Active Radio Frequency Sensing for Soil Moisture Retrieval

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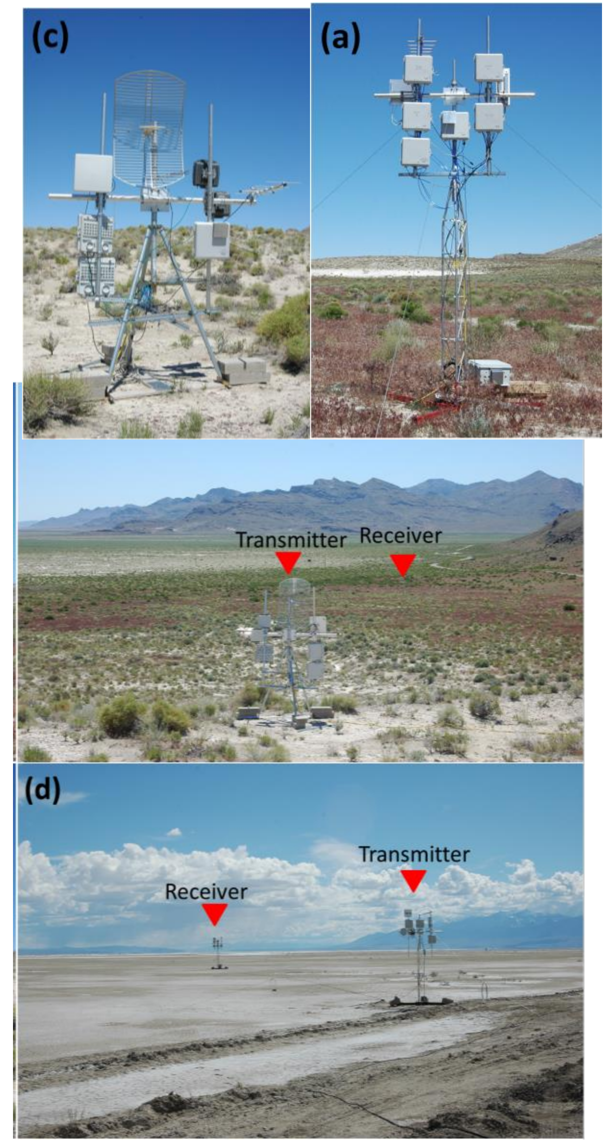
Summary of DUGWAY Experimental Set-Up

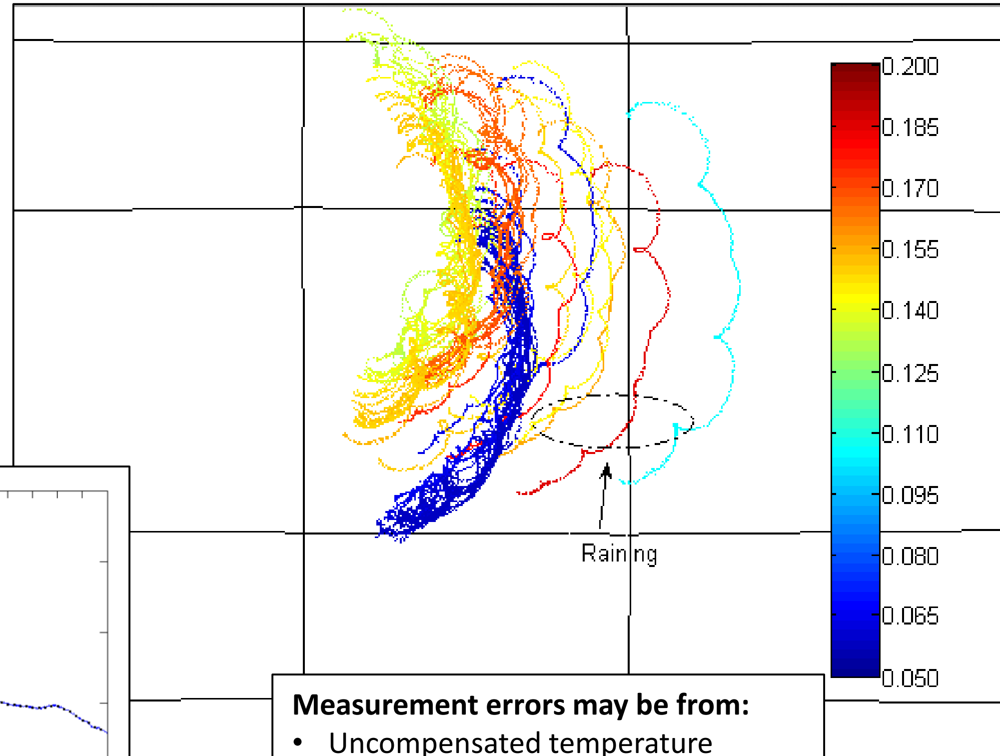
- Deployed system near Sapphire Mountain at the Small Gap for soil moisture change detection and estimation
  - 0.42 km distance between tx and rx
  - Antennas deployed on 4m masts AGL, one on a plateau. 18m height difference
  - Collected data at 2.4 GHz, 915 MHz, and 470 MHz
  - Our analysis of the Small Gap data previously **focused on the 2.4 GHz** signals

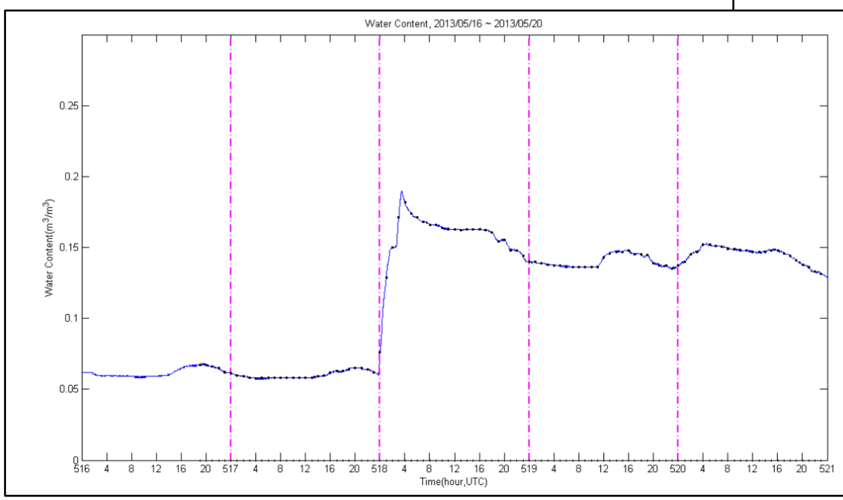
- Deployed system at Playa for subsurface water level detection and soil moisture sensing
  - 250' distance between tx and rx
  - Antennas deployed on 4m masts
  - Collected data at 2.4 GHz, 915 MHz, and 470 MHz
  - Deployed near station (human activity is potential interference)



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:

