Analysis of coincident L-band radiometer and radar measurements with respect to soil moisture and vegetation conditions

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Abstract
Active and passive microwave remote sensing data offer complementary information on the properties of the observed scene. This study investigates the relationship of L-band radiometer and radar signals to vegetation and soil during four field campaigns conducted in United States between 1999 and 2008. The study shows complex relationship between radiometer observed reflectivity and radar observed backscatter over various landscapes, as expected. Vegetation classification was attempted with different in situ and remote sensing parameters but only a purely empirical combination of Vegetation Water Content and cross-polarized backscatter was able to successfully divide the observations into broad categories of high and low vegetation. The study suggests that a combination of radar and radiometer signal is necessary for establishing a parameter that can fully describe the vegetation state.

Keywords: Backscatter, brightness temperature.

Introduction
Microwave radar and radiometer measurements can be applied to the detection of soil moisture. One of the main challenges in the utilization of backscatter and brightness temperature for soil moisture retrieval is to remove the effect of vegetation from the observation. One of the benefits of using L-band frequencies (1-2 GHz) for the detection of soil moisture is their relative insensitivity to vegetation compared to higher frequencies. However, also at L-band the effect is significant and requires careful treatment [Njoku and Entekhabi, 1996]. The proposed NASA Soil Moisture Active and Passive (SMAP) mission is to measure global soil moisture and boreal land surface freeze/thaw state [Entekhabi et al., 2010]. The mission would be due for launch in late 2014. It would be one of the first-tier missions set forth by the latest National Research Council Earth Science Decadal Survey [National Research Council, 2007]. To fulfill its objective SMAP satellite would carry onboard conically scanning radar (active) and radiometer (passive) L-band instruments that would perform simultaneous and coincident measurements of the Earth’s surface. The combination of data from the two instruments would allow unprecedented combination of accuracy (0.04 cm³/cm³), spatial resolution (10 km) and temporal frequency (2-3 days) for global mapping of
soil moisture. Understanding of the geophysical relationship between radar backscatter and radiometer brightness temperature measurement under realistic conditions, including vegetated surface, is needed for optimal utilization of SMAP measurements. This is the motivation for this study. The relationship of airborne L-band radar and radiometer measurements is investigated against in situ parameters including soil moisture and vegetation characteristics.

**Data and Processing**

This study utilizes the data collected in soil moisture field experiments carried out in USA between 1999 and 2008. The campaigns applied to this investigation include:

- Southern Great Plain 1999 (SGP99) experiment in Oklahoma, July 8-14, 1999 [http://disc.gsfc.nasa.gov/fieldexp/SGP99/];
- Soil Moisture Experiment 2002 (SMEX02) in Iowa, June 25-July 8, 2002 [http://nsidc.org/data/amsr_validation/soil_moisture/smex02/];
- Cloud, Surface and Atmosphere Interaction Campaign 2007 (CLASIC) in Oklahoma, June 11-July 6, 2007 [http://acrf-campaign.arm.gov/clasic/];
- SMAP Validation Experiment 2008 (SMAPVEX08) in Maryland, September 29-October 12, 2008.

The campaigns took place over croplands and ranges during different seasons of summer and the measurements covered a wide range of soil moisture conditions with varying vegetation level. The in situ data includes samples of soil moisture, soil temperature, vegetation and surface roughness coincident with the remotely sensed data. The data set consists of almost 800 in situ records including soil moisture samples collected from 125 individual fields [Colliander et al., 2012].

PALS (Passive and Active L- and S-band) airborne instrument [Wilson et al., 2001] functions as a simulator for SMAP measurements in that it has simultaneous and coincident active and passive L-band measurement and it has the same incidence angle of measurement. The radiometer and radar frequencies are 1.41 and 1.26 GHz, respectively. The PALS was mounted on two different aircrafts in different configurations over the course of the campaigns. In SGP99 and SMEX02 the aircraft was a C-130 and the instrument was equipped with horn antenna [Njoku et al., 2002; Narayan et al., 2004]. In CLASIC and SMAPVEX08 the aircraft was a Twin Otter and the instrument was equipped with a microstrip antenna [Yueh et al., 2008; Bindlish et al., 2010]. The flight altitude of the aircrafts ranged from 1000 m to 3000 m and the beam width from 13° (horn) to 20° (microstrip) resulting in footprint of about 300 m to 1300 m. The relative accuracy of radar and radiometer were less than 0.2 K and 0.2 dB, respectively, throughout the campaigns.

