RF Polarimetric Moisture Sensing

Tom Pratt
University of Notre Dame
(tpratt@nd.edu)
(574) 631-0973

The College of Engineering at the University of Notre Dame

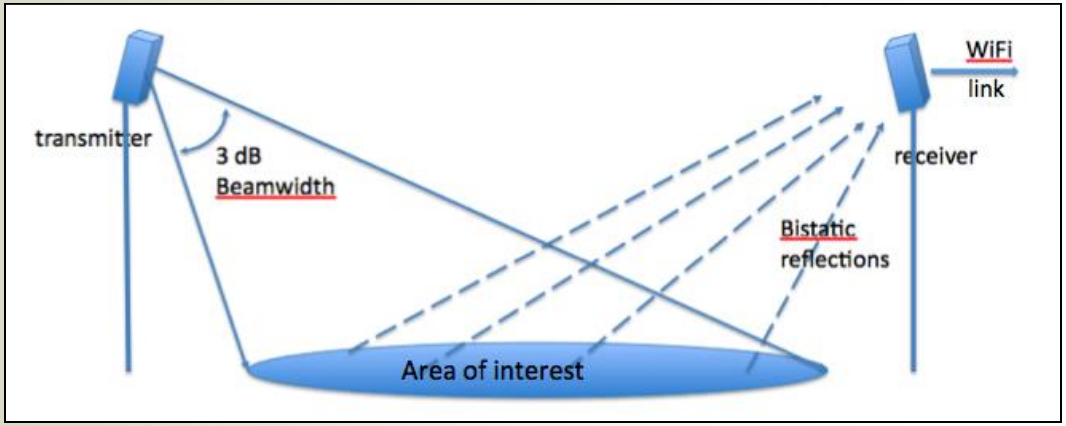
Team of Researchers

- Tom Pratt (co-PI)
- Zi Lin (Graduate student)
- Neil Dodson (Engineer)
- Niels Seim (ESTEEM student)

Collaborators

Silvana DiSabatino (Prof)
Laura Leo (Postdoc)
Pengkun Yang (Visiting student)
Steve Silliman (Hydrologist, Gonzaga)
Joe Fernando (PI)
Jeff Mueller (Postdoc)

Remote Detection Concept



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 illumiunated area
- Scalable coverage
- Potential to obtain time series of measurements to support digital signal processing algorithms

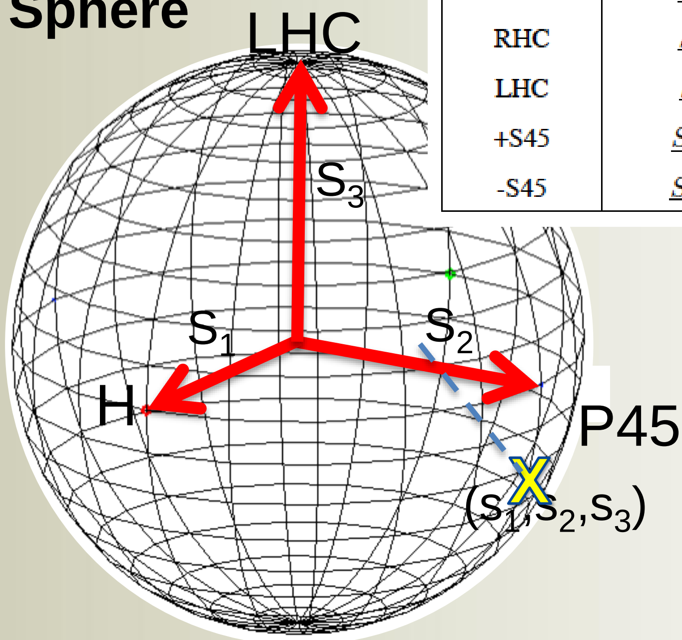
- Sensitive to changes in the soil moisture (e.g., dielectric properties)
- Conversion to absolute soil moisture measurements would require either some form of site-specific calibration or possibly could be achieved using time-series over long periods of time
- Potential for moisture vs. depth profiling using multiple frequencies

This was our first data collection campaign at km-scales

Polarization Representation

- The technique relies on the polarimetric behavior induced by scattering
- We represent these effects on a Poincare Sphere

Poincare Sphere



Polarization	Representation	S_1	S_2	S_3
V	$\underline{S}_V$	-1	0	0
H	$\underline{S}_H$	1	0	0
RHC	$\underline{S}_R$	0	0	-1
LHC	$\underline{S}_L$	0	0	1
+S45	$\underline{S}_{p45}$	0	1	0
-S45	$\underline{S}_{n45}$	0	-1	0

Every point on the Poincare sphere corresponds to a unique polarization state.

