PROGRESS REPORT
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Validation of the AMSR-E Brightness Temperature and Soil Moisture Products with Coupled Hydrologic/Radiobrightness Modeling

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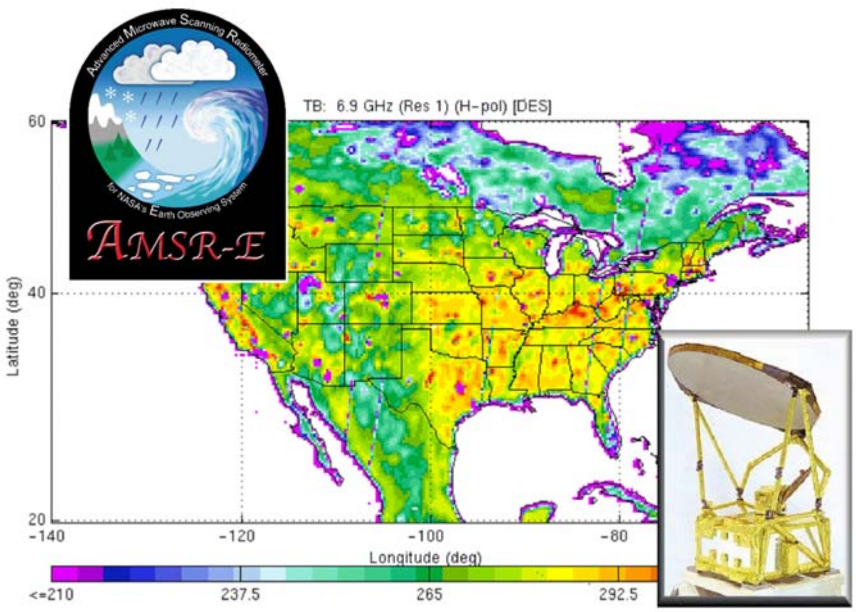
Validation Studies for Data Products from the Earth Observing System Aqua (PM) Platform and EOS-related Spectroscopic Studies



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I. SUMMARY OF RESEARCH APPROACH

Our research centers on utilizing a coupled hydrologic/radiobrightness model to provide "best estimates" of footprint-scale mean volumetric soil moisture and T_B at C and X bands with associated variance and confidence limits. This information provides quantitative validation of AMSR-derived soil moisture and C and X band T_B. Modeling is conducted at a high spatial and temporal resolution relative to AMSR observations. In so doing, we are able to evaluate a.) the errors associated with using limited GSM data or point-scale measurements of soil moisture from network stations to estimate footprint-scale mean soil moisture, b.) the errors associated with asynchronous sampling times, and c.) the relationship between surface moisture (~1 cm) and profile moisture. These analyses are necessary to characterize the accuracy of the AMSR data products at footprint scale. By applying the model in simulation mode we will assess the limits of roughness/soil/vegetation parameter values beyond which AMSR soil moisture retrievals are not possible. Comparison between these simulations and AMSR-derived T_B will identify areas where subpixel-scale heterogeneity warrants the use of effective parameter values or regions where AMSR C and X band soil moisture retrievals are not feasible.

Our hydrologic model produces soil moisture and temperature profiles that are utilized by the radiative transfer model to estimate T_B at C and X bands. Appropriate parameters for the radiobrightness model are derived by tuning the model to simulate T_B observations by the Polarimetric Scanning Radiometer (PSR). We run the model by assimilating soil moisture data from the various networks of *in situ* automated instruments, soil moisture derived from GSM data, and T_B derived from aircraft-based microwave instruments during the Soil Moisture Experiments in 2002 (SMEX02). We aggregate the high-resolution model-derived C and X band T_B to the AMSR footprint scale. We also run the model at the AMSR footprint scale using footprint mean parameters and variables. Because numerous uncertainties exist in defining the parameters and variables required for soil moisture modeling, model runs are being conducted using an ensemble of input data to derive the best estimate of the mean and variance of spatially-distributed profile soil moisture and T_B at C and X bands. The two model-derived T_B data sets are compared with the AMSR-observed C and X band T_B. The results of the ensemble runs will be analyzed and interpreted to address the AMSR validation issues.

II. ACCOMPLISHMENTS FROM THE PAST YEAR

The past year has been a busy one with much progress in this investigation. We have run our hydrologic model over the SMEX02 domain to produce soil moisture and temperature profiles that will be utilized in our radiative transfer model. In an attempt to better understand the contrast in brightness temperatures for different land cover types in the SMEX02 domain, we developed an algorithm to estimate field scale mean microwave brightness temperatures from aircraft data. This algorithm also has enormous potential for deconvolving AMSR-E data at the EASE grid scale to assess the extent to which the simplistic linear average resampling method of converting footprint values to EASE grid values is homogenizing the data set. Our independent field sampling program during SMEX02 combined with our modeling efforts also allowed us to investigate aspects of the relationship between the near-surface moisture profile, T_B and retrieved effective moisture. We also supported the SMEX03 experiment taking a leadership role in the planning and execution of sampling activities in the northern Alabama study area. Results from these activities are summarized below. Web pages are currently being overhauled and updated with this information.

