# RF Polarimetric Moisture Sensing

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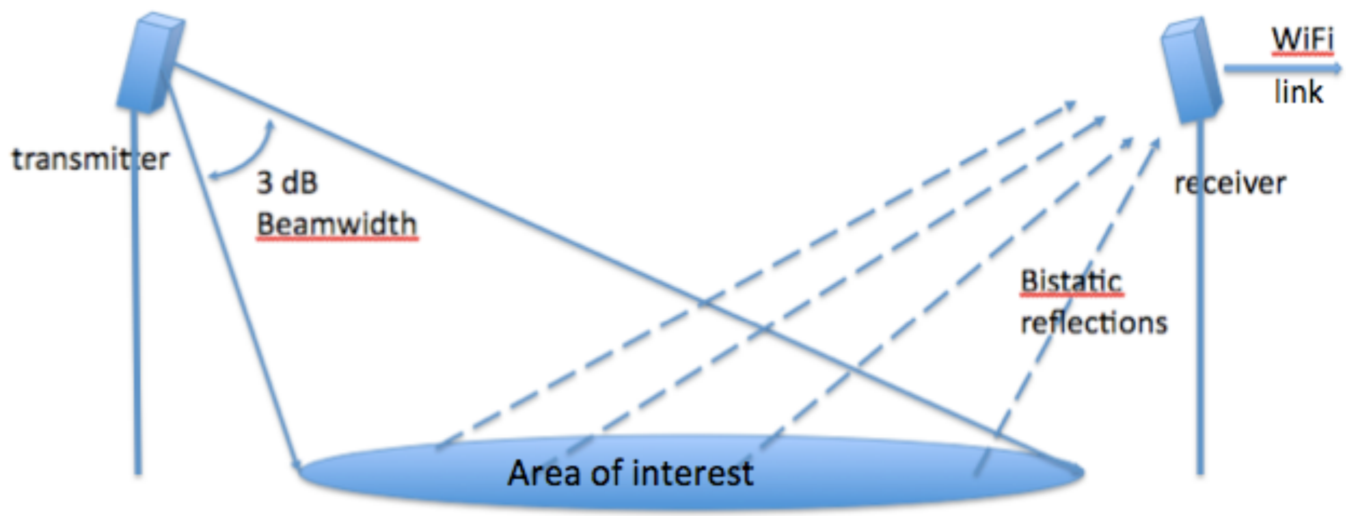
# Remote Detection Concept




**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

Provides "average" readings over illuminated area

- Scalable coverage
- Time series of signatures associated with the response from the target area
  - The response may also be sensitive to changes in temperature, salinity, and vegetation

Change detection method detects changes in the response

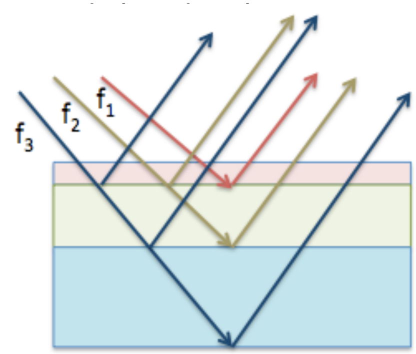
- Conversion to absolute soil moisture measurements would require either some form of site-specific calibration or possibly could be achieved using time-series over long periods of time

Potential for coarse profile versus depth using multiple frequencies

# Microwave Polarimetry Overview

- Microwave polarimetry typically employs VV, HH, VH, and HV intensity characterizations, and uses the responses in a diversity sense (e.g., Behari, <u>Microwave Dielectric Behavior of Wet Soils</u>)
- Some researchers do advocate measuring the received polarization state, including null polarizations, but do not take advantage of dispersion effects (e.g., Boerner, <u>Introduction to Synthetic Aperture Radar (SAR) Polarimetry</u>)
- In contrast, we monitor the polarization state vs. frequency components of the reflected signal, providing a unique form of detection that has demonstrated effectiveness in diverse applications
- In our case, we detect changes in the polarization/frequency behavior
- Provides ability to collect time series with good sample support that can be used with signal processing to filter and improve change detection performance
- Has potential to yield soil moisture estimates without calibration by leveraging the time series data and knowledge of precipitation events (which likely can be determined by the sensor)
  - With full range of states observed (saturation to dry state)
- It may also be possible to elicit coarse profile of moisture versus depth
  - Based on use of multiple frequencies and assc
  - Leverage time-series measurements

Utilization of lower frequencies yields measurements with contributions from deeper layers in the soil




Skin depth can be approximated as

$$\delta = \lambda\sqrt{\epsilon'}/2\pi\epsilon''$$

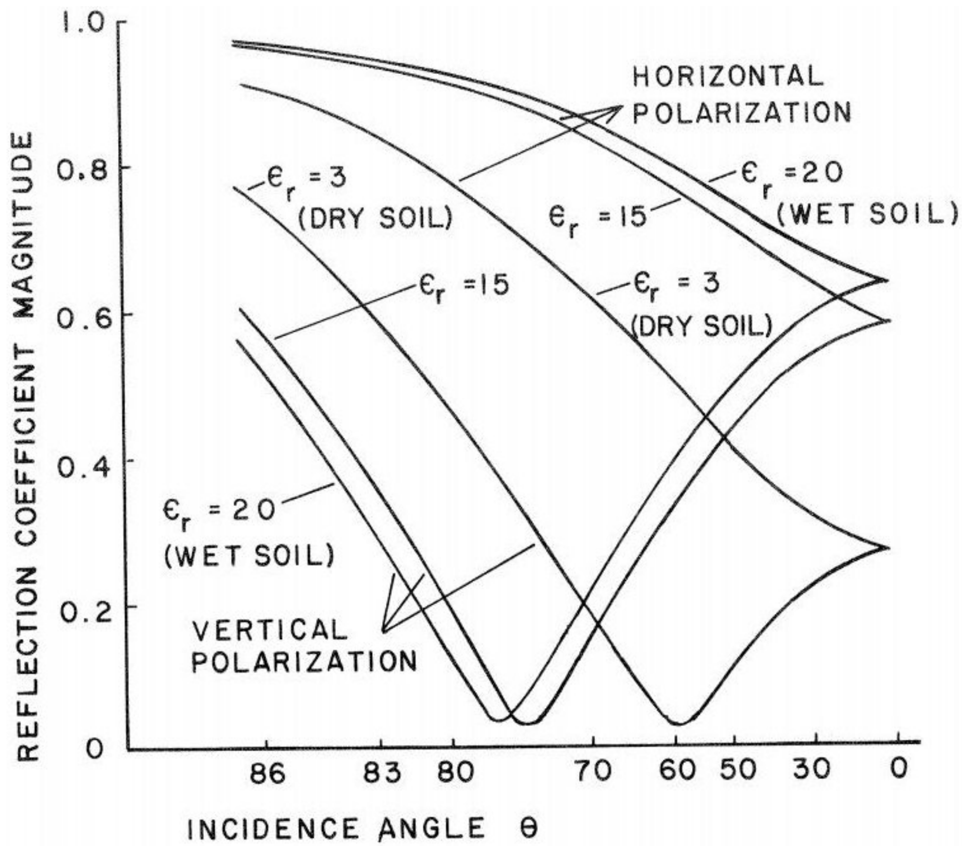
where the complex dielectric constant is $\epsilon=\epsilon'+j*\epsilon''$

and the complex relative dielectric constant is $k=\epsilon/\epsilon_0$

# Theory for Polarization Response

- Reflection coefficient is a function of tx/rx polarization, the angle of incidence and the impedance of materials at the interface

