ASSESSING THE POTENTIAL OF FULLY-POLARIMETRIC SIMULTANEOUS MONO- AND BISTATIC AIRBORNE SAR ACQUISITIONS IN L-BAND FOR APPLICATIONS IN AGRICULTURE AND HYDROLOGY

Jean Bouchat [1], Emma Tronquo [2], Hans Lievens [2,3], Niko Verhoest [2], and Pierre Defourny [1]

[1] Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[2] Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium
[3] Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven, Heverlee, Belgium

ABSTRACT

Theoretical studies have shown that the use of simultaneous mono- and bistatic synthetic aperture radar (SAR) data could be beneficial to agriculture and soil moisture monitoring. This study makes use of extensive ground-truth measurements and synchronous high-resolution fully-polarimetric mono- and bistatic airborne SAR data in L-band to assess and compare the sensitivity of mono- and multistatic systems to maize crop variables, soil moisture, and surface roughness. Its results suggest that bistatic data, even with a very small bistatic angle, provide valuable additional information for maize crop biophysical parameter retrieval. However, this does not appear to be the case for soil moisture retrieval over bare soils.

Index Terms— bistatic SAR, L-band, soil moisture, hydrology, maize, agriculture

1. INTRODUCTION

Bistatic synthetic aperture radars (SAR) are radar systems of which the transmitter and receiver are physically separated. This characteristic allows for the acquisition of images using various geometries and configurations, thereby capturing multidimensional scattering effects which could not be recorded by monostatic systems alone.

In agricultural areas, radar measurements are influenced by both vegetation and underlying soil, making it difficult to differentiate between their respective contributions. Soil moisture retrieval depends on the presence of vegetation cover, but also on other factors such as surface roughness. Several studies reported an expected mitigation of the adverse impact of surface roughness on the retrieval of soil moisture with the combined use of mono- and bistatic scattering data [1, 2], otherwise commonly referred to as multistatic. As for the above-ground vegetation, it has been shown that certain bistatic configurations might limit the contribution of the underlying soil, thus making it possible to better distinguish the signature of the vegetation in the scattered signal and improve the retrieval accuracy of vegetation variables, e.g., biomass [3] and plant height [4].

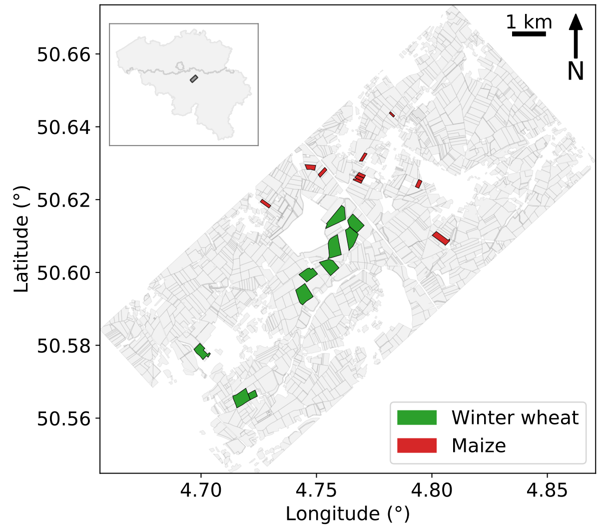

Fig. 1. BELSAR area of interest, with the reference winter wheat and maize fields in green and red respectively, and all the other agricultural fields inventoried on the anonymous cadastral map for agricultural land provided in Wallonia's Système Intégré de Gestion et Contrôle (SIGeC) in grey.

Despite these considerable expected advantages, the number and importance of bistatic SAR applications for crop monitoring and hydrology have remained low. It seems that this scarcity can be in part attributed to a lack of experimental data sets combining multistatic SAR acquisitions and in situ measurements.

This study uses the first high-resolution fully-polarimetric mono- and bistatic SAR data set in L-band ever acquired over Belgium to assess the potential of multistatic acquisitions for agriculture and soil monitoring applications. To that end, their

This study was conducted in the framework of the BELSAR-Science project jointly supported by the STEREO program of the Belgian Federal Science Policy Office (BELSPO) and the PRODEX program of the European Space Agency (ESA).

sensitivity to maize crop biophysical variables as well as to the soil moisture and surface roughness in bare agricultural fields is evaluated by means of regression analysis, and the results are then compared with monostatic measurements.

2. DATA

2.1. Site description

The BELSAR airborne and field campaign took place during the 2018 growing season, between May and September, in the BELAIR HESBANIA test site, near Gembloux. The site, which corresponds to a typical intensive agricultural landscape of Belgium, is mostly covered by relatively large, homogeneous and flat fields with a uniform topsoil texture of silt loam.