The backscatter and brightness temperature obtained over the in situ sites were matched up with the in situ samples producing a consistent data set over all campaigns [Colliander et al., 2012]. In the subsequent analysis the backscatter is analyzed against reflectivity, which is obtained through brightness temperature and physical temperature of the surface as follows [Ulaby et al., 1981]:

\[
r_p = 1 - \frac{T_{R,p}}{T_{ph}} \quad [1]
\]
where $r_p$ is the reflectivity, $T_B$ is the brightness temperature, $T_{ph}$ is the physical temperature of the surface and the subscripted $p$ marks the polarization. The physical temperature of the surface was determined as the average of the skin temperature and temperature at the depth of 5 cm, which were available in the data set. The important difference between reflectivity and backscatter is that reflectivity corresponds to the fraction of how much of incident radiation is reflected in total while backscatter corresponds to the fraction of how much of incident radiation is reflected back to the direction of incidence [Peake, 1959].

Additional parameter used in the analysis is the so-called Radar Vegetation Index (RVI), which is retrieved from the co-polarized and cross-polarized backscatter signal. It is defined as follows [Kim and van Zyl, 2004]:

$$RVI = \frac{8\sigma_0^{hv}}{\sigma_0^{vv} + \sigma_0^{hh} + 2\sigma_0^{hv}} \quad [2]$$

where $\sigma_0$ is the normalized radar cross-section (NRCS) and the subscript denote the polarization of the transmitted and received signal: $vv$ denote NRCS measured from the vertically transmitted and vertically received signal, $hh$ denote NRCS measured from the horizontally transmitted and horizontally received signal, and $hv$ denote the vertically transmitted and horizontally received signal.

**Results**

The results of the analysis of backscatter and reflectivity values obtained in the field campaigns are presented in the subsequent sections. The analyses focus on comparing backscatter values against reflectivity with respect to additional observed parameters. The interaction of microwave emission and scattering with vegetation covered surface is a very complex process [Ulaby et al., 1982, 1986]. Figure 1 shows a qualitative classification of landscape types on an $r$-$\sigma_0$ diagram (backscatter vs. reflectivity) to four general categories. This is similar to the qualitative diagram in [Ferrazzoli and Guerriero, 2010], but drawn against reflectivity instead of emissivity. The quadrants of the diagram divide the $r$-$\sigma_0$ space in vegetated and non-vegetated landscapes with either wet or dry surface. The diagram lends itself to visualize the principal mechanisms of natural landscapes affecting the backscatter and emission processes. Non-vegetated dry surfaces fall into the first quadrant. The wetness of the surface is of course a relative term here and causes changes to both backscatter and reflectivity. Also, the surface roughness has significant impact on the backscatter and reflectivity (although less on reflectivity) [Du et al., 2000]. When wetness of the surface increases significantly but roughness is low the surface falls into the second quadrant. In an extreme case this category represents water surfaces, but similar relationship of backscatter and reflectivity are observed over wet and smooth bare soil surfaces. When the roughness increases so does the backscatter but the reflectivity has opposite trend. However, if the surface is very wet the reflectivity remains high too and the surface falls into the third quadrant. This combination of reflectivity and backscatter could also be observed for surfaces with vegetation over water surfaces, where vegetation increases backscatter while water surface increases reflectivity. Finally, when significant vegetation cover is added over natural soil surfaces the reflectivity decreases, but the scattering from the vegetation makes the backscatter remain high and the
landscape falls into the fourth quadrant. The thickness of the vegetation is a relative term as well. In the following subsections the results are analyzed in the context of this diagram.