A. Hydrologic Modeling

Soil moisture and temperature profiles were generated for the entire SMEX02 domain using our hydrology model SHEELS (Simulator for Hydrology and Energy Exchange at the Land Surface; Crosson et al., 2002). Meteorological data from the USDA SCAN site in Ames, Iowa and rainfall input from NOAA Stage III multisensor precipitation estimates were used as input. Through a series of SHEELS simulations, the soil parameters were calibrated to minimize any soil moisture biases with respect to *in situ* measurements. When the SMACEX flux tower data were recently obtained and analyzed, we discovered that the SCAN downwelling solar radiation data seemed to be too low. We have made a preliminary adjustment to these data and repeated the model simulations, but the effects on soil moisture appear to be minor.

B. Model Tuning for Brightness Temperature Simulation

Two methods were used to determine the best combinations of radiative transfer model input parameters for corn and soybean conditions during SMEX02. In the first method, hydrology model parameters were first tuned to minimize any soil moisture biases with respect to *in situ* measurements. The model profiles were then used as input to the radiative transfer model to estimate L-band brightness temperatures for each corn and soybean field in the SMEX02 domain. These estimates were compared with Passive and Active L and S band (PALS) observations and the surface roughness and vegetation b parameter were adjusted to minimize the mean differences between model and PALS L-band T_B. Data for July 2 and July 7, representing dry and wet conditions, respectively, were used in the calibration process. The best comparison with PALS L-band T_B was obtained using higher roughness values for June 25 than for July 7. As a compromise, the optimal surface roughness values for corn and soybeans were found to be 0.9 cm and 2.15 cm, respectively, and the vegetation b parameter values were set to 0.09 and 0.07.

The second calibration method was based on the soil moisture retrieval algorithm and served as both a sensitivity analysis and a parameter calibration exercise. A suite of 100 retrievals using L-band H-pol PALS brightness temperatures were performed to represent mean conditions for corn and soybean sites on June 25 and July 2, 6, 7 and 8. For each day and crop, representative T_B, T_{sfc} and T_{10cm} values were used as input to the inverse algorithm. T_B was defined as the mean of all 'pure PALS measurements' for the given day and crop. Pure PALS measurements are those centered over a corn or soybean field that is large enough that 95% of the energy sensed by the radiometer is from a single field. The retrieved soil moistures were compared with means from *in situ* measurements for the respective crop and day. Results of this analysis confirmed the conclusions of the first method—for the two dry days, higher roughness values were needed to produce soil moisture estimates consistent with observed values. For the three wetter days, a very consistent combination of parameters yielded good agreement with observations, but the roughness values were lower than for the dry days.

C. Development of Optimal Deconvolution Method

An optimal de-convolution (ODC) technique was developed to estimate microwave brightness temperatures of agricultural fields with contrasting biomass using microwave radiometer observations. Typically, the instantaneous field of view (IFOV) of air or space borne sensors is significantly greater than the spacing between adjacent footprints, i.e. the surface is over-sampled. Creating gridded data on spatial scales finer than the IFOV from the sensor observations results in significant smoothing. In an attempt to better understand the contrast in brightness temperatures for different land cover types at scales less than that of the footprint, we developed a technique to take advantage of microwave sensor over-sampling. The ODC technique uses the antenna response function of a microwave remote sensor to de-convolve the observed brightness temperature into field scale brightness temperatures. The sensor antenna response function is approximated on the plane normal to the beam axis and then projected onto the horizontal (Earth) surface to calculate the volume of this surface for each field scale element within the sensor footprint. Then a solution for an over-determined system of equations is found by minimizing the mean absolute difference between ODC-estimated and observed brightness temperatures. The resulting optimization improves the characterization of surface heterogeneity reflected in brightness temperatures, especially with respect to distinct transitions created by land cover boundaries.

The ODC technique can be effectively applied to other airborne microwave sensors supporting validation work, and may serve an invaluable role in validating soil moisture retrieved from space based sensors, such as the AMSR-E and HYDROS. The technique could be applied at the AMSR-E footprint scale to assess the extent to which the simplistic linear average resampling method of converting footprint values to EASE grid values is homogenizing the data set. This may prove especially useful in areas where there is strong T_B contrast among land cover types and significant influence by water bodies. A publication on the ODC technique has been accepted for publication in the journal *Remote Sensing of Environment*.

D. PALS Processing and Analysis

We tested the ODC technique using data from the PALS microwave instrument. PALS is a recent contribution to the inventory of aircraft-based instruments. The simultaneously passive and active instrument operates at L band (1.41-GHz radiometer and 1.26-GHz radar) and S band (2.69-GHz radiometer and 3.15-GHz radar) with dual polarization (fully polarimetric radar). The instrument is flown on a C-130 aircraft with the antennas viewing out the rear door directed downward behind the aircraft at an incidence angle of 45°. The instrument is non-scanning, thus a single-footprint track is sampled along the flight path. During SMEX02, PALS data were collected along 11 flight lines in the Walnut Creek region south of Ames, Iowa on eight days between June 25 and July 8, 2002.