HH and VV Characterizations




From [1]

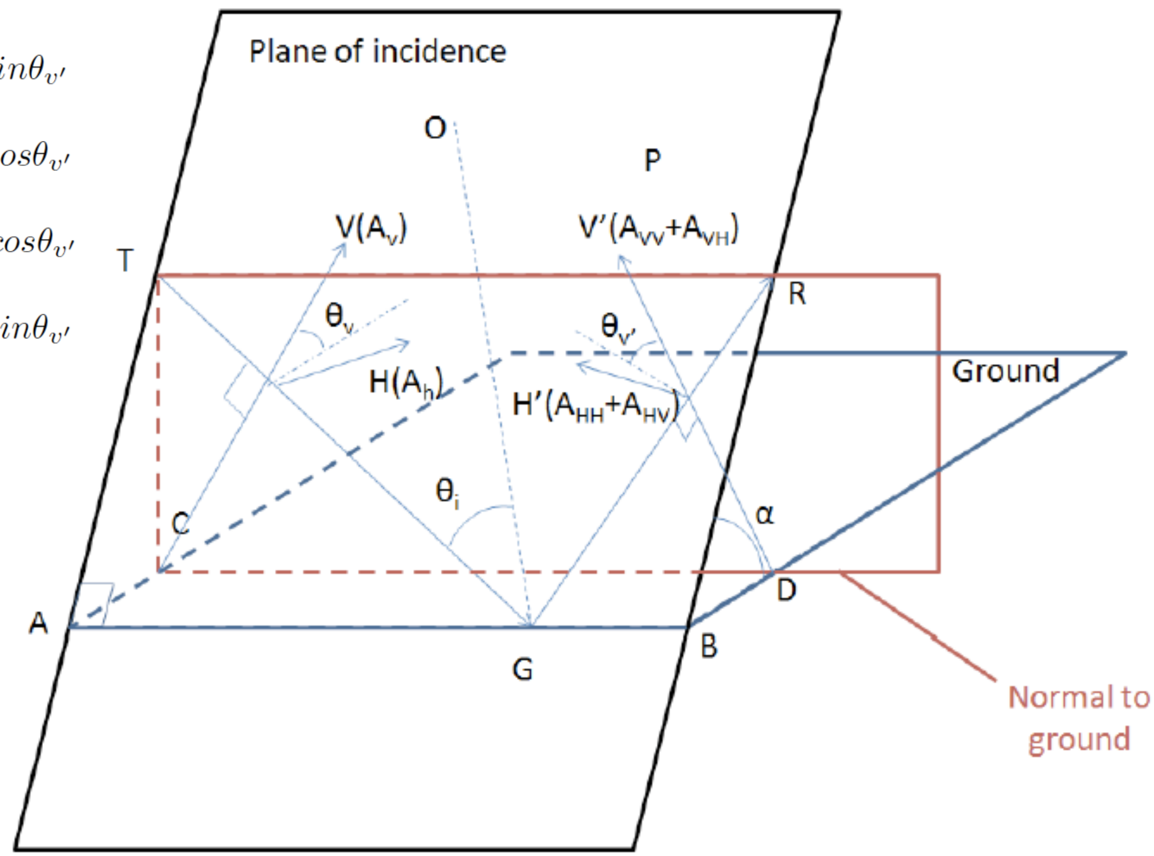
- Impedance of soils will vary with the relative permitivity (i.e., the complex dielectric constant), which changes with moisture level and frequency
  - Temperature and salinity also impact dielectric constant
- The collection of path responses yield a signature that changes as the dielectric properties change
- Our approach relies on v-v and v-h coherent responses (or h-v and h-h coherent responses), which is a different approach than has been reported elsewhere

# Reflection Theory Development

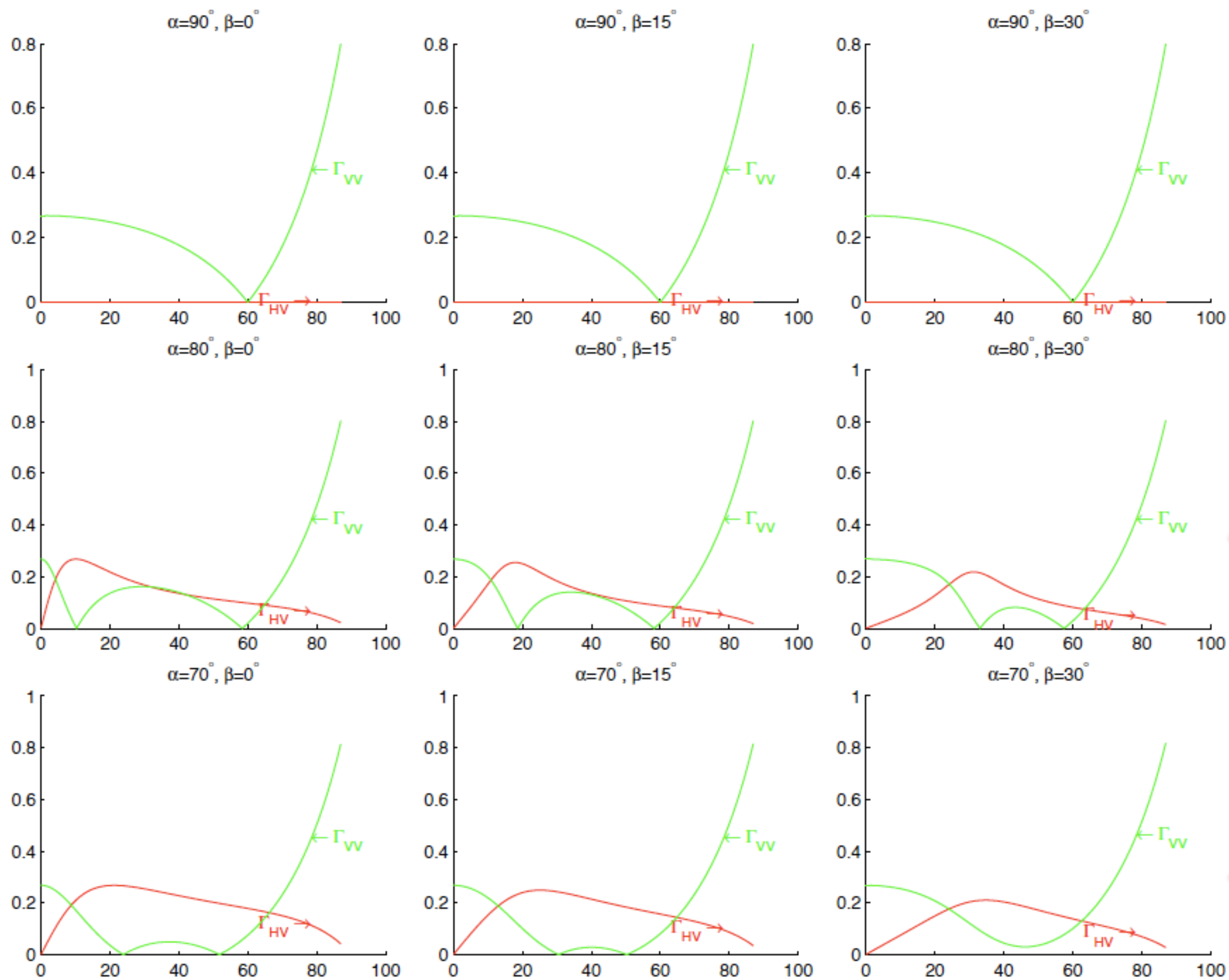
$$\Gamma_{VV} = \frac{A_{VV}}{A_v} = \Gamma_{R\|} cos\theta_v cos\theta_{v'} + \Gamma_{R\perp} sin\theta_v sin\theta_{v'}$$
$$\Gamma_{HV} = \frac{A_{HV}}{A_v} = \Gamma_{R\|} cos\theta_v sin\theta_{v'} - \Gamma_{R\perp} sin\theta_v cos\theta_{v'}$$
$$\Gamma_{HH} = \frac{A_{HH}}{A_h} = \Gamma_{R\|} sin\theta_v sin\theta_{v'} + \Gamma_{R\perp} cos\theta_v cos\theta_{v'}$$
$$\Gamma_{VH} = \frac{A_{VH}}{A_h} = \Gamma_{R\|} sin\theta_v cos\theta_{v'} - \Gamma_{R\perp} cos\theta_v sin\theta_{v'}$$