**Backscatter vs. Reflectivity and Land Cover**
Figure 2 shows backscatter values against reflectivity obtained in the four campaigns discussed in Section 2. A distinction is made between different land cover types. The plots show that the relationship between backscatter and reflectivity for dense vegetation classes (corn and soy) is different from the relationship for sparse vegetation classes (wheat, grass and bare ground). Note that each class contains measurements over range of vegetation maturity. The dense vegetation classes have maximum reflectivity of about 0.15 for the vertical polarization and 0.25 for the horizontal polarization, while the maximums for the sparse vegetation classes are 0.25 and 0.40, respectively. This provides more quantitative basis for the qualitative diagram presented in Figure 1.

**Backscatter vs. Reflectivity and Soil Moisture**
Figure 3 shows backscatter against reflectivity with the value of the respective in situ soil moisture measurements. The average soil moisture value for each $r$-$\sigma^0$ combination is indicated with color. For producing these figures a $r$-$\sigma^0$ grid was created and all soil moisture values falling into a given grid point were averaged (the same method is applied also in the subsequent plots). Additionally, the standard deviation (STD) of the mean brightness temperature and backscatter over the in situ site was determined. STD values exceeding 4 K for brightness temperature and 2 dB for backscatter were rejected since this indicates that the heterogeneity within the collocation area induces uncertainties in the mean value that cannot be accounted for.

The plots in Figure 3 show that the soil moisture tends to increase toward increasing reflectivity and backscatter, as expected. There are, however, regions where soil moisture remains relatively constant while reflectivity and backscatter changes as was predicted in the qualitative diagram of Figure 1. These will be examined in more quantitative way in the following section. Additionally, Figure 3 shows a rough division between observations made under high vegetation conditions.
(Vegetation Water Content (VWC) > 2.5 kg/m² or VH >-22) and under low vegetation conditions (the rest). See Section 3.4 for more details on the basis of this categorization.

Backscatter vs. Reflectivity and Vegetation Water Content
Figure 4 shows backscatter against reflectivity with VWC. VWC is mainly descriptive of the attenuation of the vegetation layer [Levine and Karam, 1996]. The plot shows that in the region where VWC has high values (more than 2.5 kg/m²) the reflectivity is limited to less than 0.1 and...
0.15 for vertical and horizontal polarization, respectively (some sporadic high VWC values are also found outside these limits). This is consistent with the lossy layer effect of vegetation. Furthermore, in the region where the VWC has high values the vertically polarized backscatter is not less than about -20 dB and not more than about -10 dB, while the minimum and maximum are -25 dB and -5 dB respectively. In the case of horizontal polarization the backscatter value is not less than -20 dB while the minimum is about -25 dB, but the high-VWC region does reach the maximum backscatter. As discussed above it is expected that the backscatter is higher from vegetated surface than from bare surface as the lower limit of the high-VWC region would indeed indicate.

In contrast, the high backscatter values in the region where VWC is low suggests that there are some additional backscattering enhancing effects (other than soil moisture, see Fig. 3). These observations (made mostly in SMAPVEX08 campaign) indeed contain senescent vegetation which has low VWC but has a significant impact on the backscatter, but less so on the brightness temperature. This is a clear indication of the known effect of the dry biomass on the backscatter and the fact that VWC is inadequate descriptor of vegetation when it comes to backscatter.

![Figure 4 - Vegetation Water Content (VWC) against vertically (left) and horizontally (right) backscatter and reflectivity.](image)

**Backscatter vs. Reflectivity and Polarization of Backscatter**

As concluded in the previous Section backscatter is affected by VWC but depends on the structure and the dry biomass of the vegetation as well. Backscatter (and brightness temperature) has also polarization dependency as a function of a vegetation layer. Figure 5 shows the polarization ratio ($\sigma_{hh}^0/\sigma_{vv}^0$ or HH/VV) against vertically and horizontally polarized backscatter and reflectivity. HH/VV values tend to be on the high side (more than 1 dB) where VWC is high (more than 2.5 kg/m$^2$). Low values of HH/VV (less than -1 dB) are found where the vegetation is generally low (VWC less than 2 kg/m$^2$) and the surface is very wet (more than 0.25 m$^3$/m$^2$). In general it seems that HH/VV has correspondence with the VWC of Figure 4.

