Peatland subsurface water flow monitoring using polarimetric L-band PALSAR

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Abstract—
The potential of L-band PALSAR for monitoring water flow beneath the peat surface is demonstrated on a bog near Lac Saint Pierre (Canada). Two polarimetric ALOS acquisitions collected at spring and fall under different water conditions are used. The Touzi decomposition [1], which was shown to be very promising for peatland characterization using the C-band Convair 580 SAR [2], is applied. Like in [2], the information provided by the multi-polarization (HH, HV, and VV), the scattering type magnitude (the Cloude α or the Touzi α_s), the single scattering eigenvalues and the entropy, cannot detect the presence of water underneath the peat surface. The Touzi scattering phase ϕ_{α_s} is shown to be the only target scattering decomposition parameter that can detect water flow variations beneath the peat surface. The fall acquisition that took place after two days rain permits demonstrating that the wave can penetrate deep into the acrotelm layer to detect the rain water that has sinked rapidly into the peat layer of high hydraulic conductivity. The spring acquisition at dry conditions permits better discrimination of poor fen from bog. Similar performance have been observed in a subarctic peatland in the Wapusk National Park using PALSAR data collected between June and September 2010. While the multi-polarization information could not detect any hydraulic changes in a sedge bulrush fen, ϕ_{α_s} can detect the peatland subsurface water level variations between the June starting permafrost melting season (13 cm active layer) and the more advanced July melting seasons (27 cm active layer). However, the scattering type phase could not detect the water level change between July and August of more advanced melting conditions (active layer thickness of 60 cm). The L-band wave does not go so deep into the fen to detect the presence of the subsurface (deeper than 27 cm) water.

I. Introduction

ALOS-PALSAR has been investigated for the assessment of the climate change stress on subarctic peatlands at the Wapusk National Park [3]. Unfortunately, it was only possible to collect polarimetric PALSAR acquisitions under saturated snow and water-ice conditions (May or June). Polarimetric PALSAR acquisitions can only be collected over Canada during the months of May-June, and subarctic peatlands are still covered by snow during this period. The analysis of the free snow data set of June 2007 leads to interesting results [3]. Unfortunately, the saturated water-ice conditions did not permit taking full advantage of the long wave penetration capabilities of L-band PALSAR for peatland characterization.

We were more lucky in term of PALSAR acquisitions with the Baie des Mines peatland located near the Lac Saint-Pierre (Trois-Rivières, Canada). Two polarimetric ALOS acquisitions took place on the Baie des Mines peatland at spring and fall (November 2006 and May 2007), during the calibration phase. The two acquisitions were collected under dry and wet conditions, and this permit deriving very promising results regarding polarimetric PALSAR capability for peatland subsurface water flow monitoring [4]. These results were presented in the 3rd ALOS-PI [4], and JAXA has kindly accepted our request for completeing spring-summer acquistions on subarctic peatland in the Wapusk National Park (WNP, near Churchill). Very interesting preliminary results, which are generated using the Touzi decomposition, are presented in this paper.

In the following, la Baie des Mines peatland site is first described. The Touzi decomposition is applied on the PALSAR data sets and the results obtained are presented in Section III. Similar investigation is completed in the subarctic peatland site of WNP presented in Section IV. June, July and September ALOS data are analyzed and the results obtained are presented in Section V. The requirement for polarimetric acquisitions during summer and fall seasons is brought out for more effective use of polarimetric PALSAR long wave penetration capabilities for subarctic peatland monitoring.

