REFEREE #1:

I have several major comments:

1) The authors need to incorporate more physical interpretations of volumetric scattering and vegetation characteristics as they relate to ALT. The authors emphasize the technique, but if they want to capture the imagination of this journal's readership, they must expand the physical interpretation. We know vegetation influences ALT based on probing data and plant type, but these backscatter measurements offer direct, pixel-by-pixel measurements of the vegetation physical characteristics associated with ALT variability. How does this effort relate to efforts to use backscatter to measure biomass? What physical characteristics drive the backscatter strength: vegetation height, total biomass, or leaf density? How do these characteristics relate to the thermodynamics that drive ALT? This is the true science advancement of this paper.

We thank you for pointing out the lack of information regarding vegetation characteristics that drive both X-band backscatter and ALT dynamics. We have revised the paper and expanded the discussion section accordingly. We would like to refer to the file which includes the tracked changes.

2) The authors must include the exact mathematical form of the curve fits, the regression coefficients, and associated uncertainty. Others cannot reproduce these results without the form and coefficients. The uncertainty is absolutely essential to interpreting the results.

We now included the form and std error for the regression lines. Functions are now also included in the figures

The mathematical form of the regression line is given in Figure 6. The standard error of the intercept is 14.00 and 0.96 for the slope respectively.

The standard error of the intercept is 9.21 for 22nd July 2014 and 11.60 for 10th August 2015 and 15.80 and 20.21 for the slope respectively.

3) The authors should include a map of ALT and uncertainty for the entire X-band scene, not just the CALM sites. This is what the readers and I really want to see. Such maps are more useful and interesting to the readers than the curve fit plots. I recognize the technique does not work as well for ALT < 70 cm, but this is fine as long as the uncertainty reflects this.

We added the ALT map for the entire X-band scene. We included the std error of slope and intercept of the regression line. Uncertainties have been published for the probe measurements from the CALM site (4 cm) and we therefore included χ^2 for the CALM grid (which is validation site only). We also added R² for every VD site separately to illustrate the accuracy of the product (see Table 2). We further removed the statement that the approach is limited to ALT depths larger than 70 cm as this cannot be sufficiently quantified over our study area due to lack of ALT sampling data (and limited occurrence at the site) within the lower range.

4) Drop all functions except the linear curve fit. Figures 5 and 6 clearly indicate no statistical difference between the three functions within the data range. Using three curve fits adds volume, but not value to the paper. I know of no theoretical basis for

choosing any one of these functions over the others, so I recommend the authors stick with the simplest form: the linear curve fit.

We revised the paper and dropped the other functions. (See file of tracked changes + adaption of Figures and Table 2)

5) Drop the comparison to NDVI. The backscatter technique does appear more robust than the NDVI technique, but I am not sure how much value this adds to the paper. The NDVI method is only one of several methods identified by the authors, and definitely not the best, so I do not see why the authors focus on this particular technique. Besides, the stated goal was to evaluate backscatter, not compare with the NDVI method.

We incorporated the NDVI technique in order to compare the X-band backscatter method to an already established "traditional" method. Furthermore the NDVI was used in order to discuss the differences between the sites VD-1 and VD-2, which show similar ALT values while backscatter values seem to differ. We appreciate your comment and revised our manuscript in order to clarify our intentions.

...Its thickness is typically measured locally, but a range of methods, which utilize information from satellite data, exist. <u>Mostly, the Normalized Difference Vegetation Index (NDVI) obtained from optical satellite data is used as proxy.</u>

... We therefore investigated the relationship between ALT and X-Band SAR backscatter of TerraSAR-X (averages for 10 x 10 m window) in order to explore the possibility of delineating ALT on a continuous and larger spatial coverage in this area <u>and compare it to the already established method</u> of using NDVI from Landsat (30 m).

6) Rewrite the manuscript using the active voice. Readers find the passive voice difficult to follow.

We adapted the manuscript in places, where we think the passive voice could lead to confusions.

We therefore investigated the relationship between ALT and X-Band SAR backscatter of TerraSAR-X ...

We used in situ records from several sites in the proximity of a long-term monitoring site on Yamal and discuss the results with respect to previous approaches which use remotely sensed information as proxy for ALT.

In August 2015 we carried out a dedicated vegetation survey of each CALM grid point, where we determined the dominant vegetation cover within a 3 x 3 m area.

Furthermore we conducted moisture measurements at the CALM grid. We used the Delta-T Wet Sensor with HH2 handheld to measure the moisture content of the top 5 cm at each grid point on three dates in August 2015.

We compiled a data set based on TerraSAR-X which allows the investigation of this relationship.

Minor Comments:

 P1, L3, Table 1; P2, L16; P2, L23-4: The techniques listed in Table 1 are not 'limited' to ALT < 70 cm. The wording implies the techniques do not work for deeper active layers, which is not true. For example, Schaefer et al. [2015] and Gangodagamage et al. [2014] estimated similar ALT because that is the actual ALT around Barrow, AK. Other studies using similar techniques measured ALT

> 70 cm in different areas, such as Liu et al. [2012] around Prudhoe Bay and Pastick et al. [2013] around Yukon Flats.

We removed the statement that these techniques were limited to ALT < 70 cm and clarify that they were simply conducted in areas with shallow ALT. We thank you for pointing out these papers, however also Liu et al. [2012] found ALT of 50 – 80 cm which is in the lower range of values we are dealing with in our study. Pastick et al. [2013] on the other hand not only used remote sensing data, but also climatic data. It is therefore not a pure remote sensing approach.

The applicability has been demonstrated mostly for shallow depths of Active Layer Thickness (ALT) below <u>approximately</u> 70 cm.

Most previous remote sensing approaches (Leverington and Duguay, 1996; McMichael et al., 1997; Sazonova and Romanovsky, 2003; Schaefer et al., 2015) have utilized data with spatial resolutions of 30 m and coarser and <u>were conducted in areas with shallow ALT</u> (less than <u>approximately</u> 70 cm, see Table 1).

• P1, L16: The authors need more recent and comprehensive references for carbon emissions, such as Schaefer et al., [2011] or Schuur et al. [2013].

Thank you for suggesting these papers; we included them as references

At global scale, increased ground temperatures could facilitate further climatic changes by releasing greenhouse gases that are currently sequestered in 20 the upper layer of permafrost by increasing the annual thaw depth (Kane et al., 1991; Gomersall and Hinkel, 2001; Shiklomanov and Nelson, 1999; Schaefer et al., 2011; Schuur et al., 2015).

• P1, L4-5: Although this may be true for Yamal, it is not true in general. All the papers in Table 1 as well as others not included show spatial patterns of ALT.

The statement referred to the sentence before about Yamal. We have now merged them.

Changes in active layer thickness have been already observed for Yamal (Leibman et al., 2015), <u>where</u> active layer thickness spatial patterns are unknown outside of the sites with in situ measurements.

• P2, L6-26: The authors need to rewrite this section with a more logical flow of ideas. The authors need to clearly separate modeling techniques to estimate ALT from the upscaling techniques based on probing. They start out with the Stefan model and Kudryavtsev models, but suddenly switch to Gangodagamage et al. [2014], who used a probing data to scale up lidar data, a technique that is remarkably similar to what the authors describe with backscatter. Then they switch to InSAR, then to soil moisture, and back to upscaling probing data.

We appreciate your comment and hope that the made changes provide a better flow. We would like to refer to the file which includes the tracked changes.

• P2, L31-4: The authors need to explain why they think backscatter relates to ALT. The authors state their hypothesis, but do not explain why backscatter should relate to ALT. What have people done in the past relative to backscatter

and biomass in permafrost regions? How does biomass relate to ALT? How is x-band an advantage? Why not use C-band or L-band?

Very little work has been done on shrub biomass in tundra with X-band. Only Duguay et al. 2015 looked into shrub height. But we have now added some general comments on volume scattering. See the last paragraph of the introduction section of the revised manuscript.

• P3, Fig1: This figure should outline the X-band scenes used in the study.

We added the outline to the map

• P4, Tab1: The authors should identify the general area of the studies, such as Barrow for Gangodagamage et al. [2014]. The text should explain that all these studies except Schaefer et al. [2015] used regressions of ALT against a remotely sensed characteristic to scale up probing data. The exception is Schaefer et al. [2015], who used InSAR to measure seasonal subsidence and did not use probing regressions.

