

# SOIL MOISTURE EXPERIMENTS 2005 (SMEX05): PASSIVE MICROWAVE POLARIMETRIC SIGNATURES OF SOIL MOISTURE AND VEGETATION

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## ABSTRACT:

Microwave remote sensing provides a direct measurement of soil moisture; however, there have been many challenges in algorithm science and technology that we have faced on the path to providing global measurements. Field experiments, especially those involving both ground and aircraft measurements, provide the linkage between spatial scales necessary for both algorithm development and validation. Soil Moisture Experiments 2005 (SMEX05) was designed to address algorithm development and validation related to several current and scheduled satellite systems that can provide soil moisture. The Airborne Polarimetric Microwave Imaging Radiometer (APMIR), an aircraft simulator of WindSat, was flown on a P3B aircraft over an agricultural domain (corn and soybean) in Iowa, USA. Early morning flights were conducted for several weeks from late June to early July 2005. Efforts in SMEX05 to focus on the early morning time frame offered an opportunity to understand the effect of dew on microwave emissions, which could contribute to improved microwave soil moisture algorithms for satellites with early morning observation times. From the analysis on the preliminary data it was found that 1) the effect of dew on both H and V is small and 2) as dew evaporates the emissivity increases, which suggests a "standing water" effect. Expected differences between forest and crop sites and between polarizations were observed. These preliminary results will be refined following further calibration of the APMIR data.

## 1. INTRODUCTION

Microwave measurement of soil moisture at large scale is crucial for understanding the land-atmosphere interaction, global circulation, and carbon cycling. Major efforts are being made towards the goal of routinely providing accurate satellite-based soil moisture products. Operational moderately low frequency instruments include the Advanced Microwave Scanning Radiometer - EOS (AMSR-E), WindSat radiometer and Conical Scanning Microwave Imager/Sounder (CMIS), and exploratory L-band radiometer, Soil Moisture and Ocean Salinity Mission (SMOS). All of these are capable of retrieving global soil moisture. However, there are still many issues in algorithm science and technology that need to be carefully considered. For example, research is needed to fully exploit the operational satellite instruments, recognizing limitations of these sensors in terms of Radio-Frequency Interference (RFI) mitigation, spatial resolution and vegetation attenuation; and the effects of early morning dew, intercepted rain, and topography also need to be evaluated. Carefully designed field experiments, especially those involving both ground and aircraft measurement, provide the opportunities to study these issues and the datasets necessary for algorithm development and validation.

## 2. SMEX05 DESCRIPTION

Soil Moisture Experiments 2005 and Polarimetry Land Experiment (SMEX05/POLEX) was designed to address algorithm development and validation related to all of the current and scheduled soil moisture satellite systems. Intensive ground sampling concurrent with aircraft and satellite observations were conducted during the experiment. Key objectives of SMEX05 include: 1) exploration of the unique polarimetric information for soil moisture and vegetation, 2)

investigation of the diurnal effects associated with soil, vegetation and atmosphere at the 6 am/6 pm observing times of satellites such as SMOS and WindSat, 3) study the effect of dew on microwave emission, 4) evaluation and mitigation of RFI at low frequencies, and 5) enhancement of WindSat and Aqua AMSR-E soil moisture algorithms.

### 2.1 Experiment Site

In order to satisfy the requirements of the multiple objectives of SMEX05, a regional study area in Iowa and the more intensively measured Walnut Creek watershed were selected to provide a data set for the analysis of polarimetric observations for a range of vegetation structures and water contents. Walnut Creek Watershed is an ideal study site since it has been the focus of research by the USDA ARS National Soil Tilth Lab. It was also the region used in SMEX02.

