SENSITIVITY OF TERRASAR X-BAND DATA TO SURFACE PARAMETERS IN BARE AGRICULTURAL AREAS

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ABSTRACT

The relationship between X-band Synthetic Aperture Radar (SAR) observations and soil moisture (SM) and surface roughness (SR) is investigated over well-monitored bare agricultural fields, using TerraSAR-X observations at 37.8° (VV and HH polarization) and 42.3° (VV and VH). TerraSAR backscatter increased with increasing SM but exhibited limited sensitivity, the highest (0.14 dB/m^3/m^3) being in the 0 - 0.03 m^3/m^3 SM range and for smooth conditions (SR < 1.5cm) and 37.8°. In such conditions HH- and VV-pol exhibited very similar sensitivity to SM. The impact of SR on the X-band signal was significant in the 0.5 - 1.5 cm range with a positive correlation for all polarizations and angles analysed, with observations at wider angles 42.3° being the most sensitive to SR.

***Index Terms*—** SAR, Soil Moisture, TerraSAR, Remote Sensing

1. INTRODUCTION

Synthetic-aperture radar (SAR) techniques are particularly attractive in the context of global soil moisture (SM) monitoring because they held the potential to monitor SM under any weather conditions and at very fine spatial resolution (down to 10's m) [1]. The German TerraSAR sensor provides multi-polarized X-band (9.5 GHz) SAR backscatters at ~1m resolution with time-steps varying between 1-5 days. Only a few studies have analysed the relationship between TerraSAR measurements and SM using field data, and these were concerned only with HH-polarization data acquired over European agricultural sites [2-6]. Those studies reported sensitivities of the HH-polarized X-band signal to SM (measured at 0-5 cm depth) ranging from 0.29 - 0.43 dB/m^3/m^3 for incidence angles 26°-52°. Moreover, the HH-pol X-band signal was more sensitive to SM at low incidence angle (20 - 25°) than at high incidence angle (40 - 50°). The highest sensitivity to surface roughness (SR) was observed at 50° for wet soils (SM > 0.25 m^3/m^3). This sensitivity however, weakened over rough surfaces (Surface heights Root Mean Square, rms > 1 cm). A complete understanding of the interplay between SM and SR for different soil types, incidence angles and polarizations is crucial to develop methods for coupling the data of different configurations in order to retrieve SM from dense time-series of TerraSAR data. The objective of this paper is to complement previous studies undertaken for HH-pol and European sites by analyzing the relationship of TerraSAR data to SM and SR at multiple polarizations (HH, VV and VH) over bare agricultural sites in Australia.

2. GROUND AND SAR DATA

The TerraSAR and ground SM and SR data used in this study were collected during the SM Active Passive Experiment (SMAPEx) conducted from September 5 - 23 in the Yanco study area in south-eastern Australia [7]. The Yanco site is a semi-arid agricultural and grazing area located in the western plains of the Murrumbidgee catchment (Longitude 146°10' E, Latitude 34°50' S). The site is flat and composed of silt loamy soils with average percentages of 12% clay and 36% sand. Approximately one third of the area is characterized by intense irrigation activity. Moderate rainfall in the first half of the experiment was followed by a dry-down period. Table 1 summarizes the timing of TerraSAR acquisitions and SMAPEx-3 airborne and ground data during the study period.

During SMAPEx-3 nine airborne flights were undertaken using L-band Imaging SAR with a revisit time of 2-3 days for L-band algorithm development for NASA's Soil Moisture Active Passive (SMAP) mission. Within this context, four X-band TerraSAR observations of the SMAPEx study area were available during the observation period (see Table 1). The scenes were acquired in stripmap mode (0.9 m x 2.4 m slant single-look resolution) and two configurations, VV & HH polarizations at 37.8° (ascending) and VH & VV polarizations at 42.3° (descending).