$$\Gamma_{R\perp} = \frac{n_1 cos\theta_i - n_2 cos\theta_t}{n_1 cos\theta_i + n_2 cos\theta_t}$$
$$\Gamma_{T\perp} = \frac{2n_1 cos\theta_i}{n_1 cos\theta_i + n_2 cos\theta_t}$$

$$\Gamma_{R\|} = \frac{n_2 cos\theta_i - n_1 cos\theta_t}{n_1 cos\theta_t + n_2 cos\theta_i}$$
$$\Gamma_{T\|} = \frac{2n_1 cos\theta_i}{n_1 cos\theta_t + n_2 cos\theta_i}$$



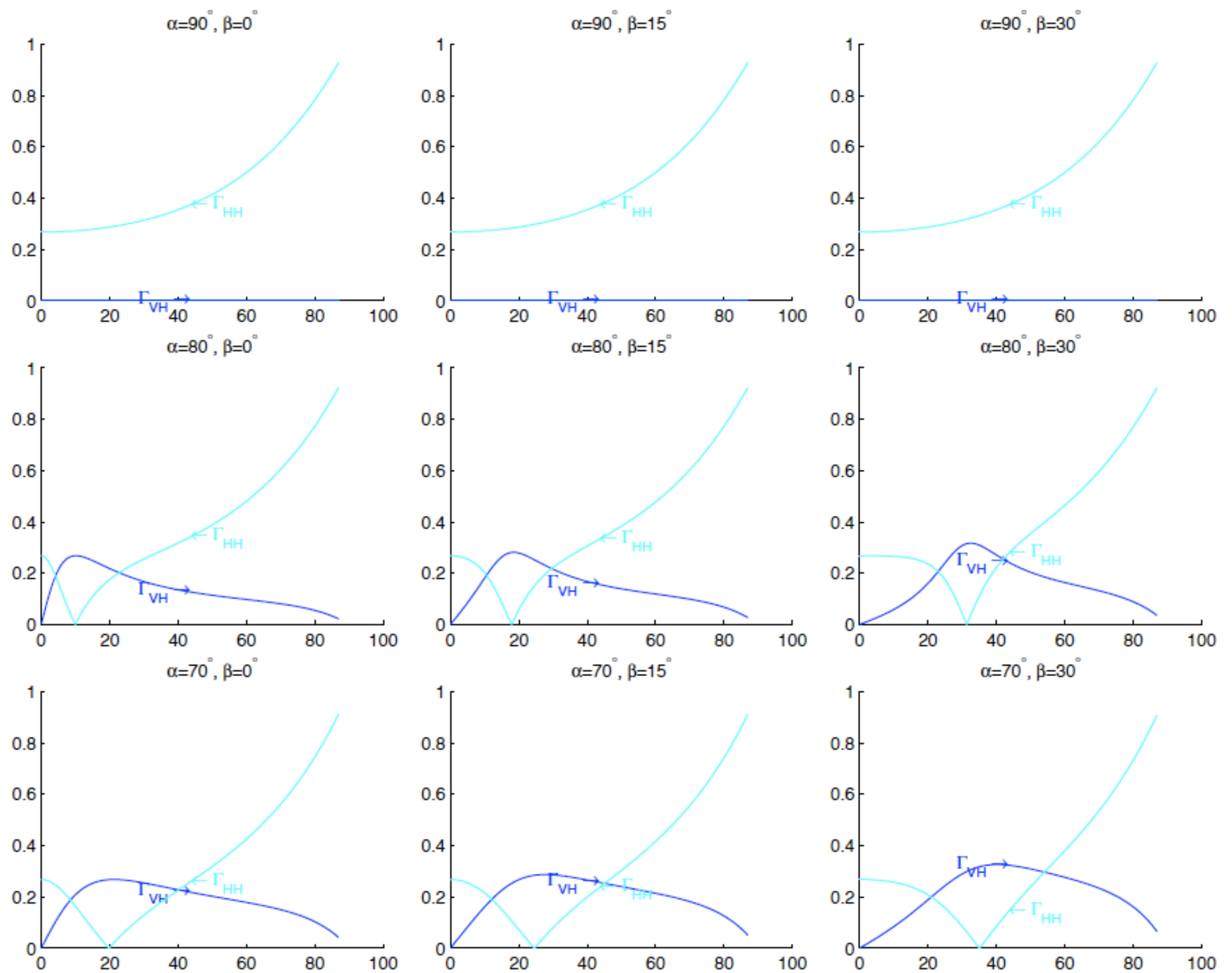
# Vertical Transmission Component




smooth surface

rough surface

# Horizontal Transmission Component

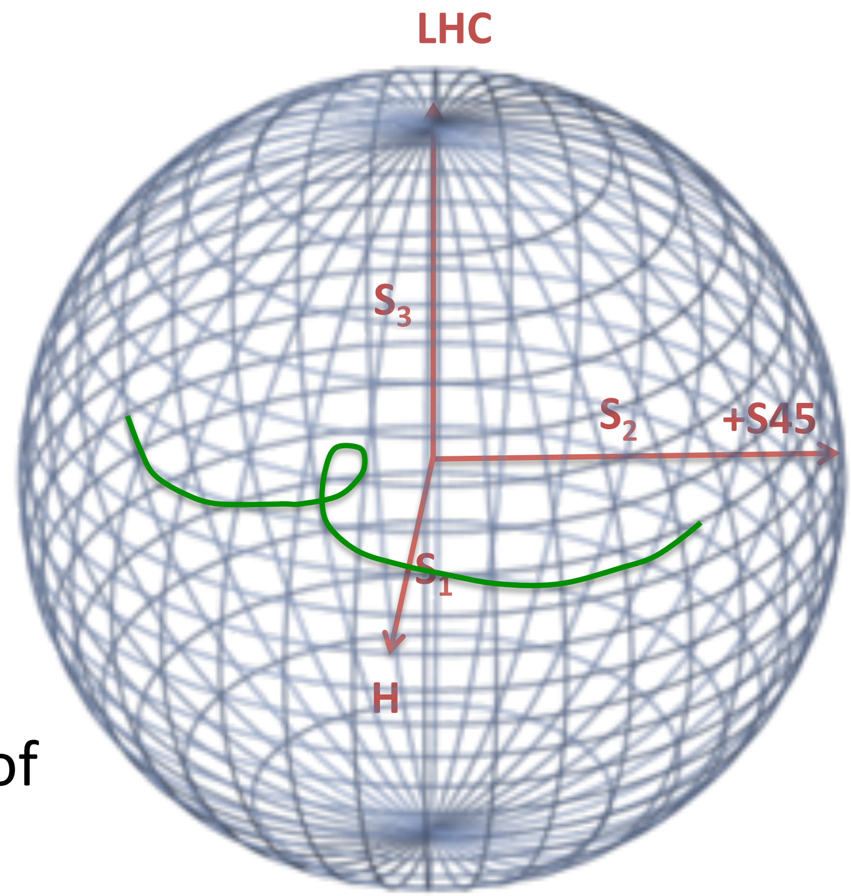



smooth surface

rough surface

# How does this relate to our approach?

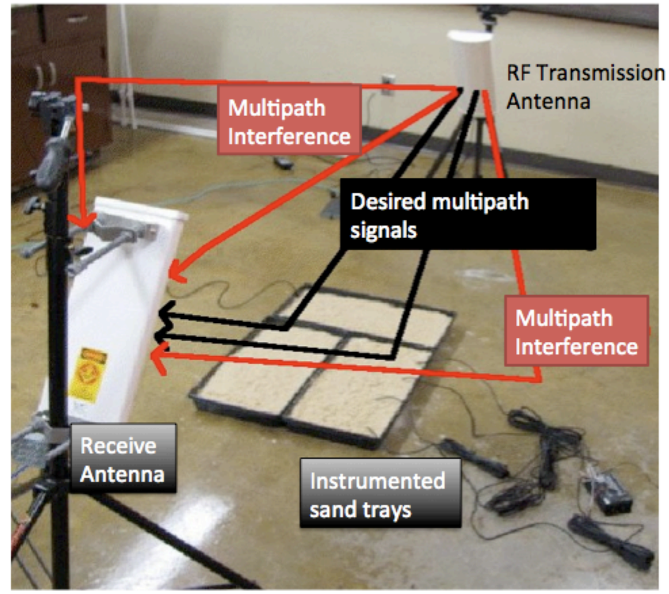
- We consider the aggregate response from all bistatic reflections between the transmitter and the receiver
  - Coherent sum over all bistatic reflections
- Induces polarization mode dispersion
  - Due to delay spread and polarization coupling