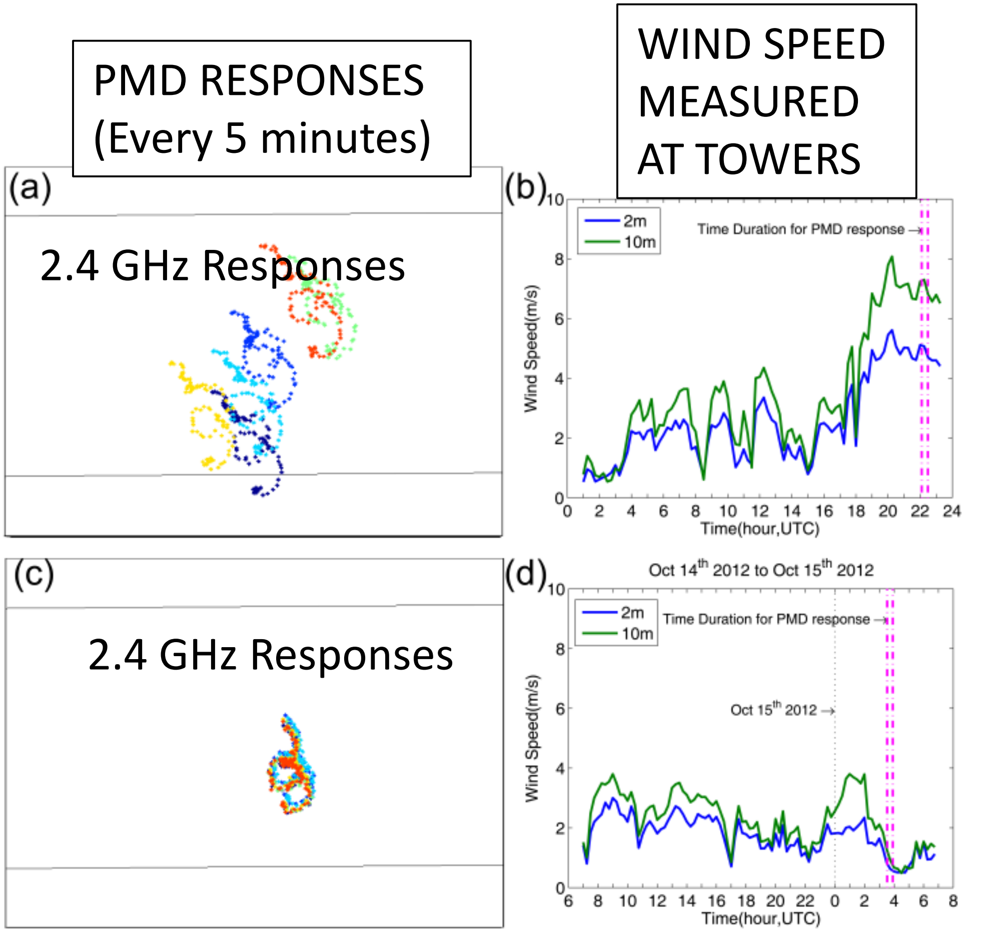
- Uncompensated temperature effects
- Wind (antenna position) effects
- Difference in probe location relative to RF target area
- Impact of changes in RF environment

This fell short of our expectations to prove the efficacy of the technique, yielding only moderate correlations between PMD measurements and soil moisture, likely due to other external factors.

2.4 GHz Data

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

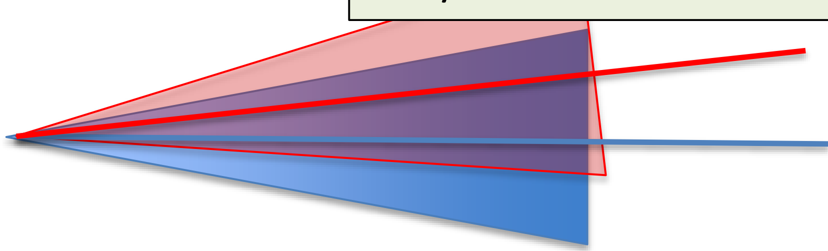


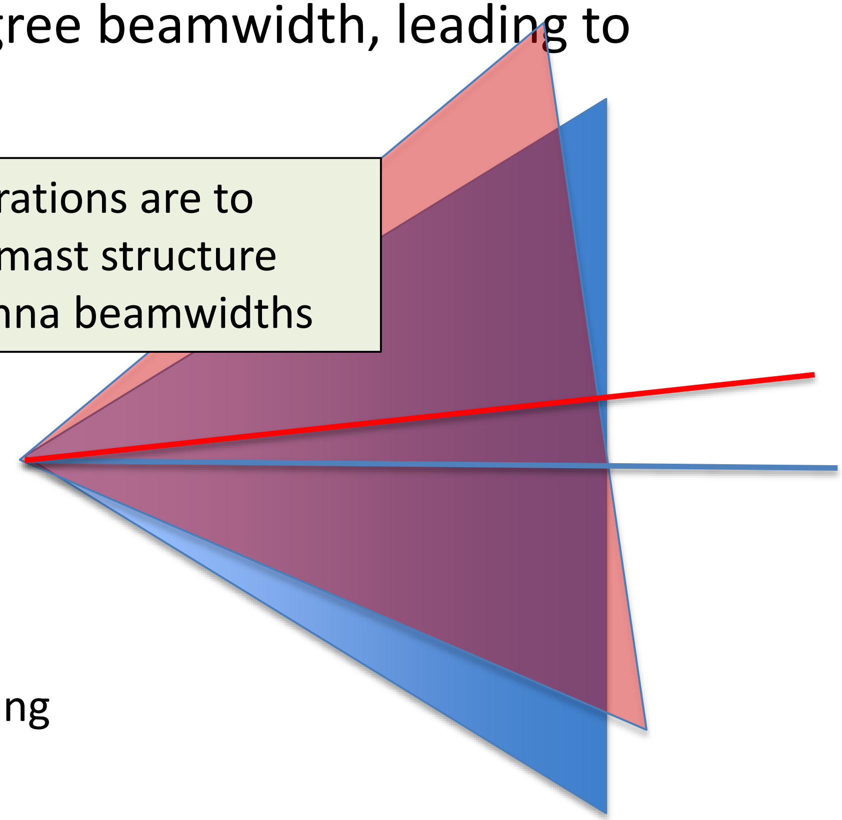
Such vibrations could be beneficial in a system that tracks the angle deviation and that can collect data at sufficiently high rates.

Antenna Mast Vibration Effects

- The impact of wind is directly related to the antenna beamwidths and the angle deviation of the antenna mast vibrations caused by the wind
- For larger beamwidths, the percentage change in the illuminated area is smaller, leading to reduced impacts of wind
- The 2.4 GHz antenna had a 22-degree beamwidth, leading to increased vulnerability to wind

Solutions to address vibrations are to improve the stability of mast structure and/or to increase antenna beamwidths



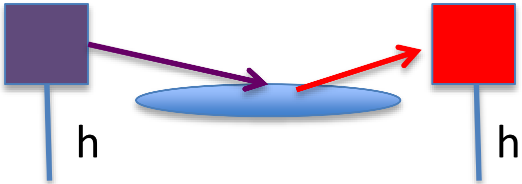


The percentage of "new scatterers" is more significant for narrowbeam antennas assuming the same antenna mast angular deviation

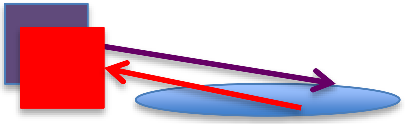
Monostatic vs Bistatic

- Technique can be implemented with monostatic or bistatic sensing topologies
- Implications
  - Waveforms
    - Tx/Rx Synchronization
  - Backscatter versus forward scatter
  - Tx/Rx Isolation

Bistatic: Tx and Rx are separated



Monostatic: Tx and Rx are collocated

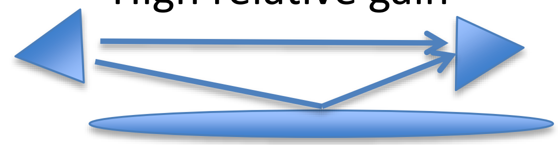


We anticipate that low grazing angles, while less selective, still can provide effective sensing performance, provided that the system is installed to be largely motionless in the presence of wind and if the signal-to-noise ratio is sufficient. The use of two transmit polarization adds additional diversity to help discriminate states.