TerraSAR data was verified using 34 high-precision ground-control points collected using differential GPS, with a resulting accuracy of better than 10m. A total of 33 bare fields monitored during SMAPEx-3 were imaged by TerraSAR. These included a variety of tillage conditions (rolled, harrowed, ploughed and seedbed). Extensive ground monitoring of SM was conducted on each day of L-band coverage. SM was measured at 250 m-spaced locations. The 33 fields were monitored in rotation with a weekly revisit

Table 1 Acquisition Dates (dd.mm) of the TerraSAR data, cumulative precipitation (three days prior to acquisition), Rainfall recorded on the day (brackets) and mean and standard deviation (brackets) of 0 - 5cm Soil Moisture (SM) measured across the 33 bare fields analysed. DP[a] = Dual-Pol, ascending (HH, VV, 37.8°), DP[d] = Dual-Pol, descending (VH, VV, 42.3°).

SMAPEx-3 Date	Rain [mm]	Ground SM [%v/v]	TarraSAR-X
4.09	0 (0)	-	DP[a]
5.09	0 (0.2)	25.6 (8.3)	-
7.09	3.6 (3.4)	11.5 (1.8)	-
9.09	0 (3.4)	-	-
10.09	1.6 (1.6)	12.3 (4.8)	DP[d]
13.09	1.6 (0)	19.4 (8.1)	-
15.09	0 (0)	9.3 (4.0)	DP[a]
18.09	0 (0)	14.2 (12.6)	-
19.09	0 (0)	15.4 (8.4)	-
20.09	0 (0)	-	-
21.09	0 (0)	10.9 (5.6)	DP[d]
23.09	0 (0)	19.1 (14.1)	-

time, resulting in concurrent SM and TerraSAR observations for each field on 2 dates. Field-average SM covered a large range of wetness conditions, from 0.02 m^3/m^3 (completely dry) to 0.45 m^3/m^3 (near saturation). SR was measured once at 14 of the plots using 3-m long manual surface profilers at 1-3 locations depending on the field. The surface heights Root mean Square (rms) and correlation length (L) of the surface profiles, calculated after removal of periodic tillage structure from the profile, ranged between 0.5 – 4.6 cm and 2.6 - 30.8 cm.

3. METHODOLOGY

In order to reduce the measurement error noise associated with the SAR instrumental noise and speckle, X-band backscatter coefficients (σ^o) were linearly averaged for each field. With field sizes ranging from 1 - 50ha, the number of single-look pixels averaged per field was 4700 - 158000, resulting in negligible speckle noise (< 0.06 dB). Residual co-registration error was overcome by removing the boundary pixels (within 30m) before averaging σ^o. Ground SM and SR measurements were also averaged within each plot. The number of measurements averaged for each field was between 1 - 10 (SM) and 1 - 3 (SR), according to field size.

Since SM was sampled coincidently with L-band coverage, some X-band coverages did not have same-day coincidence with ground SM monitoring (September 4). In these cases SM from the closest available date (September 5) was matched with X-band coverage (see Table 1). Analysis of monitoring stations indicate that changes in SM during such a period were smaller than 0.01 m^3/m^3. Finally, data points were eliminated if surface tillage or irrigation had occurred between ground sampling and matching SAR acquisition.

The vectors of average X-band backscatter and SM and SR were then used to assess the statistical correlation and sensitivity of SAR observations to surface features.

4. RESULTS

The relationship between field-average σ^o and SM is shown in Fig. 1 for the four TerraSAR configurations. σ^o varied between approximately -14 dB and -8 dB (~ 6 dB dynamic range) for both HH- and VV-pol at 37.8°, with HH-pol σ^0 slightly higher than VV (by 0.5 dB on average). This range decreased to between -15 and -8 dB for VV at 42.3°. The VH-pol σ^0 was much lower (-21 to -17 dB, a 4 dB dynamic range) as expected for bare soils from theoretical considerations.