2.2. Airborne SAR data

The radar data for this study was collected during a series of 5 flights with two planes carrying a bistatic SAR system. The flights took place approximately one month apart. The SAR images were acquired and processed with MetaSensing's airborne SAR system [5] and software. The radiometric and polarimetric calibration were performed according to the procedure described in [6]. The bistatic system consisted of two left-looking airborne sensors, with an operating frequency of 1.375 GHz, and a bandwidth of 50 MHz, delivering quad-pol single-look complex (SLC) monostatic and bistatic SAR focused data with a 1 m spatial ground resolution. The baseline between the transmitting/receiving antenna and receiving-only antenna was set at 25 m, and the flight altitude at 2500 m. This configuration, that could be referred to as quasi-monostatic, limited the scope of this study to measurements in the backscattering region with very small bistatic angles.

2.3. In situ data

Synchronously with each of the flights, biophysical variables of vegetation and soil were recorded in 8 maize and 10 winter wheat fields in the imaged area. The location of the area of interest and these reference fields is depicted in fig. 1.

Maize crop biophysical variables were collected in 3 representative plots inside each of the 8 reference fields, and then averaged at the field level. These plots were selected for their representativity according to their normalized difference vegetation index (NDVI), which had been computed from Pleiades images days prior to the start of the campaign. For each of the three plots in each reference field, green area index (GAI) measurements were derived using the CAN-EYE software from 10 digital hemispheric pictures, one every 3.75 m, with an approximate nadir view 1 m above the crop canopy. In addition, plant height was measured with a ruler for 9 different plants in each plot. Finally, the vegetation

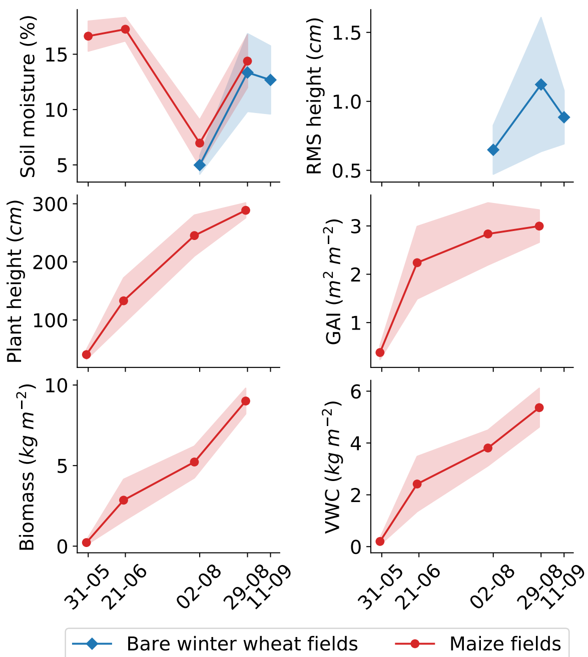

Fig. 2. Time series of in situ measurements in the 18 reference fields (8 maize and 10 bare winter wheat) in the BELSAR area of interest. In red are the in situ data collected in the 8 vegetated maize fields. In blue, the soil moisture and RMS height from recently harvested winter wheat fields. The translucent areas represent two standard deviations around the mean.

biomass was determined by destructive sampling and oven drying. In each plot, all the plants along 3 sowing lines of 1 m were harvested and weighted on the field to determine their fresh weight. A random sub-sample was then collected, weighted, and oven-dried in a micro-perforated bag at 60°C for 72 hours in order to determine their dry matter content, from which volumetric water content (VWC) was derived.

Volumetric soil moisture measurements were conducted using Time Domain Reflectometry (TDR) sensors with 11 cm rods. At least 10 locations per reference field were monitored with 3 repetitions per location. All soil moisture measurements within each field were averaged to provide field average soil moisture values. The range of soil moisture values is 3.03-18.9 vol%, which depicts very dry conditions, especially in July. Soil surface roughness was determined using a pin profilometer of 1 m, with a spacing of 1 cm. Roughness profiles along and across the direction of tillage were acquired to determine root-mean-square (RMS) height. At least five profiles per reference field were taken in both orientations on each acquisition date. Maize fields could not be monitored during their growing season. By means of linear regression analysis, it was found that the mean of RMS height across and along the direction of tillage gives the best correlation with both monostatic and bistatic scattering signals and will therefore be used in this study.

The time series collected are represented in fig. 2.

3. METHODOLOGY

The aim of this study is to compare the potential of simultaneous mono- and bistatic SAR data, further referred to as multistatic, with traditional monostatic data for agriculture and hydrology applications. To do so, the mono- and bistatic scattering coefficients σ_0 in power units are averaged at the field level for each linear polarization. Then, for every possible pair of polarizations, ratios of backscattering coefficients (monostatic) as well as backscattering to bistatic scattering coefficients (multistatic) are computed. Finally, all ratios are converted to decibels (dB). A regression analysis is then conducted to assess the sensitivity of these ratios and that of single polarized monostatic measurements to the vegetation and soil variables. Their comparative performance is quantified by their coefficients of determination (r^2).