We added a column stating the study areas (see file of tracked changes) and revised the mentioned text within the introduction chapter.

Recently, subsidence rates have been used as input for modelling ALT (Schaefer et al., 2015). Synthetic Aperture Radar has been exploited using interferometric analyses (InSAR, provides seasonal ground subsidence) in combination with soil properties to estimate ALT without using empirical relationships with probing data (Schaefer et al., 2015).

• *P6, L5; P8, Fig2: The authors need to explain this figure, which I did not understand. One sentence is not enough. How did the authors use this data?*

The figure shows the relationship of topography and vegetation types and that certain topographic features are linked to specific vegetation covers. As is stated in the introduction, both slope and vegetation cover can be linked to ALT and as can be seen from the figure, they are also connected to each other. Further elaboration can be found in the discussion section of the revised manuscript.

Although we did not use any topographic information in our delineation of ALT we point out the potential of refining the backscatter approach by incorporating topographic information in the revised manuscript.

Figure 2. Comparison of topographic units (source CALM metadata, Earth Cryosphere Institute SB RAS) and vegetation type (survey of August 2015) at the CALM grid, <u>illustrating</u> the interrelation of certain topographic features and specific vegetation covers.

The redistribution of water and consequently also the occurring vegetation is in turn controlled by lithology, but also by topography (see Figure 2), which has been shown useful in delineating ALT (Peddle and Franklin, 1993; Leverington and Duguay, 1996; Gangodagamage et al., 2014). Although we did not use topographic information in our study in order to derive ALT, it is indirectly introduced into our measurements through its effects on vegetation and moisture. For future studies the potential of refining the backscatter approach by incorporating topographic information could be explored. • P6, L26-31: The authors should delete this paragraph. TanDEM-X data can be used for InSAR, but that is not what the authors did. The authors essentially created regressions of ALT vs backscatter, not InSAR.

The DEM was used in our study to perform the Range-Doppler Terrain Correction. The paragraph describes its origin. We renamed the chapter from 'TerraSAR-X acquisitions' to 'X-band data' in order to prevent confusions.

• P7, L23- 4: Why would a relationship between NDVI and ALT indicate a relationship between backscatter and ALT?

We made the following changes in the manuscript to clarify this:

Based on results of previous studies which utilized the vegetation index NDVI (Table 1) <u>and</u> <u>the mutual dependency of NDVI and radar backscatter on vegetation coverage</u>, it is expected that a relationship between X-Band backscatter measurements and ALT is given.

• P7, L27 to P8, L2: The authors need to explain the technical terms associated with SAR that the broader audience of the Cryosphere will not understand. They need to define: Range Doppler correction, radiometric normalization, sigma-zero (the primary parameter), speckle, and near neighborhood. The average permafrost scientists will have no clue what these terms mean.

We added short descriptions of the used terms.

Utilising the software NEST (Next ESA SAR Toolbox) Range-Doppler Terrain Correction was performed with a TanDEM-X Intermediate DEM (~ 12 m resolution) in order to orthorectify the images and to compensate for distortions due to topographical variations and the tilt of the sensor. Images were processed to a pixel spacing of 2 m and a radiometric normalization was applied to account for incidence angle dependent sensitivity. The so called resulting σ_0 values were then converted into dB. The term backscatter refers in the following to these values, which represent the normalised measure of the radar return. SAR data are affected by so called speckle which is a noiselike effect. It can be understood as an interference phenomenon due to a number of scatterers within each resolution cell. The images were therefore further averaged over time and a spatial filter (average value of the cells in the neighbourhood was calculated: 5 x 5 cells – 10 m) was applied to subdue this noise.

• *P8, L6: What ALT values? From the CALM sites? Later the authors use the same ALT to 'validate' the regression, which seems circular.*

The CALM site data were only used for validation. The map over the entire CALM site (not only the in situ points) was produced in order to demonstrate and discuss the uncertainties. Sites VD-1, VD-2 and VD-3 were used for calibration only. We revised the manuscript to emphasize this.

Backscatter as well as NDVI values for the sites VD-1, VD-2 and VD-3 were extracted and compared to the mean ALT values of 2014 and 2015 of each measuring point.

Validation has been undertaken using ALT measurements at the CALM grid. <u>RMSE was</u> calculated representing the modelled ALT (linear regression of all VD sites) versus the measured ALT at the CALM site.

• *P8, L4-5: The authors need to explain how and why they choose these classes.*

The chosen class range allows a representative number of values for the statistics. We now clarified this in 'Methodology' section.

<u>ALT values were separated into 10 cm classes and the backscatter classes ranged 1 dB,</u> <u>allowing a representative number of sampling points per class (7 and 13 points minimum per class respectively).</u>

• *P8, L7-8: Stick to the linear function, as I state above. Show the exact form here.*

We now included the forms (see above).

• P8, L20: The authors need to explain figures 3, 4, and 5. One sentence each does not suffice.

We extended the text explaining figures 3, 4, and 5 and want to point out that they are further discussed within the Discussion chapter.

The assumption that backscatter increases with increasing amount of vegetation could be confirmed for the Vaskiny Dachi area (Figure 2). There is a difference of about 2 dB between the median for shrubs less than 20 cm and those larger than 60 cm. σ0 values for the grass/sedge class do however exceed these values. Cryptogam crust backscatter is at the same order of magnitude as shrubs between 20 and 60 cm height. Although the sparse vegetation at these areas consists mostly of lichen and volume scattering within is negligible, these spots often show higher surface roughness or even hummocks which may lead to a rise in backscatter amount. The boxplot of Figure 3 which shows the relationship between soil moisture and vegetation types at the CALM grid reveals that lowest soil moisture is encountered for areas with cryptogam crust, while higher shrubs and especially sedges dominate in areas of high soil moisture.

Class statistics (Figure 4) indicate a relationship between σ 0 and larger thaw depths (> 70 cm). Low backscatter values dominate in areas with low ALT and high backscatter values coincide with high ALT. However, the median σ 0 for shallow ALT does not decrease with decreasing ALT at the same rate as for deeper ALT.

The Scatterplots of the filtered σ 0 and ALT values of the sites VD-1 to VD-3 also indicate this correlation (see Figure 5). It also becomes apparent that the change in slope, that is visible in the boxplot of Figure 4, is caused by different backscatter values of the sites VD-1 and VD-2 (Figure 5). Nevertheless σ 0 increases generally with increasing ALT.

Figure 4. <u>Boxplots showing median, minimum and maximum values, first and third quartile and outliers of the ALT and backscatter values of the sites VD-1, VD-2 and VD-3.</u> Left: σ0 statistics for Active Layer Thickness (ALT) classes (10 cm). Right: ALT statistics for backscatter classes (1 dB).

• P9, L7-8: The authors must explicitly define 'coefficient of determination in the methods section, exactly how they calculated it, and what it means.

We included the formula and definition.

$$R^2 = 1 - \frac{\sum (y_i - f_i)^2}{\sum (y_i - \bar{y})^2}$$

The coefficient of determination ($\sum^{(y_i - \bar{y})^2}$, the proportion of the variance in the dependent variable that is predictable from the independent variable) was calculated for ...

• *P8, L8: The authors need to estimate the ALT uncertainty as a function of backscatter. RMSE is OK, but we really need an uncertainty estimate.*

According to the suggestion above we included the form of the regression and the std error as well as χ^2 . Furthermore we calculated R² for every VD site separately to illustrate the accuracy of the product.

• P11, L7-8: The authors need to explain why September would differ from August in terms of backscatter. I strongly suspect that leaves have fallen off the plants and the ground surface has started to freeze, altering the backscattering characteristics.

We now included the explanation, which you already indicated. Although freezing would also alter the backscatter a weather station near the respective research area doesn't indicate freezing in the respective year.

A season related reduction of leaves on shrubs could lead to a decrease in volume scattering and therefore lower backscatter values.

• P11, L14-5: Please explain the 'restrictions of the used approach.'

The explanation is given in the next sentences. We have now changed the sentence to clarify this.

For these points the following restrictions of the used approach become apparent.

• P11, L19-20: The moisture content will definitely contribute to backscatter, but the authors need to explain how. The authors should identify the expected penetration depths for dry and wet tundra.