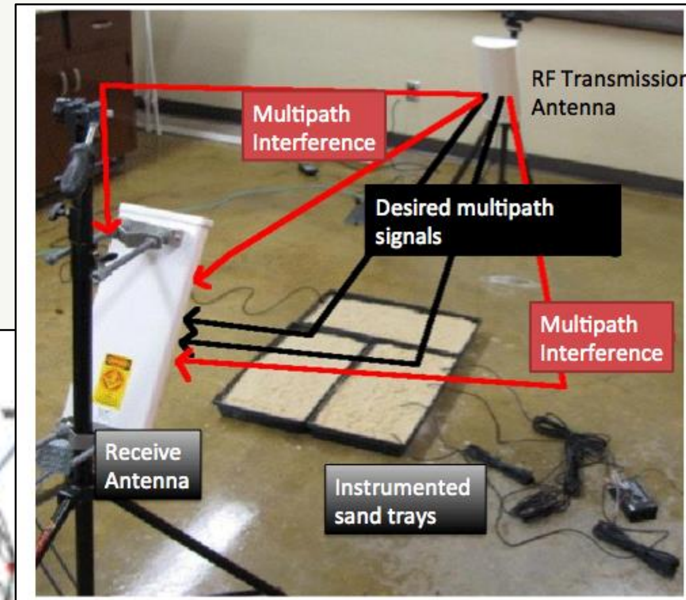
All polarization states can be uniquely represented

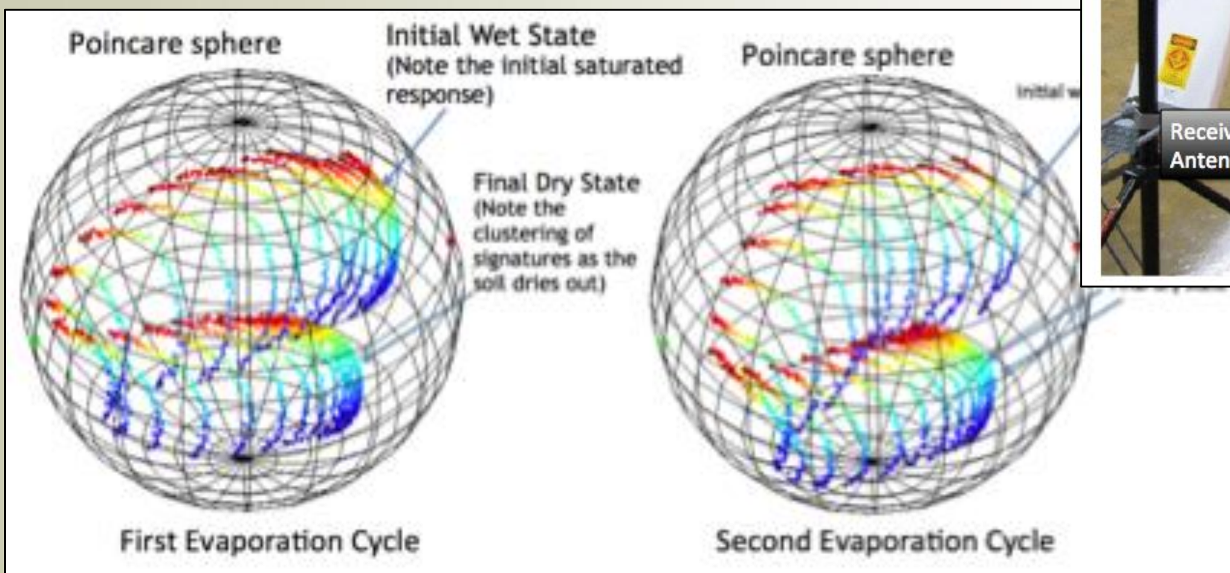
All signal polarizations falling on the unit sphere have a degree of polarization equal to unity

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



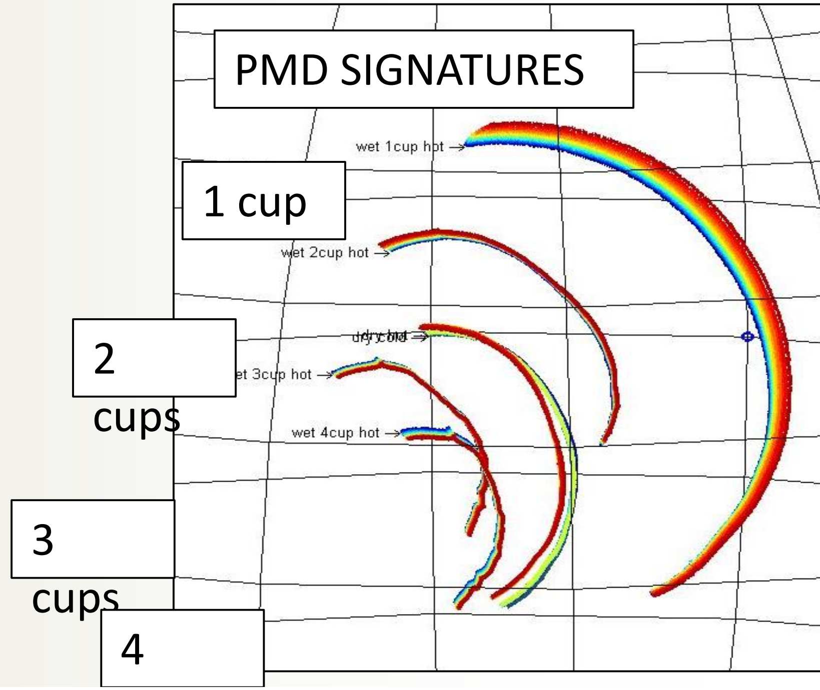


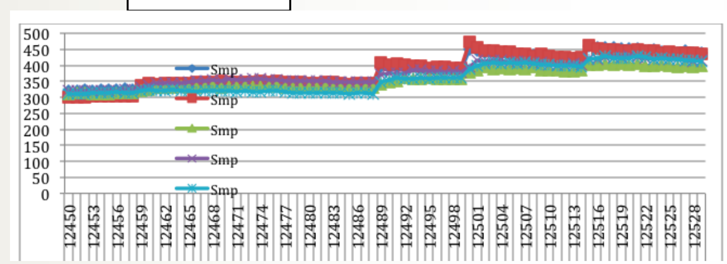
Experiments validated the ability to calibrate the PMD responses

