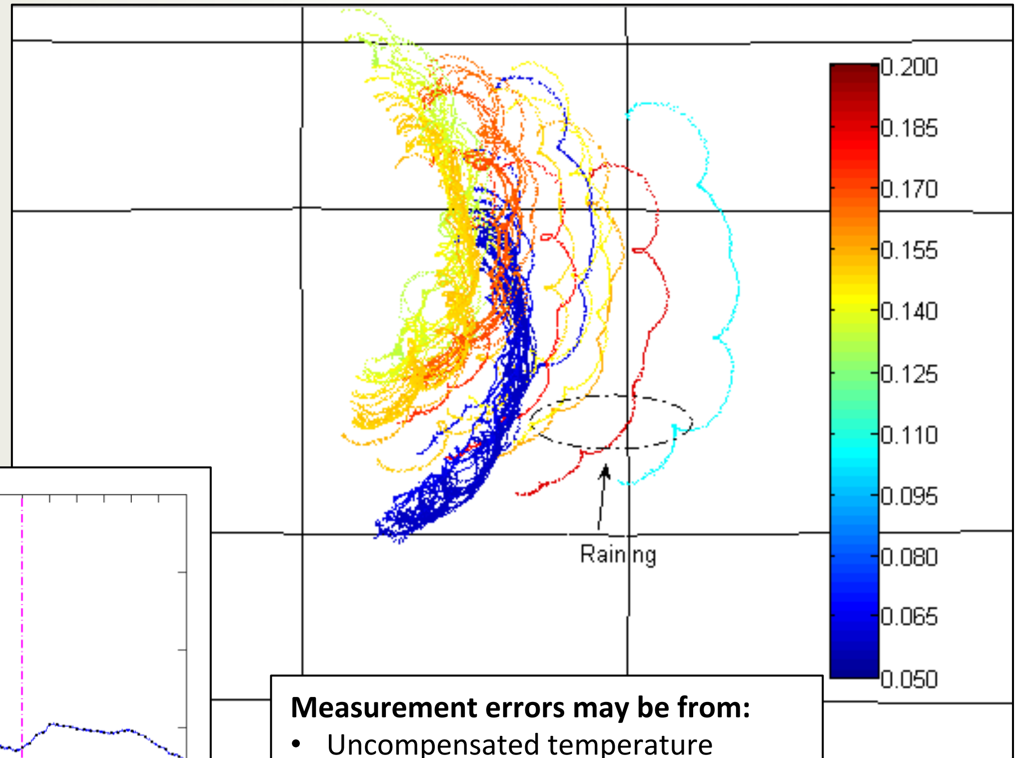
Temperature Dependence

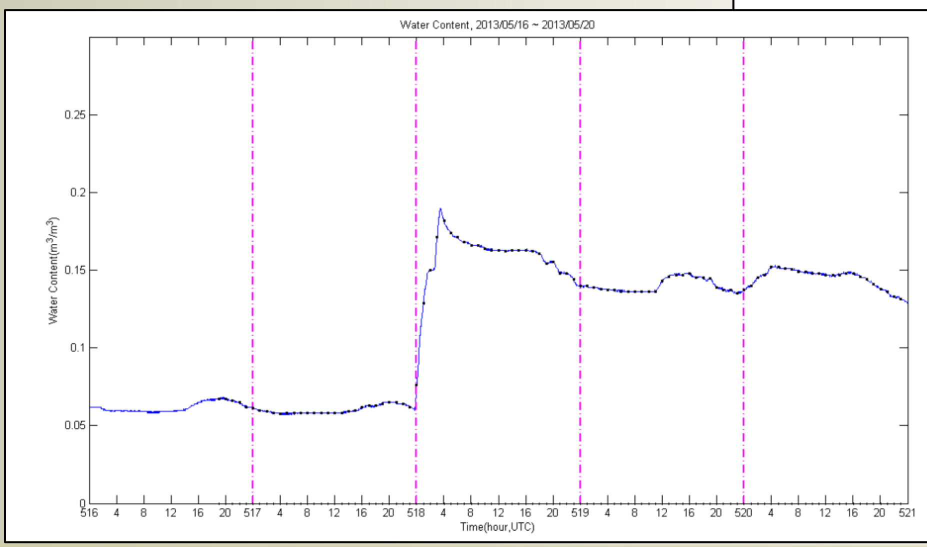
- Ground probes were used to monitor ground temperature at 2 cm depth
- During dry period (without rain for many days), the probe responses and RF responses were compared
- Suggest the potential to compensate for temperature variations.