PALS data comprise along-track T_B observations nominally spaced about 100 m apart. The IFOV of each observation is elliptical measuring about 350 m across track and 450 m along track. Thus, there is considerable footprint overlap in the along-track direction. Because the longest dimension of agricultural fields in the study area are typically either 400 or 800 m, there is considerable oversampling of each field by adjacent PALS observations. In reality, the dominant crop types in the study area, corn and soybean, have distinctly different brightness temperatures. Because of the high degree of oversampling, we can utilize the ODC technique to deconvolve the observed brightness temperatures into field-mean values. Field boundaries from a segmentation-based land cover classification were used to define the 'segments' within each footprint, the contributions from which were integrated over the antenna response function projected to the surface from the known look angle. In order to co-locate the land cover segments and PALS observations (called postings), the same fine resolution cell grid is used. All cell weights within a segment are integrated to determine the segment's fractional contribution to the overall posting. These contributions, normalized over all integrals within the field of view, yields a segment Gaussian fraction ranging from 0 to 1. Because of over-sampling, several PALS observations cover the same land cover segment but with varying Gaussian fractions. We de-convolve the observed brightness temperatures into field scale segment brightness temperatures with an optimization algorithm to partition contributions among adjacent field scale segments to PALS observations. The ODC-synthesized sensor brightness temperatures are calculated as the summation of all contributing land cover segment brightness temperatures multiplied by their respective Gaussian fractions. Since there are more equations (number of postings) than unknowns (segment TB), there is not a unique solution. Therefore, a solution is defined to minimize the difference between these ODC reconstructed posting brightness temperatures and the observations.

The optimal deconvolution approach produces better estimates of field or segment brightness temperatures as compared with conventional interpolation techniques (Figure 1). ODC-estimated brightness temperatures were shown to agree better with PALS pure postings segment T_B based on analysis in which the pure postings were withheld, thus providing an independent verification source. ODC estimates were also shown to better match the dynamic range of brightness temperatures between corn and soybean fields, whereas interpolated T_B unrealistically dampened the transitions between contrasting fields (Figure 1 and 2). Such increased fidelity in estimation of brightness temperature may result in improved retrieved soil moisture.

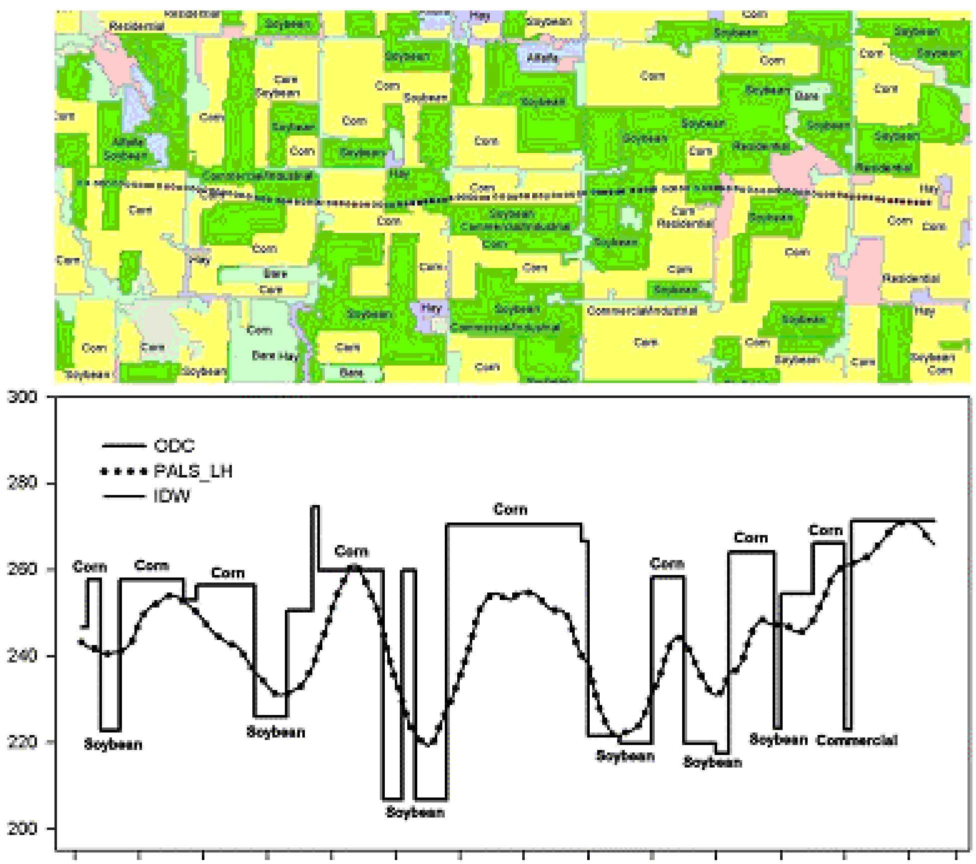

Figure 1. Transect of PALS postings (L band, H-polarization), land cover segmentation, inverse distance weighted (IDW) interpolation and underlying segment ODC brightness temperatures for July 7, 2002. The IDW or other similar methods reproduces the observations and results in considerable smoothing whereas the ODC method estimates field mean values thereby preserving sharp contrast between land cover types. Note that the IDW technique underestimates the range of T_B values in nearly all cases.

