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Field-scale remote sensing of soil moisture based on polarimetric characterization of microwave reflections

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Abstract

A field-scale remote soil moisture sensing technique that exploits polarization mode dispersion (PMD) associated with radio frequency (RF) signal propagation is considered in this paper. Microwave polarization responses from rough surface scattering are quantified using a dual-polarized receiver system to estimate PMD responses. Changes in PMD response are elicited by changes in the dielectric properties due to soil moisture changes. The ability of PMD characterizations to remotely detect changes in soil moisture, with responses that exhibit good correlation to ground probe measurements, is demonstrated using a prototype with widely separated transmitter/receiver system deployed at the MATERHORN field experiments conducted at the US Army Dugway Proving Ground, Utah.

Keywords: remote sensing, soil moisture, polarization mode dispersion, radar

(Some figures may appear in colour only in the online journal)

1. Introduction

Estimation of soil moisture is important in many hydro-meteorological applications, for example: estimation of the efficiency of agricultural practices, recharge to groundwater systems and slope stabilities following precipitation, and monitoring the impact of mining operations. The surface moisture is a key input to mesoscale meteorological models, and substantial improvements in predictive capability have been observed with better specification of surface moisture (Hillel 1980, Bian *et al* 2009, Parsons and Bandaranayake 2009, Zhu *et al* 2009, Fernando *et al* 2015). The measurement of soil moisture is therefore an important challenge in a number of modeling and field optimization processes and is a subject that has attracted attention from the early days of vadose zone research (Hillel 1980, Topp *et al* 1980) to recent applications in the realm of soil science (Idso *et al* 1975, Dalton *et al* 1984, Bian *et al* 2009, Hain *et al* 2009, Liu *et al* 2009, Mattia *et al* 2009, Parsons and Bandaranayake 2009, Petropoulos *et al* 2009, Stacheder *et al* 2009, Qin *et al* 2009, Zhu *et al* 2009).

A thorough bibliography of early methods used to measure soil moisture is contained in a book by Morrison (1983) and research on remote sensing of soil moisture has been reviewed by Schmugge (1983) and Engman *et al* (1995). More recent educational material of the International Atomic Energy Agency (Evett *et al* 2008) provides additional descriptions and comparisons of sensing technologies, including neutron moisture meters. In general, noteworthy methods estimate soil moisture either locally (e.g. at the meter scale or smaller) through direct or indirect measures on local sediments or at larger scales (tens of meters to watershed scale) through remote techniques. Local techniques are based predominantly on capacitance or resistance measurements in soils, including time domain reflectometry (TDR), frequency-domain reflectometry (FDR), and soil block measurements (Morrison 1983, Dalton *et al* 1984, Stacheder *et al* 2009). Remote sensing techniques offer capability for aggregate soil moisture sensing (Huisman *et al* 2003). By measuring electromagnetic energy reflected or emitted from a soil surface area, remote sensing can provide information on moisture content over large regions (~1 km scale), which is the typical grid-scale of mesoscale models. Such information can lead to increasingly accurate weather prediction through improved soil moisture analysis and the use of high-fidelity soil thermal conductivity parameterizations in predictive models (Zhang *et al* 2013, Massey *et al* 2014), thus yielding important societal and defense applications.

Previous schemes to detect soil moisture have included a microwave radiometer (Loew *et al* 2009) used to infer soil moisture from polarization component magnitudes using non-coherent detection of ambient reflected microwaves over small areas for assimilation into precipitation models. A different passive ground-based sensing approach employs an *in situ* GPS receiver for near surface soil measurements (Small *et al* 2008, Larson *et al* 2008a, 2008b). This sensing method exploits signals from the GPS constellation and measures SNR variations induced by satellite motion to infer soil moisture levels through subsequent model simulation. The technique reportedly offers resolutions on the order of 300 square meters, assumes a single dominant multipath component, and relies on approximately 45 min of satellite motion to generate an estimate. The Soil Moisture Active Passive (SMAP) project measures the backscattering coefficients of satellite-broadcasted radar signals of differing polarizations (yielding σ_{HH}, σ_{VV}, and σ_{HV}) to construct look-up tables corresponding to soil moisture content (Kim *et al* 2014). This and similar techniques rely upon accurately measured signal amplitudes, taking into account not only the surface reflections but also surface roughness and vegetation cover, which can affect the accuracy of the estimated soil moisture.