Tx/Rx Isolation

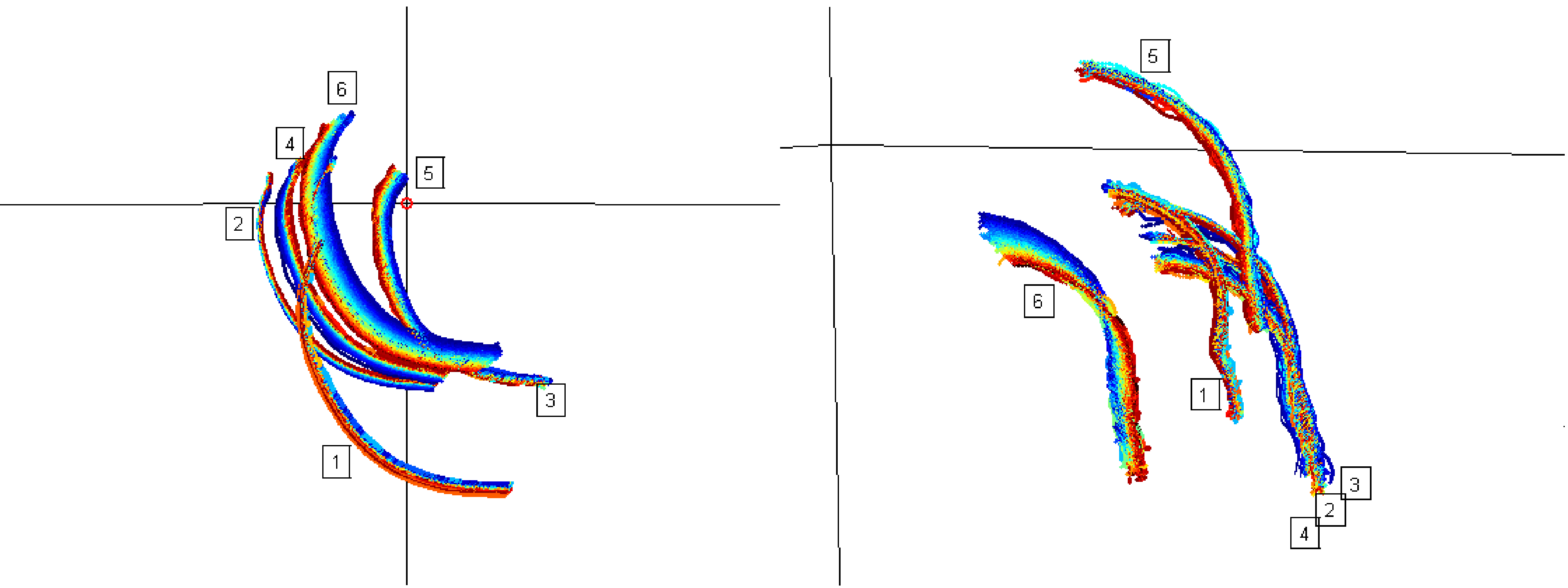
Lab Data with Low Grazing Angle

High relative gain



PMD curves

- horizontal(left)/vertical(right)

