CAN BOG BREATHING BE MEASURED BY SYNTHETIC APERTURE RADAR INTERFEROMETRY

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ABSTRACT

Accounting for relatively large seasonal and short term peatland surface vertical displacements with Synthetic Aperture Radar Interferometry (InSAR) poses a problem of possible propagation of ambiguity errors. Notwithstanding, the absence of continuous high temporal resolution peatland surface levelling measurements for validation has been something characteristic. Based on the ground levelling from a raised bog, we demonstrate the Sentinel-1 distributed scatterer (DS) time-series InSAR technique underestimates real surface displacements and hereby we question the accuracy of the approach over peatlands. When the relative surface change from 6-day interferograms is used instead of accounting for the absolute change, the estimation accuracy improves (Spearman's rho 0.82, p-value < 0.002) because 6-day in situ surface changes are usually small and do not need InSAR phase unwrapping. Despite a serious unwrapping problem in peatlands, DS time series contain useful signal and differential InSAR (DInSAR) might have potential for assessment of short term peatland surface displacements in favourable conditions.

***Index Terms*—** InSAR, Surface deformation, Peatland, Phase ambiguity, Sentinel-1

1. INTRODUCTION

Better understanding of seasonal peat surface displacements initiated by changes in water table (bog breathing) [1] is needed to improve spatial models of greenhouse gas emissions [2]. Synthetic Aperture Radar Interferometry (InSAR) is a promising tool for the task in regard to the remote location and difficult accessibility of majority of the peatlands [3] and the need for a large scale assessment [4]. Nevertheless, accounting for relatively large peatland surface vertical displacements [5, 6], which are occasionally extremely large and rapid [7], poses a problem of possible propagation of ambiguity errors and causes unreliability of the InSAR results [8, 9]. The concern has been to a great extent overlooked and the absence of high spatial and temporal resolution ground levelling data for validation has been characteristic to InSAR research in peatlands [10, 8].

In this paper we present the ground levelling measurement results from a raised bog in Estonia, characteristic for the Northern temperate raised bogs, and show how the Sentinel-1 distributed scatterer (DS) time-series InSAR technique [11] underestimates the real magnitude of surface deformations over the ice and snow free period in the year 2016. Therefore, we question the feasibility of the time-series approach to measure (absolute) surface differences with respect to one common master acquisition in peatlands. Instead, we demonstrate that using the relative surface difference of 6-day image pairs form DS time series or single 6-day differential interferograms (conventional DInSAR approach) can yield much less biased results because of the reduced need for unwrapping. Also, we argue that the useful signal to capture peatland surface vertical displacement is contained in the DS time series.

2. METHODOLOGY

The ground levelling measurements are form Umbusi raised bog (58.57°N, 26.18°E) at observation plot 6 (a hummock micro site) and cover the ice and snow free period of the year 2016. The plot situates in the intact portion of the natural bog, 200 m from a deep peat layer penetrating drainage ditch. The influence of drainage does not affect the studied plot. The thickness of peat at the plot is $\sim$8 m. The levelling device recording the distance to the ground was attached to a metal bar which penetrates the peat layer and is anchored in the underling stable mineral ground. Change in ground height was recorded with hourly interval at 3 mm resolution.

The satellite Sentinel-1 A and B (S1A and S1B) vertical-vertical (VV) polarization ascending orbit (relative orbit number 160) data were used. The DInSAR processing covers the period form 1 July to 29 Oct 2016 being limited by the overlapping period of SAR acquisitions in early summer and by ground levelling data in late autumn. The DInSAR processing done with SARPROZ software resulted in thirteen small temporal baseline interferograms. A 12-day temporal baseline available before and a 6-day temporal baseline after the launch of Sentinel-1 B. Interferometric coherence estimated (weighted by the amplitude; calculated before filtering) and Modified Goldstein phase filtering applied in a window size of 10 range (rg) and 3 in azimuth (az) pixels. The resultant square footprint on the ground with a side of ∼40 m. Flattening and the topographic phase removal and no multi-looking applied. Thereafter, the interferograms were referenced to the locations of the DS reference points to account for atmospheric effects. In that way, the reference would always be set at 0 π and the unambiguous change could only be found among the phase changes not greater than $\pm 1\ \pi$ (a quarter of the radar wavelength) [12, 13]. In order to widen the span where the unambiguous change can be found, we rotated the ambiguous phase (setting the reference level anywhere between $\pm 1\ \pi$) to find the best phase fit and identify phase shifts along the transect stretching from the drain at the border of the bog to the central part of the bog where natural conditions are prevailing (the study plot 6 and beyond). In such a way, the dynamics seen along the transect indicated the direction of the peat surface change (subsidence or uplift) and consequently a reference could become set (anywhere between $\pm 1\ \pi$) so that the subsidence could be found in the span of up to $-2\ \pi$ and the uplift in $2\ \pi$.