4. RESULTS AND DISCUSSION

Discrepancies between the coefficients of determination reported in fig. 3 for the cross-polarization channels HV and VH of the monostatic system suggest that the reciprocity theorem does not hold true for the vegetated maize field measurements in this data set. The theorem states that, in monostatic systems, the cross-polarization channels should return the same signal. It does seem to be valid to a reasonable degree, however, for bare soils in harvested winter wheat fields. The reason for this difference between vegetated and bare fields is probably due to the theorem being only valid for quiet environments, an assumption that is not always verified in real conditions as also reported in [7].

4.1. Maize crop biophysical variables

For maize crops, the coefficients of determination suggest that the multistatic system might be more sensitive to the vegetation biophysical variables compared to the monostatic one. The multistatic system does indeed allow predicting, from the best performing polarization ratio for each vegetation variable, 74 (HH/HH), 73 (HH/HH), 61 (HH/HH), and 70% (HH/HH) of the variance in maize plant height (H), green area index (GAI), biomass (B), and vegetation water content (VWC), outperforming the monostatic system by 20 (VH), 1 (VH), 7 (VV), and 6% (VH), respectively. With regards to the soil moisture under canopy, both the monostatic and the multistatic systems have similar r^2 scores, respectively 51 (HV and VH) and 52% (HV/VH), but they are significantly lower than the scores for the canopy variables. This might be caused by the attenuation of the signal by the vegetation.

For the monostatic system, the single vertical co- and cross-polarizations, VV and VH, have similar performance

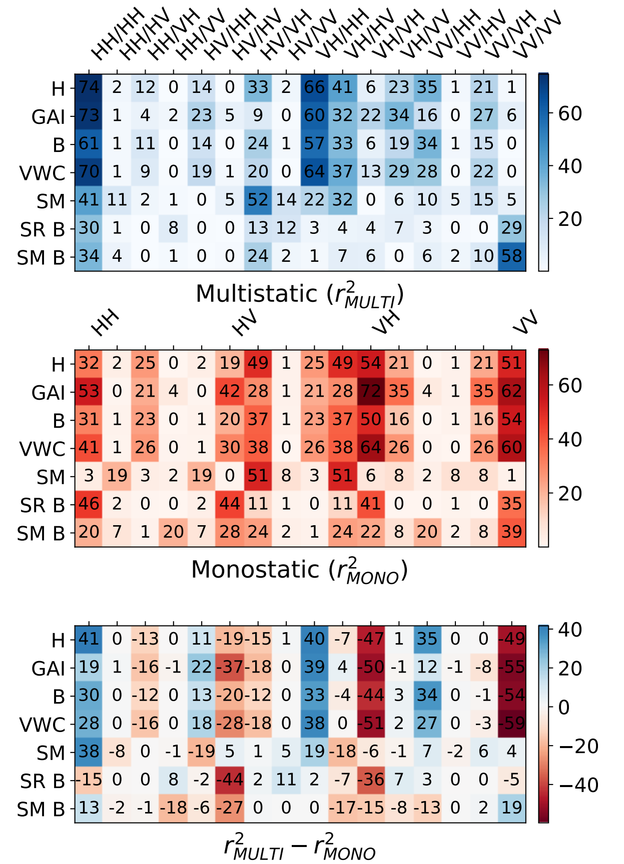

Fig. 3. r^2 scores (%) of simple linear regressions between multistatic ratios (top), i.e. monostatic divided by bistatic, monostatic ratios (middle), and, for maize crops, plant height (H), green area index (GAI), biomass (B), vegetation water content (VWC), soil moisture under canopy (SM), as well as, for bare winter wheat fields, soil moisture (SM B) and mean RMS height (SR B), along with the difference between both scores (bottom).

and significantly outperform all other single polarizations and ratios. For its multistatic counterpart, however, the best choice for maize monitoring would be the horizontal co-polarized ratio HH/HH, followed by VH/HH. It is noteworthy that the vertical polarization VV does not seem to bring any gain in terms of sensitivity to vegetation variables to the multistatic system.

4.2. Soil moisture and surface roughness in bare fields

The sensitivity of both monostatic and multistatic radar system to soil moisture is assessed in recently harvested, and hence bare, winter wheat fields.

The single co- and cross-polarized backscatter data, HH, VV, HV and VH, is sensitive to soil moisture on bare fields, i.e. the field average backscatter data increases with soil moisture. Especially for VV a relative high correlation is found ($r^2 = 39\%$). However, the single polarized backscatter signal also shows high r^2 scores for surface roughness, which might indicate that the backscatter is sensitive to surface roughness. This makes the soil moisture retrieval from single polarized backscatter observations challenging, particularly for HH polarization for which a high r^2 score is found for surface roughness ($r^2 = 46\%$).