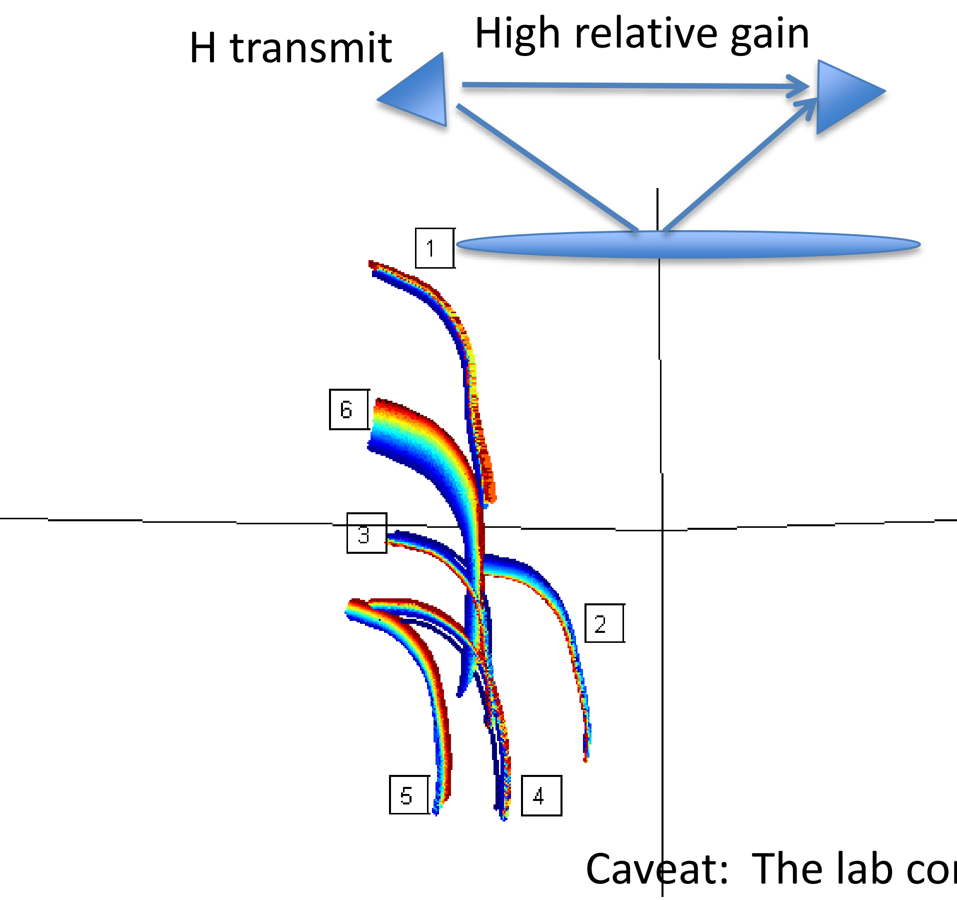


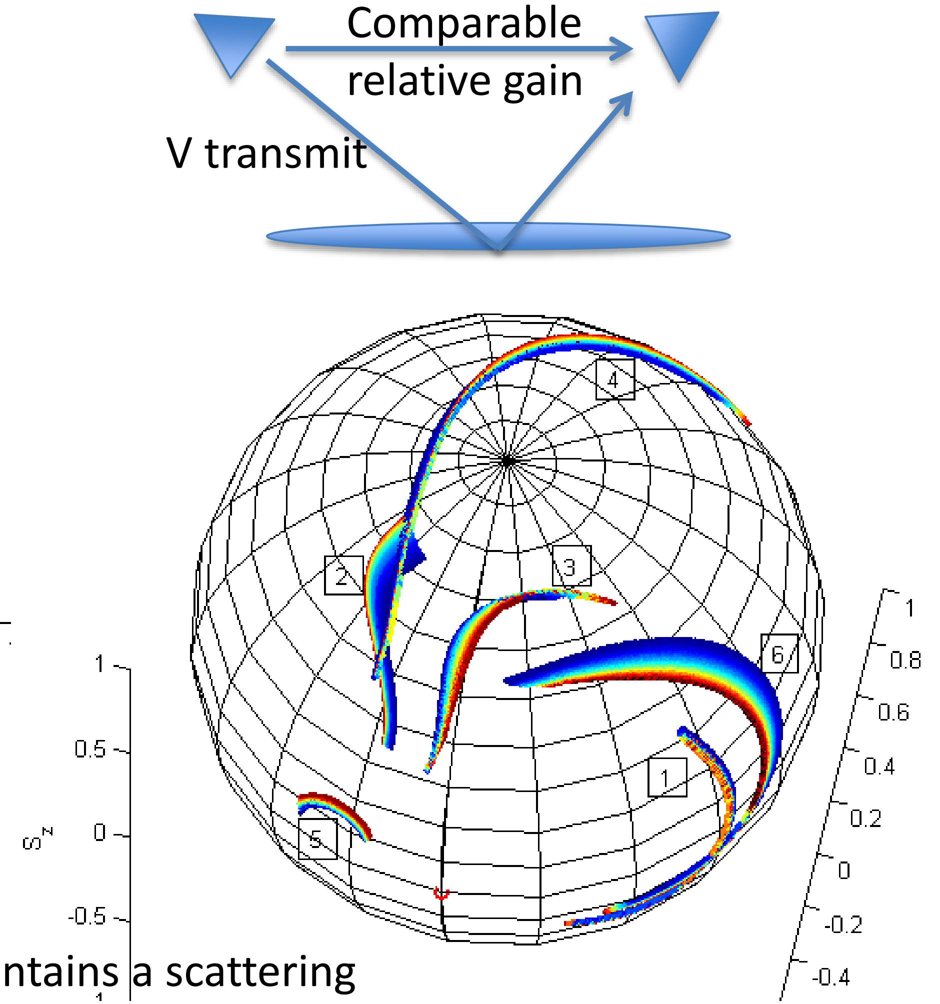
2.4 GHz with highly directive antennas

Tx/Rx Isolation

Lab Data with High Angle of Incidence

PMD curves



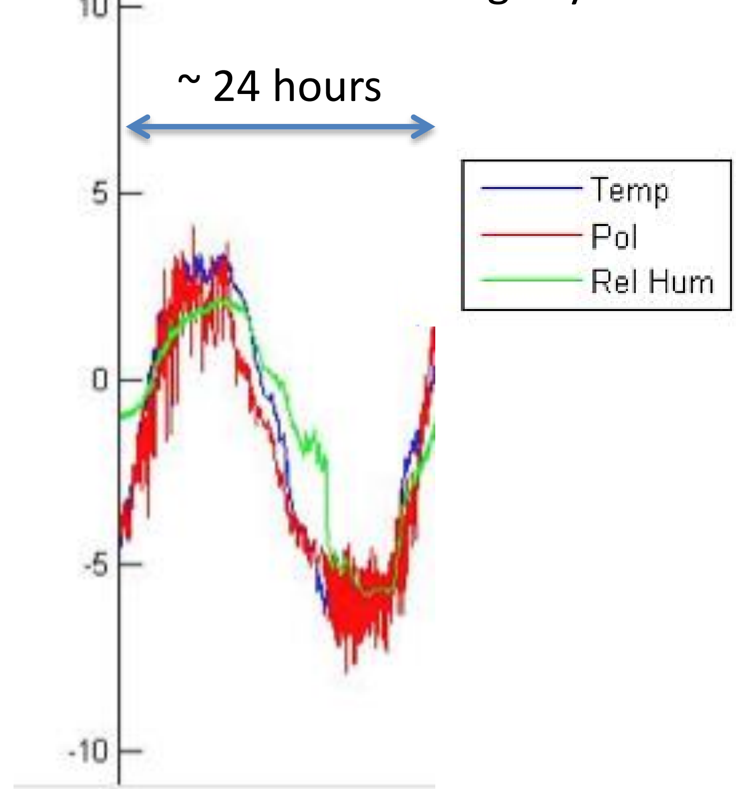


Caveat: The lab contains a scattering environment atypical of terrain

Temperature Dependence

- Prior laboratory results investigating temperature sensitivity showed slight variability in the PMD response to temperature, where only the sand (and not the equipment) was heated.
- Dugway results also showed dependence on temperature. In the outdoor environment, the equipment was also heated, a condition that originally was not emulated in the lab
- A question arose as to whether or not temperature-dependent variations were due in part to heated receiver equipment. This could impact how temperature is compensated.

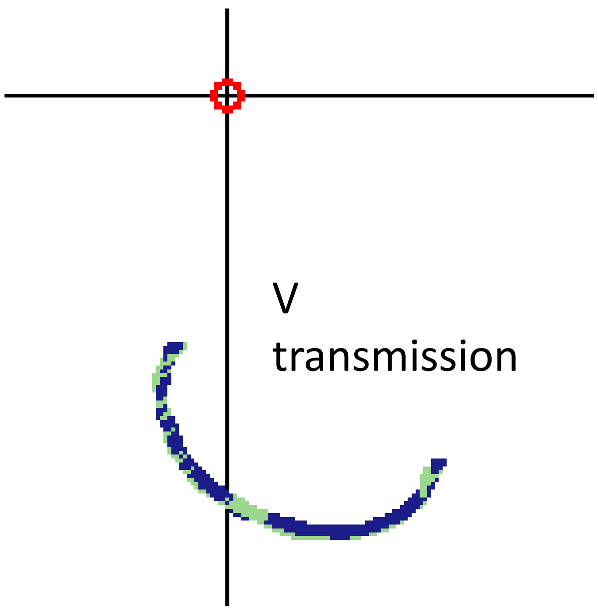
Results from Dugway Tests

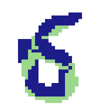


2.4 GHz response

Results Illustrating Equipment Insensitivity to Temperature

Equipment response to a “static” environment as a function of temperature (over a 17 degree variation), where the temperature is color coded. The change in response as the temperature changes is observed to be quite small.





Zoomed in: the changes here are very small

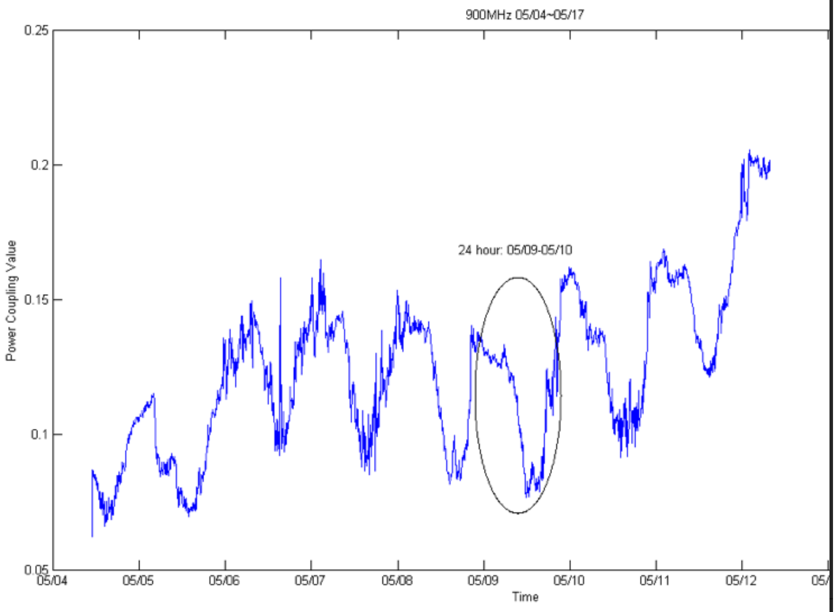
Our recent lab results confirmed the expectation that our equipment does not produce any substantive change in the measured response when the equipment is heated.