In the DS time-series processing [11], Sentinel-1 ascending relative orbit number 160 acquisitions from 2014–2020 were included. Thereafter, the part of the time series from 2016 were extracted and referenced to the median of a cluster of stable reference points (8 points available ∼4 km away) to account for atmospheric effects (also the tropospheric phase simulated from ERA5 reanalysis data is removed before the DS calculation step). Only DS points with coherence > 0.9 were included in the analysis. The DS pixel footprint on the ground approximates to a square of a ∼200 m side.

The radar line of sight (LOS) altitude measurements were projected into the vertical direction (u_{LOS}) using the local incidence angle of the plot 6, assuming no horizontal motion in the peat [14]. The Spearman's rank-order correlation (r_s) was applied to estimate correlations. The levelling plot 6 is not covered by a DS point, therefore the nearest DS points surrounding the plot (15 points 125–230 m away) are used to represent the plot 6 in calculations. Correlation between the DInSAR time series from the plot 6 and from the DS point locations in the vicinity are 0.83 (p-value < 0.001).

3. RESULTS

Hummocks and ridges are the stable-most micro site elements in the bog while surface fluctuations at hollows and lawns are larger. Nevertheless, even during the summer of 2016 (we could not include the spring snow melt induced surface maximum in our study due to the unavailability of Sentinel-1 data before July 1), the difference between the maximum and minimum in situ recorded surface height on the dates of SAR acquisition is more than 5 cm. The surface height difference from the yearly maximum would have been larger and surface height differences between years significantly larger (as indicated by the water table fluctuations in the bogs of Endla mire complex [15] 35 km north of Umbusi bog). Contrary, the relative surface height change between the consecutive SAR acquisition dates is considerably smaller and was only once larger than the Sentinel-1 LOS height of ambiguity in 2016 as shown in Figure 1. Nevertheless, we have to consider that the portion of hummocks and ridges versus hollows and lawns varies by different bogs and even by parts of the same bog.

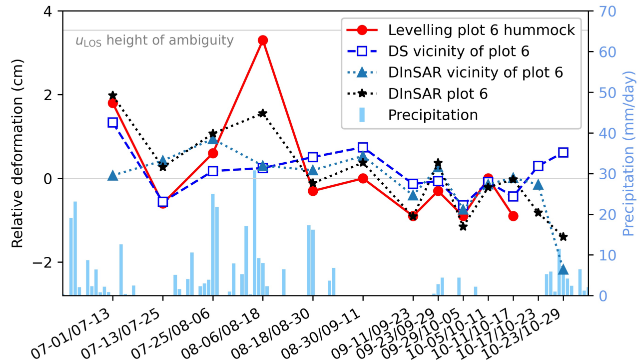

Fig. 1. The DS and DInSAR line of sight altitude change projected to vertical direction (uLOS) compared to relative in situ vertical surface deformation between consecutive SAR acquisition dates at the Umbusi plot 6 hummock. The daily precipitation sum corresponds to the latest of the dates of the image pair.

In accordance with the known difficulty of correct unwrapping of the ambiguous phase [9], long temporal baselines and coinciding large in situ surface changes result in the DS time-series approach underestimating the real surface change, in line with what [8] have found. Despite the underestimation, the DS InSAR line of sight deformation projected to vertical dimension (u_{LOS}) is following the trend in the levelling data (r_s 0.76, p-value 0.004) (Figure 2a). Similarly, [16, 17] ignored the concerns of the absolute accuracy of InSAR and demonstrated the potential of the characteristics of the InSAR time series to be used to quantify peatland condition.

If the temporal baseline is reduced (according to the recommendations by [8]) to the minimal possible (12 or 6 days in our case) via converting the absolute values of DS time series into changes between two consecutive acquisitions, then there is no need anymore for ambiguity resolution in most cases (Figure 2b). The correlation between the relative changes at the plot 6 hummock and the median relative u_{LOS} DS deformation at the DS point locations in the vicinity of the plot 6 is 0.77 (p-value 0.005). The conventional DInSAR technique yields similar results. The r_s of levelling data with the DIn-