II. Description of the wetland site and PALSAR acquisition conditions

La Baie des Mines peatland (46.22.30N, 72.42.53W) is a 700 ha raised boreal peat dome site located 12 km west of Trois-Rivières (Canada). Figure 1 presents the peatland classification based on forest inventory, which was provided by the Ministère des Ressources Naturelles et de la Faune du Québec. Shrub bog and sedge fens are regrouped in the open peatland class of Figure 1. The wetland includes four main wetland classes: shrub bog, treed bog, poor sedge fen, and swamp. The shrub bog has a complete ground cover of sphagnum mosses with a shrub canopy dominated by ericaceous shrubs (such as Labrador Tea). Although most of the peatland is composed of bog vegetation, areas of poor fen also occur. Poor fen vegetation is composed primarily of sedges and an understory of sphagnum mosses. The bog soils are not affected by the mineral-enriched ground waters from surrounding soils, since precipitations, fog and snow are the primary water sources. In contrast to the ombrotrophic bogs the minerotrophic fens are connected to small streams and may also receive water from surrounding uplands. As such, poor fens of high water retention are continuously irrigated with subsurface water even under no rainy conditions. The treed bog class is mainly dominated by conifers (black spruce, tamarack, and pine).

Two polarimetric ALOS acquisitions took place on the Baie des Mines site at spring and fall seasons on the 13^{th} of May 2007 and the 10^{th} of November 2006. The May acquisition took place under dry conditions; no rain for 14 days, and warm weather with a temperature between 10 and 20 degrees. The November data set was collected under cool weather (with a temperature that does not exceed 5 degree) and wet conditions; about 10 mm rain has been accumulated during the 2 days (8 and 9 of November) that precede the acquisition. The rain stopped one day before the acquisition of the 10^{th} of November.

In summary, the two acquisitions took place in very different peatland hydrology conditions. Since the L-band SAR should be sensitive to wetland groundwater conditions, we should expect a significant change in radar backscattering at HH, HV and VV polarization. Unfortunately, the detection of water flow beneath the peat surface does not seem to be possible with the radiometric multipolarization information, as discussed in the following.

III. Baie des Mines peatland characterization using polarimetric PALSAR

A. *Peat subsurface water flow change detection using the multipolarization information*

Figure 2 presents the composite color of HH, HV and VV for the spring and fall acquisitions. Water level change can be noted in the swamps, as seen in Figure 2. However, no change can be detected in the open peatland. The multi-polarization information looks similar for the two acquisitions even thought significant changes in the bog hydrological conditions are expected. This significant change can be detected with the dominant scattering type phase, as discussed in the following.

B. *Detection of peat underneath water flow change using the Touzi decomposition*

The Touzi decomposition is applied on the two data sets using a processing window that includes about 65 independent looks for unbiased estimation of the target scattering parameters [5], [6]. A multi-look image with almost a square pixel is first generated by replacing each 3 pixels in azimuth with their average (in term of Mueller matrix). The Touzi and Cloude ICTD are then applied on the multi-look image using a 7x7 processing window. The dominant scattering parameters as well as the Cloude α and entropy are investigated for the peatland hydrology change detection. Like HH-HV and VV intensities, the Cloude α and entropy failed to detect any change in the bog subsurface water flow. Similar results are obtained with the single scattering eigenvalues and the dominant scattering type magnitude α_{s1}. Figure 3 and 4 present the dominant scattering type magnitude α_{s1} and phase $\phi_{\alpha_{s}1}$ for the May and November acquisitions. As can be noted, while no changes can be detected with α_{s1}, the scattering type phase $\phi_{\alpha_{s}1}$ detects major changes (pink to dark blue in Figure 4) that represents the significant variations of the water flow beneath the peat surface between the dry and wet (May-November) peatland conditions. The presence of water beneath the peat surface appears in pink in the $\phi_{\alpha_{s}1}$ image using the same phase coding of Figure 4 in [2]. For a better understanding of the scattering phase behavior in the open peatland, ground field measurements have been recently collected in November 2009. It is worth noting that ground field measurements could not be collected during the PALSAR acquisitions, since no advisement on the dates of data acquisition was communicated to us prior to PALSAR acquisition.