- The responses at the orthogonally-polarized ports of the receiver are employed to form the metric
  - We refer to the result as a **polarization mode dispersion signature**




The measured signature can be visualized on a Poincare Sphere

# Experimental Illustration

- Technology is based on exploitation of propagation phenomenon known as polarization mode dispersion (PMD)
- Identified for wireless in ~2006 in experimental results
- Three patents pending based on finding
  - Interference Suppression for wireless propagation (Walkenhorst & Pratt)
  - Adaptive Transmission for wireless propagation (Pratt & Walkenhorst)
  - RF Sensing (Pratt)




The polarization response provides an indication of changes in the soil moisture that occur over time periods less than 1 hour.

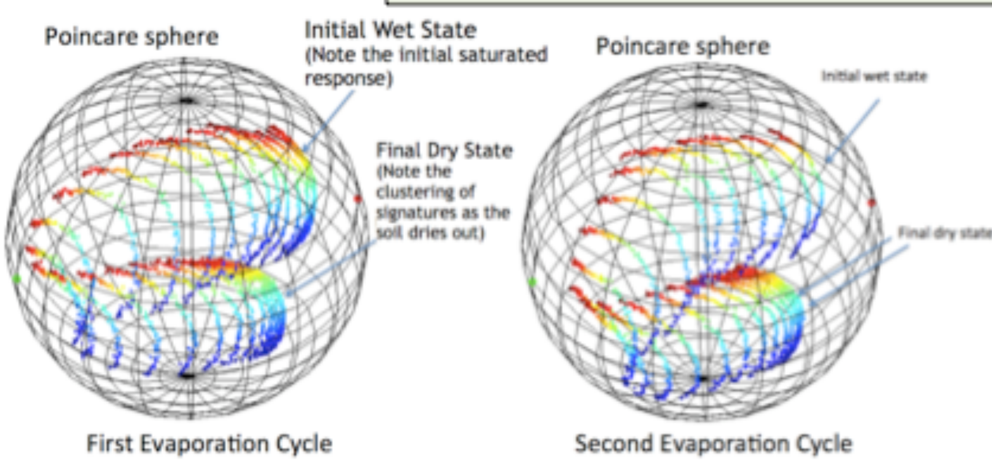
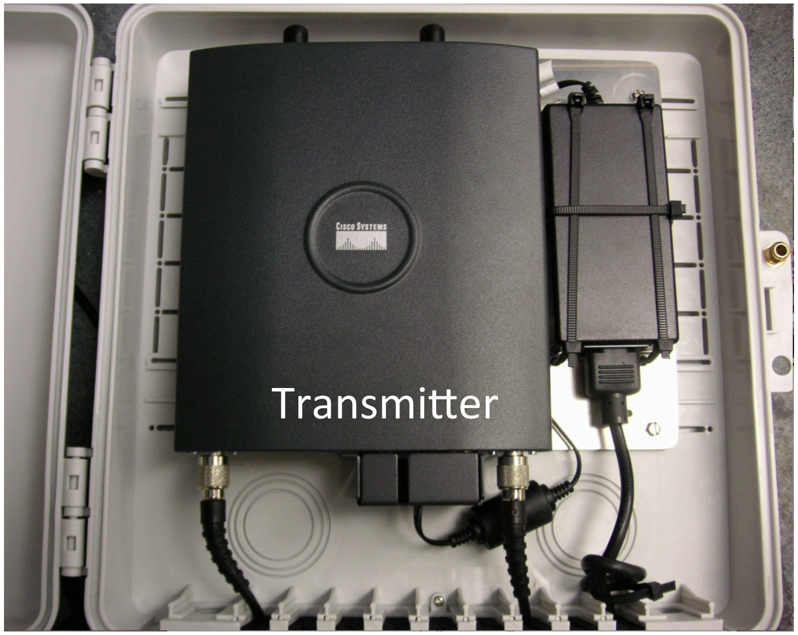
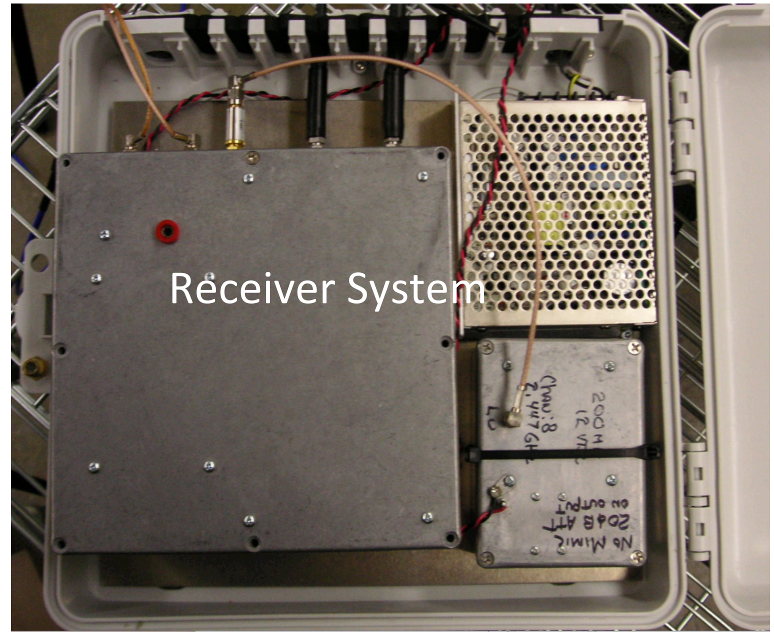