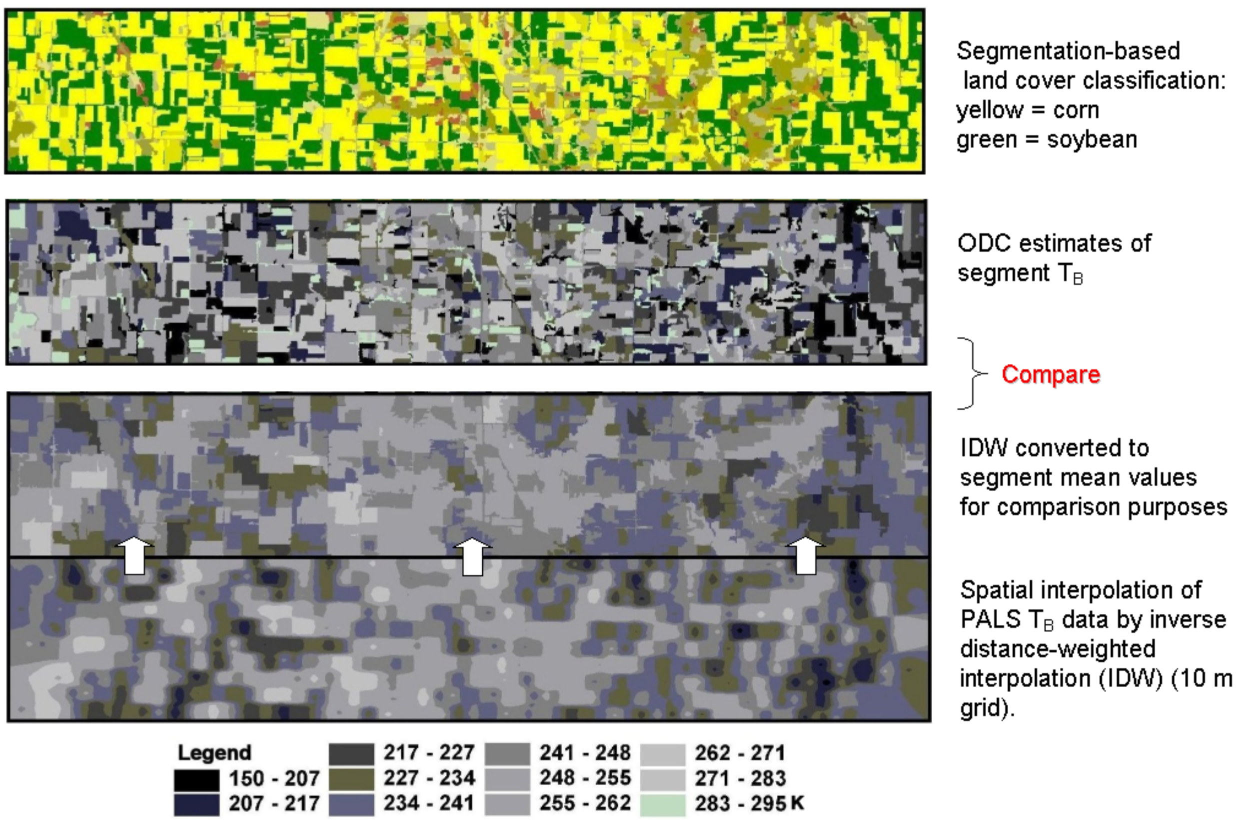

Figure 2. ODC segment T_B, inverse distance weighted (IDW) interpolated brightness temperatures averaged over each segment, and IDW estimates on a 10 m grid for the SMEX02 watershed study area on July 7, 2002. Yellow in the segments represent corn, whereas green represents soybeans.

E. Effect of Near-surface Profile on L and C Band Brightness Temperatures

Because observations of brightness temperature are more heavily weighted toward energy emitted closer to the surface, a source of error in soil moisture remote sensing validation studies stems from comparing mean observed moisture (ground truth) with retrieved (remotely sensed) moisture based on an effective brightness temperature. In validation studies, one commonly adjusts poorly constrained frequency-dependent parameters, such as corrections for scattering and vegetation optical properties, to minimize errors between retrieved and observed moisture. We chose to examine the magnitude of this error by simulating brightness temperature based on observed near surface moisture profiles versus mean moisture profiles.