Temperature Sensitivity Tests

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

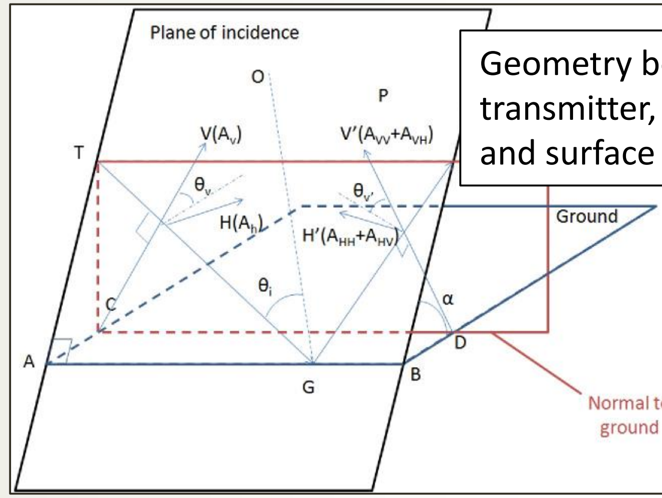
Temperature tests using heat lamps





Electromagnetic Scattering

- Scattering responses developed for signal with arbitrary incidence
- Model generates polarization reflection coefficients for spatially dispersed facets
- Responses depend upon incidence angle, other geometry parameters, and the transmit polarization state



Geometry between transmitter, receiver and surface reflection

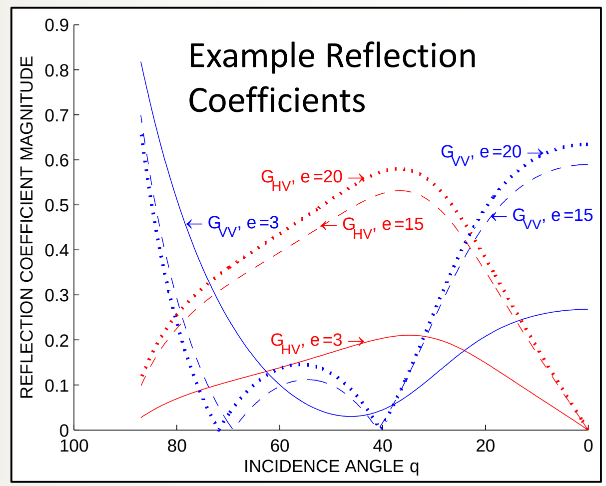
Polarization-based Reflection Coefficients

$$\Gamma_{VV} = \frac{A_{VV}}{A_v} = \Gamma_{R_\parallel} \cos\theta_v \cos\theta_{v'} + \Gamma_{R_\perp} \sin\theta_v \sin\theta_{v'}$$

$$\Gamma_{HV} = \frac{A_{HV}}{A_v} = \Gamma_{R_\parallel} \cos\theta_v \sin\theta_{v'} - \Gamma_{R_\perp} \sin\theta_v \cos\theta_{v'}$$

$$\Gamma_{HH} = \frac{A_{HH}}{A_h} = \Gamma_{R_\parallel} \sin\theta_v \sin\theta_{v'} + \Gamma_{R_\perp} \cos\theta_v \cos\theta_{v'}$$

$$\Gamma_{VH} = \frac{A_{VH}}{A_h} = \Gamma_{R_\parallel} \sin\theta_v \cos\theta_{v'} - \Gamma_{R_\perp} \cos\theta_v \sin\theta_{v'}$$

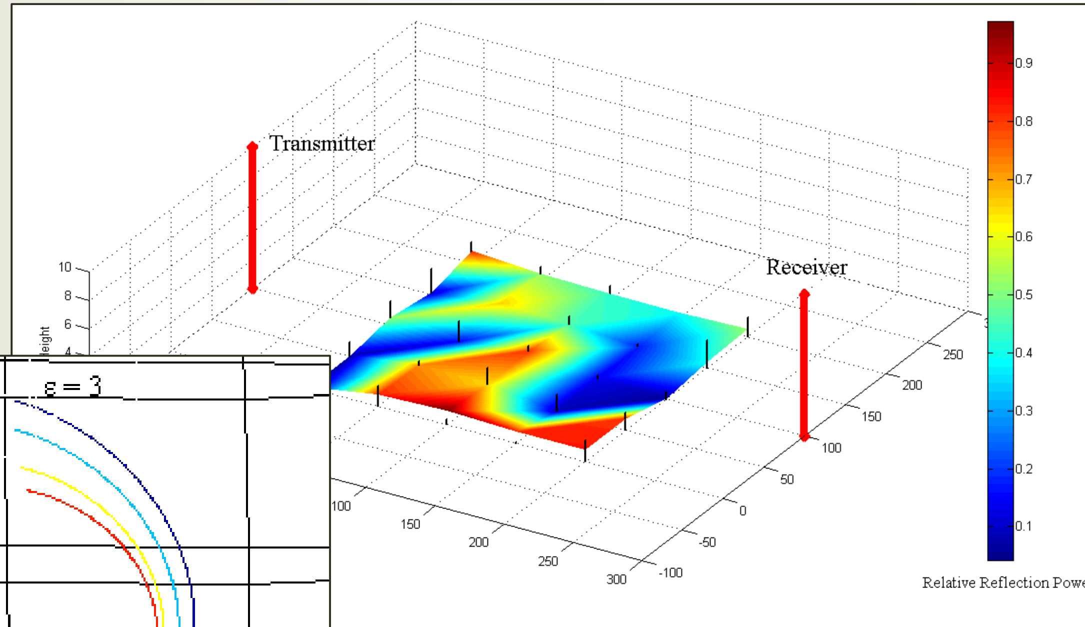


Surface Contour Model

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

Eventually, we will turn to topographic data to pursue this approach for topography-aided calibration