Figure 3 indicates that, in general, the ratios of the backscattering coefficients of the monostatic radar system show low r^2 values for surface roughness, which suggests a reduced sensitivity to surface roughness compared with the single polarized observations. Furthermore, the co-polarized ratio HH/VV and cross-polarized ratio HV/VH show relatively high r^2 scores for soil moisture ($r^2 = 20\%$ and $r^2 = 24\%$ respectively) and low ones for surface roughness, especially for HH/VV. These ratios of backscattering coefficients seem to be sensitive to soil moisture. This would suggest that using two polarizations of backscatter observations simultaneously might mitigate the impact of surface roughness in soil moisture retrieval. As for the ratios of scattering coefficients of the multistatic radar system, they also show low r^2 scores for surface roughness. However, the r^2 scores for soil moisture are low as well. Only for the multistatic ratios HH/HH and VV/VV the r^2 score for soil moisture is relatively high ($r^2 = 34\%$ and $r^2 = 58\%$ respectively). Unfortunately, the r^2 score for surface roughness is also high for these configurations. This suggests that the bistatic radar configuration of the BELSAR campaign might not be suitable for soil moisture retrieval over bare fields.

It should be noted that the BELSAR bistatic observations were only available in the backscattering region and not in the more theoretical promising forward region and that bistatic angles between transmitting and receiving antennas were very small. Given this, it was expected that the bistatic SAR data would not provide more useful information on soil moisture retrieval than traditional monostatic observations.

5. CONCLUSION

The sensitivity analysis performed in this study suggests that multistatic SAR systems are more sensitive to maize crop biophysical variables than purely monostatic ones. Conversely, with regards to soil moisture and surface roughness in bare soils, the simultaneous use of mono- and bistatic scattering data does not appear to provide additional information.

However, the results of this study were derived from data acquired with a very small bistatic angle ($\sim 1°$), in a quasi-monostatic configuration. From theoretical studies, it is expected that multistatic systems with significantly larger bistatic angles would further improve the accuracy of maize and soil variables retrieval [8]. A larger data set with a greater range of acquisition geometries would thus be needed to draw general conclusions about the performance of multistatic systems for applications in agriculture and hydrology.

6. REFERENCES

[1] Valery U Zavorotny and Alexander G Voronovich, "Bistatic gps signal reflections at various polarizations from rough land surface with moisture content," in *IGARSS 2000. IEEE 2000 International Geoscience and Remote Sensing Symposium. Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Environment. Proceedings (Cat. No. 00CH37120)*. IEEE, 2000, vol. 7, pp. 2852–2854.

[2] Nazzareno Pierdicca, Luca Pulvirenti, Francesca Ticconi, and Marco Brogioni, "Radar bistatic configurations for soil moisture retrieval: A simulation study," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 46, no. 10, pp. 3252–3264, 2008.

[3] Andrea Della Vecchia, Paolo Ferrazzoli, Leila Guerriero, I Cacucci, M Marzano, Nazzareno Pierdicca, and Francesca Ticconi, "Optimization of bistatic radar configurations for vegetation monitoring," in *2006 IEEE International Symposium on Geoscience and Remote Sensing*. IEEE, 2006, pp. 1220–1223.

[4] Leila Guerriero, Nazzareno Pierdicca, Luca Pulvirenti, and Paolo Ferrazzoli, "Use of satellite radar bistatic measurements for crop monitoring: A simulation study on corn fields," *Remote Sensing*, vol. 5, no. 2, pp. 864–890, 2013.

[5] Karlus A Camara de Macedo, Simone Placidi, and Adriano Meta, "Bistatic and monostatic insar results with the metasensing airborne sar system," in *2019 6th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*. IEEE, 2019, pp. 1–5.

[6] Alexander G Fore, Bruce D Chapman, Brian P Hawkins, Scott Hensley, Cathleen E Jones, Thierry R Michel, and Ronald J Muellerschoen, "Uavsar polarimetric calibration," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 6, pp. 3481–3491, 2015.

[7] Felix Totir, Gabriel Vasile, Lionel Bombrun, Stefan Constantinescu, Angela Ionita, Florin Serban, and Dan Raducanu, "Recent polarimetric sar models for danube delta monitoring using palsar images," in *5th International Workshop on Science and Applications of SAR Polarimetry and Polarimetric Interferometry (POLinSAR 2011)*, 2011, pp. 8–pages.

[8] Nazzareno Pierdicca, Marco Brogioni, Fabio Fascetti, Jeffrey D Ouellette, and Leila Guerriero, "Retrieval of biogeophysical parameters from bistatic observations of land at l-band: A theoretical study," *IEEE Transactions on Geoscience and Remote Sensing*, 2021.