During SMEX02, we made daily observations of the near-surface soil moisture and temperature profile on four fields in the local scale study domain. Radiative transfer modeling was conducted at L and C band (H-polarization) using data collected daily at each of the four study sites. Data collected on 13 days were used for the analysis. Brightness temperatures were computed using the observed soil moisture profiles for the 0-6 cm layer provided by the sliced core measurements at six locations at each site each day. Brightness temperatures were also computed using a mean moisture value for the 0-6 cm layer derived from the cores. Figure 3 shows the relationship between brightness temperatures computed using the observed versus mean (uniform) near-surface moisture profiles. Under wetter conditions (lower T_B), the brightness temperatures computed at both L and C band with the different profiles are in close agreement because under wet conditions, soil moisture profiles tend to be quite uniform. Under drier conditions, however, the brightness temperatures computed with mean profiles tend to be low relative to temperatures computed with observed profiles. This bias is much greater at C band than it is at L band. Under dry conditions, L band brightness temperatures computed with mean profiles average about 10 K lower than temperatures computed with observed profiles. Differences of as much as 20 K are not uncommon and in a few cases are as high as 30 K. Under dry conditions, C band brightness temperatures computed with mean profiles average about 15-20 K less than temperatures computed with observed profiles. In a few cases, the difference is as much as 30-35 K.

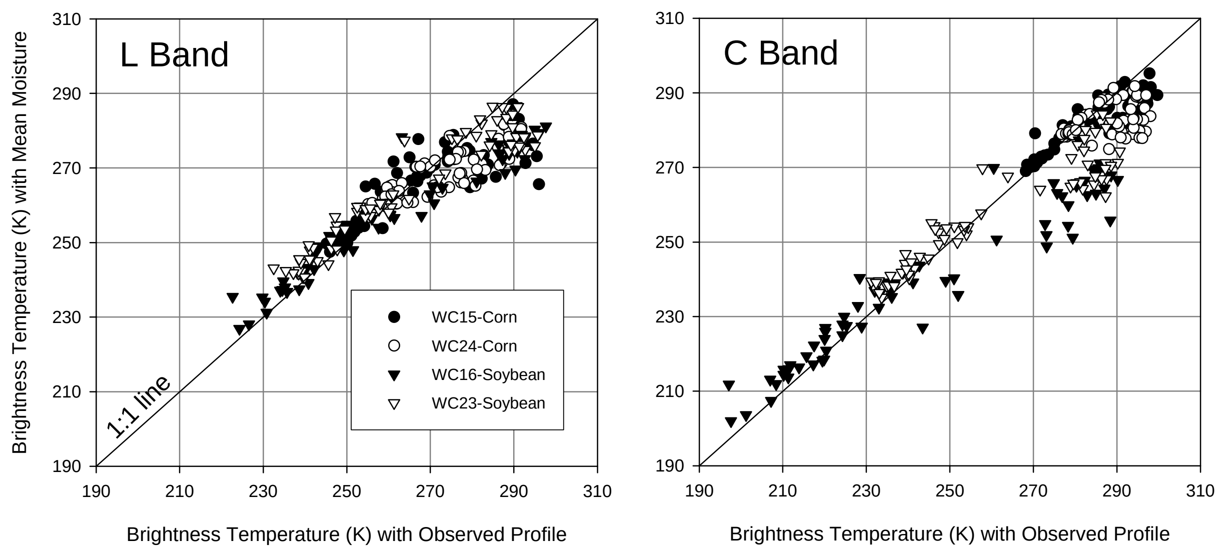

Figure 3: Comparison between brightness temperatures (L and C band) computed with observed moisture profiles and with mean near-surface moisture for four study sites.

F. Converting Brightness Temperatures to Effective Moisture Values

After quantifying significant differences in T_B from observed and mean moisture profiles, we investigated the extent to which the 'error' could be eliminated by converting brightness temperatures to effective moisture values rather than mean moisture values. Again, our SMEX02 data were used in a forward radiative transfer model to generate brightness temperatures at L and C bands. The brightness temperatures were subsequently inverted to retrieve soil moisture. A significant discrepancy was noted between the retrieved and observed moisture. Under relatively dry conditions, the observed moisture overestimates retrieved moisture by about 0.05 volumetric water content (vwc) and underestimates retrieved moisture by about 0.10 vwc under relatively wet conditions (Figure 4). This discrepancy exists in part because retrieved moisture is a depth-dependent effective value whereas observed moisture is a profile mean value. Although the inverse algorithm lumps errors from a number of sources, using the same soil and vegetation properties in the forward and inverse algorithms minimized the errors from many of these sources thereby permitting us to study this phenomenon.

We characterized the emitting depth responses as a function of depth for each observation and used them as weighting functions to convert the observed mean moisture to observed effective moisture. This effectively removed nearly one-half of the discrepancy noted between retrieved effective moisture and observed mean near-surface moisture. The only remaining difference between the forward RTM and the inverse algorithm is the manner in which the temperature profile is handled. We computed temperature coefficients from the RTM-generated temperature profiles for use in calculating effective temperature in the inverse algorithm. Doing so reduced some of the variability in the relationship between retrieved effective moisture and observed effective moisture, but reduced the bias only slightly. The source of the remaining bias is unknown at this time, but we believe that there is probably a residual temperature effect that is not accounted for in the current retrieval algorithm.