The importance of soil moisture in generating mesoscale circulation (Ookouchi *et al* 1984), and the sensitivity of large scale models for soil moisture parameterizations (Beljaars *et al* 1996, Ek *et al* 2004) have led to the identification of moisture as a key parameter of investigation in the *M*ount*a*in *Te*rrain Atmosp*h*eric M*o*deling and Obse*r*vatio*n*s (MATERHORN) Program (Fernando and Pardyjak 2013, Fernando *et al* 2015), which was designed to improve mountain terrain weather prediction at mesoscales. Therefore, in developing the MATERHORN science plan, a technology component was included to develop moisture measurement techniques at 1 km (averaged meso-scale grid) scales, thus alleviating the need for conventional local (meter scale) measurements of moisture in compiling surface boundary conditions for models. A proposed technology solution, proposed by Pratt *et al* (2011), was based on the polarization mode dispersion (PMD) in the radio frequency (RF) signal incident at the receiver to monitor moisture changes.

The PMD as used here is to be understood as a spread in the received signal polarization state, which is described by the Stokes 4-vector and whose normalized components S_1, S_2, and S_3 may be plotted as the x, y, and z coordinates on the Poincare unit sphere. The spread occurs as a function of the frequency components of the received signal and depends on the group delay difference between the orthogonally-polarized propagation modes, the associated power delay profiles, the signal bandwidth, and other factors. The approach provides control over resolution scales via the antenna characteristics and the deployment geometry between the transmitter and the receiver. It offers potential to provide a continuous monitoring capability with potential update rates on the order of tens-to-hundreds of milliseconds. The technology relies on the changing dielectric properties of the soil with moisture (Pratt *et al* 2011), which impacts the co-polarized and cross-polarized reflection coefficients associated with scattering from the ground between the transmitter and the receiver, and ultimately the PMD response.

Analysis of the PMD response of RF signals as proposed by Pratt *et al* (2011) is applicable over areas of the size of mesoscale grids, and may be analyzed in real time, leading to the possibility of soil moisture content information on an as-needed basis. In addition, because the technique measures the polarization of the signal as a function of frequency, not only is the amplitude used in retrieval of soil moisture levels (as in previous soil moisture retrieval methods) but also the phase. In principle, then, the PMD technique offers an increase in the available information that can be utilized to calculate corresponding soil moistures. In view of these advantages, hardware for PMD analysis using RF signals was designed and deployed in the first MATERHORN field experiment (MATERHORN-X-1), a thirty-day field campaign conducted during September and October 2012 at the Granite Mountain Atmospheric Science Testbed (GMAST) of the US Army Dugway Proving Ground, Utah (Fernando *et al* 2015). This first test was conducted at a site designated as the Small Gap. A second series of testing was also completed during the May 2013, with experiments conducted both at the Small Gap site as well as a location designated as the Playa.

2. Experimental setup

2.1. September and October 2012, Small Gap site

The Small Gap is an alluvium semiarid high-elevated basin (~1300 m above sea level) between Granite Peak (lat. 40.127 995, long. −113.271 37, elevation 2137.87 m above sea level) and Sapphire Mountain (lat. 40.059 385, long. −113.259 702, elevation: 1414.88 m above sea level). The soil in the region consists of a combination of mixed alluvial-fan and colluvial deposits (Holocene to upper Pleistocene) about 6 m in depth with windblown silt overlying lacustrine silt, clay, marl, and some sand. The surface commonly contains distinctive vegetation stripes (characteristic landforms of sheetflow plains in arid to semiarid regions) (Oviatt *et al* 2003) and may locally include thicker eolian deposits and transgressive deposits. In this case the cover unit thickness is likely less than 1 m.

The sensing technology proposed by Pratt *et al* (2011) was tested at the Small Gap site using a multi-frequency developmental prototype sensor system, with a separation

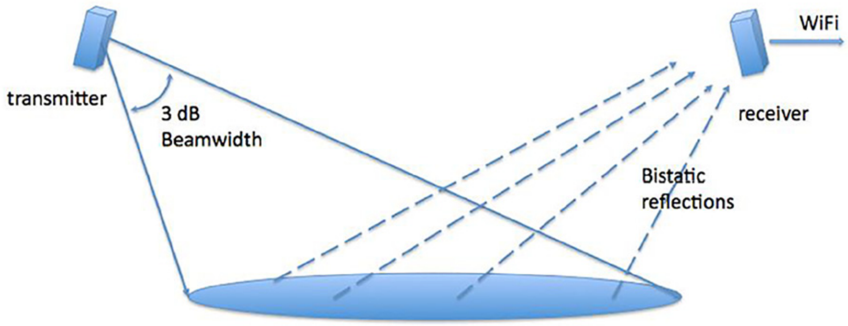

Figure 1. Sensor deployment geometry. From Pratt *et al* (2011) with permission from the American society of Agricultural and Biological Engineers.

