RF Sensor Advances and a Theory for Soil Moisture Retrieval

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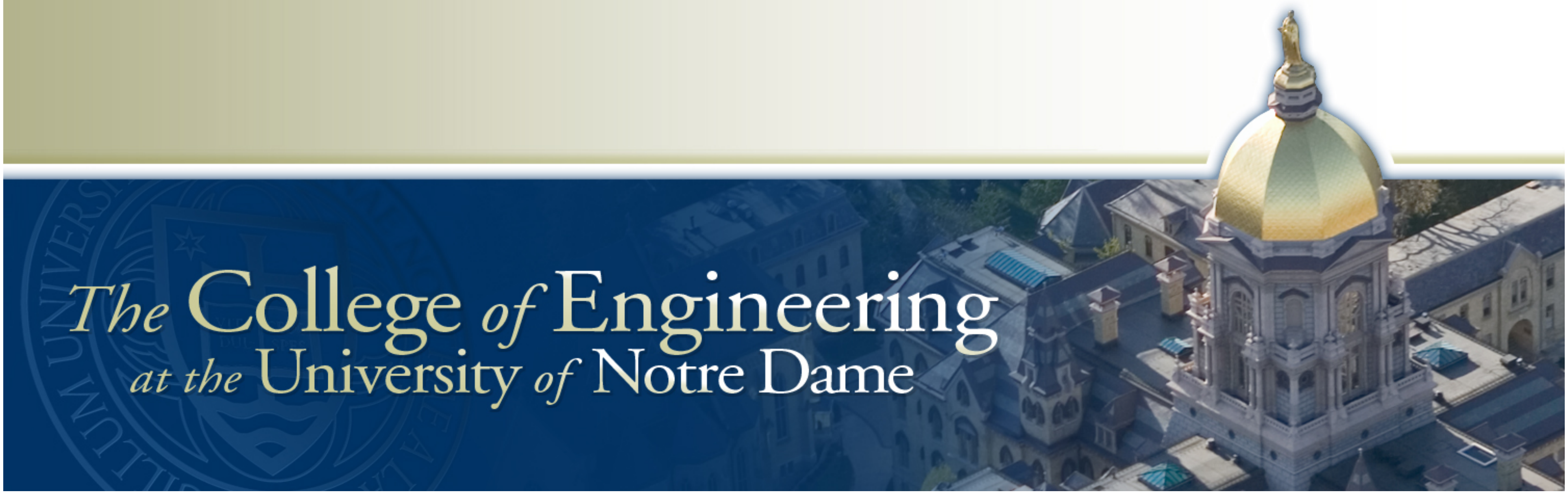


Objectives

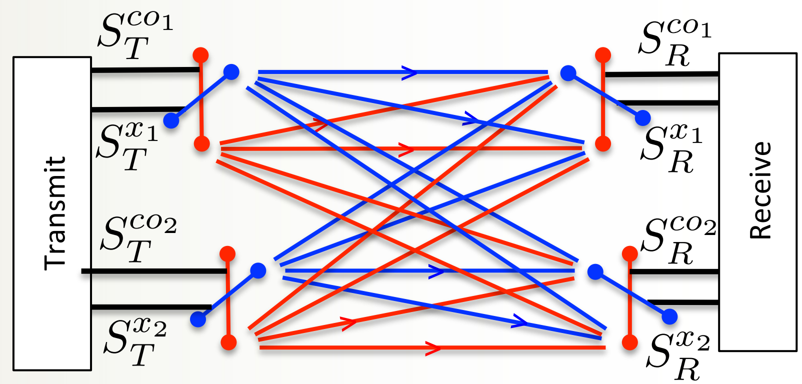
- Following lessons learned from the Dugway experiments, a goal has been to develop an improved sensor prototype with **full-polarization Tx/Rx** capability, **system self-calibration**, and **range gating**

- Also to develop a more direct soil moisture inversion approach

- Conduct measurements to employ new sensors and prove the developed concepts

Outline

- Advances in RF Sensors
  - 2x4 Coherent MIMO System
  - 2x2 DP-MIMO Radar
  - 1x2 Passive Receiver
  - 4x4 Channel Sounding

