IMPROVEMENT OF SNOW PHYSICAL PARAMETERS RETRIEVAL USING SAR DATA IN THE ARCTIC (SVALBARD)

Dedieu JP [1] , Negrello C [2] , Jacobi HW [1,3] , Duguay Y [4] , Boike J [5] , Bernard E [6] , Westermann S [7] , Gallet JC [8] , Wendleder A[9]

[1] *Institut des Géosciences de l'Environnement (IGE), CNRS, Université de Grenoble Alpes, France*
[2] *CNAM-ESGT, Le Mans, France*
[3] *Observatoire des Sciences de l'Univers de Grenoble (OSUG), Grenoble, France*
[4] *Université de Sherbrooke, Sherbrooke, Québec, Canada*
[5] *Alfred-Wegener-Institute (AWI), Potsdam, Germany*
[6] *Laboratoire ThéMa, CNRS, Université de Franche-Comté, Besançon, France*
[7] *Dept. of Geosciences, University of Oslo (UiO), Oslo, Norway*
[8] *Norwegian Polar Institute (NPI), Tromso, Norway*
[9] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen-Weßling, Germany*

ABSTRACT: Arctic snow cover dynamics offer a changing face in terms of temporal duration and water equivalent, due to recent climate change conditions (Callaghan et al., 2011; Lemke & Jacobi, 2012). Indeed, the Arctic is now experiencing some of the most rapid and severe climate change on earth. In this context, innovative and improved methods are helpful to enhance management of the snow-pack resource for climate research, hydrology and human activities. The characteristics of Arctic snow are different from "temperate" snow (i.e. the Alps), in terms of thickness, internal structure, thermal conductivity, and metamorphism. Ground observation often indicates wind slab at the snow surface, internal rounded grains, depth hoar at the bottom, and often internal ice layer or at the interface with ground surface (Dominé et al., 2016; Gallet et al., 2017, for spring snow). This work is part of the "Precip-A2" project (OSUG, Grenoble-France), focusing on snow and its interaction with the atmosphere, especially in terms of chemistry, radiative processes and precipitation. The application site is the Brøgger peninsula, focused on Ny-Ålesund area, Svalbard, Norway (N 78°55' / E 11° 55'). One sub-task of the Precip-A2 project is dedicated to X-band radar measurements (ground and space-borne) to retrieve physical properties of arctic snow.

KEYWORDS: Snow, Arctic, Radar, Remote Sensing

1. INTRODUCTION

Active radar (SAR) images are used in this study, as they do not suffer of clouds coverage and polar night, unlike optical sensors. Snow mapping at the melting season at all frequencies using amplitude images is well documented, due to the liquid water content at the snow surface (Nagler et al., 2000). Dry snow height retrieval is possible with fully polarimetric data at C-band, such as the ones provided by the Canadian Radarsat-2 satellite (Dedieu et al., 2012; 2014). A strong impact of the vegetation response is also observed on the snow backscattering in arctic context (Duguay, 2017).

The aims of our specific task is to apply an innovative method to retrieve (i) snow cover and (ii) snow depth from dual-pol SAR data at X-band (Leinss et al., 2014; 2016) over open spaces without vegetation. Output results were compared respectively with (i) simultaneous optical data from Sentinel-2 dataset (10m), and (ii) a consistent ground network including large international partnership (Fr, De, No, It). Collaborating Institutions are given with the co-author list.

The application site is the Brøgger peninsula, focused on Ny-Ålesund area, Svalbard, Norway (N 78°55' / E 11° 55').

* *Corresponding author address:*
Jean-Pierre DEDIEU, Institut des Géosciences de l'Environnement (IGE);CNRS / Université de Grenoble-Alpes, France. Tel: +33 456 520 977
email: jean-pierre.dedieu@univ-grenoble-alpes.fr

2. DATA AND METHODOLOGY

A set of 10 SAR images was provided by the German Space Agency (DLR) during winter and spring of 2017 from the TerraSAR-X sensor (3.1 cm, 9.6 GHz) in dual co-pol mode HH, VV (2.5 m resolution). Descending and ascending orbits were programmed under 35-38° incidence angles, to avoid topographic constraints. Complementary dates were provided in late spring and snow-free season by the DLR catalog, under the regular lower incidence angles (27-29°) of the sensor.

The data were processed using the ESA SNAP Toolbox, with the extraction of a co-polar phase difference (CPD) set between HH and VV polarization, then projected to ground range by DEM from the Norwegian Polar Institute (5m resolution). The total application area covers 206 km^2, covering most of the Brøgger peninsula.