IV. Phase sensitivity to peatland subsurface water flow for identification of poor fen within the open peatland

Ground field measurements have been collected within the subset outlined in Figure 1. Peat vegetation and thickness measurements, and ground photographs are collected in more than 40 samples. Peat thickness varies from 1 m to 3 m within the subset under study. The analysis of the scattering type phase $\phi_{\alpha_{s}1}$ (of Figure 4) with reference to the ground field measurements leads to the following remarks:

A. *November acquisition:*

1. Shrub bog class: The pink color, which indicates the presence of underneath water (like in [2]) is dominant in the November acquisition. During the short time (two hours) after the rain has stopped, the rain water should have started sinking into the acrotelm bog layer. The subsurface water level depends on the local topography, and the water sinks more rapidly to the bottom of the acrotelm in some parts of the bog (in dark blue on Figure 4), whereas the water level is higher in other parts (in pink). The L-band wave cannot penetrate to the deep acrotelm bottom level (or within the catotelm bog sublayer), and $\phi_{\alpha_{s}1}$ is coded dark blue in Figure 4 when no subsurface water is detected.
2. Bog-Fen separation: Like in [2], $\phi_{\alpha_{s}1}$ is also sensitive to fen shallower subsurface water, and $\phi_{\alpha_{s}1}$ looks pink in the fen areas of Figure 4. As mentioned above, the acquisition took place shortly after the rain stop, and this does not give enough time to the rain water to sink deeply into the bog acrotelm. This makes hard fen-bog discrimination since the L-band wave reachs the subsurface water in both fen and bog. Only the parts of the bog in which the rain sinked rapidly to the bottom of the bog acrotelm layer can be

separated in dark blue. Bog-fen discrimination is easier under dry conditions, as discussed in the following.

B. May acquisition:

The analysis of $\phi_{\alpha_s 1}$ of Figure 4 for the May acquisition, and the comparison with the November acquisition leads to the following conclusions:

1. Shrub bog class: The bog appears in dark blue in the $\phi_{\alpha_s 1}$ image. Most of the open peatland pixels have moved from the pink color (in November) to the dark blue (in May), as seen in Figures 4. Fifteen days after the heavy rain and high temperature (about 10 to 20 degree Celsius), we would expect that the rain water has sinked deep into the the acrotelm base, and slightly into the actotelm sublayer of low hydraulic conductivity. In contrast to the November acquisition of shallower subsurface water, the subsurface water level should be much deeper (about 40 to 50 cm), and the L-band wave cannot penetrate so deep to detect the presence of water. New experiments are required with water level and hydraulic conductivity measurement during the data acquisition for the estimation of the exact depth of penetration of the L-band wave through the peat, as a function of the bog peat geophysical parameters (including the local slope).

2. Fen appears pink in the $\phi_{\alpha_s 1}$ image. Unlike the radiometric multi-polarization information, $\phi_{\alpha_s 1}$ is sensitive to the fen subsurface water supplied with ground water from small streams and surrounding uplands. In contrast to the ombrotrophic bogs whose water supply is only from rain water, the minerotrophic fens are connected to small streams and may also receive water from surrounding uplands. Unlike bogs, the poor fen peat has a higher capacity of water retention, and the water moves slowly through the fen [7], [8], [9], [10]. Fifteen days after the heavy rain, we would expect that the rain water has drained through the poor fen, which remains supplied with ground water from small streams. The water flow beneath the fen peat surface is not too deep (10 to 20 cm [10]). However, the presence of this subsurface water cannot be detected with the radiometric information provided by HH, HV, and VV, α_{s1} , the Cloude α, and the entropy.

3. Consequently, $\phi_{\alpha_s 1}$ permits the identification of poor sedge fen within the open shrub peatland, as seen in Figure 4. The recent in-situ field measurements allowed us to confirm the presence of fen in the areas that appear pink in the November acquisition.