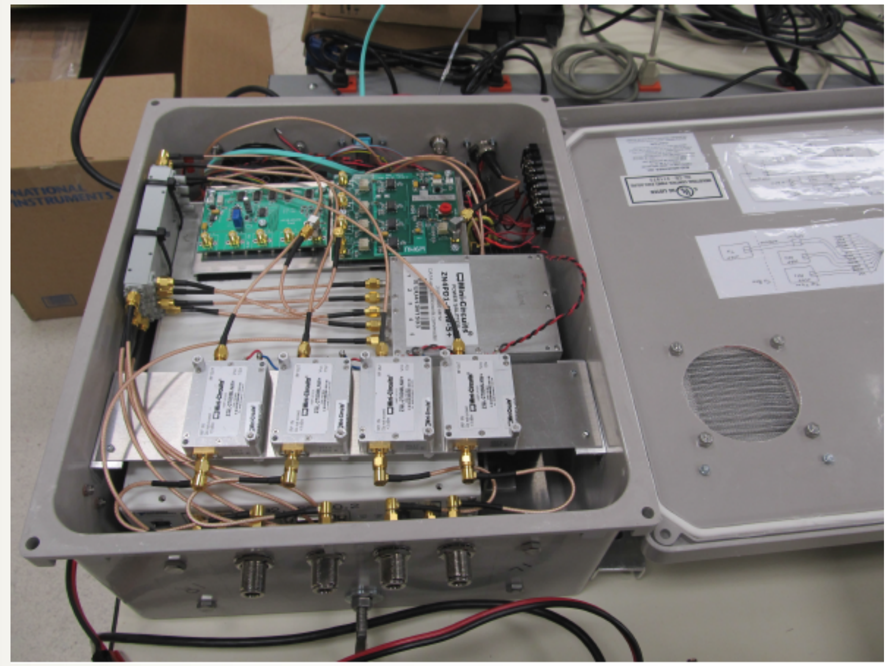


- Proposed time domain channel sounding technique for retrieving soil moisture-- theory
- Testing Platforms
  - Field Research Vehicle/Experiments
  - Potential for in-flight testing with aerial mapping aircraft
  - SATCOM signals

2x4 MIMO Sensor

The MIMO sensor offers significant improvements in hardware capability

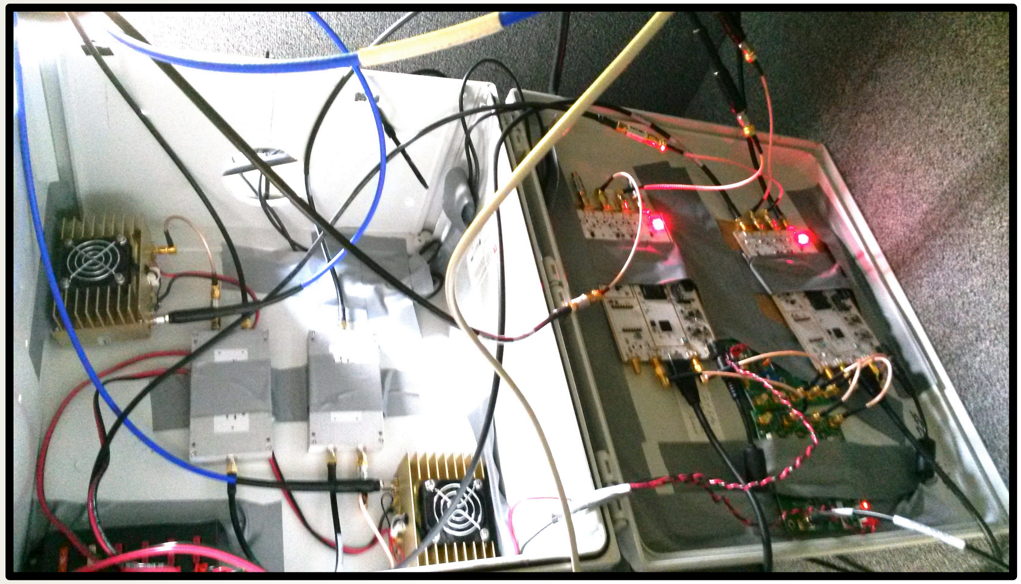
- Tunable over wide frequency band up to 6 GHz
- Arbitrary waveform designs
- Calibration circuitry
- Transmit and receive diversities
- Ranging capability function has not yet been verified
  - Would lead to radar capability
- Beamforming capability
- Recent bandwidth extension from 40 MHz to 160 MHz
  - Implications for ranging resolutions
    - 2.5 m instead of 10m