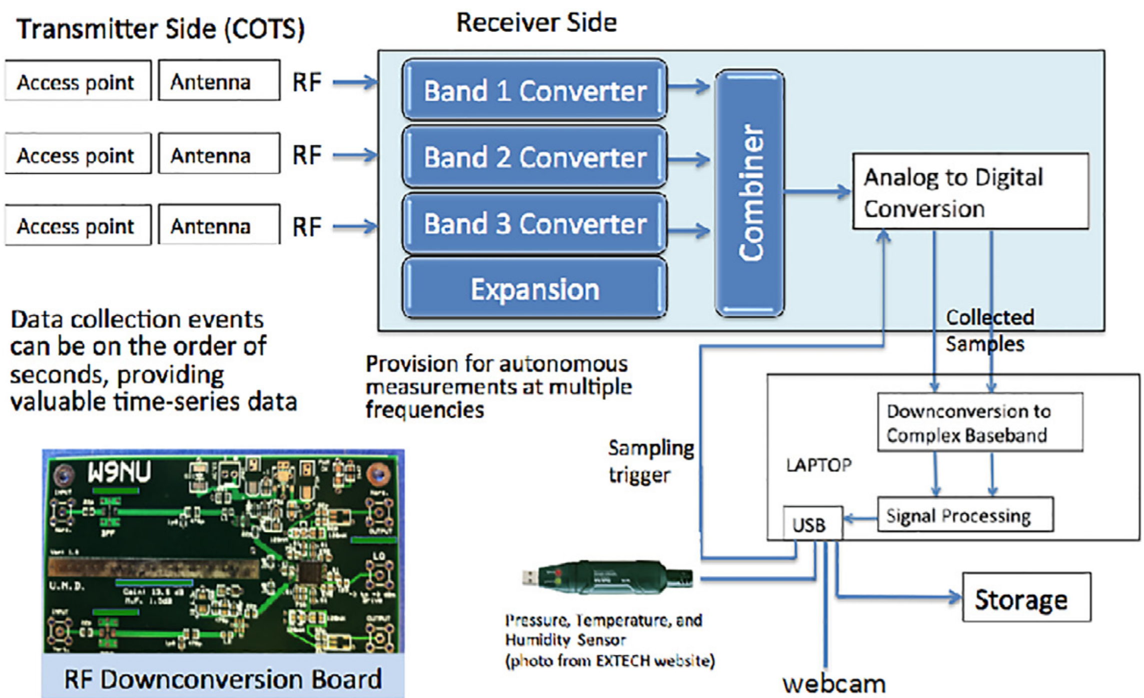

Figure 2. Block diagram of data collection system.

between the transmitter and the receiver of approximately 0.4 km. The sensor deployment geometry, a block diagram of the receiver subsystem, and photographs of the transmitter and receiver systems and their relative deployment geometry are depicted in figures 1–3, respectively. The system was operated using the 2.4 GHz frequency band, which is useful to characterize surface and near surface moisture due to the relatively small ground penetration achieved at this wavelength. A capacitance-based soil moisture probe (Decagon, 5TM) was deployed at a depth of 2 cm to *in situ* monitor the near-surface soil moisture. Two 10 m towers were deployed to collect weather information. The towers took measurements at three heights (2 m, 5 m, and 10 m) and were equipped with shielded relative humidity and temperature probes (Vaisala, HMP45). The 2 m and 10 m levels were also instrumented with 3D sonic anemometers (R.M. Young, 81000) to collect wind speed and direction data at 20 Hz. The coordinates of the towers and RF sensor system transmitter and receiver sites are indicated in tables 1 and 2. A map of the locations of the transmitter and receiver sites is indicated in figure 4(a).

The specific receive antenna had an azimuth beamwidth of roughly 90° and an elevation beamwidth of 75°. The transmit antenna azimuth and elevation beamwidths were approximately 21°. The resulting 6 dB footprint on the ground plane from the antenna patterns was roughly 75 m $\times$ 340 m, where the relative contributions from facets within the footprint depend upon the product of the transmit and receive antenna gains in the direction of each facet as well as the corresponding reflection coefficients. An illustration of the footprint is depicted in figure 5(a). The RF sensor system collected RF samples every 5 min over non-contiguous 12 h IOP. The data recorded included both the amplitude and phase information of the radiation interacting with the soil as a function of frequency.

The aim of the fall deployment was to test the system and identify possible challenges of technology implementation. The need for several design improvements were identified during the data analysis, as will be described later.