Backscatter coefficients exhibited overall a limited sensitivity to SM changes. Both HH- and VV-pol σ^0 at 37.8° increased in response to increased SM up to 0.3 m^3/m^3 domain, whereby σ^0 remained constant for SM up to 0.45 m^3/m^3. Regression analysis over the full SM range (see Table 1) indicates that the sensitivity of HH- and VV-pol σ^0 to SM at 37.8° was 0.05 and 0.04 dB/%m^3/m^3, which correspond to a change in σ^0 of a mere 1.8 and 2.2 dB between 0-0.45 m^3/m^3. However, when limiting the analysis to the 0-0.3 m^3/m^3 domain, the sensitivity nearly doubled, increasing to 0.08 and 0.07 dB/%m^3/m^3, correspondent to an increase in backscatter of 3.6 and 3.1 dB between 0-0.45 m^3/m^3 respectively for HH- and VV-pol (see Table 1). Therefore, at the lower incidence angles, HH-pol exhibited a slightly larger sensitivity to SM changes than VV-pol. At higher incidence angle (42.3°), the sensitivity to SM changes for both VV-pol and VH-pol was very low, resulting in a dynamic range of only 1 dB between 0 - 0.45 m^3/m^3. The availability of VV-pol observations at both angles showed that, despite the small range of angles available for this analysis (~5°), the larger incidence angle negatively impacted the sensitivity to SM.

The analysis presented so far and the values of dynamic range given in Table 1 indicate indicates that even in the case where the highest sensitivity to SM is observed (HH and VV-pol, 37.8° and SM < 0.3 m^3/m^3) only approximately 50% (~3.1 -3.6dB) of the total HH-pol and VV-pol σ^0 variability (5.9 - 6.3dB) can be attributed to SM changes. Assuming no residual calibration error in the SAR system, this variability must be associated to field-to-field variability in other surface conditions, like surface roughness, periodic tillage structures and soil texture.

The explore this further, the 33 fields were divided into three groups based on the presence and azimuthal direction of the periodic tillage structure relatively to the azimuth view angle

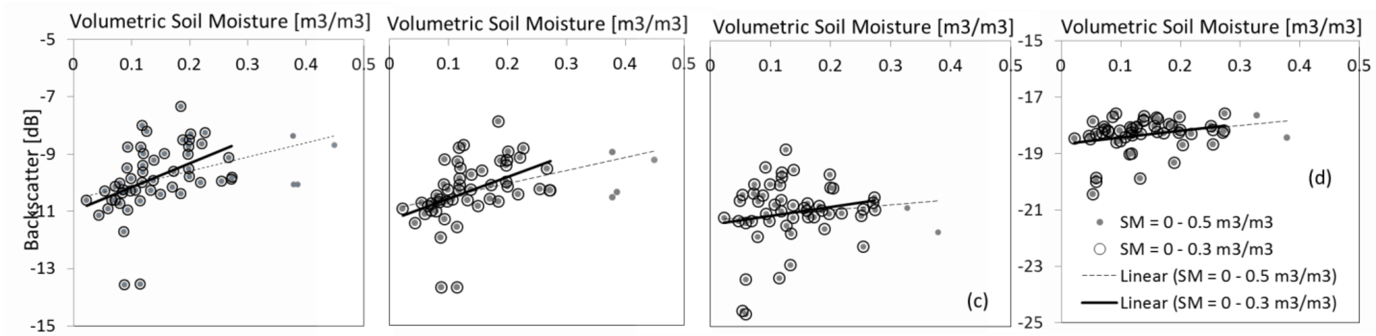

Figure 1. Relationship between ground-measured soil moisture (SM) for bare fields and TerraSAR backscattering coefficient at (a) HH-pol, 37.8°, (b) VV-pol, 37.8°, (c) VV-pol, 42.3° and (d) VH-pol, 42.3°. Each data point represents field-average values of SM and backscatter. Data point and regression lines are shown for different SM ranges, respectively 0 - 0.5 m^3/m^3 (gray dots and dashed line) and 0 - 0.3 m^3/m^3 (hollow circles and thick line). Note the different vertical axis scale for panel (d). Statistics of the linear regressions are listed in Table 1.

Table 1. Regression statistics between TerraSAR backscatter and ground-measured soil moisture (SM) for different SM ranges. R^2 = correlation coefficient, Sen. = slope of linear regression [dB/%m^3/m^3]. DR = dynamic range [dB].