915 MHz PMD Data at the PLAYA

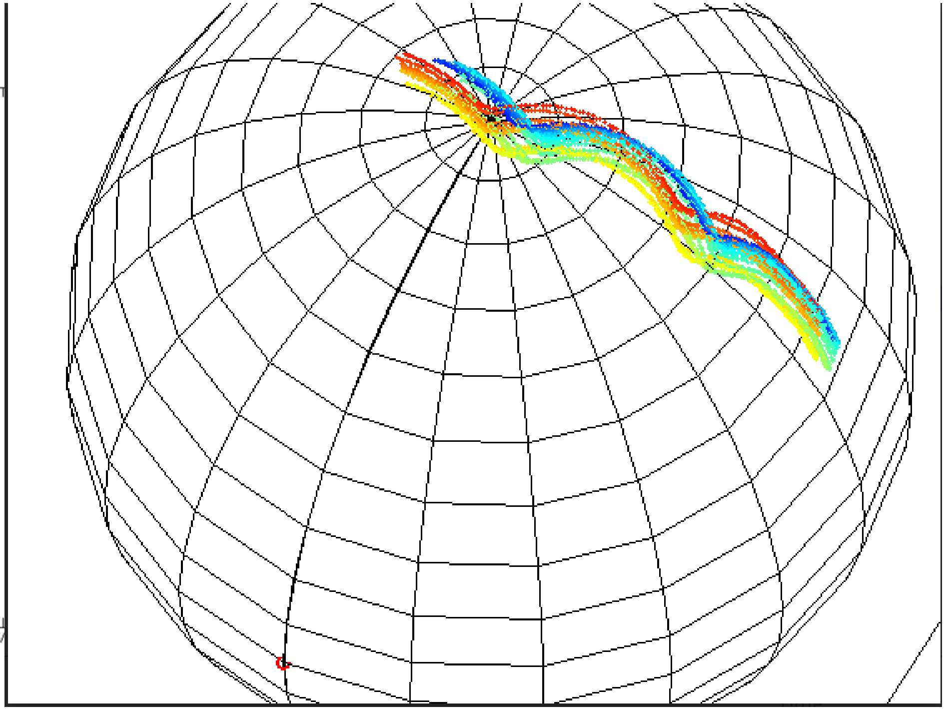
- Due mostly to wind effects seen at 2.4 GHz throughout the data, a shift in focus was made to 915 MHz at the PLAYA
  - Longer wavelengths and deeper penetration into the ground
  - Shorter range system and larger angles of incidence
  - Larger beamwidths (for the antennas used), and therefore less vulnerable to mast vibrations from wind
  - However, closer to other human activity (time varying changes in multipath structure)
- Data collected over a period of one month, with gaps in the data
  - Other data available consisted of well data, in-situ soil moisture probes at the Small Gap, and wind data from the Small Gap
- We expect the evolution of the RF responses to exhibit smooth changes in time (following temperature, subsurface water level, and soil moisture), except perhaps for rain events, when significant changes can be experienced
- Our responses are relatively smooth, but do appear to be degraded by either wind effects, human activity, and possibly other forms of interference

Examination of 915 MHz Data: Pre-Rain Response

- Cycle of data before 5/18 rain event



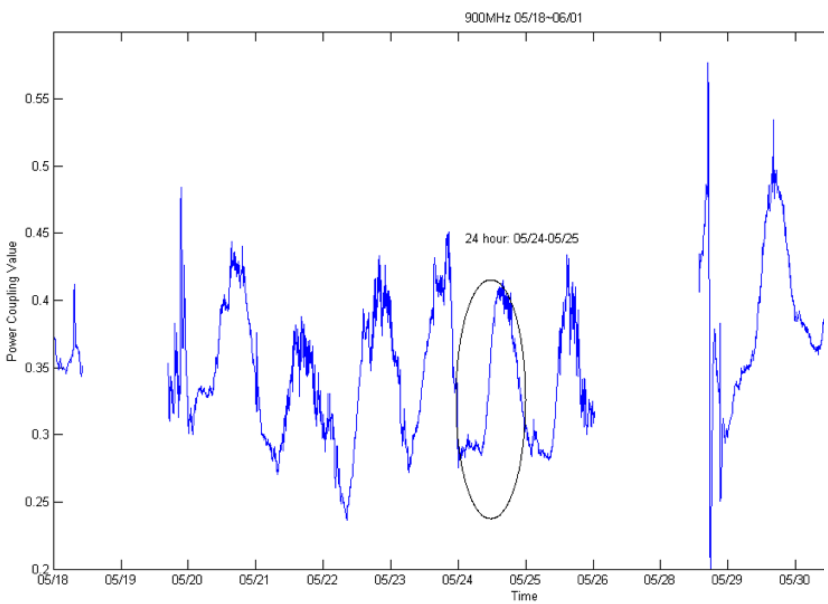
The daily cycles are induced by temperature and subsurface water level. The high-frequency noise is likely the result of wind and/or human activity

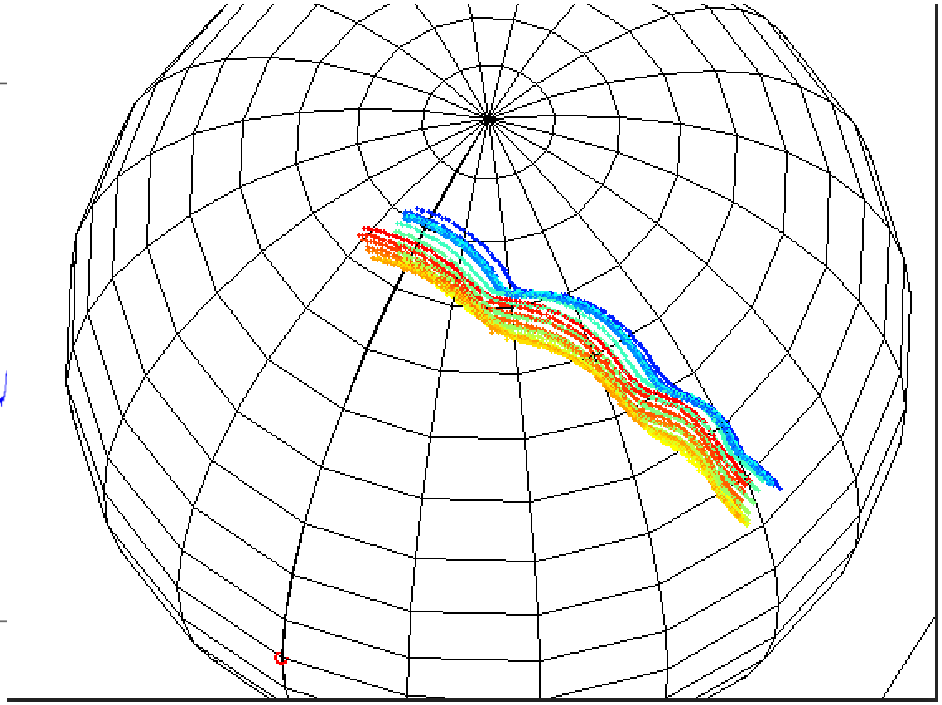


Color-coded time response shows how the PMD curves vary over the day-long cycle period. The curves have been averaged.