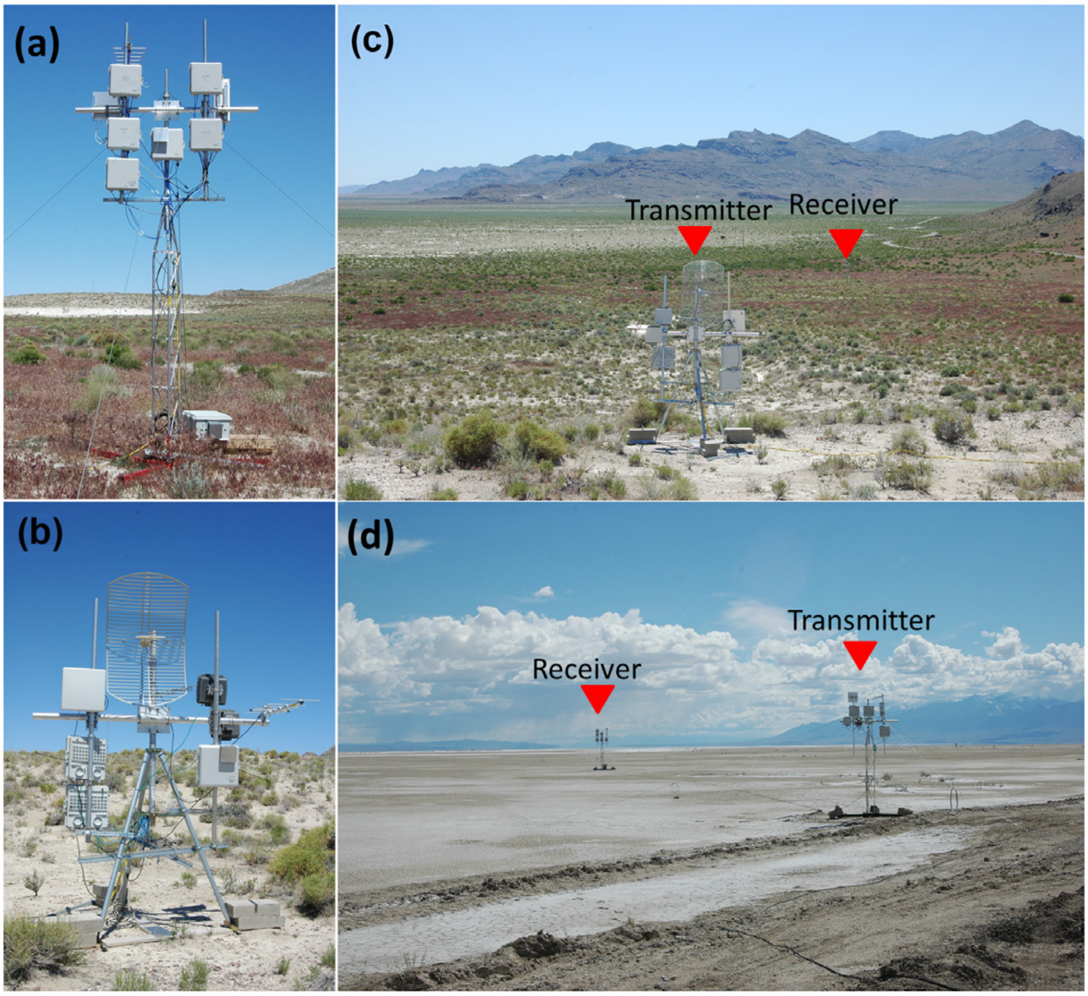

Figure 3. Photos of the (a) receiver and (b) transmitter; (c) deployment geometry at the Small Gap; (d) deployment geometry at the Playa site. From Fernando *et al* (2015). Copyright American Meteorological Society. Used with permission.

Table 1. RF sensor system and tower coordinates at the small gap site.

	RF transmitter	RF receiver	Tower 1	Tower 2
Latitude	40.066 825°	40.064 048°	40.067 383°	40.060 033°
Longitude	− 113.263 747°	− 113.260 619°	− 113.264 350°	− 113.255 617°
Elevation	1340.64°	1323.86°	1350.55°	1317.01°

2.2. May 2013, Small Gap and Playa Sites

A second series of testing, which was conducted in May 2013, utilized sensors at both the Small Gap and the Playa site, the location of which is shown in figure 4(b). The RF sensor deployment geometry at the Playa site is shown in figure 3(d). The separation between the transmitter and receiver was approximately 80 m. The antenna azimuth and elevation beamwidths were 90° and 75°, respectively, at both the transmit and receive sites. A plot of the corresponding footprint is shown in figure 5(b) and is seen to cover an area of size 80 m × 80 m. Once again, the data recorded include both the amplitude and phase information of the radiation interacting with the soil as a function of frequency. The experimental setup at the Small Gap site during the May 2013 campaign was the same as described above in section 2.1, with the exception that, for both the Small Gap and Playa sites, the sensor capabilities were improved to enable collections every minute, giving a three-fold improvement in the data rate. A primary goal for the technology during the May 2013 campaign was to demonstrate the potential of the system for monitoring near-surface soil moisture levels, using an enhanced prototype system with a three-fold improvement in data collection rates and a reduced post-processing computational load.