TerraSAR channel	Total DR [dB]	SM = 0-45%m^3/m^3			SM = 0-30%m^3/m^3		
		R^2	Sen.	DR	R^2	Sen.	SE
HH - 37.8°	6.3	0.15	0.05	2.2	0.2	0.08	3.6
VV - 37.8°	5.9	0.15	0.04	1.8	0.2	0.07	3.1
VV - 42.3°	5.6	0.01	0.02	1	0.03	0.03	1.5
VH - 42.3°	2.9	0.07	0.02	1	0.07	0.02	1

of the TerraSAR sensor: Isotropic fields (no periodic tillage structure), Perpendicular field (presence of a periodic tillage structure with relative azimuth angle > ±45°), Parallel fields (presence of a periodic tillage structure with relative azimuth angle < ±45°).

Based upon this classification, the relative impact of SM and SR on σ^0 is explored in Fig.2 using the SR measurements conducted at 14 of the 33 bare soil fields. For this analysis only data point with field-average SM < 0.3 m^3/m^3 were considered as it was shown that that is the range of stronger sensitivity of σ^0 to SM. For easiness of display, only HH-pol (37.8°) and VV-pol (42.3°) are shown in Fig. 2 (statistics for all channels can be found in Table 2).

Overall a steep increase in σ^0 was observed in response to an increase in roughness rms between 0.5cm and approximately 1.5 - 2cm, whereby σ^0 was stable for rms > 2cm. The relationship was stronger in VV-pol, in association with the poor sensitivity to SM. Perpendicular fields (having an rms < 1.5cm) exhibited the strongest sensitivity to SR. All four SAR configurations exhibited a significant correlation to rms for perpendicular fields, the correlation being higher at 42.3° (R^2 = 0.7 - 0.8 & p = 0.002 - 0.001 for VV- and VH-pol). Note that the classification into surface types (isotropic, perpendicular and parallel) effectively resulted in a classification by range of rms, since perpendicular and parallel fields, being subjected to tillage, presented smoother surfaces at the soil clod scale, once the periodic structure was removed from the profile. Therefore it can be inferred that the strong sensitivity σ^0 to SR observed for perpendicular fields reflect the behavior of smooth surfaces (rms = 0.5-1.5cm).

Correlation between σ^0 and SM was generally poor. However, for parallel fields (rms = 1 – 2 cm) σ^0 exhibited a reasonable correlation with SM for both VV- and HH-pol at 37.8° (R^2 = 0.5 with p < 0.004). The sensitivity (0.06 – 0.07 dB/%m^3/m^3) did not improve with respect to that already observed using the entire data set (0.07 - 0.08 dB/ m^3/m^3). It is likely that parallel exhibit better correlation with SM due to their limited rms range which limits the effect of SR on the signal variability allowing observation of the effect of SM. Perpendicular fields instead presented the highest sensitivity of all the cases analysed in this study (up to 0.12 - 0.14 dB/ m^3/m^3 at 37.8° for VV- and HH-pol). However, the correlation was poor (R^2 = 0.2 with p = 0.07), likely because for perpendicular fields, having rms range in the SR-sensitive domain (0.5 – 1.5 cm), the SM dependence is obscured by the SR dependence.

Isotropic surfaces presented rough conditions (rms > 2cm) and exhibited no significant correlation with either SM or SR in any channel.

6. DISCUSSION

Some of the results presented in this study confirmed previous analysis of TerraSAR data done on European soils, namely (i) the decrease in X-band sensitivity to SM for larger incidence angles, (ii) the saturation of the X-band signal for SR exceeding 1 -2 cm and SM exceeding 0.03 m^3/m^3. The most striking discrepancy with previous studies was that a much lower sensitivity of the X-band backscatter to SM changes was recorded. Even in the conditions found to be most favourable (HH-pol, 37.8° and SM < 0.03 m^3/m^3)