We included an explanation for the influence of moisture content. However we removed the remark on penetration depth at P11 as it didn't offer any solution for the discussed problem. Furthermore we are not aware of any available studies on penetration depth of X-band SAR for dry or wet tundra. But Zwieback et al. (2016,

http://ieeexplore.ieee.org/document/7486090/) observed that wetting and drying lead to phase closure errors at X-band over tundra, indicating that penetration depth is indeed changing with moisture content.

The overall backscatter intensity of a certain surface area is also influenced by surface roughness with respect to the wavelength (3.1 cm), <u>as well as by soil moisture. A higher</u> <u>moisture content leads to a higher dielectric constant and therefore higher backscatter values</u> <u>and additionally a reduction in penetration depth.</u>

Soil moisture is another factor that influences radar backscatter as well as ALT. It increases the backscatter amount due to the rise of the dielectric constant and may lead to higher ALT, caused by an increased heat flux and an enhanced conductive transfer of heat into subsurface layers (Gross et al., 1990; Shiklomanov et al., 2010). For the Yamal region the measured moisture content is influenced strongly by lithology. While sandy soils are found to be dry, clayey saline soils often hamper infiltration and show higher soil moisture or even standing water. Although barren sandy areas are dryer, they have been shown to have maximal ALT (Leibman et al., 2015) due to higher heat flux, increased by infiltration of rain water.

• *P* 13, L9-11: The backscatter technique performs better than the NDVI technique, but this does not support or refute the initial hypothesis that you can use backscatter to estimate ALT. I suggest deleting this.

We now deleted this paragraph in the revised manuscript.

• P13, L12-4: I agree that you can scale this technique to larger areas and suggest you add a map of ALT for the entire x-band scene. This is what the readers really want to see.

We now added the map.

REFEREE #2

• Pg 2: Line 11 'a great potential' -> 'great potential'

Thank you for your comments pointing out where to improve our English. Changes have been made accordingly.

- Pg 5:10 'is resulting' -> 'results'
 - has been adapted
- Pg 6:23: stating the strip length is confusing since it is not the same as the full scene size that is actually analysed.

We now removed this statement.

• Pg 6:24 maybe say how many scenes rather than just 'all'.

The number of scenes has now been included.

• Pg 7:8-9 'to the in this study' clarify

The text has been expended accordingly

• Pg 7: 12-19. I would have thought that vegetation water content and hence dielectric properties would also influence backscatter values, but this is not mentioned at all. Only vegetation structure is mentioned. An expanded discussion of the interaction of vegetation and backscatter would be good.

Thank you for pointing this out. We expanded the discussion on this topic and would like to refer especially to the changes within the Introduction chapter (see file tracking changes).

• Pg 7:23 'in the surrounding.' Do you mean 'in the surrounding area'?

Yes; this has been adapted.

• Pg 7:30 It was not clear to me if the radiometric normalization applied was to normalize radiometry between images, or to remove terrain related (incidence angle) radiometric effects within images. Clarify.

Thank you for pointing this out. We revised the manuscript and clarified this:

Images were processed to a pixel spacing of 2 m and a radiometric normalization was applied to account for incidence angle dependent sensitivity.

- Pg 8:1 suggest replacing 'account' with 'subdue'
 - has been adapted
- Pg 8:19 replace 'like' with 'as'

- has been adapted
- Pg 13:9 'can be however not used' -> 'cannot however, be used'.
 - has been adapted

• Figure 1. The location map annotation needs to be enlarged. It was not readable.

We assume this comment refers to the annotations in the bottom right corner of the left location map. As it was not possible to enlarge it we put it in the figure description.

• Figure 2. 'Flat slope' seems a strange and contradictory name

We thank you for pointing this out. The names of this figure describing the topography of the CALM grid correspond to the metadata found for this CALM grid. Here three types of slope surfaces were subdivided: concave, flat and convex. We renamed the class from 'flat slope' to 'flat' to prevent confusions.

Active Layer Thickness Estimation from X-Band SAR Backscatter Intensity

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Abstract. The active layer above the permafrost, which seasonally thaws during summer is an important parameter for monitoring the state of permafrost. Its thickness is typically measured locally. A, but a range of methods, which utilize information from satellite data<u>exist</u>. Their, exist. Mostly, the Normalized Difference Vegetation Index (NDVI) obtained from optical satellite data is used as proxy. The applicability has been demonstrated mostly for shallow depths below of Active Layer

- 5 Thickness (ALT) below approximately 70 cm. Some permafrost areas including central Yamal arecharacterized by higher Active Layer Thickness (ALT). The, however, characterized by larger ALT. Surface properties including vegetation structure are also represented by microwave backscatter intensity. So far, the potential of such data for estimating ALT has not been explored. We therefore investigated the relationship between ALT and X-Band SAR backscatter of TerraSAR-X has been investigated (averages for 10 x 10 m window) in order to explore examine the possibility of delineating ALT on a continuous
- 10 and larger spatial coverage in this area . This study shows and compare it to the already established method of using NDVI from Landsat (30 m). Our results show that the mutual dependency of ALT and TerraSAR-X backscatter on land cover types induces a connection of both parameters. A range of 5 dB can be observed for an ALT range of 100 cm (40 - 140 cm) and an R² of 0.66 has been determined over the calibration sites. An increase of ALT with increasing backscatter can be especially determined for ALT > 70 cm. The RMSE over a comparably heterogeneous validation site with maximum ALT of > 150 cm is in the range
- 15 of 20 22 cm. Deviations are larger for measurement locations with mixed vegetation types (especially partial coverage by cryptogam crust) with respect to the spatial resolution of the satellite data.

1 Introduction

Permafrost is defined as soil or rock that remains at or below 0°C for two or more consecutive years (Harris et al., 1988) and currently underlies some 25 % of the Earth's land surface (Huggett, 2007). Due to global warming extensive areas where per-

20 mafrost is presently within a degree or two of the melting point could be destabilized (Smith, 1990). At global scale, increased ground temperatures could facilitate further climatic changes by releasing greenhouse gases that are currently sequestered in the upper layer of permafrost by increasing the annual thaw depth (Kane et al., 1991; Gomersall and Hinkel, 2001; Shiklomanov and Nelson, 1 The top layer of ground subject to annual thawing and freezing in areas underlain by permafrost is defined as the active layer

(Permafrost Subcommittee, 1988). In this layer most ecological, hydrological and biochemical activities take place (Kane et al., 1991; Brown et al., 2000). Furthermore it is an essential climate variable to monitor permafrost regions (Schaefer et al., 2015), making it not only an important factor at regional but also global scale. The active layer thickness (ALT) is predominately controlled by ambient temperature, but is also influenced by insulation layers such as snow cover and vegetation, slope, drainage,

5 soil type, organic layer thickness and water content (Leibman, 1998; Shiklomanov and Nelson, 1999; Hinkel and Nelson, 2003; Kelley et al., 2004; Melnikov et al., 2004; Vasiliev et al., 2008). Due to the interaction between these often highly localized surface and subsurface factors, ALT can vary substantially over short lateral distances (Shiklomanov and Nelson, 1999; Leibman et al., 2012).

Near-surface permafrost area is projected to decrease within the next century (IPCC, 2013). Changes in active layer thickness

10 have been already observed for Yamal (Leibman et al., 2015). Active, where active layer thickness spatial patterns are unknown outside of the sites with in situ measurements.

Analytical procedures exist to estimate ALT, such as the Stefan solution (Harlan and Nixon, 1978) or the Kudryavtsev equation. While the Stefan solution links the seasonal thaw depth to the accumulated surface thawing-degree days, the Kudryavtsev equation accounts for the effects of snow cover, vegetation, soil moisture, thermal properties, and regional climate (Kudryavt-

15 sev et al., 1974; Yershov, 1998; Shiklomanov and Nelson, 1999). These methods, although accurate, are labour intensive and limited in spatial coverage (Gangodagamage et al., 2014).

While traditional in situ measuring methods like probing with metal rods are very inefficient at regional scale, remote sensing holds **a**-great potential.