Table 2. RF sensor system coordinates at the playa site.

	RF transmitter	RF receiver
Latitude	40.134 8645°	40.133 9137°
Longitude	− 113.451 0195°	− 113.451 6777°
Elevation	1288°	1288°

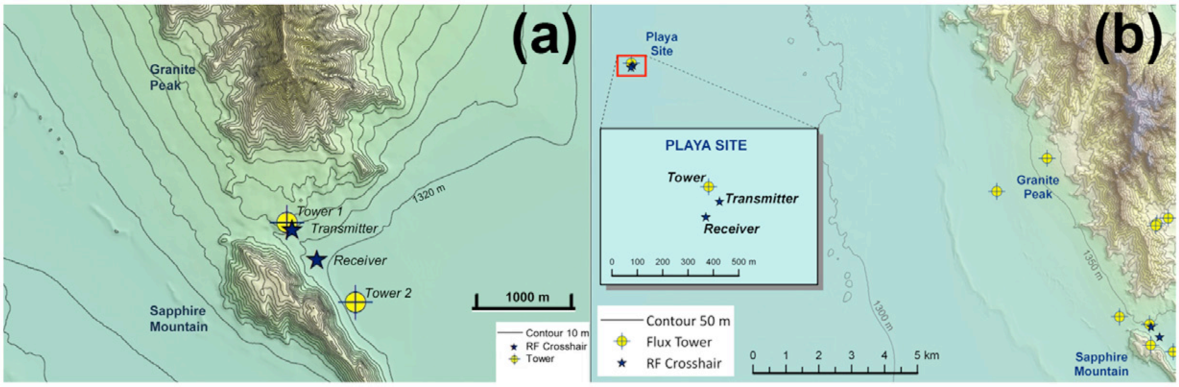

Figure 4. (a) Details of Transmit and Receive Locations (star symbols) at the Small Gap. The position of the two towers is also indicated (yellow circles). (b) The transmitter and receiver locations at the Playa site. From Fernando *et al* (2015). Copyright American Meteorological Society. Used with permission.

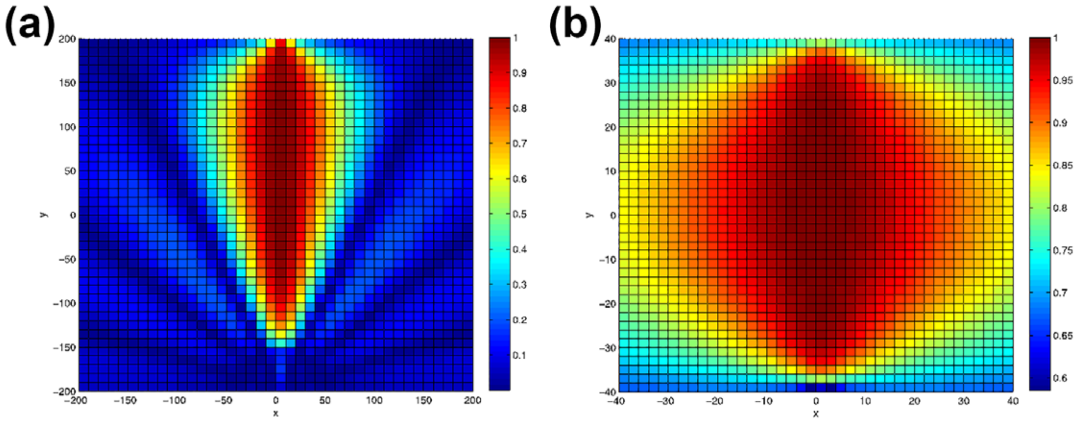

Figure 5. (a) Antenna pattern footprint at the Small Gap. (b) Antenna pattern footprint at the Playa site.