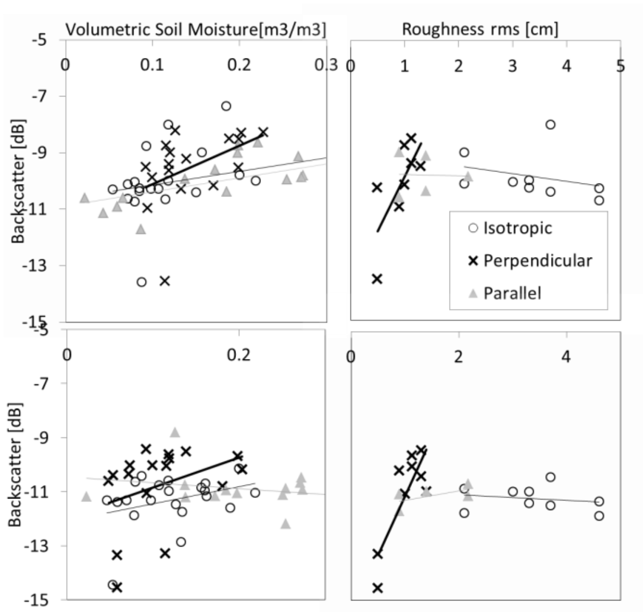

Figure 2. Relationship between TerraSAR backscattering coefficient in HH-pol, 37.8° (top panels) and VV-pol, 42.3° (bottom panels) and ground-measured volumetric soil moisture (left panels) and surface roughness Root Mean Square (rms, right panels) for bare fields. Each symbol represents field-average values and are grouped according to presence and direction of periodic tillage structure.

Table 2. Regression statistics between TerraSAR backscatter and ground-measured soil moisture (top 3 rows) and surface roughness (bottom 3 rows). Sensitivity (slope of linear regression in dB/%m^3/m^3 for soil moisture and dB/cm for surface roughness) and [R^2 (correlation coefficient)] are indicated for each channel. Highest values are highlighted in bold (by channel) and gray shade (by surface type). Regressions are calculated for soil moisture < 0.3 m^3/m^3

Surface type	HH 37.8°	VV 37.8°	VV 42.3°	VH 43.2°
Isotropic	0.10 [0.1]	0.1 [0.2]	0.06 [0.1]	0.02 [0.0]
Perpend.	**0.14** [0.2]	**0.12** [0.2]	**0.11** [**0.1**]	**0.05** [0.1]
Parallel	0.07 [**0.5**]	0.06 [**0.5**]	-0.02 [0.0]	0.0 [0.0]
Isotropic	-0.3 [0.1]	-0.19 [0.0]	-0.09 [0.0]	0.0 [0.0]
Perpend	**3.9 [0.5]**	**3.4 [0.5]**	**4.3 [0.7]**	**2.0 [0.8]**
Parallel	-0.04 [0.0]	-0.12 [0.0]	0.4 [0.4]	0.1 [0.3]

the sensitivity did not exceed 0.14 dB/%m3/m3, against the 0.29 - 0.43 dB/m^3/m^3 observed at European sites for incidence angles 26° - 52° [2-6]. Those studies had generally a larger number of soil moisture measurements per field (20 - 40 against the 1 - 10 available for this study) and longer time-series (several months). Nevertheless, since the present study is the first one to analyse the sensitivity of the X-band signal in the case of more sandy soils (12% / 36% clay / sand content as opposed to 17% / 5% sand for the European sites), the lower sensitivity observed might be the result of the different vertical gradient in sandy and clayey soils at the same SM which would affect the representativeness of the 0-5cm measurements used in both case to characterize SM. Additional analysis on sandy soils is needed to verify such conclusions.

7. CONCLUSIONS

TerraSAR data were correlated to Surface Roughness (SM) and Soil Moisture (SM) for the first time over Australian agricultural sites and in various configurations (HH- and VV-pol at 37.8° and VV- and VH-pol at 42.3°. The X-band backscatter was found to increase in response to increasing SM up to 0.03 m^3/m^3 and SR up to 1.5 cm rms, whereas it remained constant for rougher sand wetter conditions. Limited sensitivity to SM was observed, the highest (0.14 dB/m^3/m^3) being for smooth conditions (rms < 1.5 cm) and SM < 0.03 m^3/m^3 at the lower incidence angle available (37.8°), with HH- and VV-pol channels exhibiting similar sensitivity. All four polarization at both angles were well correlated with SR in the 0.5 - 1.5 cm range, the most sensitive to SR being VV- and VH-pol at the wider incidence angle available (42.3°).

8. REFERENCES

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