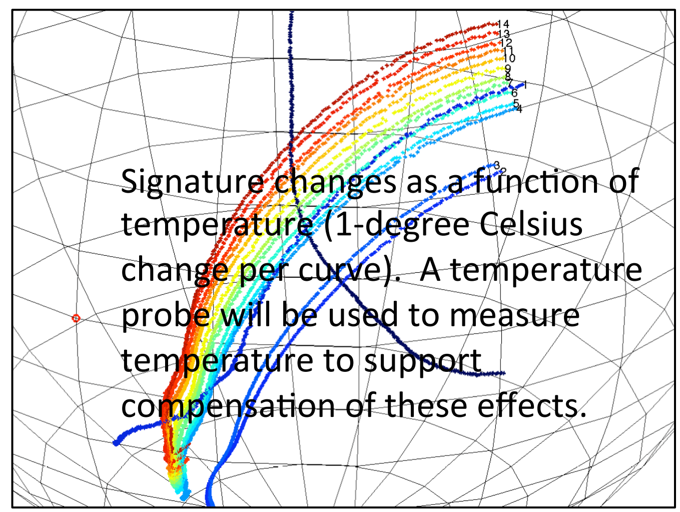

Illustration of PMD changes with moisture level changes

# Soil Moisture Sensing



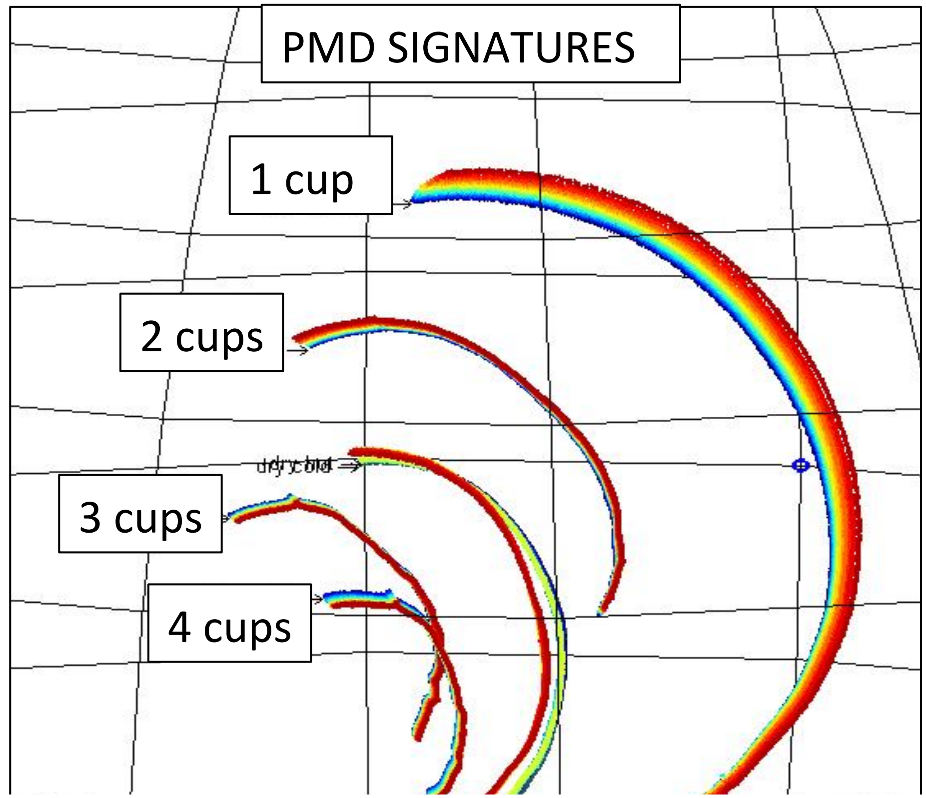

- Built-up 2.4 GHz system;  Ready for preliminary testing on campus at end of January (White Field)
- Preliminary 915 MHz and 450 MHz systems will be built-up by the end of February
- Methods to compensate for temperature sensitivities are being considered.
- Requesting testing time at Dugway in April, May, or June (e.g., 1 week) to vet system