ALT can also ALT can be derived by empirical relationships between probe measurements and a physical attribute mea-

- 20 surable by remote sensing (Schaefer et al., 2015). Investigations have been made using the Normalized Difference Vegetation Index (NDVI) (McMichael et al., 1997; Kelley et al., 2004), digital elevation data and land-cover classes (Nelson et al., 1997; Peddle and F Especially optical data have been used to retrieve vegetation characteristics (see Table 1). A combination with derivatives of digital elevation models has been shown of added value (Peddle and Franklin, 1993; Leverington and Duguay, 1996; Gangodagamage et al., 2014). Recently, subsidence rates have been used as input for modelling ALT (Schaefer et al., 2015). Most
- 25 of these studies were conducted in areas with shallow ALT (for instance in Schaefer et al. (2015) the average ALT was 30 40 em). Deeper active layers were modeled by analytical approaches (e.g., Sazonova and Romanovsky, 2003) or by incorporating only a few ALT classes (e.g., Leverington and Duguay, 1996). Application of high resolution optical satellite data has been shown possible in combination with high resolution digital elevation data from airborne measurements . Such applications are however have been shown possible but are very limited in spatial extent. Subsurface thermal properties are also derived from
- 30 landcover classes, but applicability has been demonstrated only for the permafrost transition zones so far (Bartsch et al., 2016).

Recently, subsidence rates have been used as input for modelling ALT (Schaefer et al., 2015). Synthetic Aperture Radar has been exploited using interferometric analyses (InSAR, provides seasonal ground subsidence) in combination with soil properties to estimate ALT without using empirical relationships with probing data (Schaefer et al., 2015).

Most previous remote sensing approaches (Leverington and Duguay, 1996; McMichael et al., 1997; Sazonova and Romanovsky, 2003; Schaefer et al., 2015) have utilized data with spatial resolutions of 30 m and coarser and are limited to ALT less than were conducted in areas with shallow ALT (less than approximately 70 cm⁽, see Table 1). Many regions such as the Yamal peninsula are however characterized by a larger ALT range.

- 5 Investigations have been made using the Normalized Difference Vegetation Index (NDVI) (McMichael et al., 1997; Kelley et al., 2004), digital elevation data and land-cover classes (Nelson et al., 1997; Peddle and Franklin, 1993). Synthetic Aperture Radar has been exploited using interferometric analyses (InSAR, provides seasonal ground subsidence) in combination with soil properties to estimate ALT (Schaefer et al., 2015). The utility has been demonstrated for average thaw depths of 30-40 cm and applicable to soils which are saturated all summer. Outside of such sites, ALT is underestimated. This would apply to many parts of the
- 10 Yamalregion. Previous tests in that region Deeper active layers were modeled by analytical approaches (e.g., Sazonova and Romanovsky, 20 by incorporating only a few ALT classes (e.g., Leverington and Duguay, 1996). For Yamal, previous tests indicate that ALT below 70 cm, 70 100 cm and above 100 cm can be distinguished using NDVI (Leibman et al., 2015).

SAR backscatter intensity has so far not been investigated for ALT estimation. Radar backscatter at X-band is also related to vegetation coverage, especially shrubs (Duguay et al., 2015), due to volume scattering, similarly to the NDVI. The microwave

- 15 signal interacts with leafs in the shrub canopy due to the comparable short wavelength (~ 3 cm). Leaves size of willows often exceed this wavelength and stems can have significant larger diameters (Widhalm et al., 2016). Also vegetation water content may influence the return signal, but no dedicated investigations for tundra species exist. The overall backscatter intensity of a certain surface area is also influenced by surface roughness with respect to the wavelength., as well as by soil moisture. A higher moisture content leads to a higher dielectric constant and therefore higher backscatter values and additionally a reduction in
- 20 penetration depth. X-band investigations in tundra (Lena Delta) suggest that such variations can occur (Zwieback et al., 2016), but results from Antonova et al. (2016)showed no sensitivity to precipitation over the same area.

In this study we hypothesize that there is a relationship between local ALT and X-band measurements. In , based on the influence of ALT affecting features on backscatter strength. Like ALT, backscatter is dependent on vegetation cover. Furthermore shrubs, which can be monitored with X-band data, can be related to snow cover due to their characteristic of

25 retaining snow (Domine et al., 2016). Moreover the terrain in this region is closely linked to drainage and water content which are influencing ALT. These characteristics are in turn influencing the predominant vegetation, which, including soil moisture, can be captured with microwave backscatter. We use in situ records from several sites in the proximity of a long-term monitor-ing site on Yamal have been used and results are discussed and discuss the results with respect to previous approaches which use remotely sensed information as proxy for ALT.

30 2 Study area and datasets

2.1 The Vaskiny Dachi monitoring site

The Vaskiny Dachi research station (70°20'N, 68°51'E) was established in 1988 and is situated in the central Yamal Peninsula in a system of highly-dissected alluvial-lacustrine-marine plains and terraces. It is located within a region of continuous

Reference	remotely sensed data	ALT measurement	resolution	study area	ALT	accuracy
Peddle and Franklin (1993)	SPOT imagery (land cover) and photogram- metric DEM	in situ soil probing at regular intervals througout field sam- ple sites of 60 x 60 m	20 m	Ruby Range, southwest Yukon Territory, Canada	classes: < 25 cm; 25 cm - 50 cm; > 50 cm; no permafrost	79% agreement for the four classes
Leverington and Duguay (1996)	Landsat Thematic Mapper (NDVI, land cover) and DEM data	pit measurements supple- mented by three ground probing measurements in 5 m intervals in four directions at each site	30 m	Mayo region. Central Yukon Basin, Canada	classes: < 70 cm; 70 cm - 150 cm; > 150 cm	93% agreement for the three ALT classes
McMichael et al. (1997)	Landsat Thematic Map- per and handheld ra- diometer (NDVI)	median of five ground probing measurements at each sample point	30 m	Prudhoe Bay and Happy Valley, North Slope, Alaska	average: < 35 cm	No relationship between NDVI and ALT on the North Slope of Alaska in ar- eas with little variation in relief. In areas where to- pography strongly controls the flow and redistribution of water, NDVI did account for approximately 40% of the variability
Gangodagamage et al. (2014)	LiDAR (local slope and landscape curvature) and Worldview-2 (NDVI)	probing along transects of di- verse length and at various in- tervals	2 m	Barrow, Alaska	20 -70 cm	$R^2 = 0.76$ and RMSE ± 4.4 cm
Schaefer et al. (2015)	Subsidence from multian- nual Phased Array type L- band Synthetic Aperture Radar (PALSAR)	average of calibrated Ground Penetrating Radar (GPR) measuremts within each pixel (~ 40 traces per pixel); probe measurements at two CALM sites (1 x 1 km grid with 100 m interval, 10 x 10 m plot	∼ 30 п	Barrow, Alaska	average: 30 - 40 cm; < 40 cm in areas outside of drained lake basins	\sim 76% of the study area within uncertainty of the used Ground Penetrating Radar and probing data (\sim 8 cm)



Figure 1. Location of the study area within the Yamal peninsula and CALM grid DEM with land cover information (Sources left: ArcMap Basemap: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp. Source top right: Google Earth, Image © 2016 Digital Globe. <u>Bottom left: DEM Dvornikov et al. (2016).land cover information</u> from vegetation survey of August 2015)

permafrost where tundra lakes and river flood plains are the most prominent landscape features (Leibman et al., 2015). Dense dwarf shrubs (Betula nana) are widespread on the watersheds. Well-drained hilltops are occupied by dwarf shrub-moss-lichen communities. On gentle poorly drained slopes, low shrubs and dwarf shrubs are well developed and mosses predominate. On convex tops and windy hill slopes, shrub-moss-lichen communities with spot-medallions are predominant. River valleys,

5 thermocirques, and landslide cirques with thick snow cover are characterized by willow thickets. Sedge and sphagnum bogs and flat-topped polygonal peatlands are common on flat and concave (saddles) surfaces of watersheds and terraces, in the river valley bottoms, on low lake terraces and in other depressions (Khomutov and Leibman, 2014). The study area is characterized by continuous permafrost. ALT ranges between 40 cm in peat and up to 120 cm on sandy, poorly vegetated surfaces (Melnikov et al., 2004; Vasiliev et al., 2008; Leibman et al., 2011, 2012). There are extremes observed on high-center sandy polygons, which can be 1–1.5 m high and up to 10 m in diameter, with active layer exceeding 2 m. Spatial changes in ground temperature are controlled by the redistribution of snow which is resulting results from strong winds

5 characteristic for tundra environments and the highly dissected relief of Central Yamal (Dvornikov et al., 2015). Lowest ground temperature is characteristic for hilltops with sparse vegetation where snow is blown away. The warmest are areas with high willow shrubs, due to the retention of snow, found on slopes, in valleys and lake depressions. While the spatial distribution of ALT depends on lithology and surface covers, temporal fluctuations are controlled by ground temperature, summer air temperature and summer precipitation (Leibman et al., 2015).