Figure 6 plots backscatter against reflectivity with VH ($\sigma_{hv}^0$) magnitude. VH is expected to increase with co-polarized backscattering and the plots show that this is indeed the case. On the other hand VH corresponds to volume scattering by vegetation and surface-vegetation interaction [Ulaby et al., 1986].
Figure 5 - Polarization ratio (HH/VV) against vertically (left) and horizontally (right) backscatter and reflectivity.

However, the highest VH-values are found in regions where VWC (Fig. 4) and reflectivity are low. These are the regions of the senescent vegetation layers. In this case of the combined data set of the four campaigns VH signal provides complementary source of information for predicting vegetation effects. Using the combined condition of VH > 22 dB or VWC > 2.5 kg/m$^2$ separates the data in two regimes: one with low influence from vegetation and another with high influence from vegetation (Fig. 3 shows this categorization). This approach was adopted in [Colliander et al., 2012] for classifying the observations in high-vegetation and low-vegetation categories.

Figure 6 - Backscatter against reflectivity with cross-polarized backscatter on the color scale. Vertical polarization is on the left-hand side and horizontal polarization is on the right-hand side.

Figure 7 shows backscatter against reflectivity with RVI. Overall, RVI predicts well the senescent vegetation but the values for the high-VWC regimes seem relative low. Furthermore, there are high RVI values found in the regions where there is no indication of significant vegetation layer (most of these fields are pasture). It can be hypothesized
that for the regions of high VWC the relationship of the high attenuation in the vegetation layer with respect to the certain type of vegetation structure creates a situation where the value of RVI cannot become high. On the other hand, it may be that for the region of low co-polarized backscatter the normalization with respect to the extremely low VH does not work accurately. Finally, Figure 8 shows VH against RVI with VWC. This figure provides further evidence that the RVI and VWC are not particularly well correlated under the conditions in the analyzed experiments. This is not necessarily a negative thing since VWC is only partial descriptor of the vegetation as discussed above. The evaluation lacks overall comparisons to dry biomass and structure of the vegetation layer. One challenge is that the in situ data collected in these campaigns do not consistently include dry biomass and relatively few quantified descriptions of the vegetation structure.

Figure 7 - Backscatter against reflectivity with Radar Vegetation Index (RVI) on the color scale. Vertical polarization is on the left-hand side and horizontal polarization is on the right-hand side.

Figure 8 - Cross-polarized backscatter against Radar Vegetation Index (RVI) with Vegetation Water Content (VWC).
Conclusions

A study was carried out to investigate coincident airborne L-band radar and radiometer measurements against each other and in situ measured ground parameters. The applied data set is relative extensive and covers a wide range of soil moisture and vegetation conditions, but lacks in some aspects of vegetation structural information. This investigation supports the algorithm development of the proposed SMAP mission by increasing the understanding of the relationship between radar and radiometer signatures.

The study shows that the coincident and simultaneously measured brightness temperature and backscatter respond to the changes of soil moisture in a manner consistent with the conclusions of oftentimes separated research of radiometer and radar signatures. A critical factor in the detection of soil moisture is the vegetation layer on top of the surface. It was found out that Vegetation Water Content (VWC), cross-polarized backscatter (VH) and Radar Vegetation Index (RVI) respond differently to certain types of vegetation. The characteristic differences of these parameters were investigated. Study explains most of the observed effects. However, the results do suggest that none of the indicators alone can give an exhaustive answer of the most significant vegetation effects to both radar and radiometer measurements. Therefore, it seems that a combination of these parameters or utilization of additional or alternative parameters is required to solve the vegetation state accurately to the benefit of improved soil moisture detection. The combination of reflectivity and backscatter for creating more accurate parameter for describing the vegetation effects has been investigated further in [Colliander, 2011].

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