Nearly 95% of the region and watershed is used for row crop agriculture. Corn and soybean are grown on approximately 95% of the row crop acreage, with greater than 50% in corn, 40-45% in soybean and the remaining 5-10% in forage and grains. The watershed is representative of the Des Moines Lobe, which covers approximately 1/4 of the state of Iowa. The area around central Iowa is considered the pothole region of Iowa because of the undulating terrain. Surface organic matter contents often range from 1-2 % to over 8% in a transect from the pothole areas to the eroded knolls within the same field. These features create a potential condition in the spring and extremely wet summers of a soil surface covered with random water-filled potholes. The climate is humid with an average annual rainfall of 835 mm. The heaviest precipitation months are May and June (about 1/3 of the annual total) Rainfall events in the spring and summer are often thunderstorms, providing brief and intense showers. The topography is characterized by low relief and poor surface drainage. Conventional tillage is most widely

used; however no tillage and ridge tillage have been recently introduced.

## 2.2 WindSat

WindSat is the first spaceborne polarimetric microwave radiometer developed by the Naval Research Laboratory for the U.S. Navy and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) (Gaiser et al., 2004).

The WindSat radiometer was launched as part of the Coriolis mission in January 2003. WindSat is a conically scanning radiometer providing both fore (1025 km swath) and aft (350 km swath) looking observations. The nominal earth incidence angle is in the range of 50 – 55 degrees. The inclination of the WindSat orbit is 98.7 degrees. It has a sun synchronous polar orbit with an ascending node at 6:00 PM and a descending node at 6:00 AM. The WindSat radiometer has frequencies similar to AMSR-E, but lacks the 89.0 GHz channel. Moreover, it provides fully polarimetric observations at 10.7, 18.7 and 37 GHz. The launch of WindSat has provided an opportunity to study the polarimetric signals of land surface from space. Previous studies of the Taklamakan Desert and Heilongjiang agriculture area in China showed that Windsat could observe systematic variations in the 3rd and 4th Stokes parameters from land surfaces with aligned features (Narvekar et al., 2007).

## 2.3 Airborne Polarimetric Microwave Imaging Radiometer (APMIR)

The primary aircraft instrument of SMEX05 is the Airborne Polarimetric Microwave Imaging Radiometer (APMIR). APMIR was designed and built by the Naval Research Laboratory as a tool for calibration and validation (cal/val) of the Coriolis WindSat and Defense Meteorological Satellite Program SSMIS satellite microwave radiometer sensors. Additional goals in developing APMIR were to provide data for improving retrieval algorithms and to serve as a cal/val tool for the NPOESS CMIS instrument. APMIR has multiple frequencies and polarizations to match the relevant satellite channels; however, only the C- and X-band channels were operational for SMEX05. X-band is fully polarimetric by way of polarization combining. APMIR can be operated in a non-scanning or conically-scanning mode. For SMEX05 only non-scanning was used. APMIR parameters are listed in Table 1. The sub-band design of APMIR shown in Table 1 is especially helpful to detect and mitigate RFI, which has become a serious problem for observations at C-band. In SMEX05, APMIR was flown between 6 am to 10 am local time at a 0.9 km altitude on the Navy P3B.

Table 1 SMX05 APMIR parameters based on 53 degree incidence angle and 0.9 km altitude

Channel (GHz)	Beam width (Deg)	Footprint (km)
6.6, 6.8, 7.2	9.4	0.24 x 0.42
10.7	5.9	0.15 x 0.27

## 2.4 APMIR Missions

Three different types of APMIR science missions were flown over the Walnut Creek Watershed during the experiment.

### 2.4.1 Watershed mapping

This mission is intended to provide the critical data base for soil moisture algorithm and polarization effects studies. As shown in Figure 1, a total of eight different flight lines were flown, seven of which were east-west oriented flightlines that were designed to provide nearly contiguous coverage of the watershed area. The nominal length of these lines was 45 km. Lines were flown east-west with alternating headings. It is important to note that the instrument was rotated 180 degrees in azimuth (with respect to the aircraft) so as to always point in the same compass direction. Measurement differences could occur for different pointing directions as previous experience with aircraft instruments and work in this region indicated. These can be related peculiarities of the installation, RFI, or sun angle.

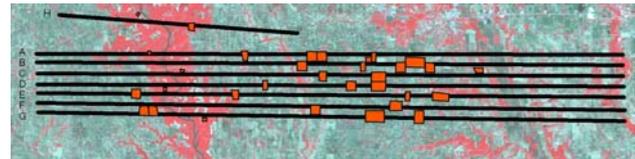


Figure 1. APMIR low altitude mapping. (Black lines are for APMIR flight lines, red rectangles are intensive sampling sites and background image is a Landsat Thematic Mapper false color image of the Walnut Creek Watershed).