Receiver portion of 2x4 MIMO System

2x2 DP-MIMO Radar

- Dual polarization radar system
- Full polarization measurements with compression (20 MHz Bandwidth– 15m resolution)
- Working towards partial compression to enable recovery of polarization mode dispersion characterizations
- Calibration circuitry
- Tx/Rx isolation in monostatic case is a current challenge due to length of transmit pulses and the small bandwidths employed

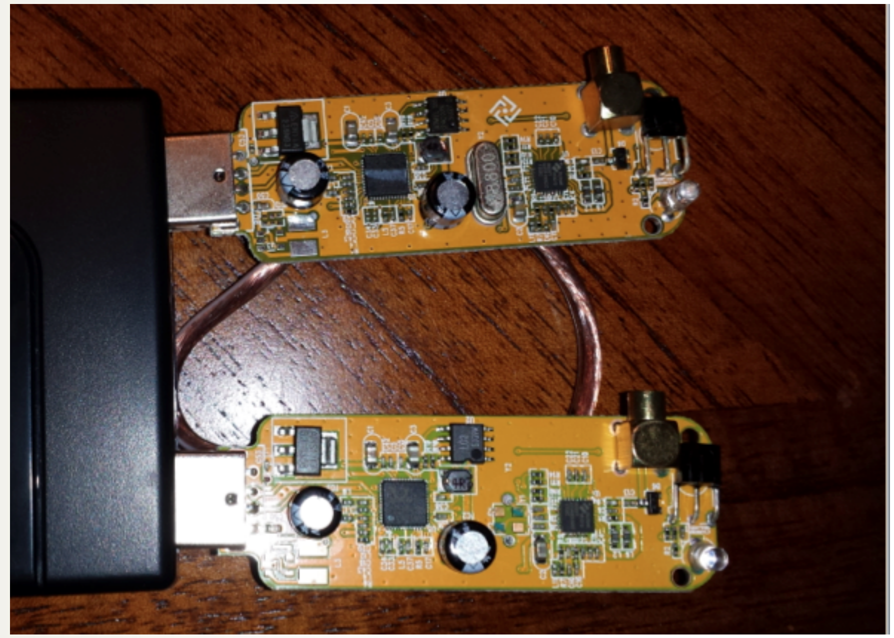


Radar prototype system in a weather-proof enclosure. The system includes two Ettus B210 boards, customized VHDL, and an array of power splitters

Inexpensive Passive Sensor System

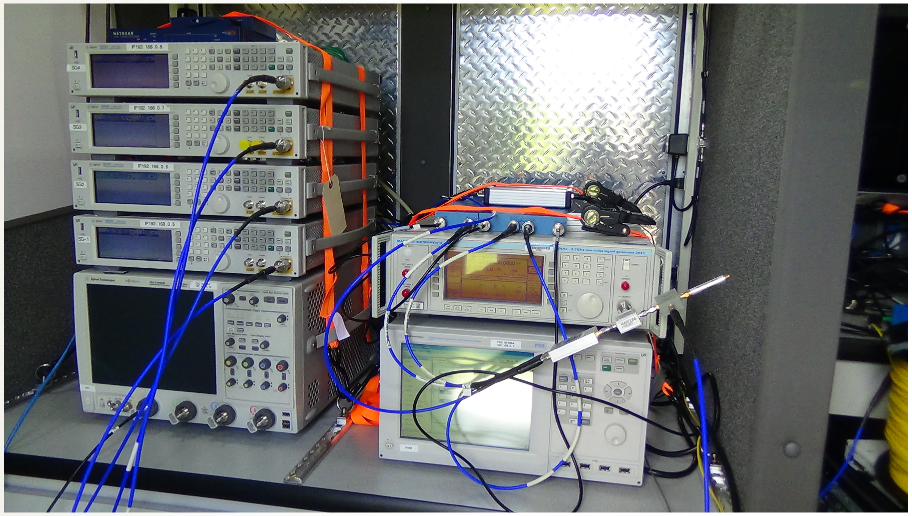
On a separate project, investigating inexpensive alternatives for low-cost deployments of the sensing technology

