Azimuthal Signature of Coincidental Brightness Temperature and Normalized Radar Cross-Section Obtained using Airborne PALS Instrument

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Abstract – Coincidental airborne brightness temperature (TB) and normalized radar-cross section (NRCS) measurements were carried out with the PALS (Passive and Active L- and S-band) instrument in the SMAPVEX08 (SMAP Validation Experiment 2008) field campaign. This paper describes results obtained from a set of flights which measured a field in 45º steps over the azimuth angle. The field contained mature soy beans with distinct row structure. The measurement shows that both TB and NRCS experience modulation effects over the azimuth as expected based on the theory. The result is useful in development and validation of land surface parameter forward models and retrieval algorithms, such as the soil moisture algorithm for NASA's SMAP (Soil Moisture Active and Passive) mission. Although the footprint of the SMAP will not be sensitive to the small resolution scale effects as the one presented in this paper, it is nevertheless important to understand the effects at smaller scale.

1 INTRODUCTION

The airborne PALS (Passive and Active L- and S-band) instrument was used in the SMAPVEX08 (SMAP Validation Experiment 2008) campaign [2] to measure the brightness temperature (TB) and normalized radar cross-section (NRCS) at L-band during a period of several days over an area spanning tens of kilometers in Maryland and Delaware. SMAP (Soil Moisture Active and Passive) is a NASA mission to measure global soil moisture and boreal land surface freeze/thaw state [1]. The satellite will carry radar (active) and radiometer (passive) L-band instruments that will perform simultaneous and coincident measurements of the Earth's surface. The airborne PALS instrument is an airborne simulator for SMAP.

Electromagnetic theory and experimental results indicate that over certain type of surface and landcover both radiometer and radar measurements may experience signal modulation over the azimuth angle with respect to the measurement location. This effect may be due to reflection symmetry of the surface (e.g. [3]) or the Bragg scattering, or the combination of the two effects. In both cases, the first order requirement for this azimuthal signature to manifest itself in the measured signal of natural targets is essentially a periodic structure on the surface, sub surface (within penetration depth), or in the layer above surface of the measured medium. Over ocean surfaces the reflection symmetry phenomenon has actually been utilized to measure the wind vector (e.g. [4], [5]). However, in the observation of the water content in the soils the azimuthal signature may cause degradation in the retrieval if the effect is not accounted for in the forward modeling. At the same time, a critical factor in the azimuthal signature affecting the measurement is the ratio between the size of the periodic surface and the instrument footprint on the ground and orientation of periodic area, or areas. A large footprint effectively averages the surface features over the entire footprint area and, when considering realistic surface conditions distributions, the net effect of possible periodic surface structures within the footprint may reduce to negligible.

It is not expected that the resolution scale of SMAP, which ranges from 3 km of the synthetic aperture radar to 40 km of the radiometer, would experience significant azimuth effects such as the ones observed in this or many other experiments. However, it is nevertheless important for the mission algorithm development to understand the fine resolution scattering and emission behavior. These results can be used, for example, for model development and validation. To this end, this paper presents results obtained on one of the SMAPVEX08 campaign days when the PALS instrument measured a crop field in 45 degree steps over the azimuth. In the analysis the azimuthal behavior of both radar and radiometer measurement signals are quantified and the geophysical explanation discussed.

2 THEORETICAL BACKGROUND

The symmetry properties of Maxwell's equations affect the scattering and emission coefficients of media with reflection symmetry. Natural objects with periodically structured surface are generally reflection symmetric. The co- and cross-polarized radar cross-section and horizontally and vertically polarized brightness temperature have even symmetry and the third and fourth Stokes parameters have odd symmetry [3].

On the other hand, constructive summation of scattered waves takes place when the orientation of the structures and the relationship between the wavelength and periodicity is aligned in certain way. This is called Bragg scattering. Whereas the reflection symmetry causes smooth signature over the azimuth angle the Bragg scattering causes sharp enhancement of backscattering at the particular azimuth angle for, for example, crop rows.