A total of 400 ground measurements were used for validation, based on automatic permanent stations or manual collection. Snow height, temperature, density, and some structural information (stratigraphy) were observed on open spaces (herb tundra) and on glaciers. Some places are well documented with 20-year recordings, as the Bayelva station (Boike et al., 2018) or 10-year for the Austre Lovenbreen glacier (Bernard et al., 2013; Schiavone et al., 2018). The support of NPI, AWIPEV and UiO was particularly helpful for snow line transects and stratigraphy measurements providing, thanks to them.

3. RESULTS

3.1 Meteorological data: consistent information is provided from meteorological sites with different location and elevation, indicating similar temporal trends as air temperature or snow depth profiles (Figures 1 and 2).

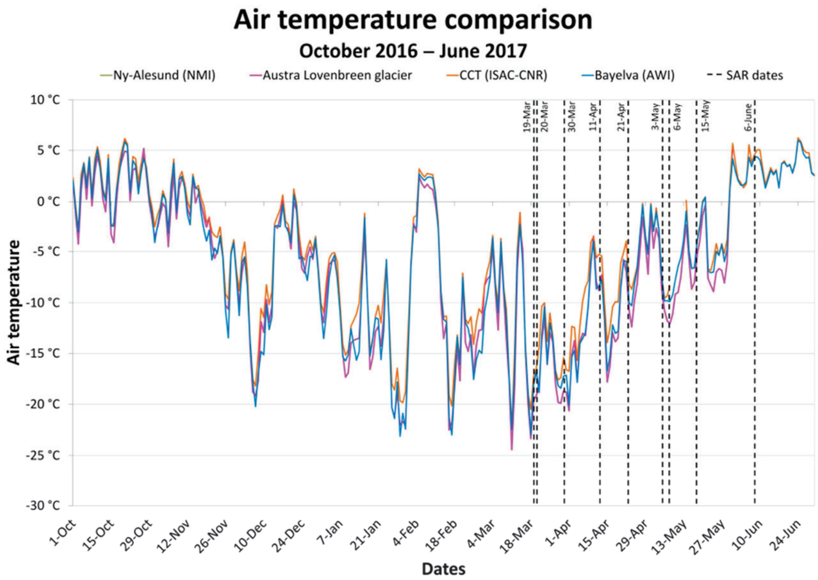

Figure 1: Air temperature temporal evolution, winter season 2016-2017, for four meteorological sites in Ny Ålesund area. TerraSAR-X acquisition dates are indicated in dashed lines (Source: AWI, ISAC-CNR, NMI, UFC).

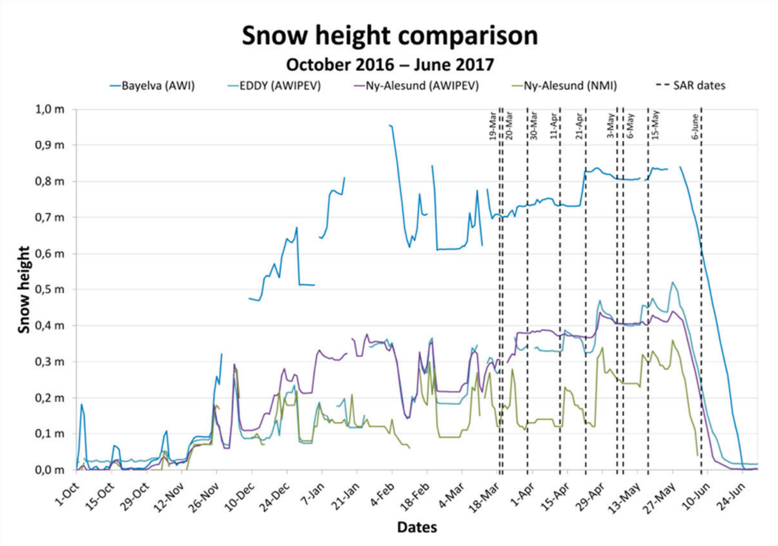

Figure 2: Snow depth temporal evolution, winter season 2016-2017, for permanent meteorological sites in Ny Ålesund area. TerraSAR-X acquisition dates are indicated in dashed lines (Source: AWI, AWIPEV, NMI).

We can observe a long-term negative air temperature from early November to late May, except for a warm flux in February, impacting a snow melting period. The TerraSAR-X time-period of acquisition (March, 19 to June, 6) covers the snow metamorphism evolution from dry to wet conditions.