10 2.2 In situ measurements

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In 1993 a Circumpolar Active Layer Monitoring (CALM) site was established at Vaskiny Dachy, placed on the top and slope of a highly dissected plain, affected by landslides, with sandy to clayey soils. The CALM program, designed to observe the response of the active layer and near-surface permafrost to climate change, currently incorporates more than 100 sites. The International Permafrost Association serves as the international facilitator for the CALM network, which is now part of the WMO Global Terrestrial Network for Permafrost (GTN-P) (Brown et al., 2000).

Within the Greening of the Arctic (GOA) project of the International Polar Year (IPY), which was funded by NASA's Land-Cover Land-Use Change (LCLUC) program, three additional monitoring sites were established in the Vaskiny Dachi area (Walker et al., 2009). Study sites were established within areas with more or less homogeneous vegetation. The site Vaskiny Dachi-1 (VD-1) has clay soils and the vegetation is heavily grazed sedge, dwarf-shrub-moss tundra. Soils at Vaskiny Dachi-2

20 (VD-2) are a mix of sand and clay, its vegetation is heterogeneous, but dominated by dwarf birch, small reed grass and sedge, cowberries and mosses. At Vaskiny Dachi-3 (VD-3) the soils are sandy and the vegetation is a dry dwarf-shrub-lichen tundra (Walker et al., 2009).

The ALT is measured by a metal probe according to CALM protocol. This involves a late season mechanical probing, in this case late August, when ALT is near its end-of-season maximum. A 1 cm diameter graduated steel rod is inserted into the soil to the depth of resistance to determine the depth of thaw (Brown et al., 2000).

ALT is measured at a spacing of 10 m within the 100 x 100 m grid at the CALM site, resulting in 121 measuring points. The VD sites feature 5 transects respectively. At VD-1 and VD-2 these transects form grids of 50 x 50 m. Transects are 12.5 m apart and ALT is measured every 5 m, resulting in 55 measurement points per site. The transects at VD-3 are arranged to areas of homogeneous vegetation (Walker et al., 2009). The site of VD-3 features higher ALT values, most likely because of the present

30 sandy soils, which yield a greater conductivity and water permeability (higher convective heat exchange). The CALM grid site is far more heterogeneous than the other VD sites and holds patches of dry cryptogam crust, grasses and mosses, low and high shrubs as well as some wet sedge spots. Cryptogam crust is encountered at the concave hilltop, while high shrubs were mostly located at the landslides (Figure 8). Here, ALT is locally higher due to high salinity of clayey deposits which contain no ice under negative temperature and do not resist to probing. A-In August 2015, we carried out a dedicated vegetation survey of each CALM grid pointwas carried out in August 2015. The, where we determined the dominant vegetation cover within a 3 x 3 m area was determined (Figure 1). The following classes are distinguished: Cryptogam crust, low shrubs (< 15 cm), medium shrubs (15 -30 cm), high shrubs (> 30 cm), grass and moss as well as a class where sedges dominate and classes of mixed vegetation. Further information on vegetation has

- 5 been collected outside of the ALT measurement sites in August 2014. Over 60 points were registered but only 36 of these points could be further used because of low homogeneity with respect to the spatial resolution of the satellite data. This survey included the most dominant classes of the region: low shrubs (< 20 cm), medium shrubs (20 -60 cm), high shrubs (> 60 cm), Cryptogam crust, and a mixture of grasses and sedges and therefore covered more types than can be found at the VD sites or the CALM grid.
- 10 Furthermore moisture measurements were conducted we conducted moisture measurements at the CALM grid. The We used the Delta-T Wet Sensor with HH2 handheld was used to measure the moisture content of the top 5 cm at each grid point on three dates in August 2015.

2.3 TerraSAR-X acquisitionsX-band data

Backscatter information from data of the TerraSAR-X mission have been used for this study. The digital elevation model available from the TanDEM-X mission has been used as auxiliary data set for TerraSAR-X data preprocessing.

The German national SAR-satellite system TerraSAR-X is based on a public-private-partnership agreement between the German Aerospace center DLR and EADS Astrium GmbH. It was launched in June 2007 and started its operational service at the beginning of 2008 (DLR, 2009). The satellite flies in a sun-synchronous, dawn dusk orbit with an 11-day repeat period. TerraSAR-X features an advanced high-resolution X-Band Synthetic Aperture Radar with a centre frequency of 9.65 GHz corresponding to a wavelength of about 3.1 cm. TerraSAR-X operates in Spotlight-, Stripmap- and ScanSAR Mode with

20 corresponding to a wavelength of about 3.1 cm. TerraSAR-X operates in Spotlight-, Stripmap- and ScanSAR Mode with various polarizations. In this study HH (horizontally sent and horizontally received) polarized images of Stripmap mode were used, which image strips of 30 km width and a maximum length of 1.5 km and at 3 m resolution (Werninghaus et al., 2004).

All images Six images from August 2014 and 2015 (three images per year) were obtained as SSC (Single Look Slant Range Complex). Available data and have been acquired in the same ascending orbit and beam (incidence angle range 27.3° - 30.3°).

- The TanDEM-X mission is an extension of the TerraSAR-X mission, coflying a second satellite of nearly identical capability in a close formation. This enables the acquisition of highly accurate cross- and along-track interferograms without the inherent accuracy limitations imposed by repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances (Krieger et al., 2007). In this study the TanDEM-X Intermediate DEM (IDEM, ~ 12 m pixel spacing, < 10 m absolute horizontal and vertical accuracy) was used for terrain correction, which, compared to the final TanDEM-X DEM product, might
- 30 have limitations with respect to product quality and completeness (DLR).

2.4 Landsat data

Landsat 8, launched in 2013, is a NASA (National Aeronautics and Space Administration) and USGS (Department of the Interior U.S. Geological Survey) collaboration, which extends the 40 year Landsat record. It carries two sensors, the Operational

Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), which spectral bands remain comparable to the Landsat 7 ETM+ and operate in the visible, near-infrared, short wave and thermal infrared. Landsat 8 flies in a near-polar, sun-synchronous 705 km circular orbit and acquires data in 185 km swaths segmented into 185 km x 180 km scenes. For this study two Level 1 terrain-corrected (L1T) scenes of 22^{nd} July 2014 and 10^{th} August 2015 were obtained in order to calculate NDVI

5 (spatial resolution 30 m) and compare the already established approach of using NDVI for ALT delineation to the in this study introduced approach of utilizing TerraSAR-X backscatter.

3 Methodology

In Microwave Remote Sensing the radar backscatter is dependent on sensor parameters like incidence angle, polarization and wavelength and also on geometric parameters such as surface roughness and vegetation structure, as well as soil properties.

- 10 Shorter wavelengths do not penetrate as much as longer wavelengths into vegetation and soil, therefore short wavelengths like X-band rather yield information about the upper layers of vegetation (Ulaby et al., 1982). The assumption for this study is that surface roughness variations play a minor role regarding spatial backscatter differences across the study site. Backscatter increases with increasing vegetation height for X-band in tundra what originates from volume scattering and double bounce (leading to higher backscatter) rather than surface roughness (Ullmann et al., 2014). It can be also expected that soil moisture
- 15 variations are not reflected in X-band measurements when vegetation cover is present. The assumption is that volume scattering and double bounce in vegetation is the main contributor to spatial differences in backscatter.