V. SUBARCTIC PEATLAND SUBSURFACE WATER FLOW MONITORING USING THE SCATTERING TYPE PHASE

A. Peatland study site

The study site is part of the Wapusk National Park in the Hudson Bay. The Hudson Bay Lowlands contain the most extensive wetlands and thickest peat deposits in Canada [11], [12], [13]. The region is home to unique concentrations of wildlife, most notably polar bears, caribou, and migratory birds. Bears rely on inland denning habitat, caribou are tied to peatland vegetation, and birds intensively graze coastal herbaceous salt marsh and fen. While it is well established that fens change naturally into bogs over time and that bogs can revert to fens, the observations over the last fifty years indicate that the rate of these changes has been significantly altered by climate change, isostatic uplift, fire, and goose grazing [11], [12], [13]. The loss of bogs will have important implications for polar bear denning habitat which is entirely within bogs with thick peat deposits [11], [12]. Earth observation satellite and in particular all weather long wavelength L-band polarimetric PALSAR, should provide the required information for monitoring the impact of climate change on the integrity of peatlands in the North of Canada.

A series of three 45-day apart acquisitions took place over the peatland study site on the 8^{th} of June, the 24^{th} of July, and the 8^{th} of September 2010. Fig 5 presents a wetland classification of the peatland study site (near the Roberge lake) extracted from a Landsat-based classification completed by Ryan Brooks [11]. The area outlined in the middle includes a sedge bulrush fen (brown) in an area dominated mainly by lichen melt pond bog and peat plateau bog. A thermistor cable was installed in a pond bog and an observation well has been installed in the fen. The active layer thickness is of 13 cm in June (at the starting of the melting season), 27 cm in July, and more than 80 cm in September. The observation wells measurements (provided by H. Stewart, WNP) indicate a water level below the peat surface of 25 cm on the 24^{th} of July, and 30 cm on the 8^{th} of September 2010. We should expect an important change of peatland hydrology during this active layer melting period, and the three data sets are analyzed in the following to demonstrate the potential of polarimetric L-band ALOS for peatland hydrology change detection.

B. Analysis of the multi-polarization information and Touzi decomposition for detection of peatland hydrology variations

Figure 6 and 7 presents the composite color of HH (in red), HV (in green) and VV (in bleu) for the June and July acquisitions, respectively. As can be noted, the radiometric information provided by the multi-polarization information cannot detect any change in the peatland hydrology between the June starting melting season, and the late of July that correspond to more advanced active layer thawing. Similar results are obtained with the Cloude-Pottier α-H, as well as with the Freeman decomposition [14]. Again, the scattering type phase is the only parameter that is sensitive to peatland subsurface flow variations, as seen in Figures 8, 9, and 10 for the June, July and September acquisitions, respectively. We use the the same color $\phi_{\alpha_s 1}$ coding, as in Section IV above. Pink color indicates the presence of subsurface water, whereas dark blue indicates no phase sensitivity to subsurface water flow. As can be noted in the fen outlined on the June scattering type phase image of Figure 8, $\phi_{\alpha_s 1}$ detects the fen subsurface water, which should lie at the bottom of the active layer (about 13 cm). In july, the fen is still drained by shallow subsurface water than can be detected (in pink) by the L-band wave (in the rich fen), whereas a large part of the fen subsurface water is too deep (more than 25 cm) to be detected by $\phi_{\alpha_s 1}$, as seen in Figure 9. In September, the fen subsurface water level is below 30 cm, and $\phi_{\alpha_s 1}$ cannot detect its presence. As a results, no pink area appears within the fen of Figure 10. Notice also the subsurface water flow changes in the melt pond bog, at the middle of the bottom of Figures 8, 9, and 10.

In summary, the preliminary results above look very promising. The thermistor cable measurements will be analyzed soon for a thorough data analysis. A field campaign is planned in the next summer to collect more in-situ data on the peatland study site.