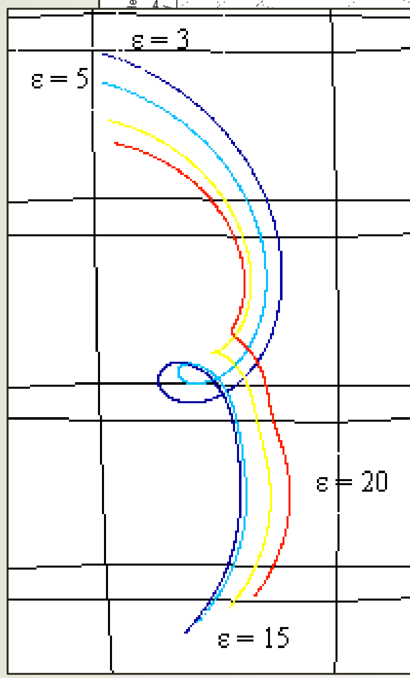
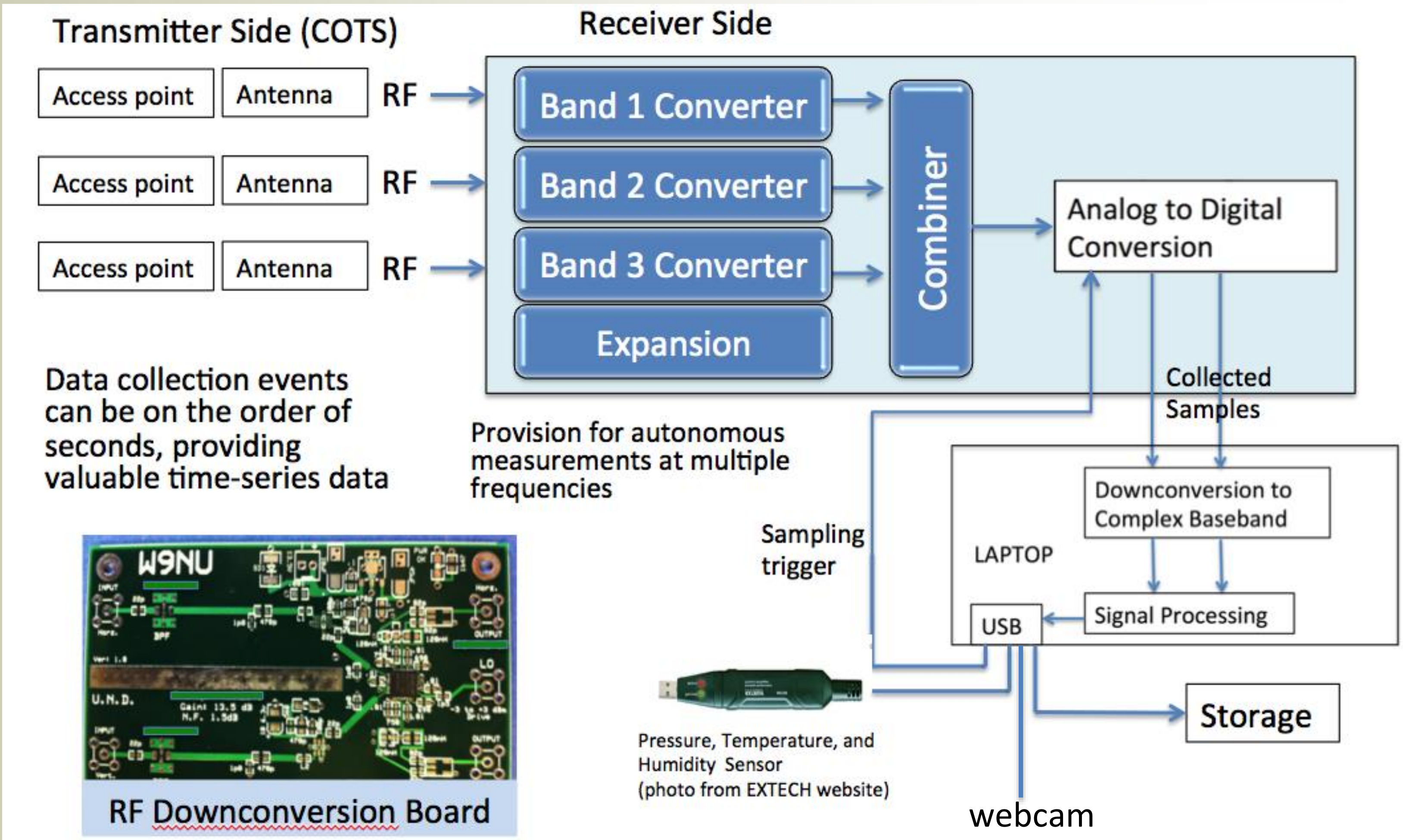