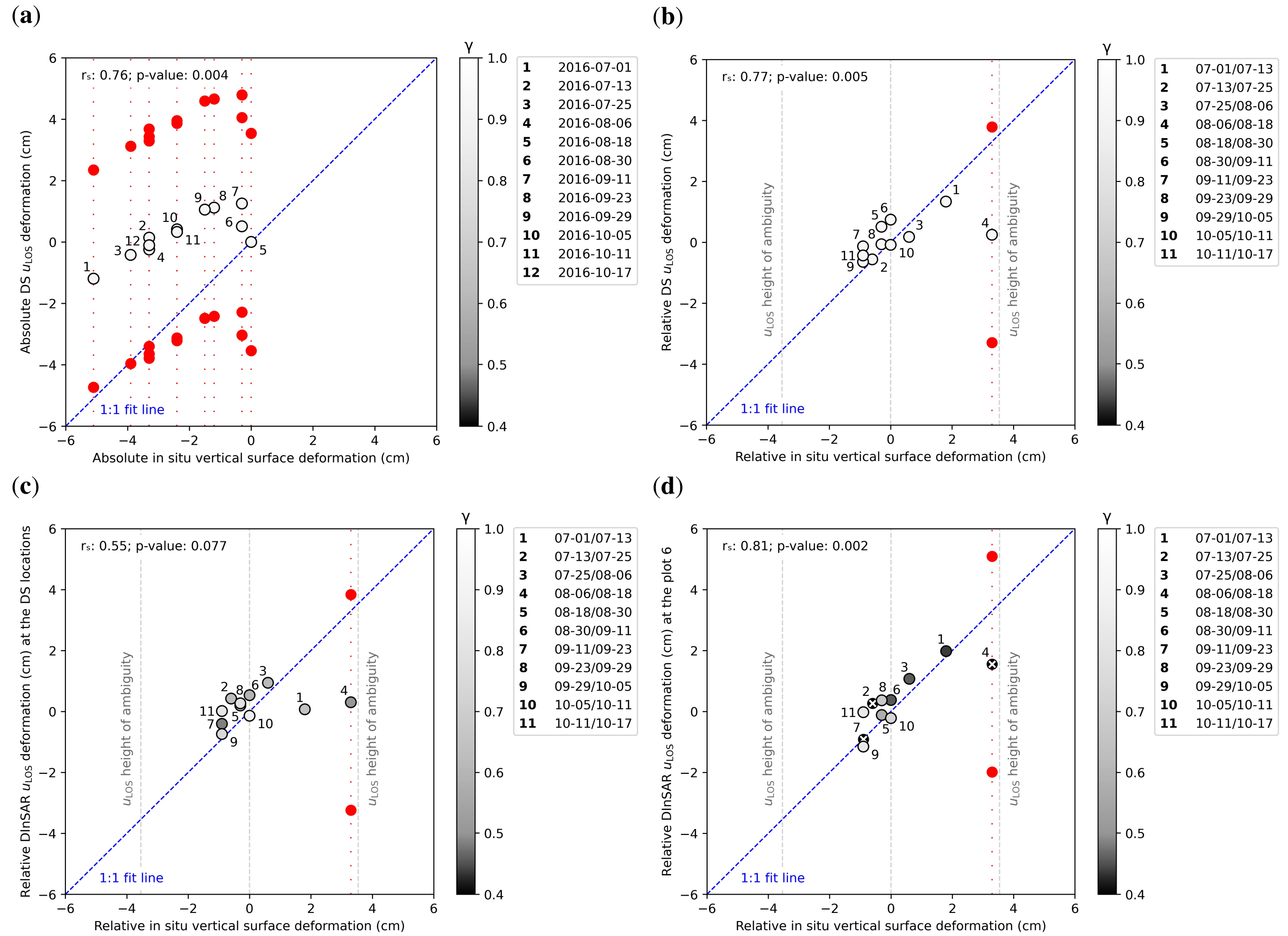

Fig. 2. Correlation (r_s) between the in situ surface deformation at the Umbusi plot 6 hummock and the InSAR line of sight deformation projected to vertical dimension (u_{LOS}) in the ice and snow free period of 2016. Red points represent u_{LOS} values if an ambiguous phase is added/subtracted. (a) The DS time series of absolute u_{LOS} deformation. u_{LOS} calculated as the median of the DS points in the vicinity of the plot 6. 2016-08-18 (the date of the maximum levelling height) taken to be the zero level. (b) The DS time series of relative u_{LOS} deformation. (a, b) The median long term average γ shown. (c) The median DInSAR relative u_{LOS} deformation at the DS point locations in the vicinity of the plot 6. (d) The median DInSAR relative u_{LOS} deformation at the plot 6. A white X on a black background marks a data point of DInSAR coherence (γ) less than 0.4 (indicating unreliable phase estimates).

SAR estimates from the DS locations is 0.55 (*p*-value 0.077) (Figure 2c) and with the DInSAR pixel accommodating the plot 6, r_s is 0.81 (*p*-value 0.002) (Figure 2d). The DInSAR results have been obtained with the stable reference points around 4 km away from the bog plot. A closer located stable reference points could improve results. We rotated the ambiguous phase along a transect in order to identify the direction of the change. Alternatively, introduction of external data such as precipitation and temperature helps to better account for correct direction of the change [9]. The precipitation in regard to the relative DS and DInSAR surface height change estimates in Umbusi bog in 2016 ate presented in Figure 1.

4. CONCLUSION

A crucial step for application of InSAR in peatlands is the estimation of the phase ambiguities derived from the relatively large surface height changes. We conclude, based on the in situ levelling data, that the direct application of time-series approach is unreliable in measuring seasonal and short term peatland surface vertical differences with respect to one common date. The DS time series nevertheless contain the useful signal. The simplest way to tackle the ambiguity problem is to reduce the need for unwrapping by reducing temporal baselines. Consequently, we have used the relative surface difference of 6-day image pairs form DS time series or single 6-day differential interferograms (conventional DInSAR). We confirmed based on our in situ levelling data that such an approach could reduce the estimation bias considerably in bog micro sites dominated by ridges and hummocks or areas of compacted peat which fluctuate at less rapid pace and at smaller amplitude.

5. ACKNOWLEDGEMENT

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