VI. CONCLUSION

This study confirms the sensitivity of the Touzi scattering phase to the peat subsurface water flow. Such information is not provided by the multi-polarization HH, HV and VV intensities, or the scattering type magnitude measured with α_s or the Cloude α. The preliminary results obtained here demonstrate the sensitivity of L-band PALSAR wave to peat subsurface water (as deep as 25 cm, according to the subarctic fen results). Further experiments are needed to validate these results with solid in-situ data collected during the PALSAR data acquisition. Like in [7], [10], water level, acrotelm thickness and hydrologic conductivity measurements of the acrotelm and actotelm layers, as well as the local slope, are required for a complete understanding of the interaction of the L-band Touzi scattering phase with the peatland geophysical parameters and underneath water flow. For this purpose, a field trip in the Wapusk National Park is currently being organized for the next summer 2011. We hope a lot that the Japan Aerospace Exploration Agency (JAXA) would make possible the acquisition of additional fully polarimetric PALSAR data on the Wapusk peatlands in the next summer. This will permit a more complete validation of the results obtained above, and will provide an excellent promotion of the upcoming polarimetric ALOS2 for operational monitoring of the subarctic peatland bog-fen transformations and their impact on wildlife space habitat. The recent JAXA announcement regarding the upcoming ALOS 2 mission with operational polarimetric modes 70 km swath (20 m resolution) and 35 km swath (4.5 and 9 m resolution) is definitely a great news for enhanced and operational monitoring of wetlands all over the world, using polarimetric ALOS2 and Radarsat2 multi-frequency complementarities.

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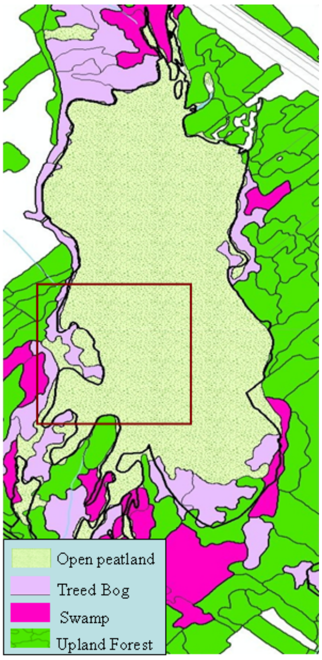

Fig. 1. *Wetland classification based on forest inventory (Minstère des Ressources Naturelles et de la Faune du Québec)*