The local vegetation patterns are influenced by terrain and soil moisture and also correlate with snow cover thickness, which are all ALT influencing factors (Shiklomanov and Nelson, 1999; Gomersall and Hinkel, 2001; Kelley et al., 2004). Areas with shrubs have higher snow cover, which prevents the ground from cooling in the winter. The ALT might be therefore also higher

- 20 than in the surrounding area. Based on results of previous studies which utilized the vegetation index NDVI (Table 1) and the mutual dependency of NDVI and radar backscatter on vegetation coverage, it is expected that a relationship between X-Band backscatter measurements and ALT is given. A-We compiled a data set based on TerraSAR-X which allows the investigation of this relationshiphas been compiled. This included for SAR common pre-processing steps to account for variations due to viewing geometry.
- 25 Six TerraSAR-X images from August 2014 and 2015 were processed (three images per year). It is assumed that within this time stable phenological conditions can be expected. Utilising the software NEST (Next ESA SAR Toolbox) Range-Doppler Terrain Correction was performed with a TanDEM-X Intermediate DEM (~ 12 m resolution) in order to orthorectify the images and to compensate for distortions due to topographical variations and the tilt of the sensor. Images were processed to a pixel spacing of 2 m and a radiometric normalization was applied to account for incidence angle dependent sensitivity. The
- so called resulting σ_0 values were then converted into dB. The term backscatter refers in the following to these values, which represent the normalised measure of the radar return. SAR data are affected by so called speckle which is a noiselike effect. It can be understood as an interference phenomenon due to a number of scatterers within each resolution cell. The images were

therefore further averaged over time and a spatial filter (average value of the cells in the neighbourhood was calculated: 5×5 mean neighbourhood cells – 10 m) was applied to account for subdue this noise.

Backscatter as well as NDVI values for the Vaskiny Dachi sites one to three sites VD-1, VD-2 and VD-3 were extracted and compared to the mean ALT values of 2014 and 2015 of each measuring point. σ_0 values have been directly compared to

- 5 ALT and also statistics for classes of backscatter have been derived (class range The relationship of backscatter values and ALT was examined by varying representations. Bloxplots for ALT classes and for backscatter classes are shown in Figure 4. ALT values were separated into 10 cm classes and the backscatter classes ranged 1 dB). These results were then further used in order to determine a relationship allowing the conversion of , allowing a representative number of sampling points per class (7 and 13 points minimum per class respectively). σ_0 values into ALT values . Three different functions were tested as well
- 10 as NDVI values were additionally compared directly to ALT by scatterplots (Figure 5). Fitted linear functions were applied to characterise the relationship between TerraSAR-X backscatter and ALT values. An automatically fitted linear function, an automatically fitted polynomial function and an adapted polynomial function which behaves better for low ALT values where measuring values are missing (see Figure 5). NDVI respectively and ALT values of the sites VD-1, VD-2 and VD-3. The coefficient of determination ($R^2 = 1 - \sum_{i=1}^{N} \frac{(y_i - f_i)^2}{(y_i - g_i)^2}$, the proportion of the variance in the dependent variable that is predictable
- 15 from the independent variable) was calculated for the regression lines which involved all VD sites, as well as for regression lines for each VD site separately (Table 2). Validation has been undertaken using ALT measurements at the CALM grid. A similar approach was followed for the NDVI records. RMSE was calculated representing the modelled ALT (linear regression of all VD sites) versus the measured ALT at the CALM site. Moreover χ^2 was determined, which also accounts for observational uncertainties. An observational uncertainty of 4 cm was assumed for the probe measurements which has been investigated by
- 20 Leibman (1998) for sandy soils (2 4 cm) in this region. The modelled and measured ALT values at the CALM grid were further compared by scatterplots depicting the different vegetation types (Figure 7) in order to investigate their impact.

Backscatter statistics have been also derived for different vegetation classes from locations of the 2014 survey outside of the ALT measurement sites (Figure 2). These locations represent relatively homogeneous sites (with respect to TerraSAR-X spatial resolution). The ALT sites, especially the CALM grid, are comparably heterogeneous and therefor of limited applicability for

25 determination of backscatter dependence on vegetation type. The relation of vegetation type and soil moisture was examined for the CALM grid using moisture measurements of August 2015 (Figure 3). Comparison of topographic units and vegetation type at the CALM grid.

4 Results

The assumption that backscatter increases with increasing amount of vegetation could be confirmed for the Vaskiny Dachi area

30 (Figure 2). There is a difference of about 2 dB between the median for shrubs less than 20 cm and those larger than 60 cm. σ_0 values for the grass/sedge class do however exceed these values. Cryptogam crust backscatter is at the same order of magnitude like as shrubs between 20 and 60 cm height. Although the sparse vegetation at these areas consists mostly of lichen and volume scattering within is negligible, these spots often show higher surface roughness or even hummocks which may lead to a rise in



Figure 2. Boxplot for backscatter values of various vegetation types. The used points were recorded within a field campaign in 2014. Backscatter values were extracted from the temporally averaged and spatially filtered image of August 2014 and 2015 acquisitions.



Figure 3. Boxplot for mean soil moisture values of three acquisition dates in late August 2015 for vegetation types at the CALM grid.

backscatter amount. The boxplot of Figure 3 which shows the relationship between soil moisture and vegetation types at the CALM grid reveals that lowest soil moisture is encountered for areas with cryptogam crust, while higher shrubs and especially sedges dominate in areas of high soil moisture.

Class statistics (Figure 4) indicate a relationship between σ_0 and larger thaw depths (> 70 cm). The Low backscatter values dominate in areas with low ALT and high backscatter values coincide with high ALT. However, the median σ_0 for shallow ALT does not decrease with decreasing ALT at the same rate as for deeper ALT.

Scatterplots The scatterplots of the filtered σ_0 and ALT values of the sites VD-1 to VD-3 also indicate this correlation (see

- 5 Figure 5). Comparing all three VD sites it It also becomes apparent that low backscatter values dominate in areas with low ALT and high backscatter values coincide with high ALT, the change in slope, that is visible in the boxplot of Figure 4, is caused by different backscatter values of the sites VD-1 and VD-2 (Figure 5). Nevertheless σ_0 increases generally with increasing ALT. The overall higher ALT values of VD-3 are reflected by their higher backscatter values. A range of 5 dB can be observed for an ALT range of 100 cm (40 - 140 cm). Some sites show a
- 10 A coefficient of determination of 0.66 was obtained for the linear regression of backscatter and ALT values (see Table 2). The mathematical form of the regression line is given in Figure 5. The standard error of the intercept is 14.00 and 0.96 for the slope respectively. R^2 for the individual VD sites showed highest values for VD-3 compared to VD-1 and VD-2, which both feature lower ALT values. The linear regression which incorporated all calibration sites (VD-1, VD-2 and VD-3) yielded an RMS error of 20 cm at the CALM grid site and 25 cm for χ^2 . Some VD points showed a backscatter variability of more
- 15 than 1 dB between the acquisitions of 2014 and 2015. An exclusion of these points would slightly increase the coefficients of determination, but no positive effect could be found with RMSE values at the CALM grid.

Coefficients of determination of below 0.66 were obtained for all tested functions (see Table 2). The resulting RMS errors at the CALM grid site range from 20 to 22 cm.

The found relationship between TerraSAR-X backscatter and ALT is not that pronounced at the CALM validation site as 20 at the other plots. Especially a patch at the highest elevation of the CALM grid was expected to show higher ALT values according to the calculations from the satellite data (Figure 7 and Figure 6). There are also some spots with slightly higher ALT than predicted. This applies to ALT larger than 125 cm. With the exception of the area around the hilltop the patterns derived with TerraSAR-X however resemble those of the in situ measurements.

A deeper active layer can be found in areas with high shrubs as well as cryptogam crust at the CALM site (see Figure 6).
Extremes of ALT can further be encountered at the clay-rich landslides with relatively sparse vegetation, classified as 'other' in Figure 6. Thinner active layers were encountered at zones with grass and moss or low shrubs (see Figure 6). Residuals increase for depths larger than 125 cm, especially in case of dominance of cryptogam crusts.

In Figure 7 a map of the calculated ALT is given for the entire TerraSAR-X scene (open water bodies are masked out). Linear features are expected to be false values as they can be attributed to artificial objects. They show low as well as high

30 ALT values depending on surface roughness and material (air strip and rail track respectively). Values across the scene range between 60 and 180 cm. ALT is higher in drained or partially drained lake basins.