Examination of 915 MHz Data: Post Rain Event

- Cycle after 5/18 Rain Event

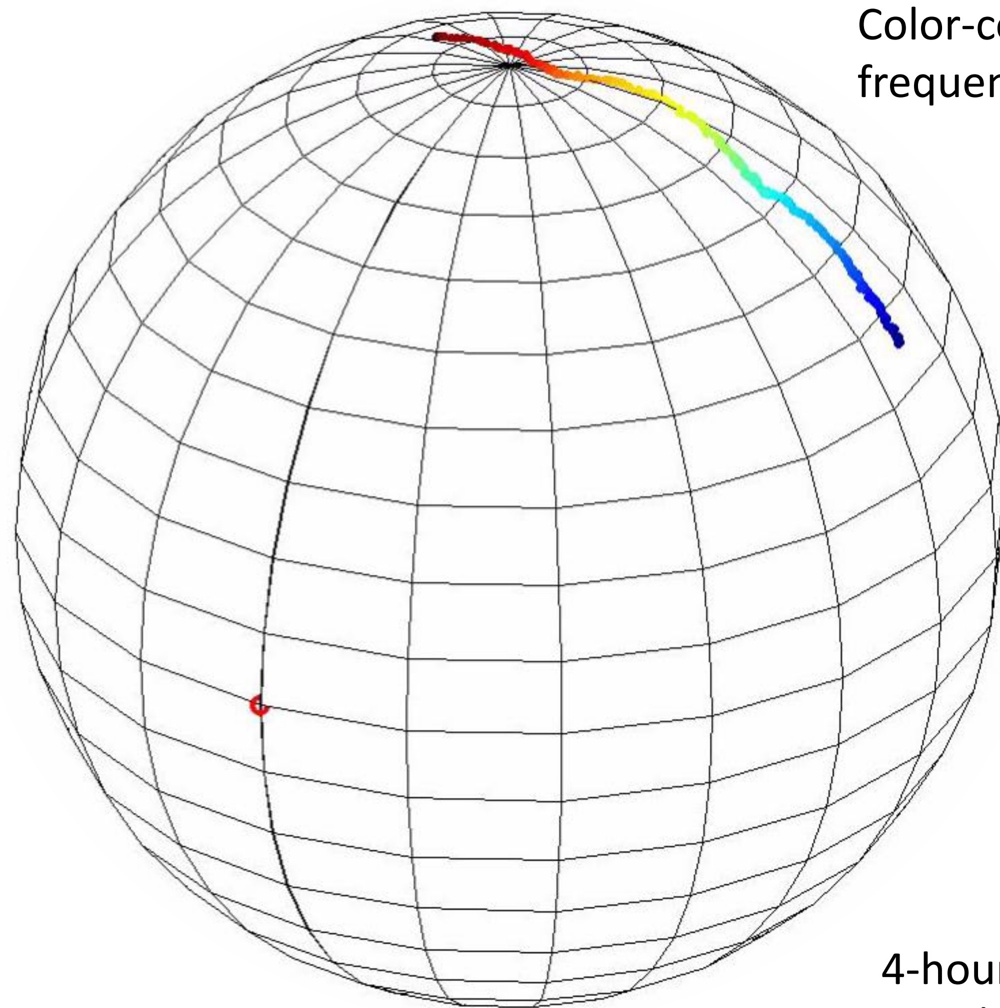




Color-coded time response shows how the PMD curve varies over the day-long cycle period

PMD Signature Time History
(915 MHz at the PLAYA site)

This movie illustrates the motion of the PMD curve before, during, and after a rain event. Each curve has been average over 5 minutes.



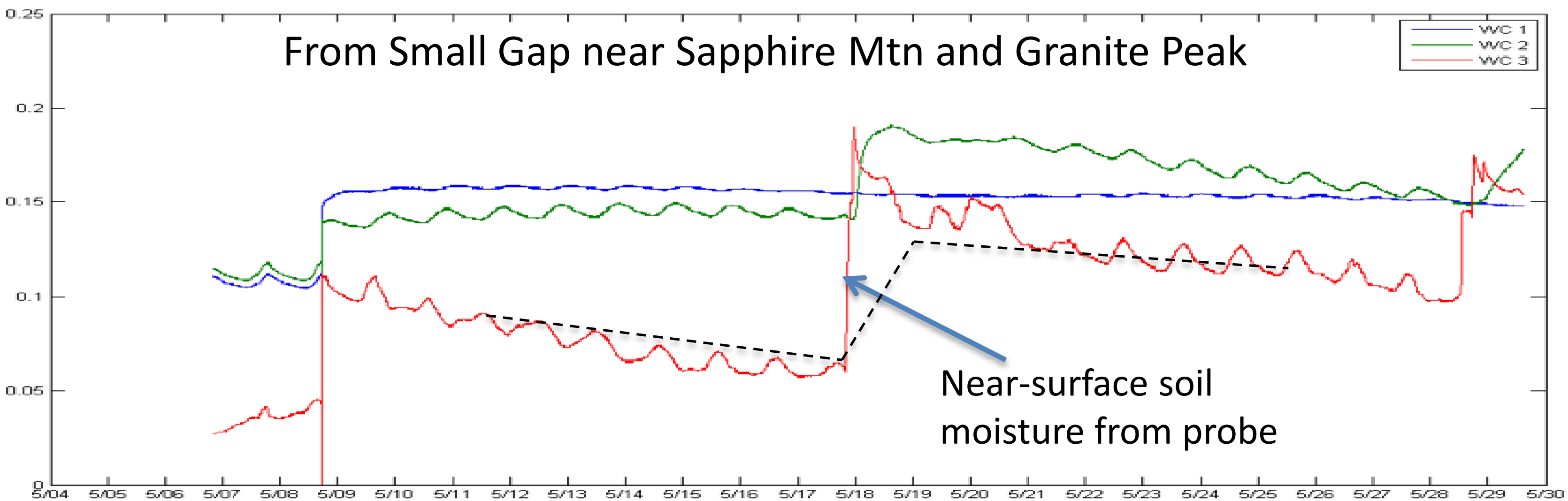
Color-coded frequency response

4-hour time period on 5/17, 17:00-20:58

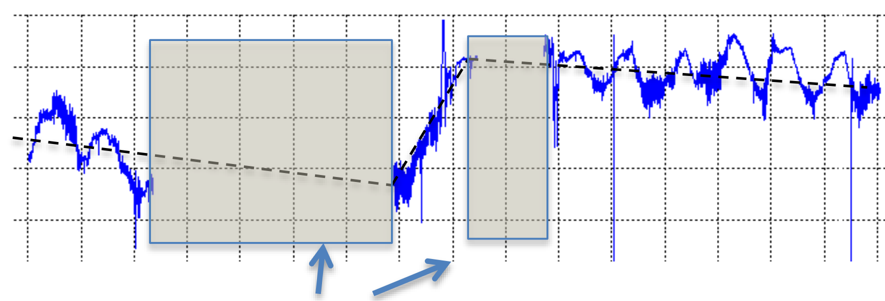
Translation of Output to a Function

- The PMD curves are translated to a time-domain function by choosing a reference point (or reference curve) and computing the deviation relative to the reference
- By selecting a reference corresponding to the maximum (such as after the heavy rain and saturated conditions), the deviation will be smaller for all other moisture states.
- Over time, we hypothesize that the dry state can also be established when a steady-state response is reached. Through this approach we anticipate that a reasonable calibration can be achieved.
  - More extended collections will be needed to prove this