Illustration of predicted responses using the surface model and the PMD formulation

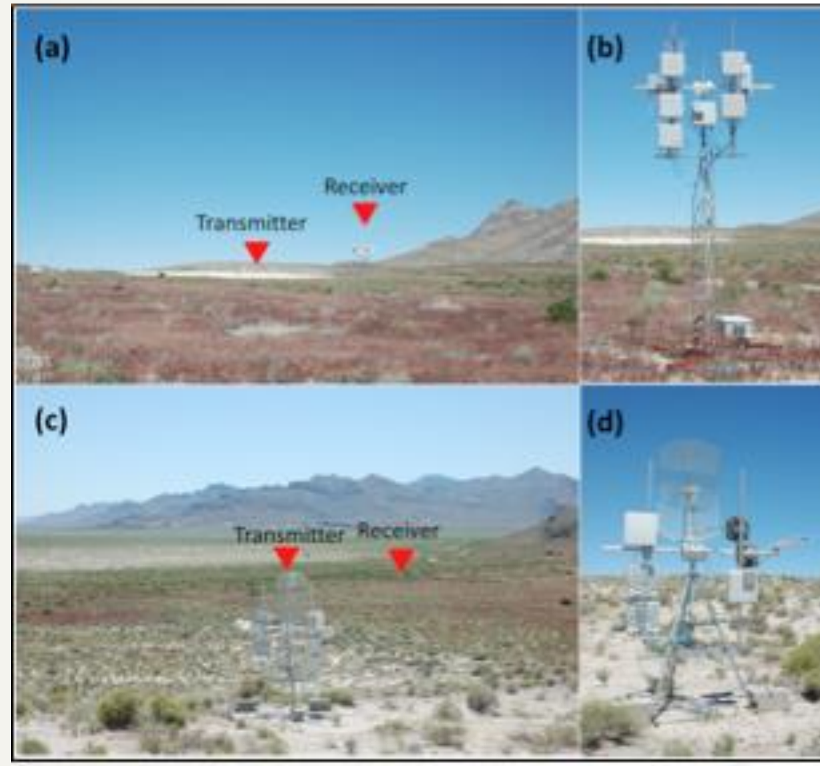
Note variations with the dielectric value

Functional Block Diagram of Collection System

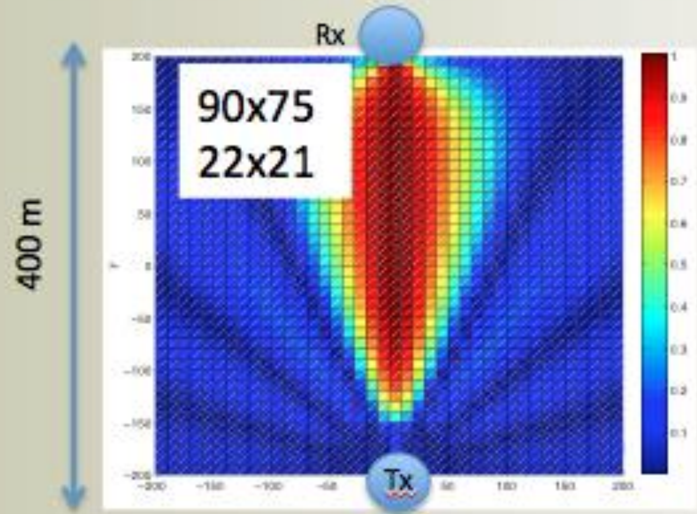


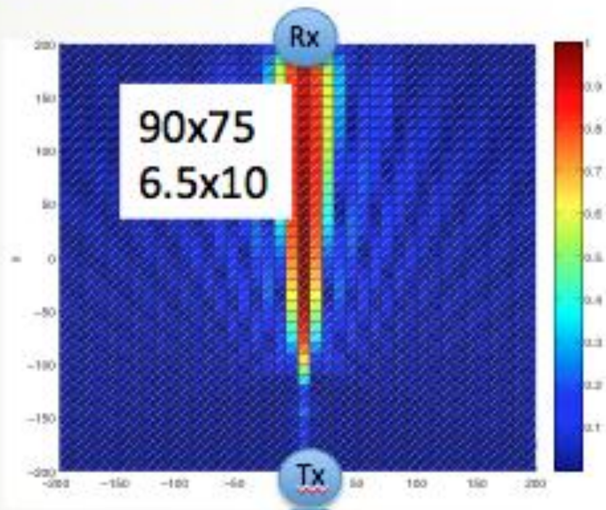
Deployment at DPG (Fall 2012)