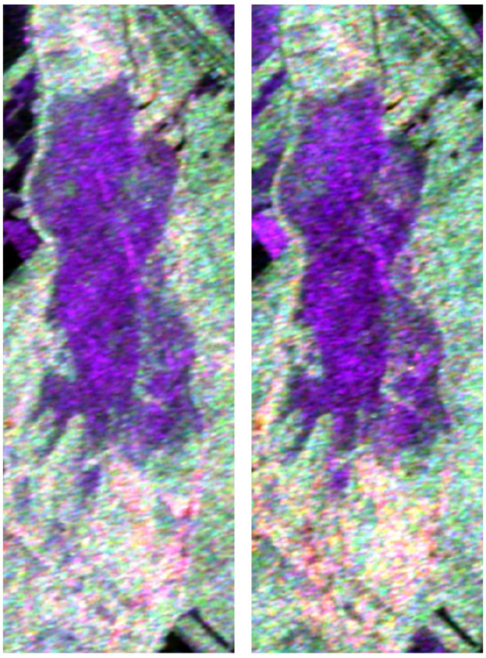
May June

Fig. 2. *Muli-polarization image (HH in red, HV in green, VV in bleue)*

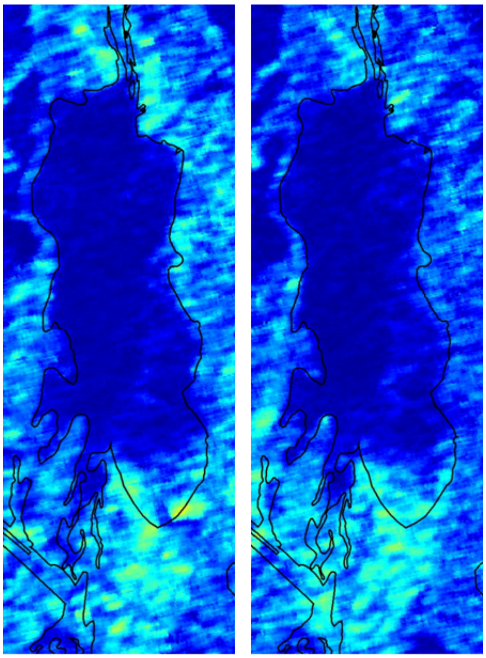
May November

Fig. 3. α_{s1} *for May and November acquisitions*

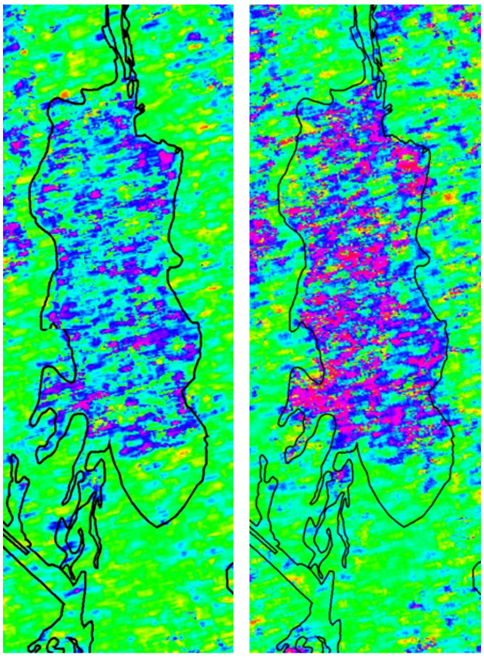
May November

Fig. 4. *Touzi scattering type phase* $\phi_{\alpha_s 1}$ *for May and November acquisitions*