### 2.4.2 Temporal variations

One of the science objectives of SMEX05 concerns the diurnal nature of microwave brightness temperature and its relationship to the characteristics of the atmosphere, vegetation, and soil. Linking the morning and afternoon observations of WindSat and those of AMSR-E requires the study of the changes that occur over the day. One that may be of concern, especially for WindSat, is the presence of dew and low-level atmospheric moisture on the brightness temperature. Very little research has been conducted to address these issues (Jackson and Moy, 1999).

In SMEX05, two east-west lines were flown repeatedly between 0600 LT and 1000 LT on June 30th with supporting ground sampling to characterize the physical variables. Figure 2 shows the flight pattern. The observed brightness temperature changes with time will be used to study the effects of dew on the microwave emission from the land surface.

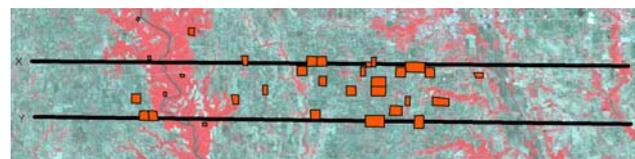


Figure 2. APMIR low altitude temporal variations (Black lines are for APMIR flight lines, red rectangles are intensive sampling sites and background image is a Landsat Thematic Mapper false colour image over the Walnut Creek Watershed).

### 2.4.3 Azimuthal effects

This mission was designed to examine the azimuthal dependence of brightness temperature for a number of fields by flying over a single point from eight different directions at low altitude in an asterisk pattern. WindSat data analysis (Narvekar et al, 2007) has indicated that such an azimuthal dependence is significant and related to measurement geometries, and thus must be quantified and separated from effects resulting from other geophysical variations. Figure 3 illustrates the general flight pattern of this mission. Each line took about 12 minutes.

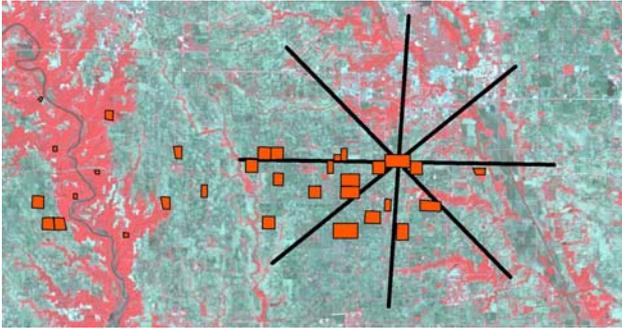


Figure 3. APMIR low altitude azimuthal effects (Black lines are for APMIR flight lines, red rectangles are intensive sampling sites and background image is a Landsat Thematic Mapper false colour image over the Walnut Creek Watershed).

### 2.5 Field Conditions and Data Collection

SMEX05 was conducted between June 15 and July 3. Soil moisture, soil temperature, soil properties and vegetation measurements were made in 16 corn, 9 soybean, 4 forest and 1 alfalfa field. In addition, dew (leaf wetness) sensors were installed at a number of locations and physical measurements of the amount of dew content were made within corn, soybean and alfalfa sites. During the experiment the vegetation water content of corn increased from 1.35 to 5.68 kg/m<sup>2</sup> and soybean increased from 0.52 to 4.17 kg/m<sup>2</sup>. A significant precipitation event occurred during the study prior to the June 26 APMIR flight.

The satellite and aircraft datasets collected during SMEX05 period are summarized in Table 2. Problems with a geo-referencing system required extensive post-processing of the APMIR data, which has delayed analyses. The calibration of the APMIR channels is currently ongoing. Preliminary data are used here and must be carefully interpreted. Only the H and V data are used here.