- Two-channel receiver based on RTL dongles
- Compensation circuitry has to be developed
- Total cost (less a computer) is expected to be around $100



Channel Sounding

- In the absence of a ranging capability with our high-bandwidth current sensors, we are turning to a MIMO channel sounding system
  - Capable of estimating channel impulse responses to identify range gates with significant energy
- Sophisticated, involves substantial signal processing to elicit results
- 4x4 dimensions provides diverse measurements of the channel responses



Transmission equipment. Four simultaneous, but separable, signals are transmitted with 80 MHz bandwidths.

Soil Moisture Retrieval Approach

- Approach uses both modeling and measurement to identify soil moisture levels
- Assumes knowledge of:
  - soil composition
  - Antenna geometry
  - Transmit signal polarization
- Approach has been evaluated in simulation to show efficacy
- Needs to be validated in experiments

Background

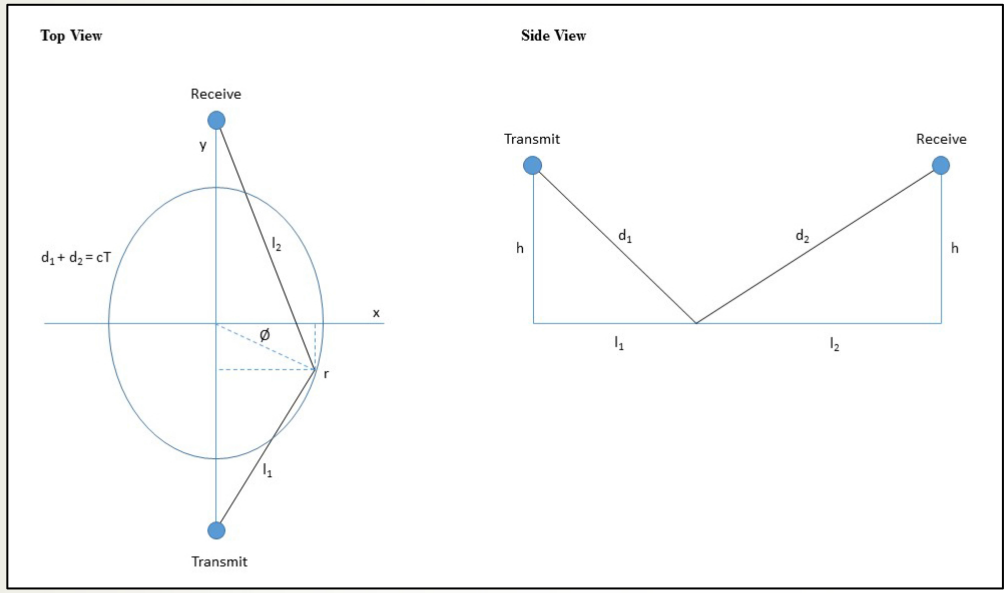
- Relevant physical parameters in microwave- based soil moisture retrieval include the **complex refractive index** of the soil sample, which is a function of microwave frequency, soil composition, soil moisture, surface roughness, and antenna Tx/Rx geometry, among other parameters [Hallikainen (1985)].

- Unknown surface roughness prevents a simple analytic inversion to retrieve the refractive index of the soil [Beckmann and Spizzichino (1963)]

- Difficulty of surface roughness has prompted several groups to develop empirical inversion techniques for retrieval of soil moisture from backscatter data [Oh (1992); Dubois (1995)]

Hypothesis

- If a dominant scattering event from a rough surface can be isolated, then an analytical physical model of the scattering event would serve as a straightforward method to invert the data for retrieval of the complex refractive index



Geometry between antennas and reflectors

Approach

- Assumes knowledge of antenna heights and relative location as well as soil composition
- Monostatic or bistatic measurement (with Tx/Rx synchronization)
- Estimate channel impulse response
- Determine impulse response delays exhibiting Ricean statistical behavior (associated with dominant scattering)
- Use full-polarization response, range information, and soil composition to find the location and volumetric moisture content

Anticipated benefit is that it circumvents difficulties associated with surface roughness as in previous microwave scattering inversion techniques