3. Experimental results

3.1. September and October 2012, Small Gap site

The analysis of the data showed that wind loading on the antenna manifold induced non-negligible measurement 'noise' due to antenna vibrations, where the magnitude of the variations in the measured PMD response were directly related to the wind speed. The effects are exemplified in figure 6(a) and depict the PMD responses, for dry near-surface soil, measured over a 30 min time period at 5 min intervals when the average wind speed was 4.90 m s^{-1} (figure 6(b)). The signatures are seen to be approximately identical in form but are at different locations on the Poincare sphere due the changing antenna position. In the absence of wind-induced vibration, the signatures would be expected to overlay each other, indicating a similar measured moisture content. In the figure 6(c), measured responses taken every 5 min over a 30 min time period are shown when the average wind speed was 0.59 m s^{-1} (figure 6(d)). Under these lower wind speed conditions, the signatures are nearly overlapping, thus demonstrating the repeatability of the signatures when antenna/mast vibration is negligible.

3.2. May 2013, Small Gap and Playa Sites

During the May 2013 campaign, two rain events occurred. Data surrounding the first rain event between 16 May and 21 May have been analyzed and are presented in this paper to illustrate the capabilities of the sensor.

The *in situ* ground probe at the Small Gap site was used to measure the near-surface soil moisture over this period as a form of 'ground truth' and a plot of the measured moisture levels is shown in figure 7. The ground probe data are accurate for the specific location where the measurement was taken, but serve only as an approximate characterization of the moisture levels within the area and region. Over the same period, RF measurements were collected at both the Small Gap and the Playa sites. To help mitigate the impact of wind vibration, the measurements, which were taken at a rate of one sample per minute, were averaged over 1 h intervals. In the case of the Small Gap data, the averaging did not help to overcome the noise introduced by wind-induced vibrations. Hence the data from the Small Gap during the May 2013 tests are not reported. The undesired sensitivities to wind can be mitigated and/or eliminated with improved stabilization of the antenna mast system and through reductions in the form factor of the system to lessen wind loading.

Results from the Playa site are shown in figure 8. The responses after averaging over a 1 h period, were plotted on a Poincare sphere and were color coded based on the corresponding *in situ* ground probe measurements. Dark blue corresponded to the lowest soil moisture levels measured by the probe and red to the highest. This plotting technique provides