Although the results in this investigation are specific to a particular study area, they have important implications in remote sensing validation studies. Inverse retrieval algorithms are based on profile-dependent brightness temperatures and return an effective moisture value. We show that when near-surface moisture and temperature profile gradients are strongly developed mean moisture observations for the surface layer will underestimate the dynamic range of remotely sensed moisture. In large-scale experiments, generalizations are necessary regarding surface roughness and vegetation parameters. Uncertainties in the estimation of these parameters tend to distribute errors uniformly about a mean (Laymon et al., 1999). Tuning a retrieval algorithm with generalized surface roughness and vegetation parameters to reproduce ground-truth observations without first converting these ground truth observations to effective moisture values may impose a bias in the algorithm that will reduce the overall range in the retrieved moisture data set. Additionally, compensating for this bias by adjusting roughness and vegetation parameters may result in some unrealistic values associated with moisture extremes. The magnitude of the bias depends on the range of moisture conditions encountered and the specific nature of the profile gradients associated with the emitting depth. Such a bias would be rather permanent in an operational remotely sensed soil moisture data set and carried forth where these data are assimilated.

A manuscript on this topic has been submitted for publication in *Remote Sensing of Environment*.

G. PSR Processing

The Polarimetric Scanning Radiometer (PSR) was flown over the watershed and regional study areas during the SMEX02 experiment. The PSR C and X band instruments replicate AMSR-E channels and provide valuable insight into AMSR-E validation. In addition, because PSR is a conically scanning radiometer like AMSR-E, it provides a stepping-stone for application of our ODC technique. Recently, calibrated PSR data were made available via the NSIDC archive. Dr. Rajat Bindlish of USDA's Hydrology and Remote Sensing Lab provided us with some additional information—azimuth angles needed for ODC processing of PSR data. On each of the 10 days on which data were collected during SMEX02, the watershed flight lines were flown at a low altitude (1500m) relative to regional flight lines that were flown at a higher altitude (8500m). The ODC algorithm required modification to account for the different azimuth angle of each observation. With these modifications, the contributions from the underlying surface can be more accurately simulated.

We are presently in the process of performing ODC analysis on the PSR datasets. Our initial analysis of C band data at the watershed scale shows little sensitivity to varying moisture conditions and also to various vegetation types. We plan on comparing the observed PSR brightness temperatures with AMSR-E brightness temperatures at X band since the SMEX02 study domain had significant RFI contamination at C band. We also plan on comparing the X band PSR brightness temperatures with the modeled estimates. We are also interested in investigating the scale dependency of ODC technique over the SMEX02 watershed domain where we have coincident data at multiple scales.