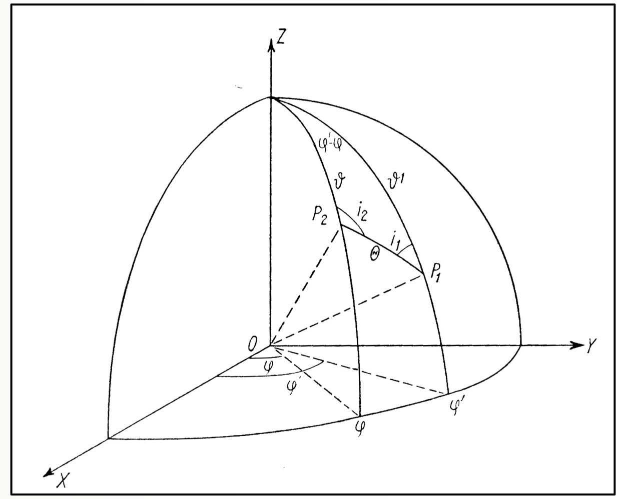
Theory

- The Stokes vector associated with the received signal is described by:

$$\vec{S} = R(\pi - i_2)M(\theta)R(-i_1)\vec{S}_I$$

where R is a rotation matrix and M describes the scattering event:

$$M(\theta) = \frac{1}{2}\begin{pmatrix} \rho_s^2+\rho_p^2 & \rho_s^2-\rho_p^2 & 0 & 0 \\ \rho_s^2-\rho_p^2 & \rho_s^2+\rho_p^2 & 0 & 0 \\ 0 & 0 & 2\rho_s\rho_p\cos\Delta & 2\rho_s\rho_p\sin\Delta \\ 0 & 0 & -2\rho_s\rho_p\sin\Delta & 2\rho_s\rho_p\cos\Delta \end{pmatrix},$$