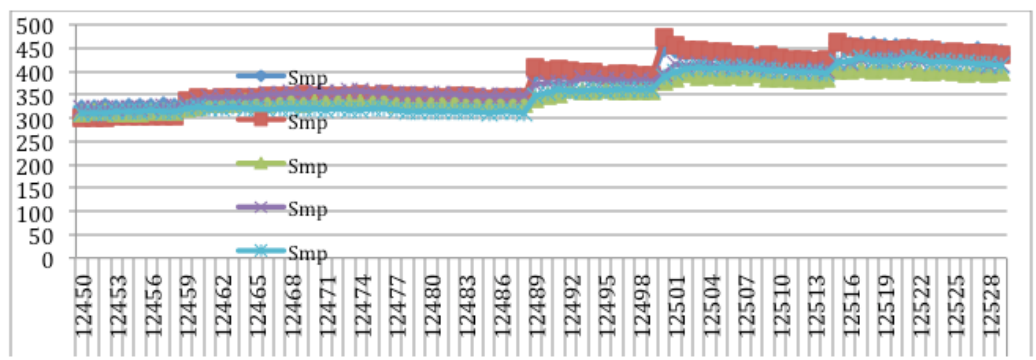


# Temperature Sensitivity Tests

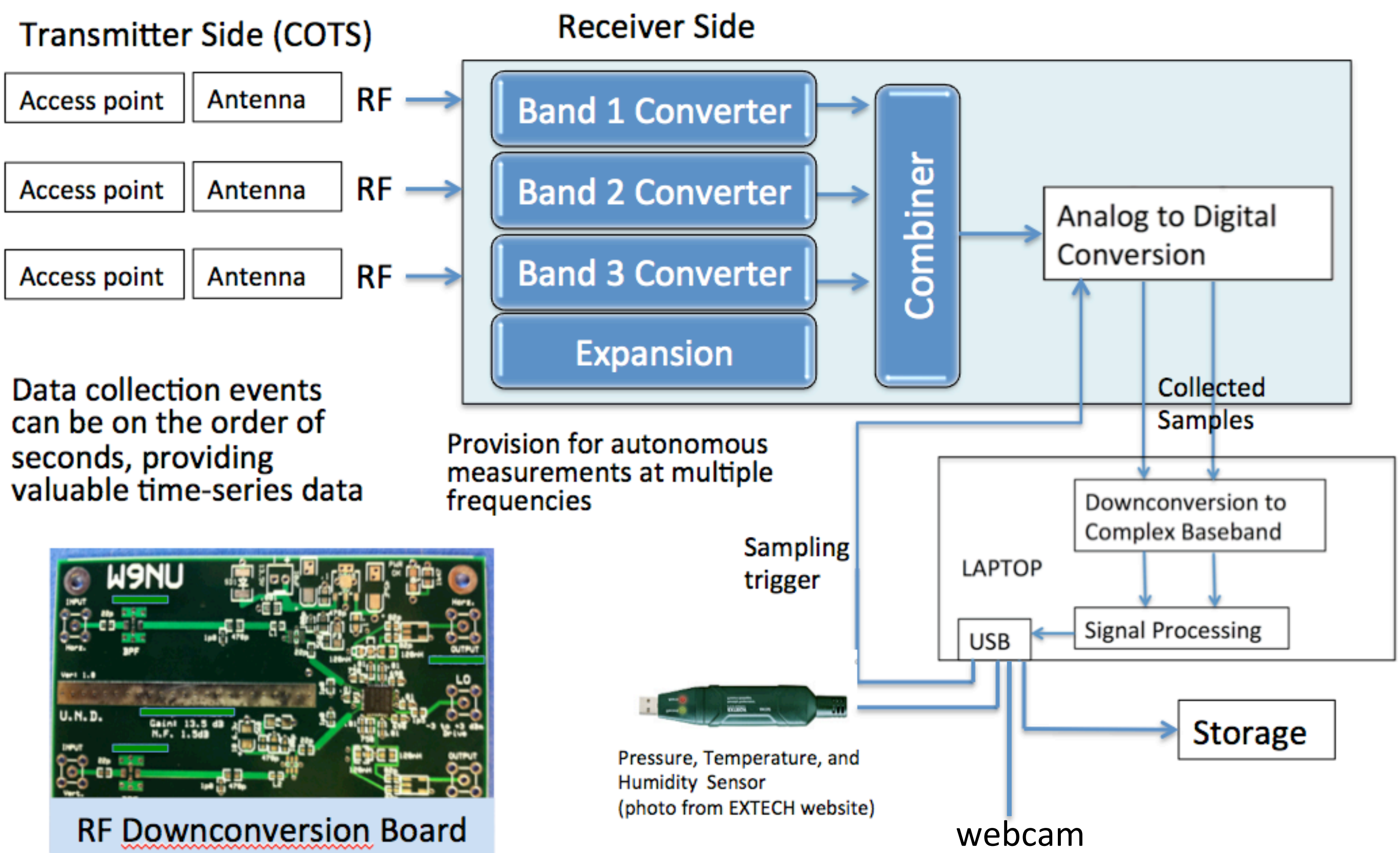
- Five heating and cooling cycles between 24C and 41C, at different moisture levels, RF = 2.4 GHz

Temperature tests using heat lamps



# Receiver Hardware Subsystems

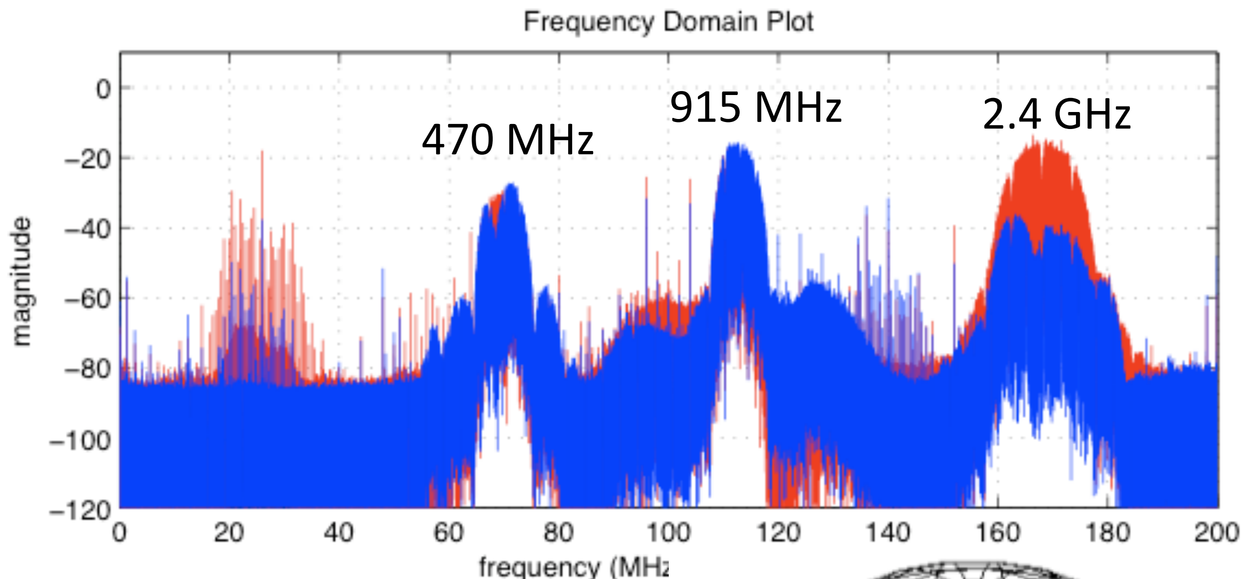


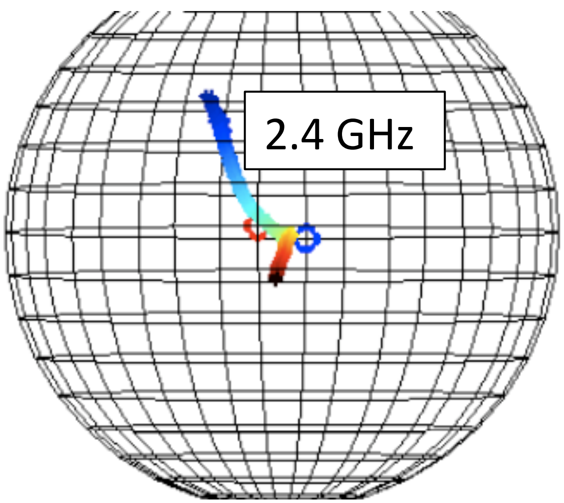
# Hardware Configuration

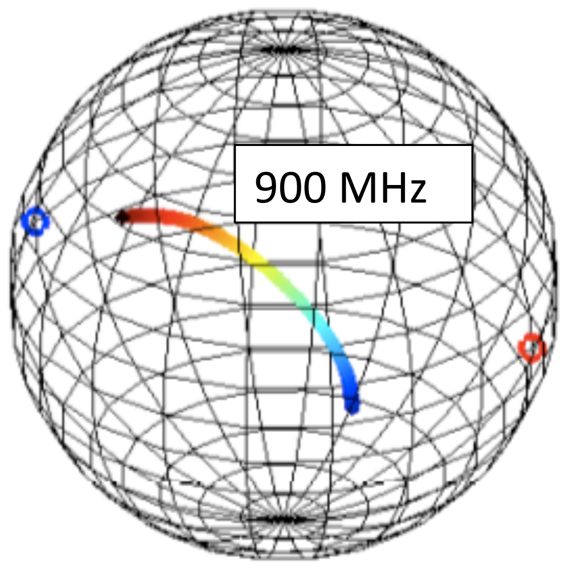
Transmitter system with three transmit antennas