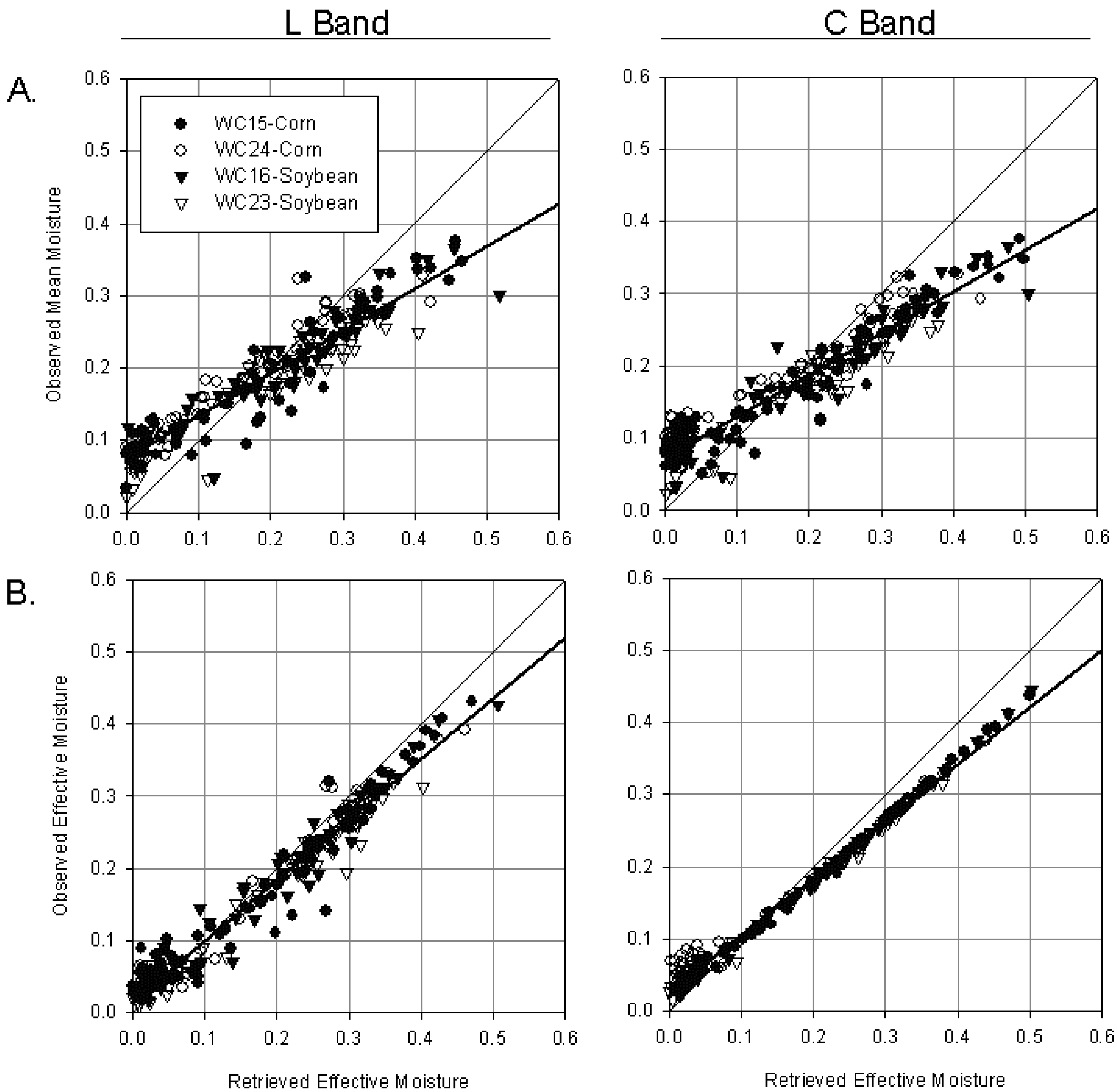

Figure 4. Comparison between (A) retrieved effective soil moisture and observed soil moisture, and (B) retrieved effective soil moisture with revised temperature coefficient and observed effective moisture. The 1:1 line and least squares regression (bold) are included.

H. Participation in SMEX03

All three investigators in this activity participated in the first phase of Soil Moisture Experiments in 2003 (SMEX03) field campaign in northern Alabama. SMEX03 is a joint USDA-Agricultural Research Service and NASA R&D experiment whose primary objectives were to validate soil moisture retrieval algorithms from NASA's AMSR-E and to test a new prototype aircraft-based sensor. To support this experiment, the NASA P-3B Orion aircraft was based in Huntsville, Alabama from June 23 to July 2. The aircraft was equipped with a payload of passive microwave remote sensing instruments to collect data on surface soil moisture. The aircraft flew five missions over northern Alabama and three missions near Tifton, Georgia. By all accounts the aircraft and instruments performed flawlessly. These missions were supported with ground sampling and measurements conducted by scientists and students from the Global Hydrology and Climate Center and Alabama A&M University. Dr. Laymon coordinated local preparations and logistical operations. Each day, eleven sampling teams dispersed to 59 sampling sites scattered across 50 x 125 km study area. These teams logged over 25,000 miles in the 10-day period. The second phase of the experiment took place in central Oklahoma from July 4 -19, and the final phase took place in Brazil in December. Data QC and associated documentation is complete for nearly all data sets and in preparation for delivery to NSIDC for archive and public access.