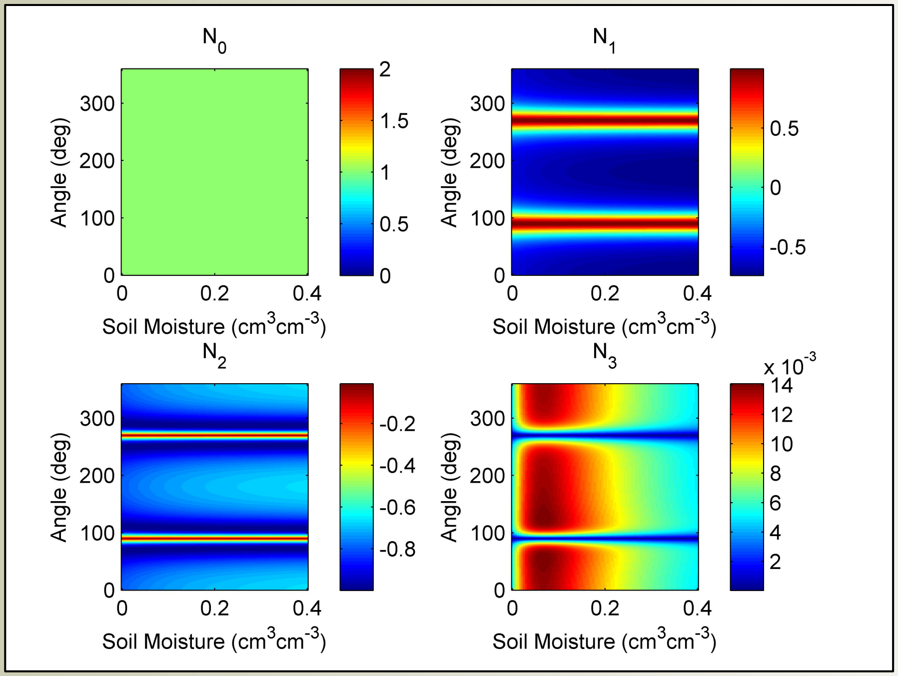


Geometry of a Mueller matrix scattering event

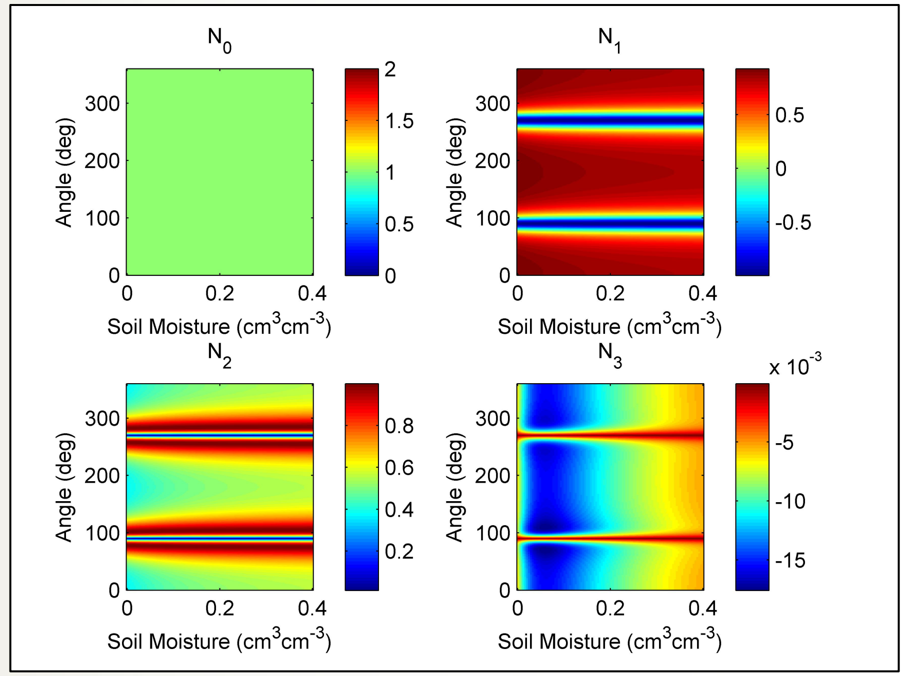
Entries are related to Fresnel reflection coefficients

Simulated Modeling Response

- The set of possible calculated normalized Stokes vectors for the incident Stokes vector and the given conditions