Table 2 Aircraft and satellite datasets and precipitation during SMEX05 (\*M - mapping; T - temporal variations; A - azimuthal effects)

Date	APMIR	WindSat	AMSR-E	Precip
June 19	M, A	X	X	-
June 20	M, A	X	-	-
June 21	M, A	X	X	X
June 22	M, A	-	X	-
June 23	-	-	-	-
June 24	-	-	X	-
June 25	-	X	-	-
June 26	M, A	X	X	X (heavy)
June 27	M, A	-	-	-
June 28	-	-	X	X
June 29	-	-	-	-
June 30	T,A	X	X	X
July 1	M, A	X	X	-
July 2	M, A	X	-	-

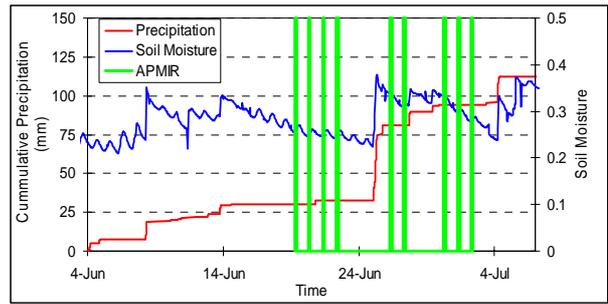


Figure 4. Accumulated precipitation, volumetric soil moisture and APMIR observation time

### 3. TEMPORAL VARIATION FLIGHTS RESULTS

For both current in-space satellites such as WindSat and the scheduled SMOS, dew effects need to be carefully studied because observations are made during a time of day when dew can occur, early morning. Previous research on this issue have come to different conclusions. In the recent studies, De Jeu et al. (2005) reported that dew noticeably increased L-band microwave emission of grass while Hornbuckle et al. (2006) observed a decrease in L-band brightness temperature for a maize canopy in which dew was present. In SMEX05, the effect of dew on land with varying vegetation cover was studied by combined aircraft and field measurements. C-band and X-band observations were used to study the effect of dew on microwave emissions, which are more likely to be affected by dew than L-band observations.

On June 30 the aircraft flew an ellipse five times between 6:45 am and 9 am (local time) over the same locations. Blocks of corn, soybean, and forest fields along the flight lines were identified (some of these included ground sampling) as shown in Figure 5. During the experiment, dew was measured by two methods, Leaf Wetness Sensor and physical sampling. The Leaf Wetness Sensor employed in SMEX05 is designed to simulate the surface area of a leaf. It is primarily used to determine the percentage of time that a surface (i.e., leaf surface) is wet versus dry. The electrical resistance of the surface is measured and gives an indication of the amount of dew present.

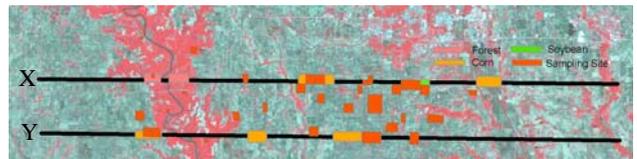


Figure 5. APMIR dew flights and studied feature blocks (Black lines are for APMIR flight lines, rectangles are selected feature blocks and intensive sampling sites and background image is a Landsat Thematic Mapper false color image over the Walnut Creek Watershed)

Physical sampling involves measuring the weight of the water collected by filter paper from sampled leaves. The total amount of dew in a square meter can be calculated by using ancillary vegetation data including row density, row spacing, and leaf count. Figure 6 shows dew measured through physical sampling in two of the corn fields as a function of time. The measured dew was as high as 0.4 kg/m<sup>2</sup> at the start of the observation period. At the end of the aircraft microwave observation period (~9 am) the dew had decreased to 0.1 kg/m<sup>2</sup>. There was no dew left after 10 am on June 30. The amount of dew was a function of the location of the sampling site.