3.2 Non-polarimetric SAR analysis shows that the TerraSAR-X ascending and descending images under high incidence angles generates less layover and shadow (8.4%) than the low incidence mode (19.2%). Then, single polarization mode (HH or VV) processed with the Nagler adaptive threshold allows to retrieve snow cover maps, afterwards compared with the Sentinel-2 simultaneous acquisition. Optical snow maps are retrieved from the Normalized Difference Snow Index (NDSI) method (Dozier, 1989). Results are well correlated (Figure 3a and b), assessing the interest of SAR images in regard of optical mode under cloud conditions (Figure 4a and b).

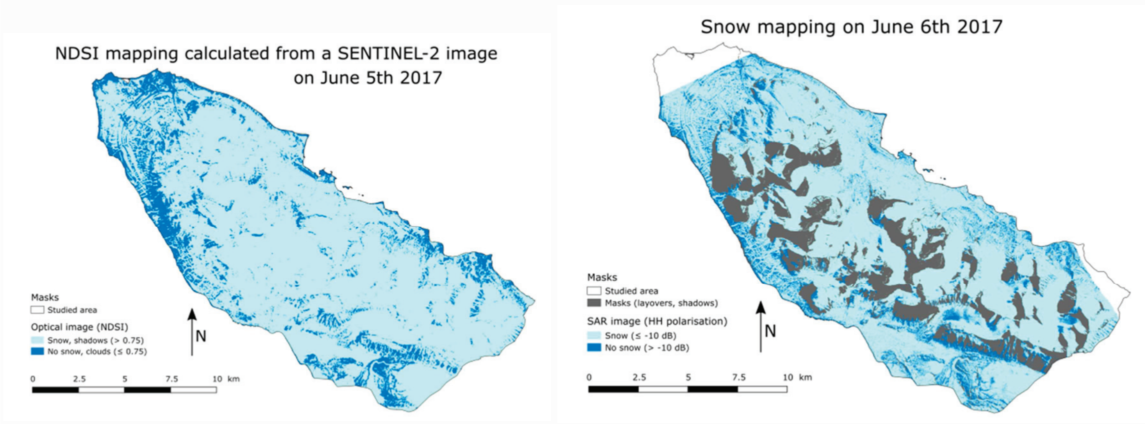

Figure 3: Cloud-free conditions: snow mapping comparison between (a) on the left Sentinel-2 image, NDSI processing, at 05/06/2017; and (b) on the right TerraSAR-X, Nagler processing, at 06/06/2017.

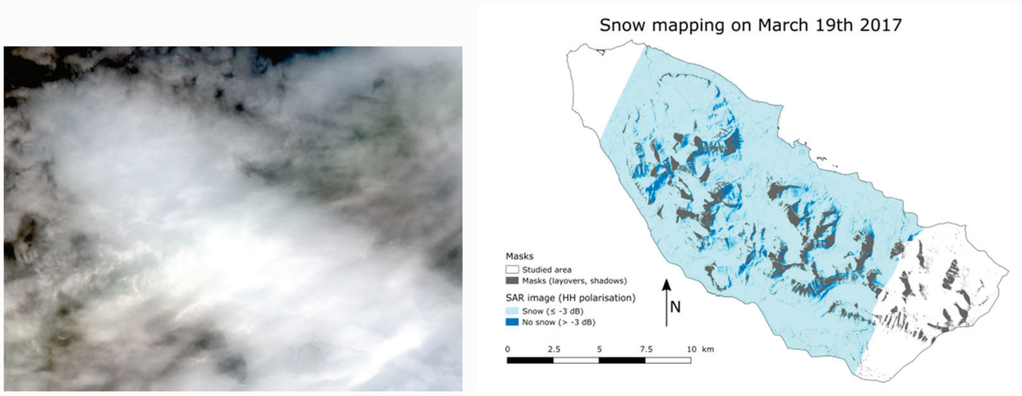

Figure 4: Cloud cover conditions: (a) on the left Sentinel-2 image of 19/03/2017, unusual for snow mapping; and (b) on the right TerraSAR-X acquisition, Nagler processing, successful at same day.

3.3 Polarimetric SAR analysis shows that the temporal evolution of the CPD values is strongly linked with the in-situ snow evolution: positive values are observed for dry snow, while negative values appear during the recrystallization process. Figure 5 exposes a transect example with different values of dry snow depth (manual collection), providing unequal correlation with the CPD outputs. Concerning permanent stations, comparison between estimated (CPD) and measured snow depth is driven for different types of snow metamorphism (wind slab, fresh snow, rounded or slightly recrystallized grains), and from the surface to the 1st ice layer (3-5 cm). The R^2 performances are ranging from 0.51 to 0.75 (Figure 6). The slope profiles are paired two by two, due to the specific location of the stations.