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

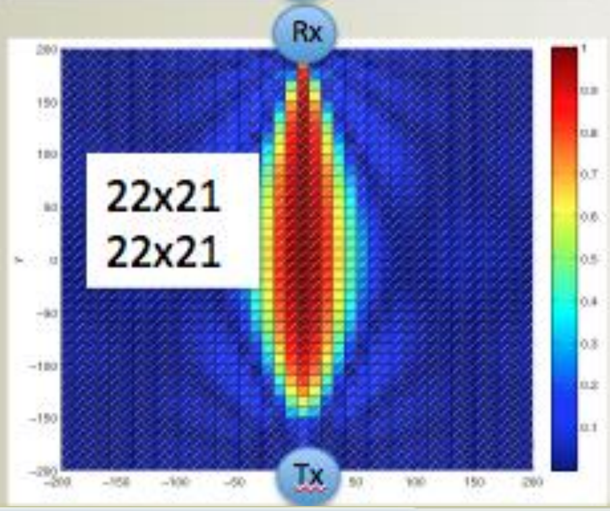


Illustrative Antenna Effects

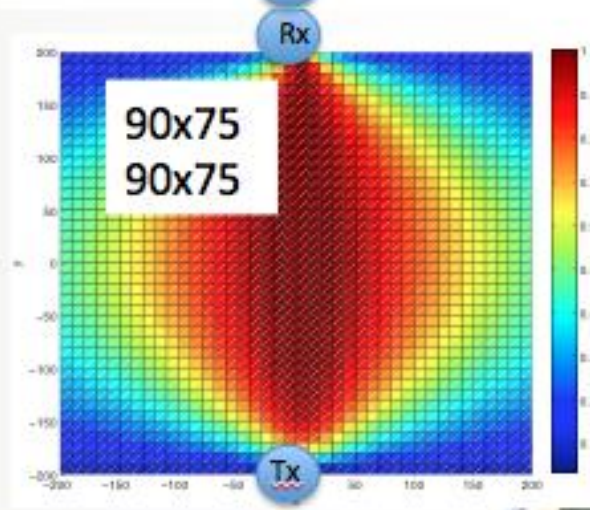




Relative illumination footprint, which is a normalized product of the transmit and receive antenna pattern gains



There are tradeoffs!

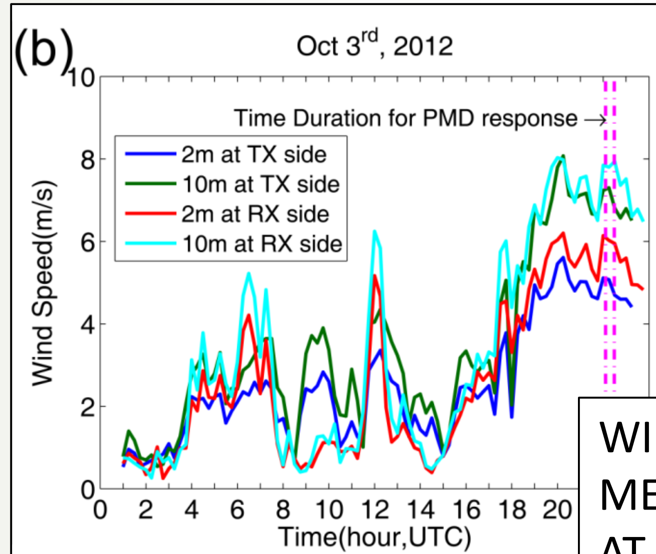


What We Anticipated…..

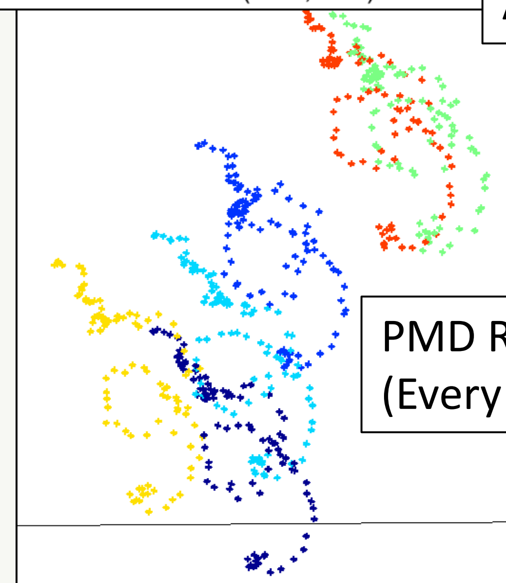
- PMD responses that vary slightly with temperature, but more substantially with soil moisture
- PMD responses that vary in position and/or shape as the soil moisture changes
- Capability to discriminate dry soil from moist soil
- Capability to discriminate saturated soil from moist soil
- Responses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

Results

- Impact of antenna vibration due to high wind on the PMD response. The responses were derived from measurements taken 5 minutes apart. In the absence of wind-induced vibration of the antennas, the responses would be approximately identical. However, because of wind, there exists a variance in the responses. The inset show the wind speed versus time, with the high wind speed interval associated with the measurements identified.



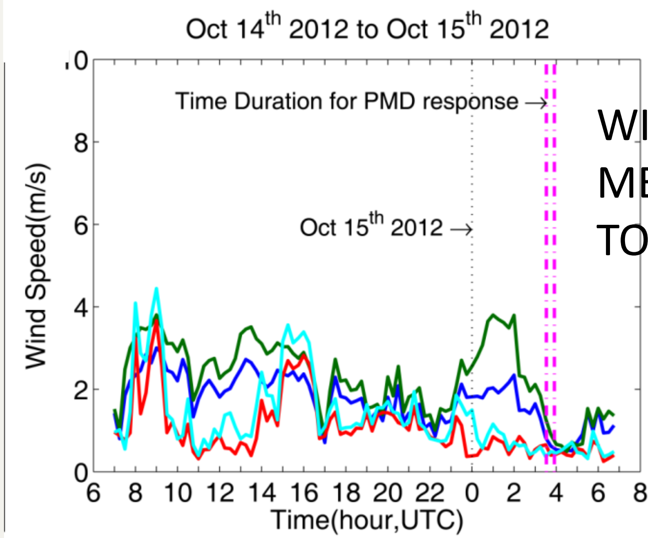
WIND SPEED MEASURED AT TOWERS



PMD RESPONSES (Every 5 minutes)

Results in Low-Wind Conditions

- Impact of low wind on the PMD response. The inset show the wind speed versus time, with the low wind speed interval associated with the measurements identified.