Derived scatterplots of NDVI and ALT values also reveal a relationship within the observed NDVI range of 0.46 - 0.65 (Figure 5). All tested functions showed even greater The standard error of the intercept is 9.21 for 22^{nd} July 2014 and 11.60 for 10^{th} August 2015 and 15.80 and 20.21 for the slope respectively. Both NDVI images showed even larger coefficients of

determination of about 0.73 - 0.760.75, than the TerraSAR-X approach (Table 2). The achieved RMSE at the validation site



Figure 4. Boxplots showing median, minimum and maximum values, first and third quartile and outliers of the ALT and backscatter values of the sites VD-1, VD-2 and VD-3. Left: σ_0 statistics for Active Layer Thickness (ALT) classes (10 cm)of the sites VD-1 to VD-3. Right: ALT statistics for backscatter classes (1 dB)of the sites VD-1-3.

is however about 7 cm larger than when using the TerraSAR-X backscatter values. Furthermore, when using only site VD-3, which has the highest range and total thickness of the active layer, the comparable to the values at the CALM grid, the linear regression for the backscatter values has a coefficient of determination of 0.622 while for NDVI values it is only 0.017 and 0.002 respectively (Figure 5). The NDVI derived ALT values for the CALM site range at most between 70 and 100 cm for

5 22^{nd} July 2014 and between 60 and 110 cm for 10^{th} August 2015, while measured values have a range of 60 - 150 cm, with values > 130 only found for saline clay (Figure ??).

Calculated ALT maps (background raster, based on X-band backscatter) for the CALM grid compared to in situ measurements (circles)

5 Discussion

- 10 Boxplot for mean soil moisture values of three acquisition dates in late August 2015 for vegetation types at The assumption that X-band backscatter variations result from mostly differences in volume scattering in vegetation over tundra does not seem to be valid for the CALM gridselected sites. Radar backscatter is dependent on volume scattering, surface roughness and soil moisture. The influence of all these effects can be perceived in Figure 2. For shrubs a major contributor to backscatter is the volume scattering that takes place within the vegetation. A rise in volume indicated by shrub height clearly gives rise to
- 15 backscatter amount. This effect is also described in Duguay et al. (2015), where areas with high shrubs show higher backscatter values.



Figure 5. Upper Left: Comparison between σ_0 and Active Layer Thickness (ALT) values at the sites VD-1 to VD-3; <u>points</u> with differences of more than 1 dB between 2014 and 2015 are marked by circles. Linear Regression for <u>site VD-3 for</u> σ_0 and Active Layer Thickness (ALT) values <u>-Middle of all sites in black</u> and for site VD-3 in red, bottomleft: Comparison between NDVI (22^{nd} July 2014 and 10^{th} August 2015) and Active Layer Thickness (ALT) values at the sites VD-1 to VD-3. Linear Regression for <u>site VD-3 for</u>-NDVI and Active Layer Thickness (ALT) values <u>-Upper right: Three different functions fitted to σ_0 of all sites in black</u> and Active Layer Thickness (ALT) values <u>(ALT) values for site VD-3 in red</u>. Middle and bottom right: Three different functions fitted to NDVI (22^{nd} July 2014 and 10^{th} August 2015) and Active Layer Thickness (ALT) values.

6 Discussion

X-Band backscatter spatial variations seem to resemble ALT for larger thaw depths only (> 70 cm). There are however differences between the training datasets. Both, VD-1 and VD-2, lie within a similarly lower ALT range, with VD-1 showing slightly lower backscatter values than VD-2. These differences can also be observed for NDVI (Figure 5) A pronounced

5 relationship was however not found for X-band in HH by Ullmann et al. (2014) over the MacKenzie Delta. They applied a smaller spatial filter of 3 x 3 and used data from the end of the growing season (mostly September) when plant decay is already expected to take place. A season related reduction of leaves on shrubs could lead to a decrease in volume scattering and



Figure 6. Comparison between predicted and measured ALT values at the CALM grid with differentiation between vegetation types for the three tested backscatter functions TerraSAR-X and NDVI approaches.

therefore lower backscatter values. Especially the acquisition of 22^{nd} July 2014 shows clearly higher NDVI values for VD-1 than for VD-2. The backscatter differences could be explained due to a slightly higher surface roughness, which is however not pronounced enough to have a sufficient influence on the sites snow cover or even ALT. This is supported by the comparison to vegetation types. The magnitude of backscatter for cryptogam crust, which predominantly occurs on sandy soils, can neither

- 5 be attributed to volume scattering in vegetation nor to soil moisture (Figure 2). Vegetation at VD-2 is very heterogeneous and also includes patches of sedges or reeds. Such sites have and 3). Surface roughness or partial interaction within the upper soil may lead to higher backscatter than shrub dominated areas. While VD-1 and to a small amount even VD-3 also show sedge vegetation, these sandier sites show a different kind of grass (carex bigelowii instead of calamagrostis holmii) for grass and low shrubs < 20 cm.</p>
- 10 The assumption that backscatter variations result from mostly differences in volume scattering in vegetation does not seem to be valid for the selected sites. It agrees with findings of McMichael et al. (1997) that the amount of vegetation alone cannot be used for ALT retrieval. High soil moisture is typical for the class segdes (Figure 3), giving rise to the backscatter amount. Additionally the so called double bounce effect, which may occur for sedges and grass in standing water, can lead to an increase of received backscatter (Figure 2).
- 15 Using backscatter intensity at only one polarization , (as available for this study) does not allow to distinguish between surface and volume scattering. Polarimetric analyses (using other combinations of H and V polarizations) may help to distinguish the scattering mechanism contributions (see e.g. Ullmann et al. (2014)). Data acquired at different polarizations are however not available for the study site.

As described in Duguay et al. (2015) areas with high shrubs show higher backscatter values . A pronounced relationship 20 was however not found for X-band in HH by Ullmann et al. (2014) over the MacKenzie Delta. They applied a smaller spatial filter of 3 x 3 and used data from the end of the growing season (mostly September) when plant decay is already expected





to take place. Our results however indicate that there is a relationship for the Vaskiny Dachi area. The above described influences on radar backscatter can be linked to ALT controlling factors. The effect of shrubs on ALT has been described contradictorily by different authors. On the one hand shrubs have been said to have a cooling effect due to shading in the summer (Blok et al., 2010; Lawrence and Swenson, 2011; Pearson et al., 2013), leading to shallower ALT. In other publications (Domine et al., 201

5 have been linked with ground warming due to the isolating effect of snow cover. Shrubs trap wind-blown snow and limit snow erosion by wind. It seems that the prevailing effect of cooling or warming may be caused by the length of winter or summer season. For the CALM site it can be shown that shrubs coincide with deeper ALT (Figure 6). However it needs to be noted that shrubs are here found on saline clay, which, as stated before, can lead to higher ALT values measured by probing. In clayey saline soils (with ALT values > 130 cm at the CALM site) the freezing point is different from zero and probes can be inserted

10 to greater depths (Leibman, 1998).

Soil moisture is another factor that influences microwave backscatter and ALT. It increases the backscatter amount due to the rise of the dielectric constant. It may lead to higher ALT, caused by an increased heat flux and an enhanced conductive transfer





of heat into subsurface layers (Gross et al., 1990; Shiklomanov et al., 2010). For the Yamal region the measured moisture content is influenced strongly by lithology. While sandy soils are found to be dry, clayey saline soils often hamper infiltration and show higher soil moisture or even standing water. Although barren sandy areas are dryer, they have been shown to have maximal ALT (Leibman et al., 2015) due to higher heat flux, increased by infiltration of rain water. Cryptogam crust is typically

- 5 found on high centred sandy polygons in the study area. For these points the following restrictions of the used approach become apparent. Most points for which the modelled ALT shows high deviations from the in situ data have or lie close to spots of cryptogam crust. The volume scattering for areas with cryptogam crusts is expected to be very low (as described in the 'Results' section) but the recorded σ_0 is comparable to medium shrub heights which have a lower thaw depth. The higher σ_0 values could be due to higher surface roughness. The moisture content itself may also contribute to σ_0 , however soil moisture values for
- 10 areas with cryptogam crust have shown to be very low (see Figure 3). Heterogeneity regarding vegetation coverage may also contribute. Especially sites with mixed types show high deviations (see Figure 6).

The redistribution of water and consequently also the occurring vegetation is controlled by lithology, but also by topography (see Figure 2). 8), which has been shown useful in delineating ALT (Peddle and Franklin, 1993; Leverington and Duguay, 1996; Gangodag Although we did not use topographic information in our study in order to derive ALT, it is indirectly introduced into our

15 measurements through its effects on vegetation and moisture. For future studies the potential of refining the backscatter approach by incorporating topographic information could be explored.