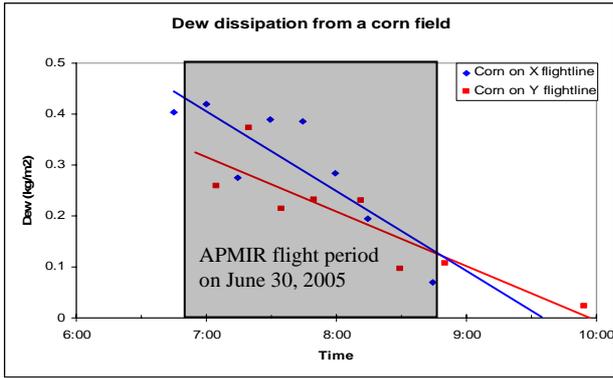


Figure 6. Dew dissipation from corn fields

The brightness temperature for each data block was calculated by averaging the APMIR measurements within the block. We attempted to adjust for temperature changes in the brightness temperature associated with time by computing emissivity using the in-situ surface temperature observations. Data from the C- and X-band H and V channels are plotted as a function of time as shown in Figures 7 to 10. In the figures, feature blocks along with the flight line X or Y are named sequentially from west to east. It can be seen from the plots that forest sites have a higher emissivity and smaller polarization difference than the other sites. At the same time, for both C-band and X-band observations, the V-polarized emissivity for all the feature blocks is always higher than H-polarized emissivity. These behaviors are consistent with theory. The figures also show that the C-band emissivity for forest sites increased by  $\sim 0.015$  while corn and soybean values increased by  $\sim 0.03$  during the flight time of about 3.5 hours. The increase in emissivity at X-band is greater than those observed at C-band. This suggests that dew has a greater effect at higher frequencies. As evident from Figure 6, there is a consistent decrease in dew to near zero over study period. This indicates that the presence of dew leads to a slight decrease of the emission from vegetated land observed here.

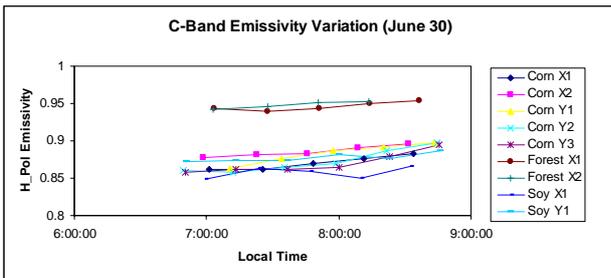


Figure 7. C-band H-Polarized emissivity variation with time

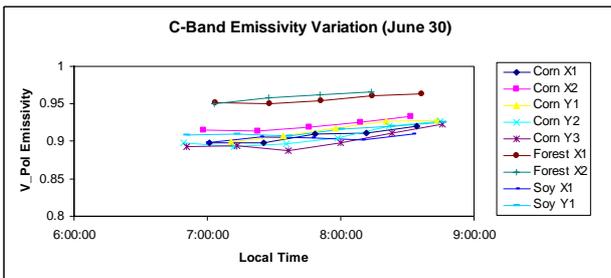


Figure 8. C-band V-Polarized emissivity variation with time

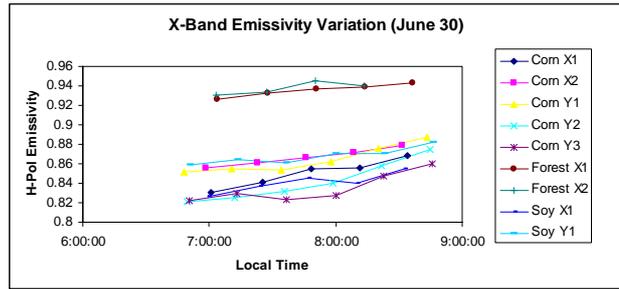


Figure 9. X-band H-Polarized emissivity variation with time

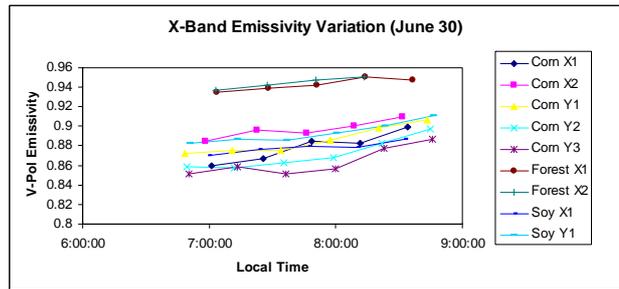


Figure 10. X-band V-Polarized emissivity variation with time

MPDI (Microwave Polarization Difference Index) was computed and is plotted versus time for both C- and X-band (Figures 11 and 12). MPDI is insensitive to surface temperature changes and a small MPDI value has been related to a possible dew event (De Jeu et al., 2005). MPDI is defined as