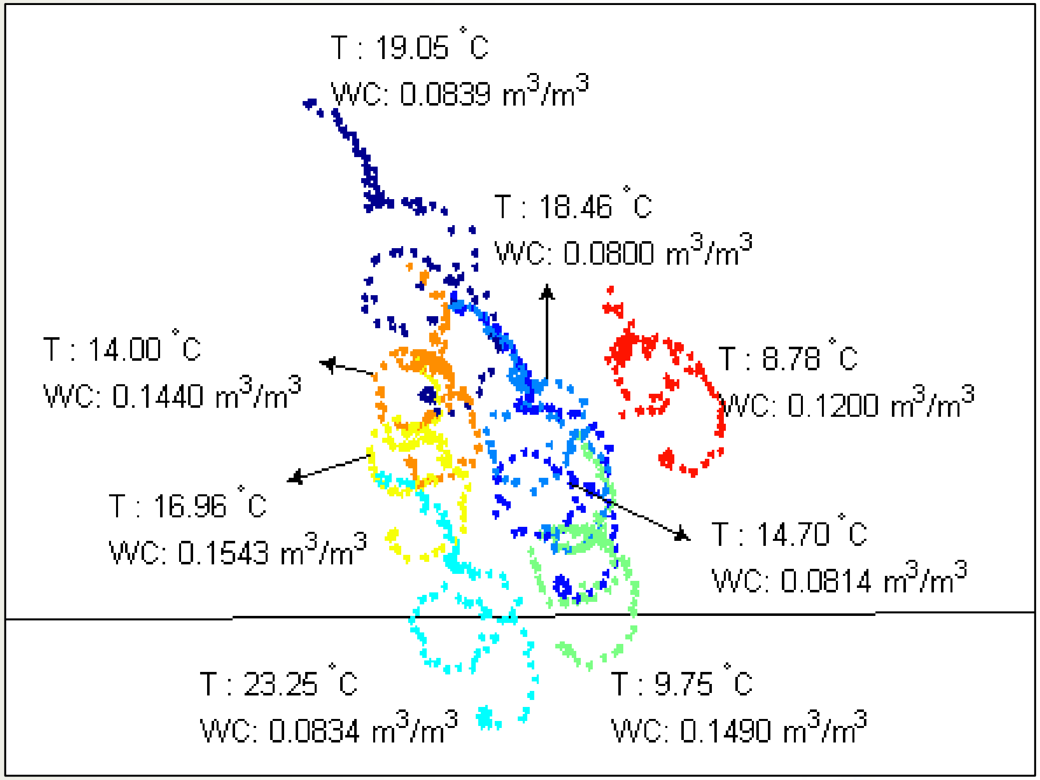
WIND SPEED MEASURED AT TOWERS

PMD RESPONSES (Every 5 minutes)

Measured Results

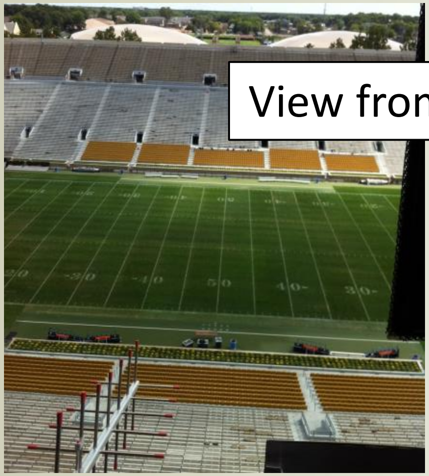
- Responses illustrate changes in PMD signatures between dry and moist states
- Exhibits location shift on the Poincare sphere, but it is difficult to know if this is actual or just an artifact of wind vibration.

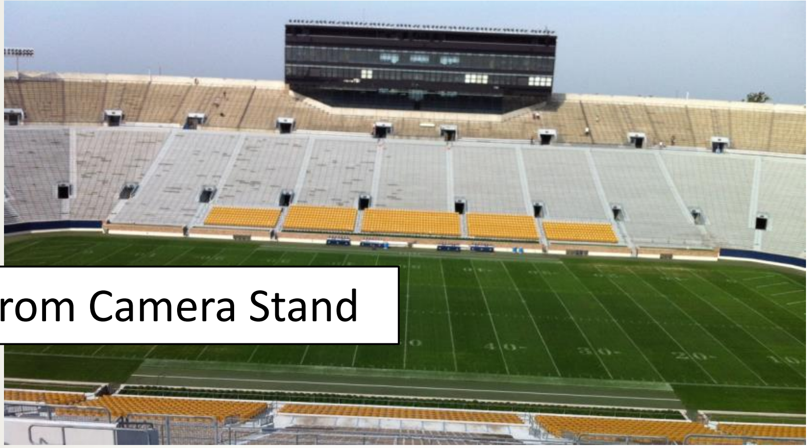
	Time	Temp	W.C.	Humidity
Dry	Oct 03 01:55~02:18	19.05	0.0839	NAN
	Oct 03 08:51~09:14	14.70	0.0814	NAN
	Oct 09 21:53~22:16	18.46	0.0800	13.24
	Oct 11 14:45~15:08	23.25	0.0834	25.78
Wet	Oct 14 04:16~04:40	9.75	0.1490	74.22
	Oct 14 14:06~14:29	16.96	0.1543	48.56
	Oct 14 23:32~23:55	14.00	0.1440	67.21
	Oct 19 04:13~04:37	8.78	0.1200	NAN