Measured Moisture Levels



RF DATA



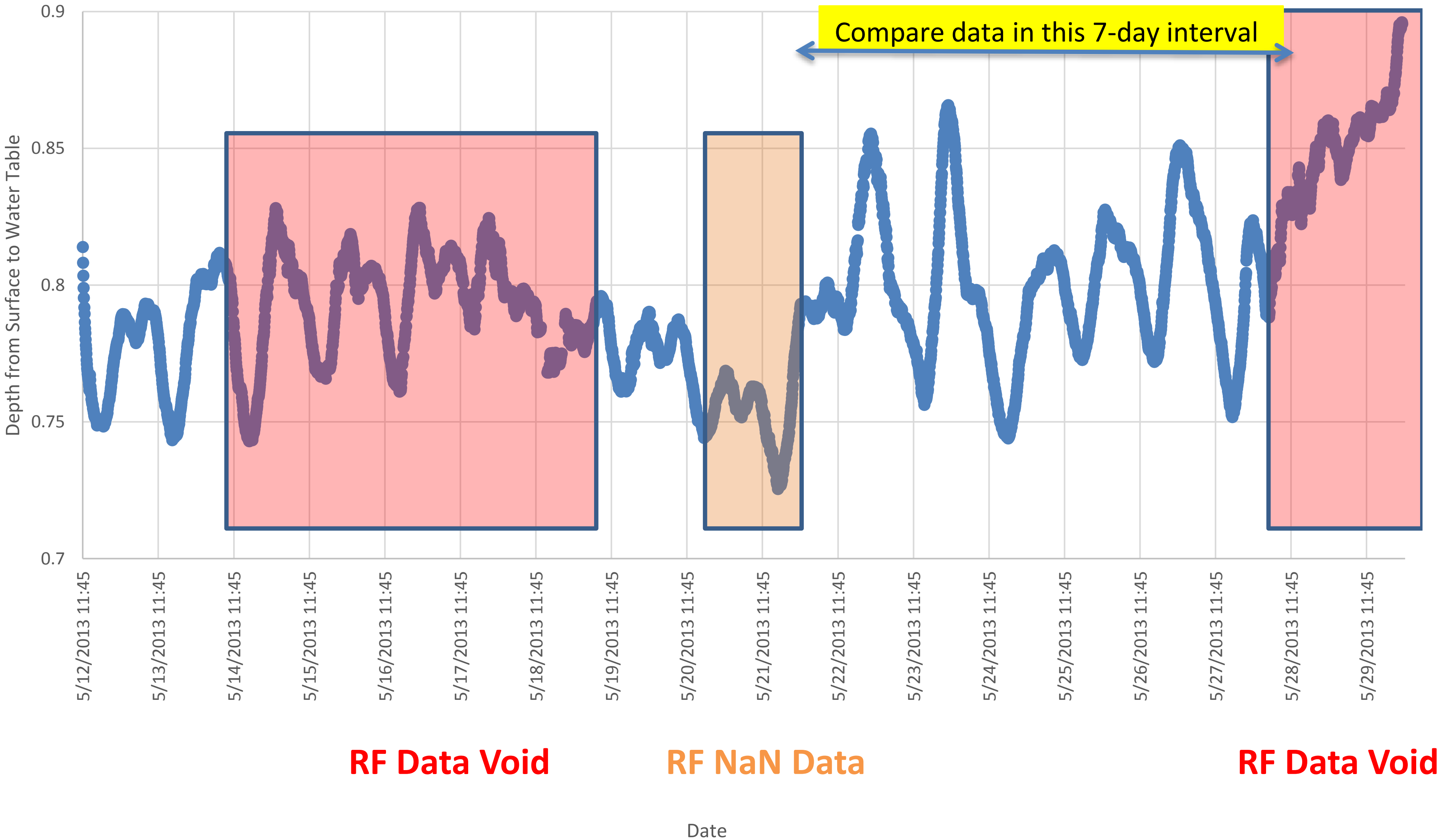
Data gaps

No temperature compensation was applied

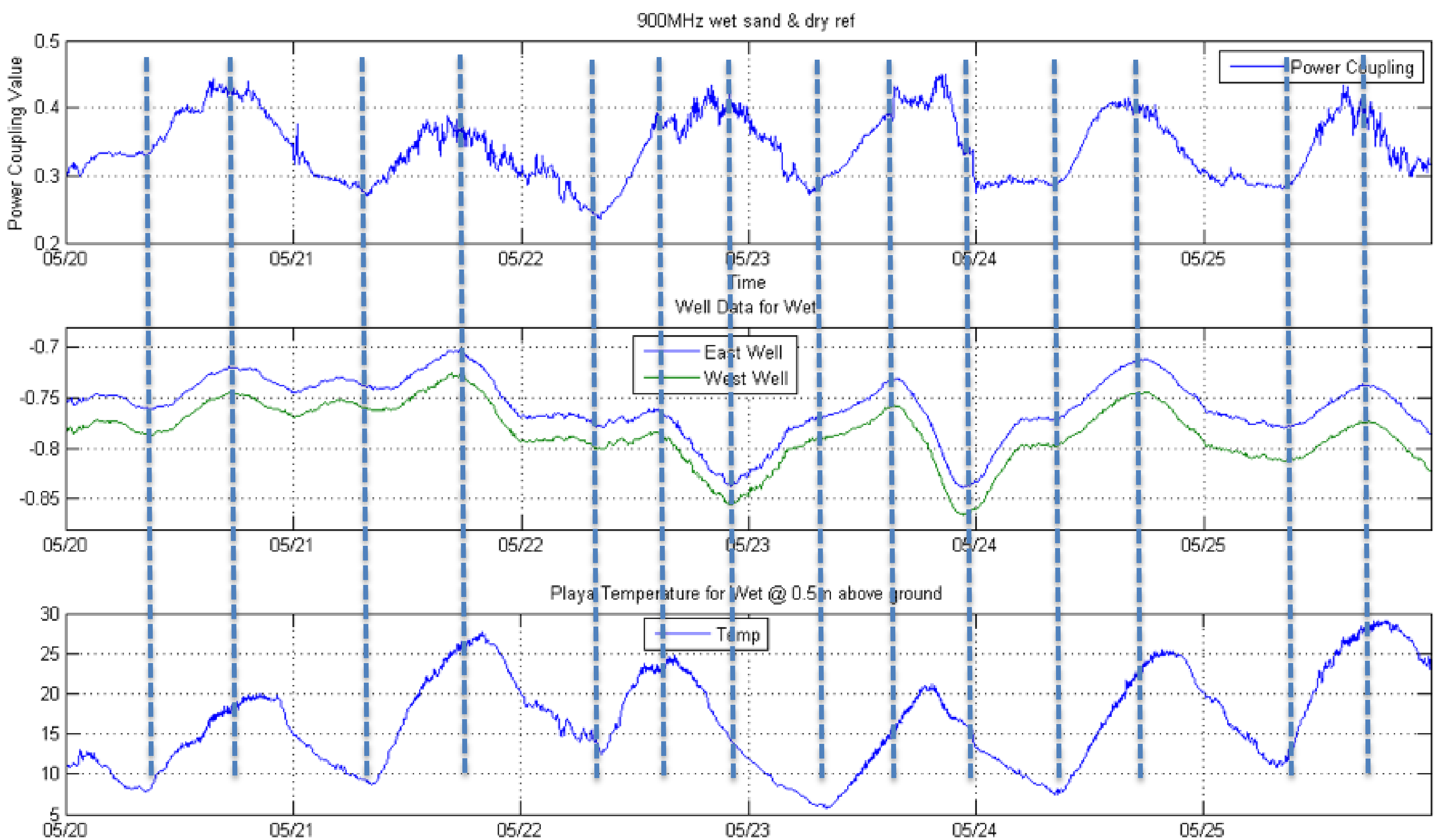
Playa Subsurface Water Level Detection Experiments