$$MPDI = \frac{T_{b\_V} - T_{b\_H}}{T_{b\_V} + T_{b\_H}} \quad (1)$$

As expected, forest sites had a lower MPDI than the other sites. However, there is not a clear trend of MPDI change with time. This may be related to the MPDI being sensitive to observation errors. Further results will be presented after APMIR data get fully calibrated.

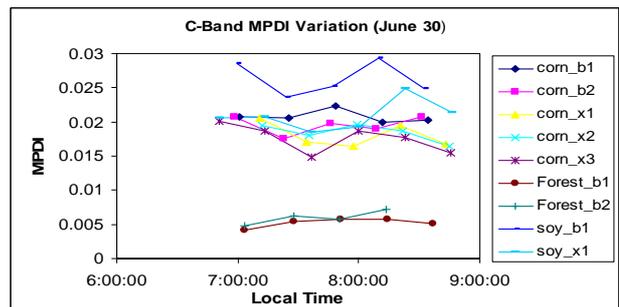


Figure 11. C-band MPDI variation with time

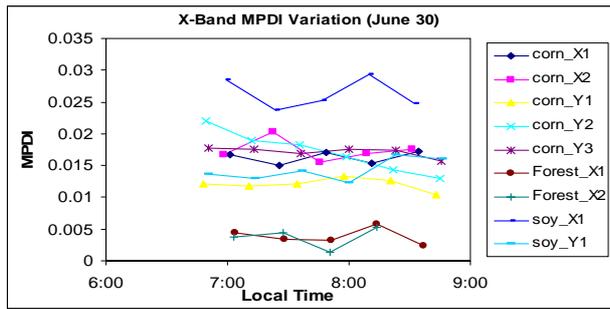


Figure 12. X-band MPDI variation with time

Analysis on the preliminary data suggests that 1) the effect of dew on both H and V is small, 2) as dew evaporates the emissivity increases, which suggests a “standing water” effect and matches the pattern observed at L band by Hornbuckle et al. (2006) and 3) expected differences between forest and crop sites and between polarizations were observed.

#### 4. SUMMARY

SMEX05 had multiple objectives related to polarimetric passive microwave remote sensing of soil moisture. Geo-referencing and calibration issues presented challenges that have resulted in some delays in processing and analysis. Some preliminary results of a sequence of flights designed to observe dew effects were presented. A small effect was observed that was consistent with the limited observations at L band. Upon completion of calibration all SMEX05 objectives will be addressed.

#### Reference

- Gaiser, P.W., K.M. St. Germain, et al., 2004. The WindSat spaceborne polarimetric microwave radiometer: sensor description and early orbit performance. *IEEE Trans. Geosci. Remote Sensing*, 42, pp. 2347-2361, 2004.
- Hornbuckle, B.K., England, A.W., Anderson, M.C., Viner, B.V., 2006. The Effect of Free Water in a Maize Canopy on Microwave Emission at 1.4 GHz. *Agricultural and Forest Meteorology*, 138, pp. 180-191.
- De Jeu, Richard A. M., Holmes, Thomas R. H., Owe, M., 2005. Determination of the effect of dew on passive microwave observations from space. *Remote Sensing for Agriculture, Ecosystems, and Hydrology VII. Edited by Owe, Manfred; D'Urso, Guido. Proceedings of the SPIE*, Volume 5976, pp. 51-59 (2005).
- Jackson, T.J., and Moy, L., 1999. Dew effects on passive microwave observations of land surfaces. *Remote Sensing Environment*, 70, pp. 129-137
- Narvekar, P.S., Jackson, T.J., Bindlish, R., Li, L., Heygster, G., and Gaiser, P.W., 2007. Observations of Land Surface Passive Polarimetry with the WindSat Instrument. *IEEE Trans. Geosci. Remote Sensing*, in press

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