PMD Correlation with Soil Moisture

- Color coded PMD response based on in-situ measurements
- Shows correlation between PMD response and soil moisture level





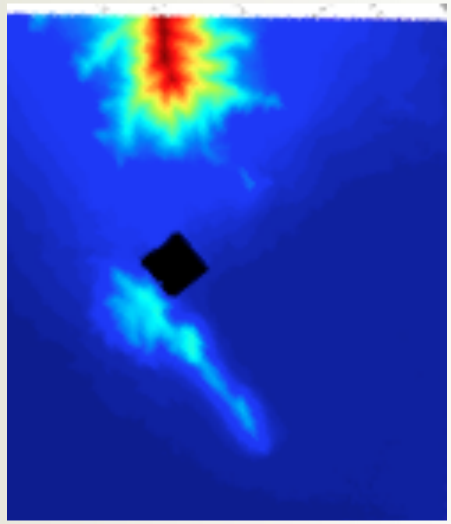
Measurement errors may be from:

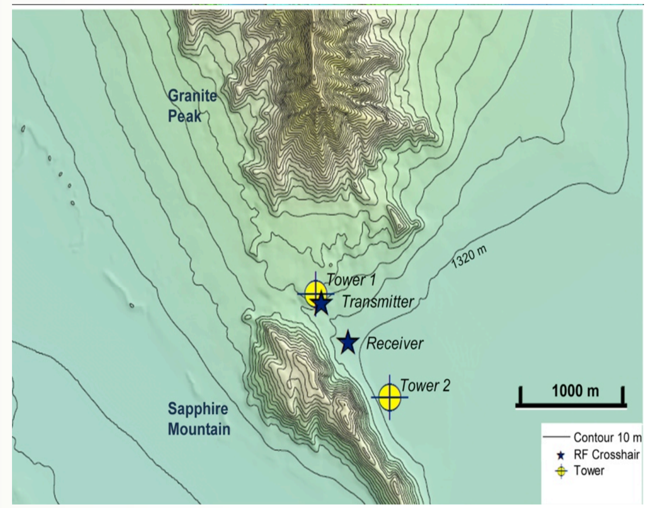
- Uncompensated temperature effects
- Wind (antenna position) effects
- Difference in probe location relative to RF target area
- Impact of changes in RF environment

Surface Contour Model

Use surface model and EMAG scattering models to estimate PMD response for different dielectric properties

The specific contour shown was randomly generated for illustration purposes only



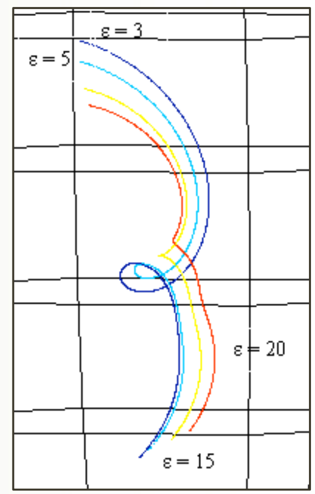


(Stratton-Chu equation with Kirchhoff Approximation)