Receiver system with three receive antennas

# Illustration of Data Products
## (Laboratory Measurements)




Signal snapshots are obtained and processed to yield measured PMD signatures

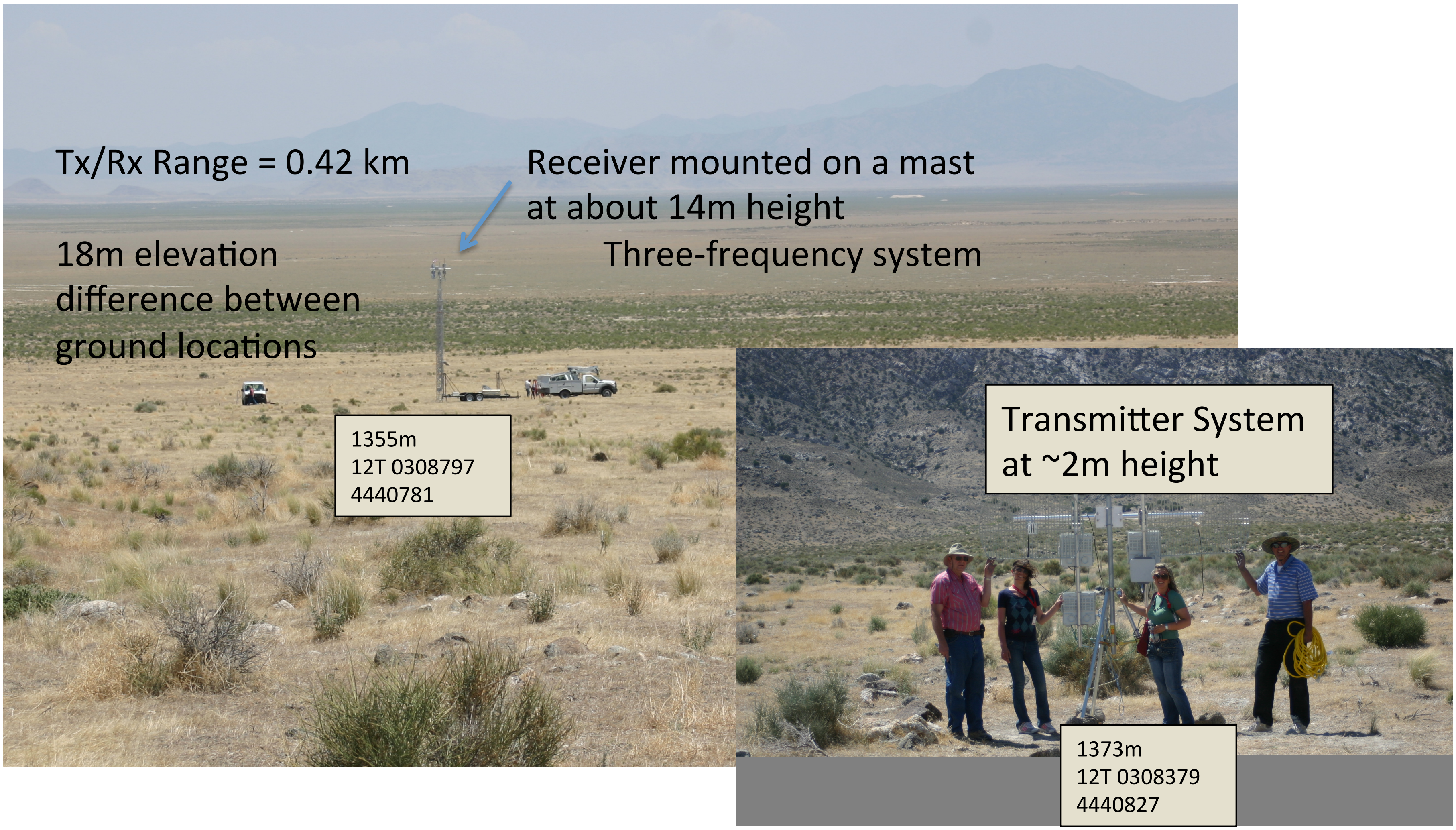
The signatures change with changes in the soil moisture

Variations due to temperature are anticipated to be small (but non-negligible) relative to changes induced by moisture

# Current State of Prototype

- Prototype currently supports operation over three simultaneous frequencies
- Employs snapshot-based operation, where 84-ms snapshots are spaced apart in time to allow signals to be stored
  - Long snapshots provide opportunity to integrate for improved PMD signature characterizations
  - Collections will be taken about every 5 to 10 minutes
- Communications (from tower to laptop)
  - USB 65’ *active* line has been unreliable, with operation typically stopping in less than 12 hours of data collection
  - USB-to-Ethernet extension solutions were not able to provide workable communications
  - USB 24’ *passive* connection has recently been found to be reliable

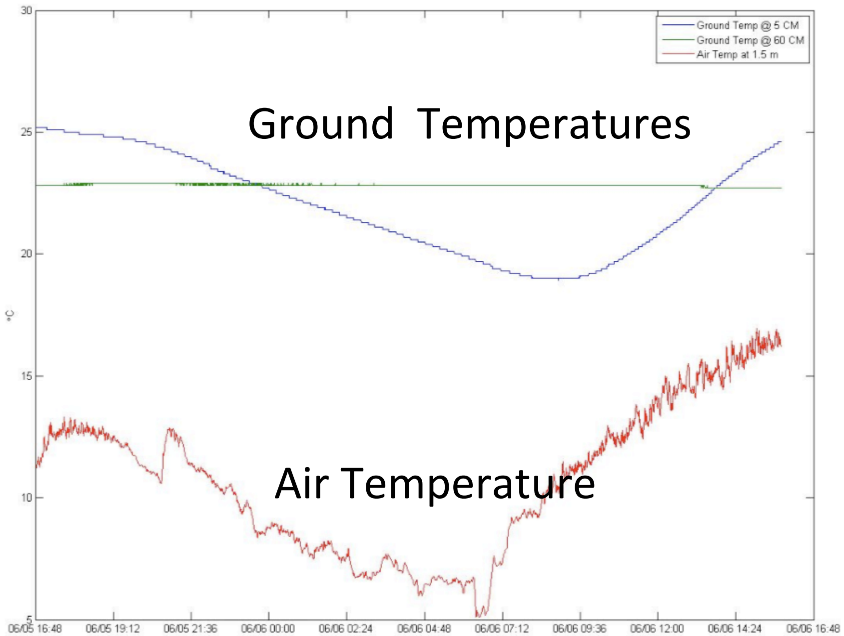
# Pre-test at DPG, June 2012
## East Slope of Granite Mountain