The equations used for modeling the effect of the reflection symmetry are usually formulated as second-order Fourier series. For brightness temperature the equations are written as [6]:

$$\begin{aligned} T_{B,p} &= T_{B,p0} + T_{p1}\cos\phi + T_{p2}\cos 2\phi \\ T_{B,q} &= T_{q1}\sin\phi + T_{q2}\sin 2\phi \end{aligned} \tag{1}$$

where T_B stands for brightness temperature; $T_{p/q1/2}$ stand for the harmonic coefficients, in which p denotes either first or second Stokes parameter, or modified Stokes parameter [7], and q either third or fourth Stokes parameter; and ϕ stands for the azimuth angle with respect to the periodic surface. And for radar cross-section the equation can be written as [8],[3]:

$$\sigma^0 = A_0 + A_1\cos\phi + A_2\cos 2\phi \tag{2}$$

where $A_{0/1/2}$ stand for the harmonic coefficients.

On the other hand, the condition for the row structure of the surface to cause Bragg scattering can be formulated as:

$$n\lambda = 2d\sin\theta \tag{3}$$

where n stands for integer denoting the multiples of the wavelength, λ stands for the wavelength, d stands for the spacing of the periodicity, θ stands for the incidence angle.

It is expected that the response of PALS in SMAPVEX08 azimuth experiment is composed of these two components: reflection symmetry and Bragg scattering.

3 EXPERIMENT

The SMAPVEX08 soil moisture field experiment took place in Maryland and Delaware from September 29 to October 13, 2008. This study focuses on a set of flights carried out over one crop field growing soy beans.

In the campaign the PALS instrument was mounted on Twin Otter aircraft with incidence angle of about 40°. The flight altitude over the field was 1 km where the antenna with 20° beamwidth allowed footprint of about 450 x 600 m. The radar of PALS operates at about 1.26 GHz and the radiometer at 1.413 GHz. In the SMAPVEX08 campaign the PALS instrument was flown with an Agile Digital Detector (ADD) for mitigation of Radio Frequency Interference (RFI) [2]. The resolution of PALS radiometer and radar are specified in <0.2 K and <0.2 dB range, respectively. PALS flew over the field in varying azimuth angles in 45° steps over the full 360°. Figure 1 shows the ground tracks of the footprint centers over the field.

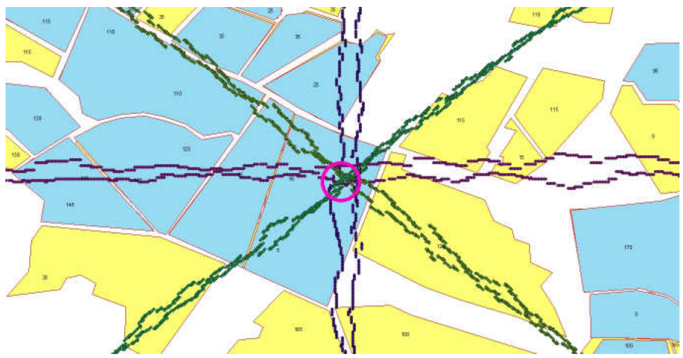

Figure 1. The ground tracks of the footprints in the 1-km altitude azimuth experiment. The magenta circle shows the area over which the data is analyzed.

The soy beans on the field were on mature state at the time of the experiment. The spacing between the rows was about 20 cm. The water content in the soil was relative high being slightly less than 0.3 cm^3/cm^3.

Figure 2 shows the row spacing which causes Bragg scattering under the conditions of the PALS measurements in SMAPVEX08 campaign as a function of the distance from the aircraft nadir point. The antenna beam and the beam incidence angles within the main lobe is collocated with the horizontal axis (the distance from nadir point) and marked with red color.

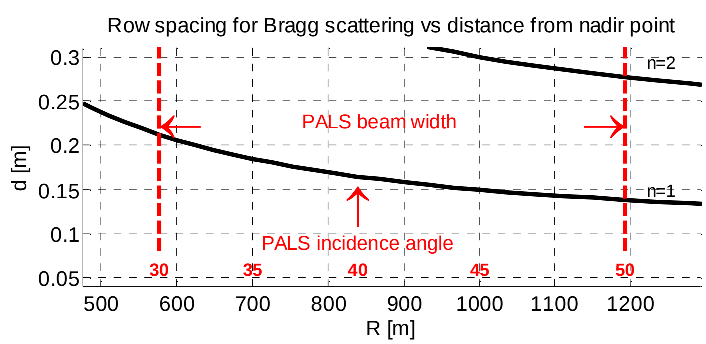

Figure 2. The row spacing allowing Bragg scattering as a function of the distance from the aircraft nadir point in case of n=1, 2 and 3 (multiples of wavelength).