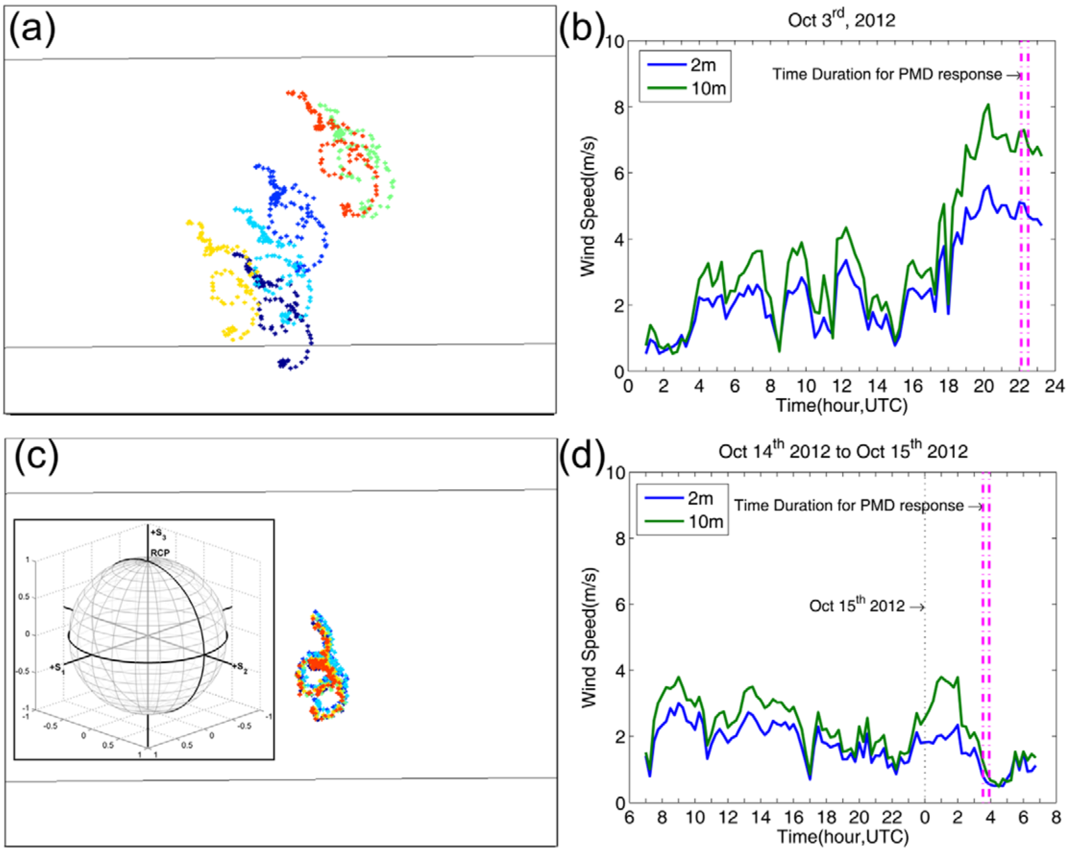

Figure 6. Impact of antenna vibration due to wind on the PMD response. (a) PMD responses under relatively high wind conditions shown in (b), where the interval is indicated by the two vertical boundary lines; (c) PMD responses for low wind conditions that are indicated in (d). The inset shown in (c) is the Poincare sphere upon which the data are plotted according to optimal visibility.

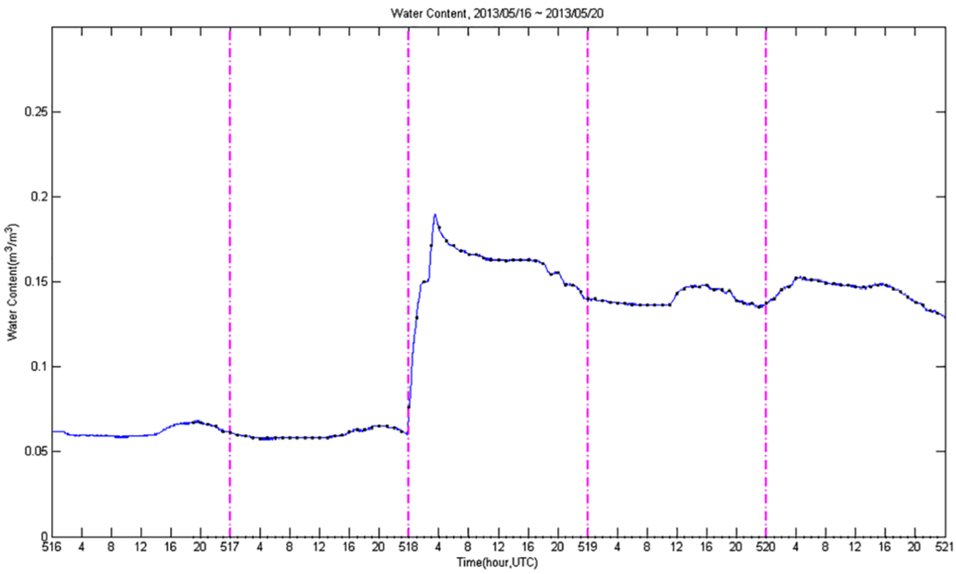

Figure 7. Soil moisture characterization using an *in situ* capacitance probe at a depth of 2 cm.

an easy way to establish correlation between the ground probe and RF measurement approaches. Correlation occurs if PMD measurements that are close on the sphere have nearly the same color, corresponding to approximately the same moisture level. The PMD curves are seen to exhibit good correlation with the ground probe data. Some noise, likely due to temperature variations, wind-induced vibration, and differences in moisture levels in the RF field of view in comparison to the ground probe, are also reflected in the figure 8. Owing to the relative close proximity of the transmitter and the receiver,