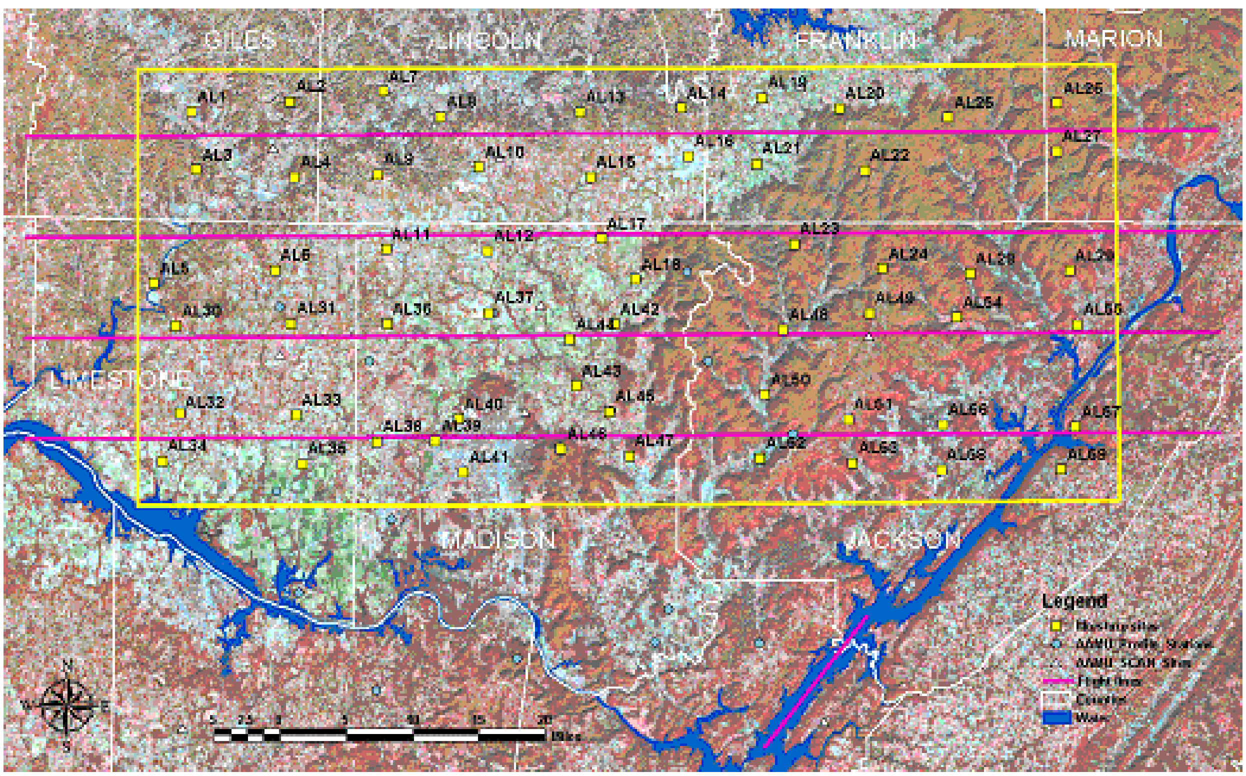

Figure 1: False-color image of the SMEX03 study area in northern Alabama and southern Tennessee. Daily sampling sites (yellow squares) and Orion P-3B aircraft flight lines (pink) are shown.

I. References Cited

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Crosson, W.L., Laymon, C.A., Inguva, R., and Schamschula, M., 2002. Assimilating remote sensing data in a surface flux-soil moisture model. *Hydrol. Processes*, **16**, 1645-1662.

Jackson, T.J., and Schmugge, T.J., 1991. Vegetation effects on the microwave emission of soils. *Rem. Sens. Environ.*, **36**, 203-212.

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Njoku, E.G., and Kong, N.-A., 1977. Theory for passive microwave remote sensing of near-surface soil moisture. *J. Geophys. Res.*, **82**, 3108-3118.

IV. Meetings Attended

1. AMSR-E Science Team Meeting, May 1-2, 2003, Huntsville, AL.

2. Soil Moisture Experiments in 2004 Planning Meeting, February 11-12, 2004, Tucson, AZ.

V. Presentations

Laymon, C., Crosson, W., and Limaye, A., 2003, Validation of aircraft and satellite remote sensing of brightness temperature and derived soil moisture using a hydrologic/radiobrightness model, P*roceedings of the 2003 IEEE International Geoscience and Remote Sensing Symposium*, Toulouse, France, July 21-25.

Laymon, C.L., Crosson, W.L., and Limaye, A.S., Analysis of uncertainties in AMSR-E brightness temperatures and retrieved soil moisture over the SMEX02 domain, P*roceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium*, Ankorage, Alaska, Sept. 20-24.

Crosson, W.L., Limaye, A.S., and Laymon, C.A., Soil moisture retrievals at field scale using aircraft-based C- and X-band Radiometer Observations in SMEX02, P*roceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium*, Ankorage, Alaska, Sept. 20-24.

Limaye, A.S., Crosson, W.L., and Laymon, C.A., 2004, Landcover-based optimal deconvolution of microwave brightness temperatures for improved soil moisture retrieval, *American Society for Photogrammetry and Remote Sensing*, Denver, CO, May 23-28.

VI. Publications

Laymon, C.A., Crosson, W.L., Limaye, A., Manu, A., Archer, F., Converting near-surface moisture observations to effective values for improved validation of remotely sensed soil moisture, submitted to *Remote Sensing of Environment*.

Limaye, A.S., Crosson, W.L., Laymon, C.A., Njoku, E.G., 2004, Landcover based optimal deconvolution of PALS L-band microwave brightness temperatures, accepted for publication in *Remote Sensing of Environment*.

Laymon, C., Crosson, W., and Limaye, A., 2003, Validation of aircraft and satellite remote sensing of brightness temperature and derived soil moisture using a hydrologic/radiobrightness model, P*roceedings of the 2003 IEEE International Geoscience and Remote Sensing Symposium*, Toulouse, France, July 21-25.

VII. Issues/Problems/Challenges

Other than some delays in data set availability, we did not experience any significant issues, problems, or challenges. Interactions with EOS investigators have been productive and uninhibited.

VIII. Plans for Completion

We are on schedule to complete our proposed effort on time. The hydrologic model will be rerun to generate field specific soil moisture and temperature profile information once the SCAN site solar radiation anomaly is resolved and a new correction for single scattering albedo is tested. In addition, an accommodation to run the hydrologic/radiobrightness model in ensemble mode is an outstanding task. Processing of the PSR data with our ODC algorithm is ongoing. These data will be used to tune the radiobrightness model to land cover type specific C and X band parameters. Following this, the RTM will be run to generate high-resolution brightness temperatures for the SMEX02 domain. We will compare our model TB results with AMSR-E observations, and compare modeled soil moisture with retrieved Level 3 soil moisture. Application of the ODC algorithm to the PSR data for SMEX02 will provide a third independent data set for comparison. The scale differences between the modeled and remotely sensed products will permit an assessment of AMSR-E product accuracies.