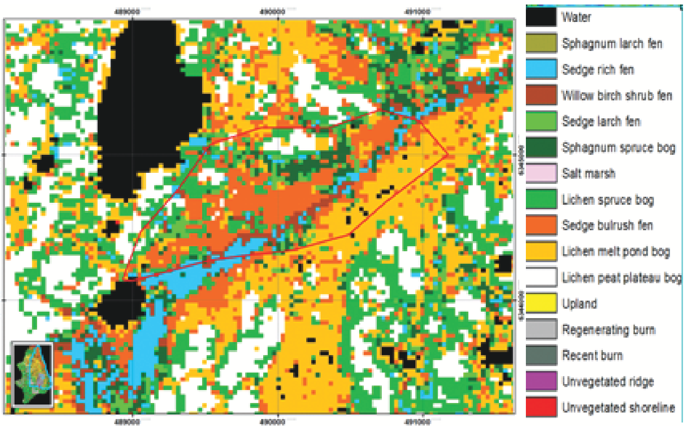

Fig. 5. *Brook's wetland classification*

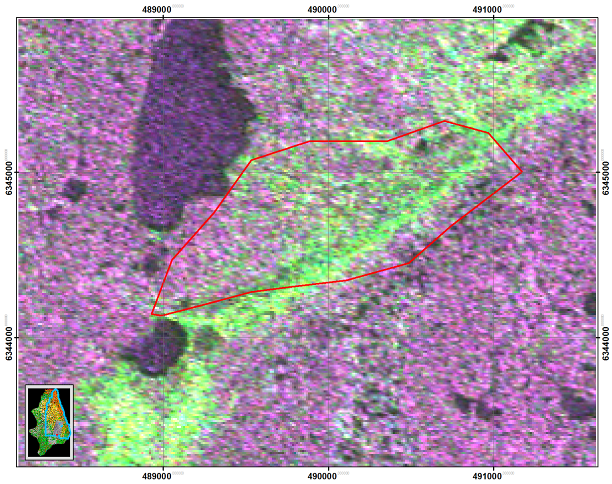

Fig. 6. *Multi-polarization image (June 8)*

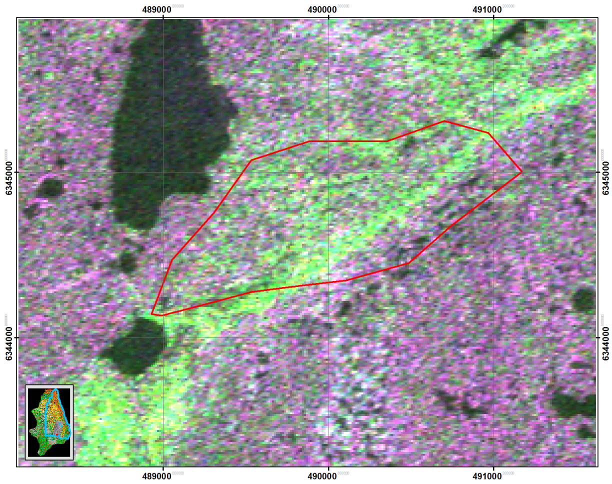

Fig. 7. *Multi-polarization image (July 21)*

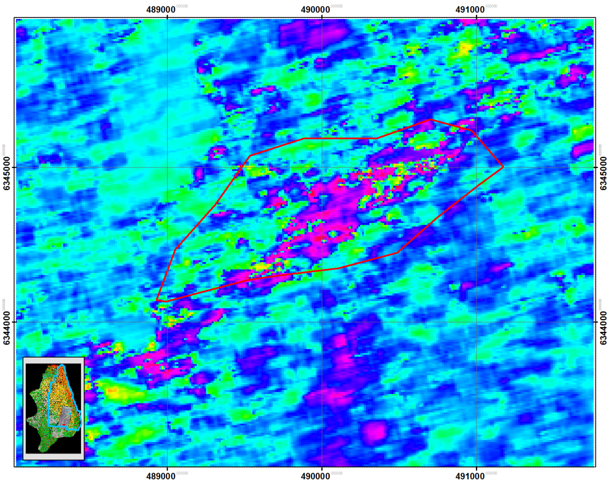

Fig. 8. *Scattering type phase (June 8)*

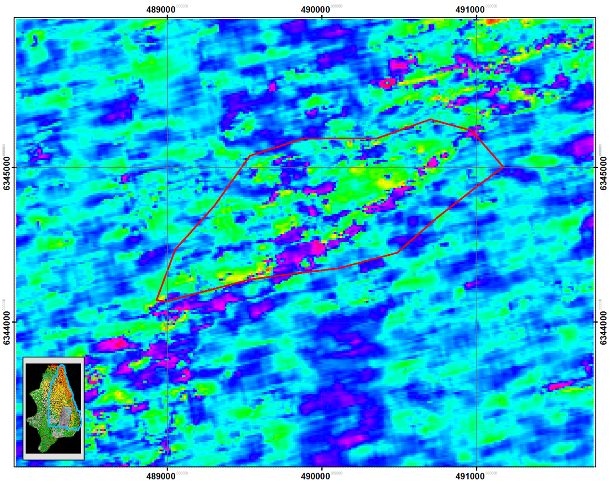

Fig. 9. *Scattering type phase (July 20)*

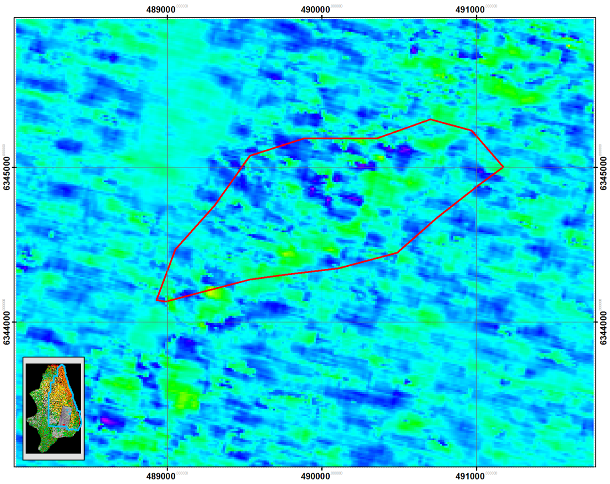

Fig. 10. *Scattering type phase (September 8)*