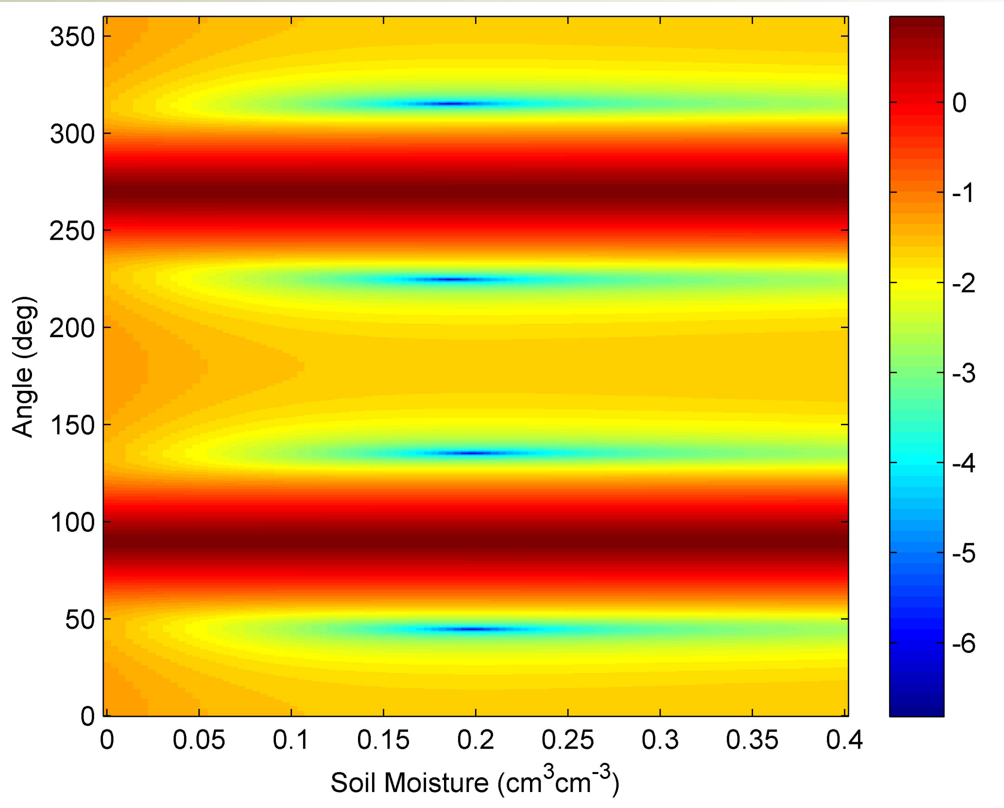
Horizontally–polarized Transmission



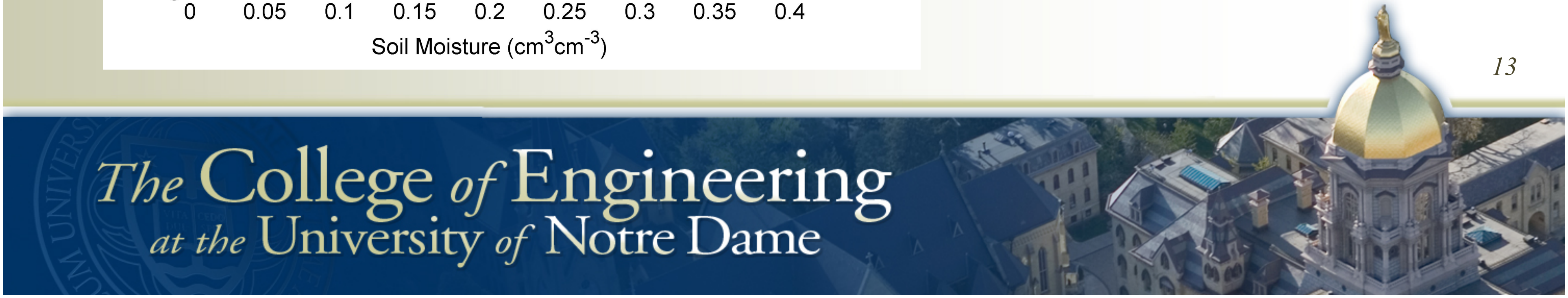
Vertically–polarized Transmission

MSE as a function of Az and soil moisture

- Compare the set of calculated Stokes vectors to the simulated received Stokes vectors.



The results suggests the possible benefits of employing sensors on opposite sides of the y-axis



Field Research Vehicles

- Two field research vehicles are a major resource in my research group
- Solar/Wind/12kW power
- 42' Mast with 36 optical fiber, camera
- 4 workstations
- 2 equipment bays using anti-vibration rack system

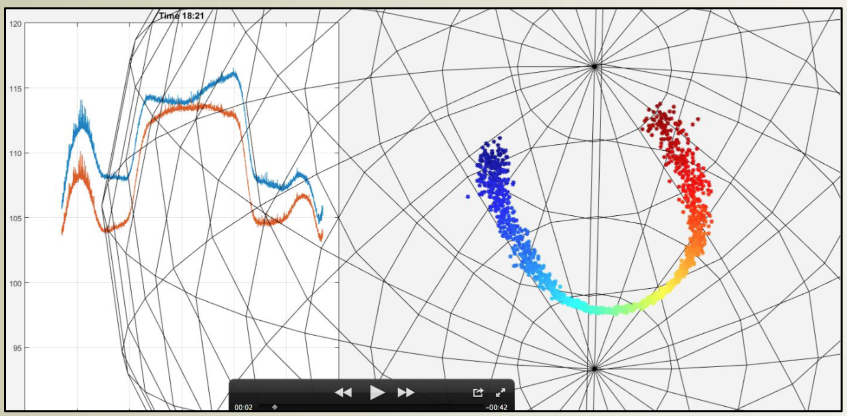
Airborne Testing

- Collaboration with local aerial mapping company to fly our equipment
- Possible research thrusts in a number of areas:

1. Scatterometry: air-to-ground propagation measurements
2. Sensor performance
    - 2x2 MIMO radar
    - 2x4 MIMO sensor system

Satellite Signals of Opportunity

- Developed satellite reception capability to monitor emissions from geosynchronous satellites
  - Potential for atmospheric boundary layer characterizations
  - Potential application to soil moisture sensing using signals of opporutnity



Measurement setup (above) and measured results (left) from a geosynch satellite operating at 11 GHz