4 RESULTS

The radar and radiometer measurements over the footprint intersection were binned based on the azimuth angle. The measurements were collected over a circular area with radius 250 m (see the magenta circle in Figure 1) and binned in 8 azimuth bins. Brightness temperatures and radar cross-sections in these bins were combined using the inverse distance squared weighting [9] to obtain representative values for TB and NRCS. Additionally, the standard deviations of the values in the bins were calculated to estimate the variance of the measurement at each angle.

Figure 3 shows the VV-polarized normalized radar cross-section (left) and the second Stokes parameter (which is defined as vertical polarization minus horizontal polarization) of brightness temperature (right) as a function of the azimuth angle (0º is parallel to the row structure). The error bars indicate the standard deviation of the measurement samples in the azimuth bins.

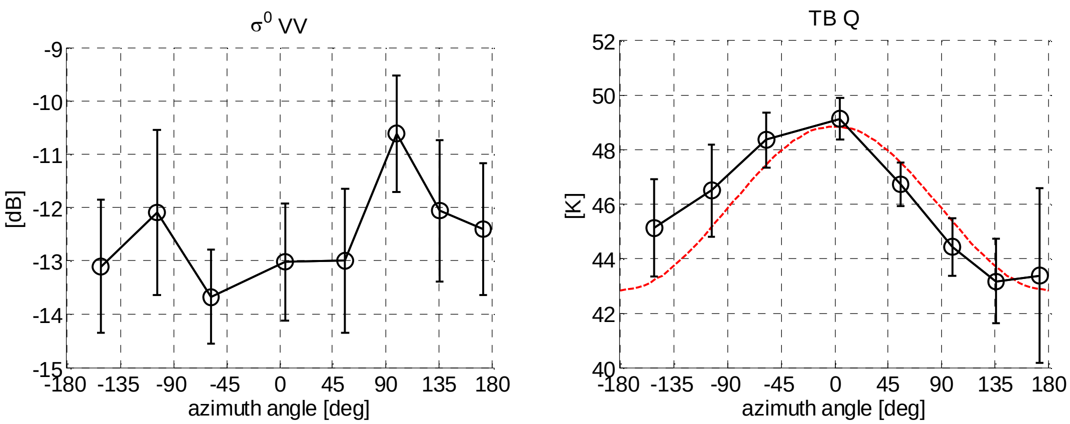

Figure 3. VV-polarized NRCS (left) and the second Stokes parameter (right) as a function of the azimuth angle. The error bars show the spread of the measurement made at that particular angle. The red dashed line on the TB plot shows a cosine curve fitted to the measurement points.

Figure 2 indicates that the row spacing of the field would cause Bragg scattering in one part of the footprint. This backscatter enhancement can be observed at -90º and 90º in Figure 3. This is consistent with Bragg scattering effect which occurs in perpendicular orientation from the row direction. The Bragg scattering contribution is in the order of 1 to 3 dB. The fact that the whole footprint does not satisfy the condition for the Bragg scattering obviously lowers the contribution (see Figure 1). The scattering symmetry effect, however, cannot be detected from the radar cross-section measurements.

In the second Stokes parameter measurement the signature is dominated by the first harmonic coefficient of the Fourier series in Equation (1). A cosine curve (dashed red line in Figure 3) is fitted to the measurement with about 3 K magnitude. This would imply that the medium under investigation, defined by mature soy beans over moist soil surface, would be reflection symmetric.

5 CONCLUSIONS

Airborne measurements of brightness temperature and normalized radar cross-section of a crop field over the azimuth were presented. The measurement results suggest that the mature soy bean field with distinct row structure invokes the backscatter enhancement under Bragg scattering conditions. Furthermore, observations of the second Stokes parameter suggest that the soil/soy bean medium has reflection symmetric properties. The result is expected for a fine resolution scale measurement of a homogeneous field surface such as the one in question. The result is useful in assessing the contribution of periodic structures on the forward models on small resolution scale. These results can then be combined at coarser resolution while accounting for the natural distribution of targets different types of targets.

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