4. DISCUSSION

The non-polarimetric analysis of TerraSAR-X images offers satisfactory results for regularly mapping snow and its spatial distribution at the Brøgger peninsula scale, as they do not suffer of clouds coverage. The polarimetric analysis indicates that the co-polar phase difference can essentially retrieve the (upper) dry part of the snow pack. Ice layers of 3-5 cm attenuate or stop the SAR signal penetration in the snow profile. We observed also in this project that this CPD method is highly sensitive to the surface conditions of snow (surface hoar, rimed gains), in respect of the X-band frequency at 3.1 cm.

On the other hand, the particular meteorological context of the 2016-2017 winter season with repeated cycles of snow metamorphism (heat fluxes, wind drifts) reduced the performance capabilities of the method, in lack of real dry snow conditions as expected from an arctic climate context. The solution would be to increase (i) the number of SAR acquisitions during the accumulation period (dry fresh snow), and (ii) simultaneous stratigraphy profiles to enhance the structural information of the snow cover related to the corresponding CPD values. In conclusion, the results of this study are assessing the interest to further improve the CPD method for climate and hydrological application in Arctic.

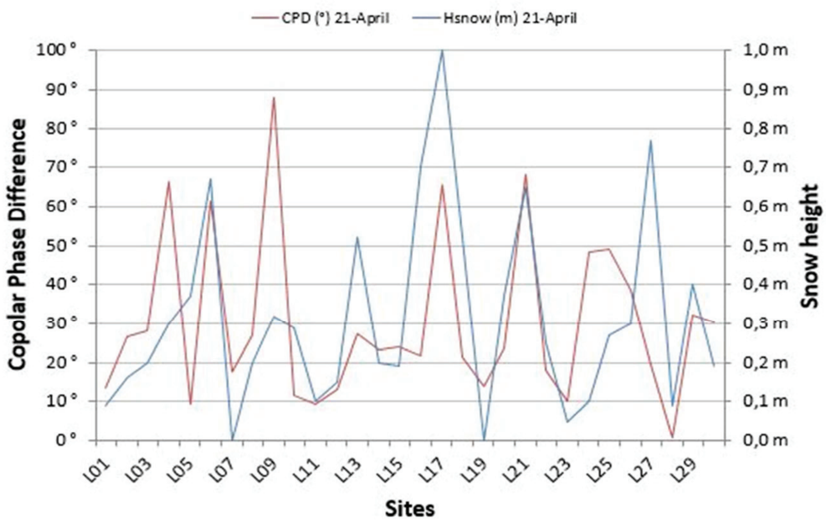

Figure 5: Copolar Phase Difference (CPD) and snow depth comparison: example of a snow line transect (manual collection) from Ny-Ålesund village to Bayelva meteorological station, 21/04/2017 (Source: AWIPEV).

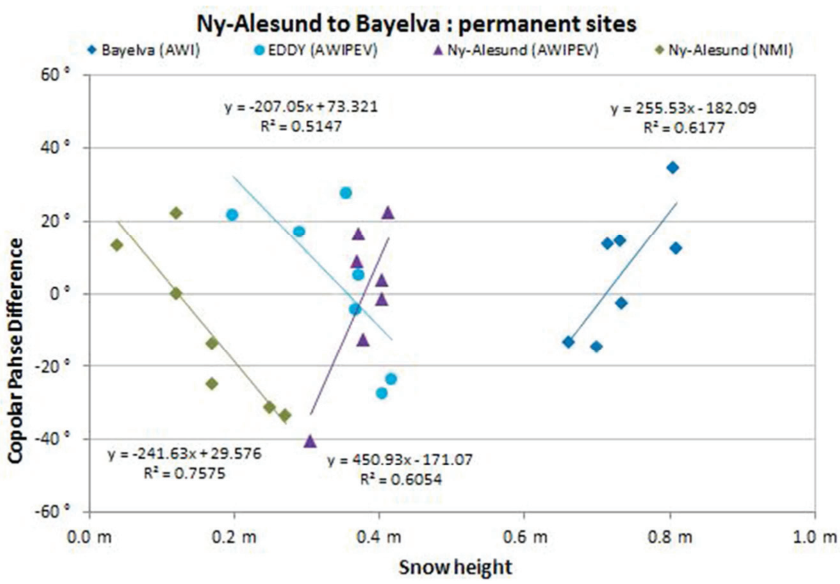

Figure 6: Copolar Phase Difference (CPD) and snow depth comparison: output results for 4 meteorological stations under different types of snow metamorphism during winter and spring 2017. Seven TerraSAR-X dates without melting conditions are taken in account.