- Goal was to determine if the RF system can detect changes in the subsurface water level at the Playa
- Data collected using system with 250’ separation between tx and rx sites, where antennas were roughly 4m above ground and directed at the ground between the antenna sites
  - Allowed for remote soil moisture sensing as well
- Evaluated 915 MHz responses
- “Truth” data provided by East Well and West Well data

West Well Data and RF Voids in Data



Playa Data @ 900 MHz



Hardware Development

- Prior system:
  - Bistatic
  - Transmitter incorporated three different transmit systems (one for eachof three frequency bands);
    - constrained to use of standards-based communications signals
    - Transmitted single polarization
  - Receiver incorporated customize RF front end and employed $8K A/D system
  - Total system cost about $15K

Transmitters: Access Points with single transmit port

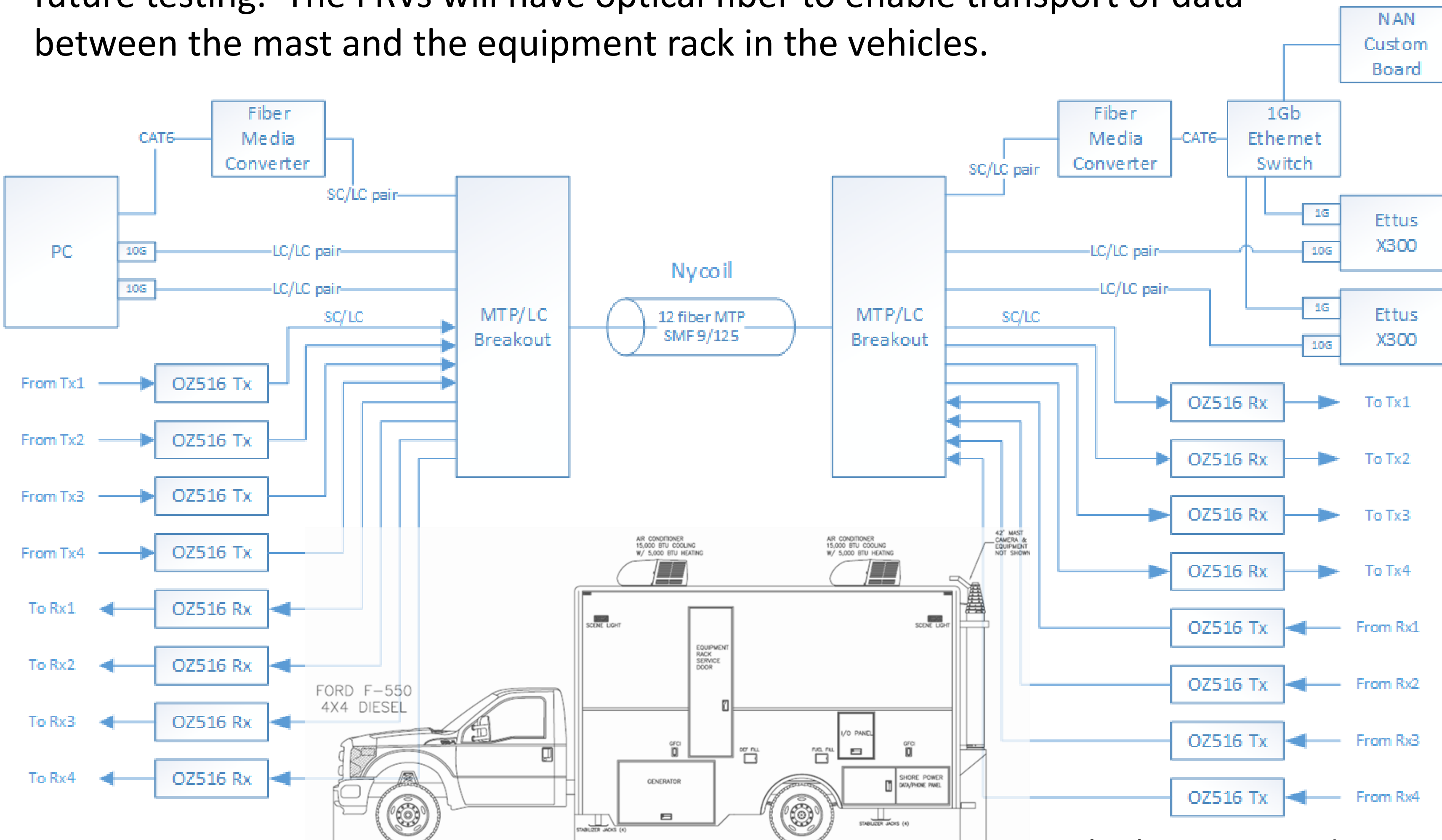
Receivers: Analog signals downconverted as needed and combined to a dual-port ADC system

Tx/Rx System Enhancements

- New system is more compact and integrates tunable RF front ends
- Can likely achieve real-time capability
  - A work in progress on other research grants
- New system is capable of driving two different antennas; orthogonally polarized signals can be employed to improve the discrimination capability
- Capability for up to 4 ports
- Improved RF chain sensitivity
- Larger bandwidths
- Arbitrary waveforms can be generated
  - E.g., linear FM chirp for high range resolution

Field Research Vehicles

Receive and Tx equipment can be placed on masts (heights up to 42') in future testing. The FRVs will have optical fiber to enable transport of data between the mast and the equipment rack in the vehicles.



Vehicles expected October 2014.

What We Envision in the Future

- Analysis of existing 400MHz and 900 MHz data
- Hardware Development and Testing
  - A compact tx/rx with at least dual pol transmission capability, tunable RF, improved sensitivity, and real-time measurement capability
  - Arb waveform capability and tx/rx sync to achieve range resolution and improved performance
  - Bistatic or monostatic antenna installations
    - eliminate wind effects and achieve good tx/rx isolation
- Signal Processing Algorithms and Tx Waveforms
  - Ability to compensate temperature effects
    - Current direction of research. STAP processing is a candidate approach to compensate for temperature effects using MMSE suppression techniques
  - Depth profiling
  - Range/Angle imaging (based on new waveforms)
- Implementation on a drone