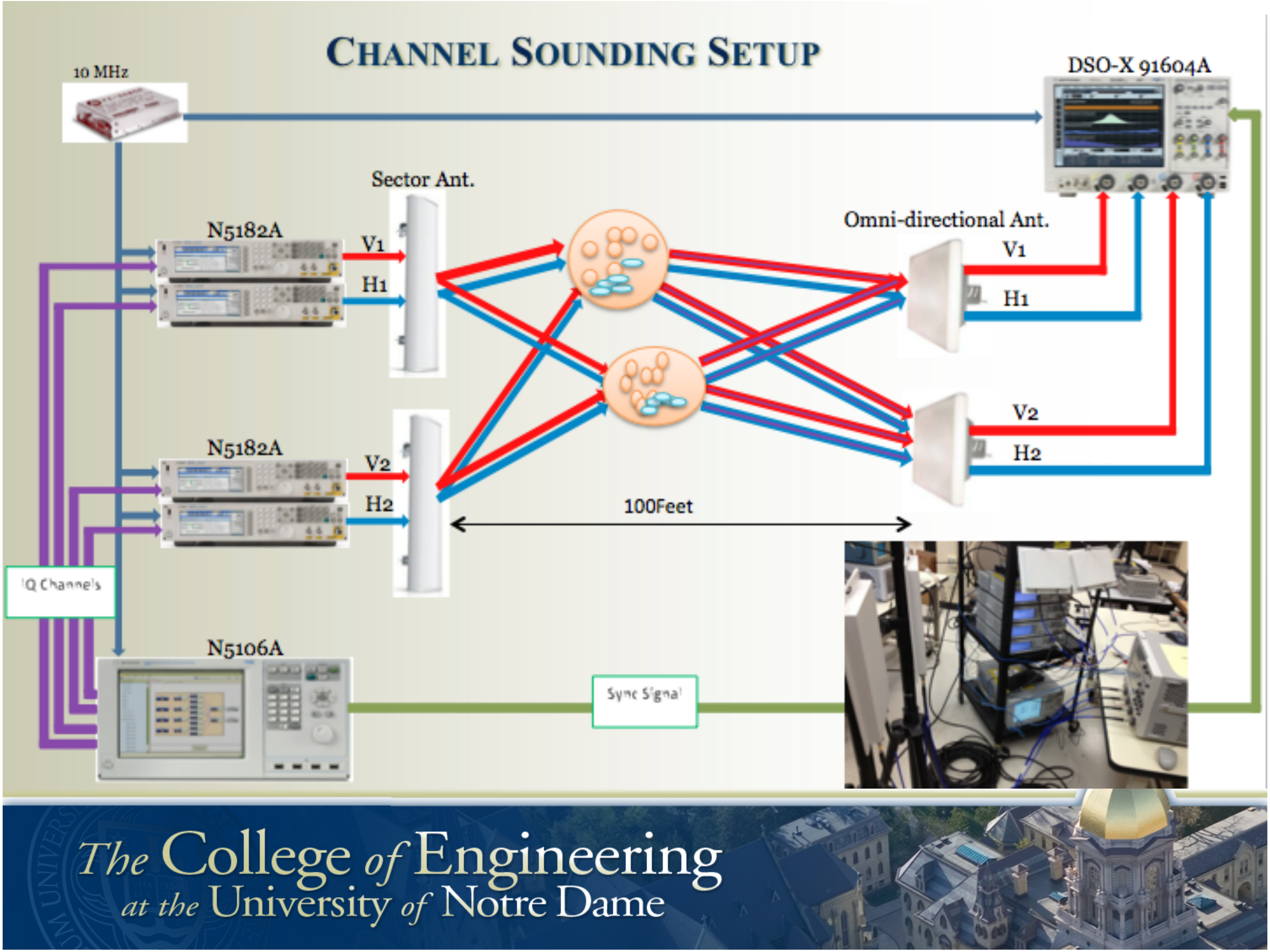
$$\boldsymbol{E}^{sc}(\boldsymbol{r}) = -ik\frac{e^{ikr}}{4\pi r}\hat{\boldsymbol{k}}_{sc} \wedge \int_S \left(\boldsymbol{n}_o \wedge \boldsymbol{E} - \eta\hat{\boldsymbol{k}}_{sc} \wedge \boldsymbol{n}_o \wedge \boldsymbol{H}\right) e^{-ik_{sc}\cdot \boldsymbol{r}_o} dS$$

Illustration of predicted responses using the surface model and the PMD formulation

Note variations with the dielectric value



Predicted responses as a function of the dielectric value



CHANNEL SOUNDING SETUP
10 MHz
DSO-X 91604A
Sector Ant.
Omni-directional Ant.
N5182A
V1
H1
V1
H1
N5182A
V2
H2
V2
H2
100Feet
IQ Channels
N5106A
Sync Signal
The College of Engineering
at the University of Notre Dame

Advancing the Technology…..

- Continue km-scale tests with a multi-frequency system to further develop and evaluate technology
  - With improved experimental set-up
- Develop and evaluate temperature compensation techniques
- Use full polarization channel sounding and theoretical response modeling to evaluate potential for converting measured responses to absolute soil moisture levels
- Demonstrate spatial profiling capability using alternative probing waveforms and antenna configuration
- Engineer a real-time, low SWAP collection system
  - Solar/wind power
- Develop depth profiling approach

Field Research Vehicles

(a future capability based on a $498K DURIP award)

- Two field research vehicles with telescoping 42' masts
- Quarters for long-term testing
- 1 KW (max) solar power and 500 W (max) wind power. Also 12 kW gas generator
- Four work station for with shared data access
- Wireless Internet through cellular provider
- Initially will be configured as a transmit vehicle and a receive vehicle to support bistatic measurements