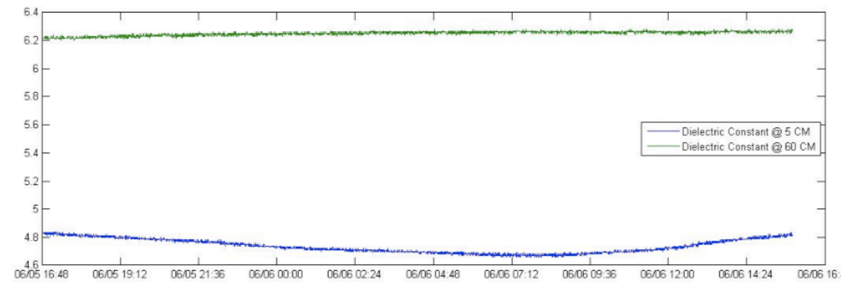
# In-Situ Sensor Measurements

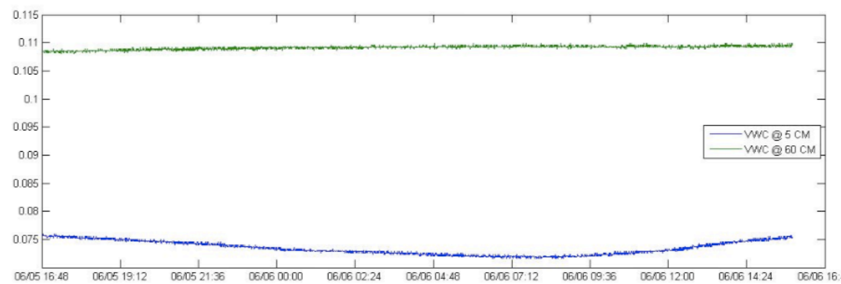
(provided by Eric Pardyjak)

Temperature Data



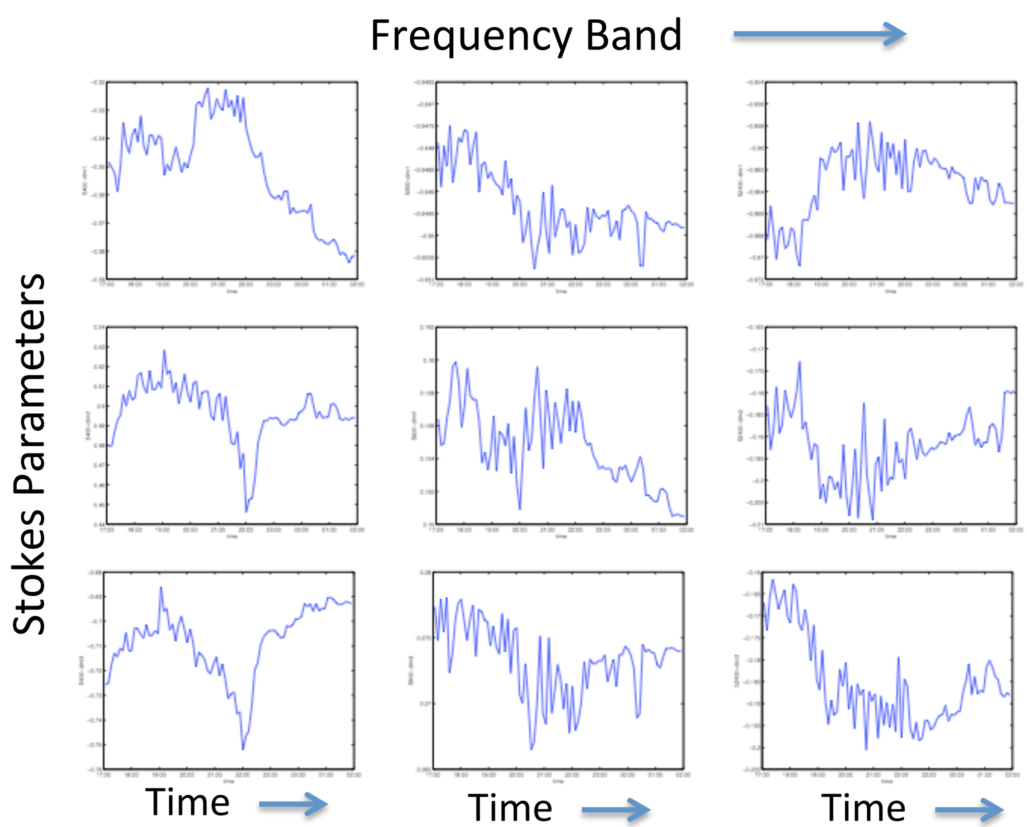

Estimates of Dielectric Constant




Note correlation between ground temperature and dielectric constant

# Pre-Test Data Products




Excursions are seen to be small. We anticipate that the measured changes are due to :

Changes in temperature

- AND -

Vibration due to wind (the system was not adequately stabilized at either the transmitter or the receiver). System will be better braced in coming tests

Additional bracing of the system for wind protection (vibration reduction) and longer integration times (4X increase) will improve the quality of the measurements for the upcoming MATERHORN tests.

# System Outputs

System Outputs (after Initial Post Processing)

| Parameter Number | Description | Sample Interval |
|---|---|---|
| 1 | Date/Time (based on computer clock) | 5 minutes |
| 2 | Temperature (from probe deployed near base of tower) | 5 minutes |
| 3 | Pressure (from probe deployed near base of tower) | 5 minutes |
| 4 | Humidity (from probe deployed near base of tower) | 5 minutes |
| 5 | Signal Power Level (for Tx signal 1 through Tx signal 3) | |
| 6 | SNR (for Tx signal 1 through Tx signal 3) | |
| 7 | Polarization parameters (for Tx signal 1 through Tx signal 3) | 5 minutes |
| 8 | Signal Frequency (for Tx signal 1 through Tx signal 3) | |
| 9 | Signal Quality Measurements (Tx 1 through Tx 3) | |
| 10 | Noise Power Level (Tx 1 through Tx 3) | |
| 11 | Video clip (15s) taken prior to every RF snapshot | 5 minutes |
| 12 | Audio clip (15s) taken prior to every RF snapshot | 5 minutes |

PMD Data time series will be used in other post-processing to estimate soil moisture states versus time of day

- External drive used for storage needs to be replaced about every 10 days

# Task Summary

- Completed design and build-up of proto system employing three frequency bands, including
  - RF front-end for each frequency band
  - Simultaneous collection of each frequency
  - Automated data collection (RF, temp/pressure/humidity, video, audio)
- Performed temperature sensitivity tests in laboratory using sand, showing that temperature dependencies are expected to introduce small errors
- Conducted preliminary tests at Dugway Proving Grounds in June 2012 to gauge the ability of the system to collect measurements at long range (0.42 km)
- Worked on advanced PMD reflection theory that will aid in numerical modeling and analysis

**Issues and Future Work**

- Communications reliability issues constrain allowable height of Rx on tower to 24’
- Weight/Size of prototype and wind loading (prototype can be scaled down with engineering work)
- Algorithms to back out soil moisture estimates and depth profiles from collected sequences need to be developed for the case without calibration
- Continue with modeling work for theoretical/numerical analysis

**Papers (pending submissions)**

- Temperature impact on remote RF polarization soil moisture sensing (pending submission)
- Cross-polarization reflectivity at a rough surface interface (paper in progress)