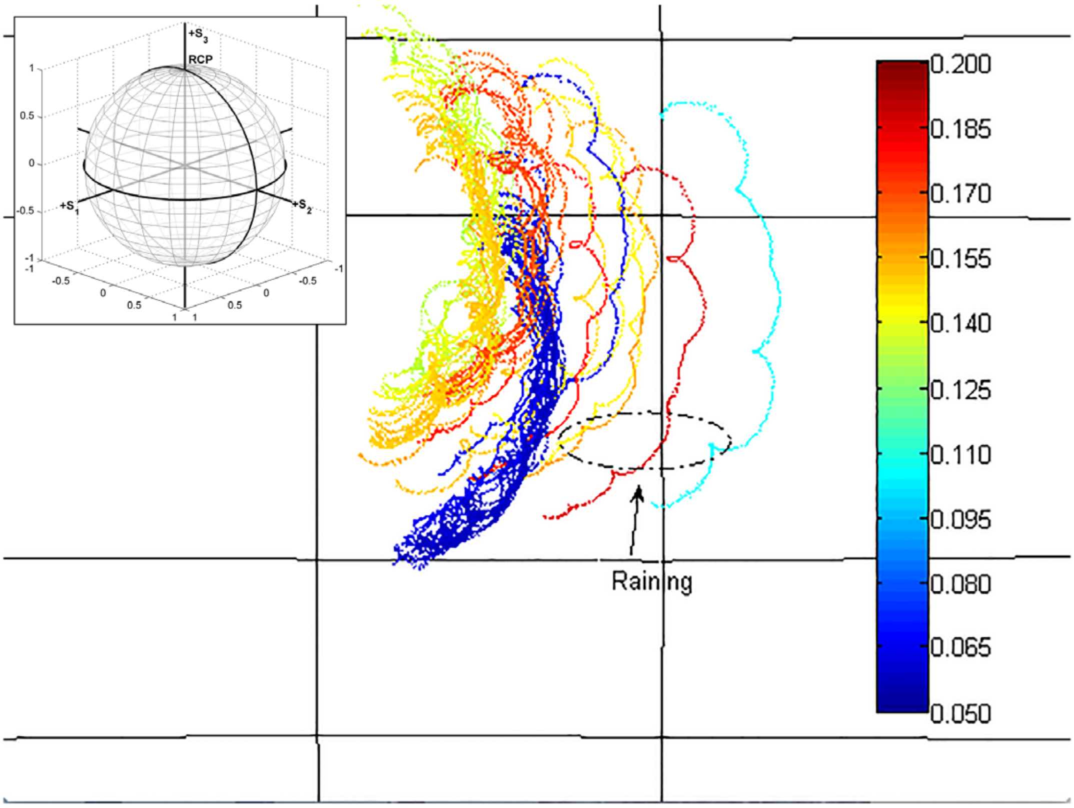

Figure 8. PMD signatures measured at the Playa site. Results are plotted on a Poincare sphere, shown in the inset, according to optimal visibility and are color coded relative to the soil moisture levels measured by a ground probe.

these measurements were found to be much less susceptible to impacts from wind.

4. Conclusions

A new approach for remote soil moisture sensing using radio frequency transmissions and reception of associated polarimetric responses from terrain-based reflections was investigated using newly developed transmitter/receiver hardware deployed during the MATERHORN field experiments. Data were collected at two different scales, on the order of 80 m at the Playa site and of 420 m at the Small Gap between Granite Peak and Sapphire Mountain at the US Army Dugway Proving Ground, Utah; these two scales are compatible with microscales and mesoscales, respectively (Orlanski 1975). Measurements at both sites were compared with soil moisture measurements from an *in situ* ground probe, and demonstrated a good correlation with the ground probe data. The particular antenna mast installation proved to be susceptible to vibration caused by the wind, and the impact of the vibrations were more severe for the field-scale deployment. Such susceptibility can be eliminated with an improved antenna mast installation.

Issues such as sensitivity and resolution also factor into the interpretation of the responses. The sensitivity is largely determined by the RF signal-to-noise power ratio (SNR) and the power ratios of the reflected powers of interest to the other received signal components (SIR). As the SNR degrades, the PMD curves exhibit increased noise, limiting the sensitivity of the measurements. Also, for small SIR power ratios, the induced changes in the polarimetric curves from soil moisture changes will exhibit smaller deviations. Long integration times can be used to build up the SNR to help mitigate the impact of these limitations. Very large SNR (e.g. >70 dB) are possible due to the very low rate of change of soil moisture.

Some form of calibration is required to relate the PMD responses with soil moisture levels. The quality of these relationships as well as the quantization and interpolations used in these relationships will impact the resulting resolution.

The MATERHORN experiments have helped to demonstrate the feasibility of the general RF approach and have shown that the PMD responses are indeed correlated with the soil moisture. Overall, the field results illustrate the favorable performance of the technique for soil moisture sensing using PMD. In the future, we plan to improve our collection and analysis capability and to explore the sensitivity and resolution of the approach. We anticipate collections that will not be sensitive to wind (through the use of better-anchored masts), and that will involve longer duration collections at each sampling interval. The longer sampling intervals facilitate identification and filtering of other external impacts on the measurements and enable high SNR estimates. Our results indicate that the approach is extremely sensitive to moisture changes. That is, without considering other external factors, a change is soil moisture will induce a measurable change in the RF response, assuming sufficient SNR, which is a motivation for incorporating long-duration sampling intervals. However, the response is also sensitive to other factors that have to be eliminated or isolated (wind vibration, human activity, temperature effects (Njoku *et al* 2003), etc), and to the extent that they cannot be controlled, their contributions can potentially complicate the interpretation of measured responses. Assuming perfect measurements, calibration is still required to invert the measured responses to soil moisture. In the future, the equipment will be augmented to transmit orthogonally-polarized signals, which can potentially be exploited using channel sounding to estimate soil moisture without requiring a calibrated inversion scheme, although soil composition estimates would likely be required.

Acknowledgments

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