Measurement Campaign

Notre Dame Football Stadium

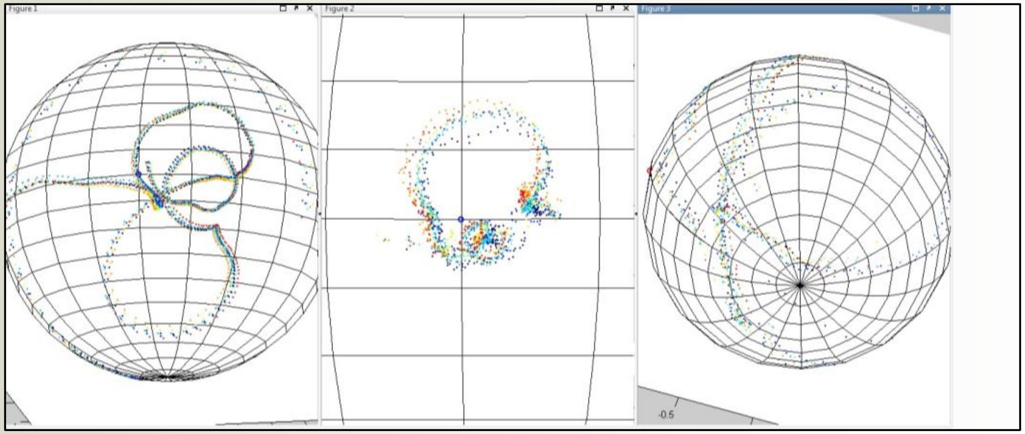




Equipment to be deployed initially over a 3-week period

3-frequency collection

Snapshot collection rate of 1/60 Hz



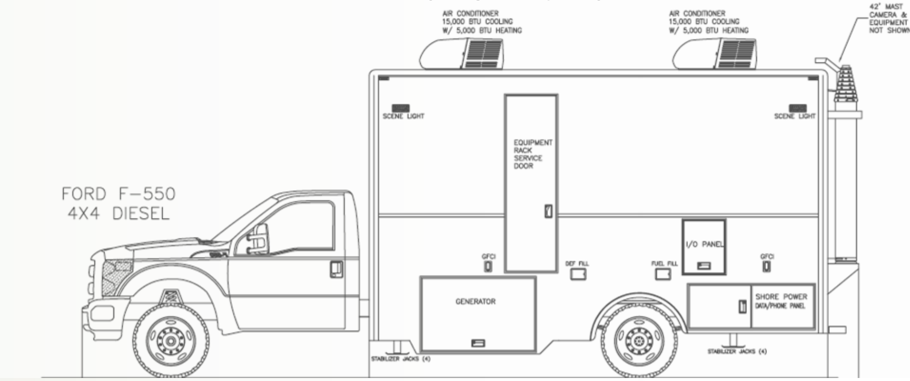
Data collected in the first hour of collection, Sept 5, 2013

Field Research Vehicles

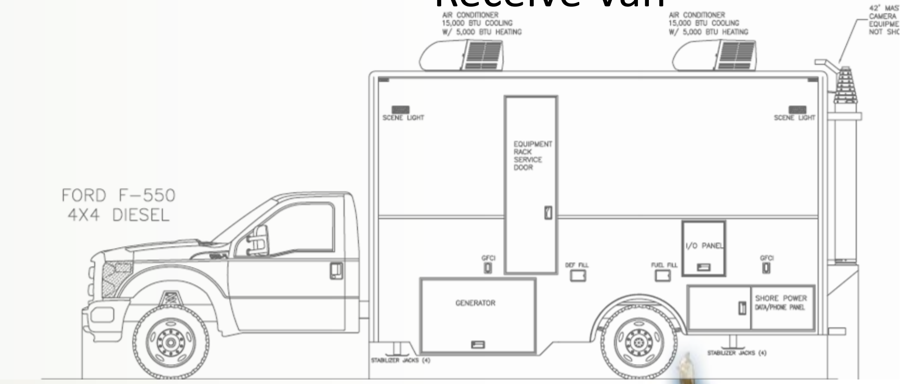
(a future capability based on a $498K DURIP award)

- Two field research vehicles with 40’ masts
- Support experimentation in:
  - communications channel characterizations
  - radar clutter/target characterizations as a function of grazing angle and bistatic/monostatic geometries
  - remote sensing applications (e.g., soil moisture sensing)
- Initially will be configured as a transmit vehicle and a receive vehicle to support bistatic measurements

Transmit Van



Receive Van



Advancing the Technology…..

Shorter Term Goals

- Continue km-scale tests with a multi-frequency system to further develop and evaluate technology
- Use theoretical response modeling capability to evaluate response trends
- Evaluate use of model with topography for potential method for converting measured responses to absolute soil moisture levels
- Develop depth profiling approach

Longer Term Goals

- Engineer a real-time, low-cost, compact collection system
  - Will dramatically change the extent to which technology can be evaluated
  - Provides sample support to enable powerful digital signal processing algorithms to be applied
  - Board-level rather than box-level
  - Substantially lower cost will enable more rigorous testing/evaluation