ACKNOWLEDGEMENT

Authors deeply thank the following institutions for all their ground data providing: AWI, AWIPEV, UiO, NPI, UdF/Thema, CNR. Authors are also grateful to the DLR Agency for TerraSAR-X images providing.

REFERENCES

Bernard E., Friedt J .M., Tolle F., Griselin M., Martin G. *et al.* Monitoring seasonal snow dynamics using ground based high resolution photography (Austre Lovenbreen, Svalbard, 79°N), 2013. *ISPRS Journal of Photogrammetry and Remote Sensing,* 75, 92-100.. doi: 10.1016/j.isprsjprs.2012.11.001.

Boike J., Juszak I., Lange S., Chadburn S., Burke E., Overduin P.P., Roth K., Ippisch O, Bornemann N, Stern L., Gouttevin I., Hauber E., and Westermann S. A 20-year record (1998–2017) of permafrost, active layer and meteorological conditions at a high Arctic permafrost research site (Bayelva, Spitsbergen), 2018. *Earth System Science Data*, 10, 355-390. doi: 10.5194/essd-10-355-2018.

Callaghan T., Johansson M., Brown R., Groisman P., Labba Ni., Radionov V., Barry R., Bulygina O., Essery R. *et al*. The changing face of Arctic snow cover: a synthethesis of observed and projected changes, 2001. *AMBIO*, 40, 17-31. doi: 10.1007/s13280-0110212-y.

Dedieu JP., Beninca de Farias G., Castaings T., Allain-Bailhache S., Pottier E., Durand Y., and Bernier M. Interpretation of a RADARSAT-2 Fully Polarimetric Time Series for Snow Cover Studies in an Alpine Context, 2012. *Canadian Journal of Remote Sensing*. Taylor &Francis. 38 (3); 336-351. doi 10.5589/m12-027.

Dedieu J.P., Besic N., Vasile G., Mathieu J., Durand Y., and Gottardi F. Dry snow analysis in alpine regions using Radarsat-2 full polarimetric data, comparison with in-situ measurements, 2014. *IEEE Transaction on Geoscience and Remote Sensing*, *Igarss*, vol 5, 3658-3661. doi 10.1109/IGARSS.2014.6947276.

Domine F., Barrere M., and Sarrazin D. Seasonal evolution of the effective thermal conductivity of the snow and the soil in high Arctic herb tundra at Bylot Island, Canada, 2016. *The Cryosphere*, 10, 2573-2588. doi: 10.519/tc-10-2573-2016.

Dozier J. Spectral Signature of Alpine Snow Cover from the Landsat Thematic Mapper, 1989. *Remote Sensing of Environment,* 28, 9-22. doi : 10.1016/0034-4257(89)90101-6.

Duguay Y. Exploitation des images Radarsat-2 polarimétriques et TerraSAR-X multipolarisation pour la cartographie des paramètres du couvert nival et de la vegetation en milieu sub-arctique, 2017. PhD Thesis, INRS-ETE, Québec, Canada, 236 p.

Gallet J.C., Merkouriaadi I., Liston G., Polashenski C., Hudson S., Rösel A., and Gerland S. Spring snow ice conditions on the Arctic sea ice north of Svalbard, during the Norwegian Young Sea Ice (N-ICE2015) expedition, 2017. *Journal of Geophysical Research, Atmospheres*, 122 (20), 10820-10836. doi: 10.1002/2016JD026035.

Leinss S., Parrella G., and Hajnsek I. Snow height determination by polarimetric phase differences in X-Band SAR data, 2014. *IEEE JSTARS*, 7 (9), 3794-3810. doi: 10.1109/JSTARS.2014.2323199.

Leinss S., Löwe H., Proksch M., Lemmetyinen J., Wiesmann A., and Irena Hajnsek I. Anisotropy of seasonal snow measured by polarimetric phase differences in radar time serie, 2016. *The Cryosphere*, 10, 1771-1797. doi: 10.5194/tc-10-1771-2016.

Lemke P. and Jacobi H.W. Arctic climate change: the ACSYS decade and beyond, 2012. *Atmosperic and Oceanographic Library*, 43, 464 p. Springer. ISBN: 978-9400720268.

Nagler T. and Rott H. Retrieval of wet snow by means of multitemporal SAR data, 2000. *IEEE Transactions on Geoscience and Remote Sensing*, 38 (2), 754-765. doi: 10.1109/36.842004

Schiavone S., Bernard E., Tolle F., Griselin M., Prokop A., Friedt J.M., and Joly D. 10 years of mass balance over a small Arctic basin. The example of Austre Lovénbreen (Svalbard). 2018. *IASC Network on Arctic Glaciology meeting*, Obergurgl (Austria).