The comparison of the produced ALT map to the ALT measurements at the CALM grid showed that some points within the validation dataset from the CALM grid are not well represented by the produced ALT map . map (Figure 7). These sites deviate also in the probe data. For instance for one of these points an ALT of > 170 cm was measured in 2014, which is about

20 almost double the values of the surrounding points, and in 2015 only 116 cm were registered. Such an extreme variability of ALT could be explained by an interface between a sandy active layer and a clayey permafrost at this location. In clayey saline soils (as can be found at the study site)the freezing point is different from zero and probes can be inserted to greater depths

(Leibman, 1998). On the other hand restrictions of the used approach become apparent. Most points for which the modelled ALT shows high deviations from the in situ data have or lie close to spots of cryptogam crust. These are typically found on the high centred sandy polygons in the study area. The comparably high ALT values are here not driven by trapped snow in winter but higher conductivity of heat throughout the summer. The surface roughness for areas with cryptogam crusts is expected to

- 5 be comparably low but the recorded σ_0 is comparable to medium shrub heights which have a lower thaw depth. The radar signal may penetrate deeper into the soil surface at such sites depending on moisture content. The moisture content itself may also contribute to σ_0 . However in situ soil moisture measurements of the top layer in the overall dry August 2015 showed lowest soil moisture values for areas with cryptogam crust, while the wettest areas were covered with sedges and high shrubs (see Figure 3). Heterogeneity regarding vegetation coverage may also contribute. Especially sites with mixed types show high
- 10 deviations (see Figure 6).

The comparison to Landsat-

Regarding the delineated ALT map for the entire TerraSAR-X scene (Figure 7) it needs to be considered that neither the calibration data (VD sites), nor the validation site (CALM grid) included lowlands with extensive wetlands, as can be found in this region. Because of the lack of ALT measurements for these areas, the shown map is only representative for parts of

15 the region, while lowlands would need further verification. The higher ALT in drained lake basins does agree with findings of Schaefer et al. (2015) around Barrow. They, however, argue that their algorithm is actually overestimating ALT at these locations.

The comparison of Landsat 8 derived NDVI values derived NDVI values and ALT revealed a negative correlation (see Figure 5), which is contrary to most studies of other regions (Gangodagamage et al., 2014; McMichael et al., 1997). However

- 20 Leibman et al. previously obtained similar results for the Yamal region at the CALM grid. Results suggest that NDVI is higher for sites with grasses, mosses and sedges than for medium to high shrubs (Salix) although the used near infrared is influenced by plant cell structure and vegetation biomass. These shrubs do, however, coincide with very wet soils (Figure 3) and are growing within partially waterlogged depressions. The sensitivity of NDVI to water (Raynolds and Walker, 2016) might have an impact over these sites. Furthermore a difference between the training datasets becomes apparent. Both, VD-1 and VD-2, lie within
- 25 a similarly lower ALT range, but especially the acquisition of 22nd July 2014 shows clearly higher NDVI values for VD-1 than for VD-2. This points to different vegetation types. A difference is also observed for the X-Band backscatter, where VD-1 shows slightly lower backscatter values than VD-2. The backscatter differences could be explained due to a slightly higher surface roughness, which is however not pronounced enough to have a sufficient influence on the site's snow cover or even ALT. Moreover vegetation at VD-2 is rather heterogeneous and also includes patches of sedges or reeds, which could increase
- 30 the amount of backscatter. While VD-1 and to a small amount even VD-3 also shows sedge vegetation, these sandier sites show a different kind of grass (carex bigelowii instead of calamagrostis holmii). Moreover a clear difference between Landsat acquisitions of 22nd July 2014 and 10th August 2015 exists due to differences in vegetation and their respective phenological cycles (Bratsch et al., 2016), which are in turn influenced by terrain features and consequent draining conditions.

Regarding the TerraSAR-X approach to map ALT in contrast to the NDVI approach demonstrates the advantages and disadvantages of the new approach with respect to previous studies. Investigations presented in this paper showed that the introduced approach of using TerraSAR-X backscatter values to delineate ALT values is suitable to provide higher than 30 m resolution estimates over unsaturated soils with ALT ranging from 7040 cm to 150140 cm in areas outside of high centred sandy polygons. One previous study that was conducted within comparable ALT ranges used NDVI and land cover information respectively derived from Landsat data in combination with DEM data to derive three classes of ALT (Leverington and Duguay, 1996).

- 5 A 93% agreement rate for three different ALT classes was obtained. In difference to our study Leverington and Duguay used "best-estimate" ALT values from either a pit value, or the average of pit and probe measurements, and fixed ALT classes. In our study we used measurements for single points from grid points within a 100 x 100 m raster of high heterogeneity. All but one measured ALT values fall into only one ALT class (70 - 150 cm) used by Leverington and Duguay. The given accuracy can therefore not be compared.
- 10 Our results confirm that the NDVI can be used to distinguish between lower and higher ALT. NDVI can be however not used to obtain the actual spread of ALT. This might be partially the result of the lower spatial resolution. High spatial resolution satellite data would be required to determine this influence.

The used TerraSAR-X data have been acquired in stripmap mode which has a swath width of 30 km. This sensor can however also acquire data over 270 km when using the Wide ScanSAR mode (40 m resolution). This would allow the transfer of the

15 approach to larger regions. The so far investigated incidence angle range is however very limited. Differences in the described backscatter-ALT relationship due to incidence angle effects would need to be considered.

6 Conclusions

The common dependency of ALT and X-band backscatter values (HH, approximately 30 degree incidence angle) on land cover types as well as the interrelation of terrain, vegetation, soil moisture and snow cover yields a correlation which can be used to

- 20 derive ALT with an RMSE of 20-22 cm depending on function type20 over a long term monitoring site on central Yamal. It can be shown that in general higher ALT values corresponded correspond with higher backscatter values for the tested ALT range of 40 140 cm. The approach does however seem to be limited to ALT depths larger than 70 cm. The accuracy is lower over sites with mixed vegetation types within the pixels. Especially contributions from areas with little vegetation (cryptogam crusts) alter the relationship between backscatter and ALT. Soil moisture and/or surface roughness are influencing the signal
- 25 <u>over these sites.</u> Polarimetric SAR analyses which allows to distinguish different scattering mechanisms might be suitable to tackle roughness these issues. This could however not be tested due to unavailability of such satellite data. Results indicate a better performance than NDVI for higher ALT, but investigations with higher spatial resolution <u>optical</u> data would be required for confirmation.

Author contributions. Barbara Widhalm has performed all data analyses, collected moisture and vegetation information at the CALM site
 and compiled the manuscript. Annett Bartsch has been contributing to the development of the concept of the approach as well as to the manuscript. Marina Leibmann and Artem Khomutov have collected the active layer measurements at the long term monitoring sites as well as the vegetation information at sites outside of the ALT monitoring sites and contributed to the interpretation and discussion of the results.

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functions dataset	R ² (VD-1, 2 and 3)	RMSE [cm] (CALM)	χ^2 [cm] (CALM)	$\left \begin{array}{c} \frac{R^2}{(VD-1)} \end{array} \right $	$\frac{R^2}{(VD-2)}$	$\begin{array}{c} \underbrace{\mathbb{R}}^{2} \\ \underbrace{(VD-3)} \end{array}$
TSX linear_TSX	0.656	20 TSX polynomial 20	$\begin{array}{c} 0.616\\ \hline (\text{for} \sigma_0 \\ \rightarrow -15.2\\ \hline \text{dB})25 \end{array}$	22 TSX adapted polynomi 0.143	$\begin{array}{c} 0.457\\ \hline \text{(for } \sigma_0\\ al > -16\\ \hline dB)\\ 0.153\\ \end{array}$	22 0.622
TSX linear (exclusion of points with high vari- ability)	0.712	21-21	27	0.172	0.167	0.622
NDVI 22 nd July 2014 linear -	0.734	27 NDVI 22 nd July 2014 polynomial 27	0.752<u>4</u>6	29 NDVI 22 nd July 2014 polynomi adapted polynomi 0.171	0.742 0.016 al al	28 0.017
NDVI 10 th August 2015 linear -	0.746	$\frac{30 \text{ NDVI}}{10^{th}}$ August 2015 polynomial 30	0.761_57	31 NDVI 10 th August 2015 polynomi adapted polynomi 0,002	0.754 0.130 al	30 0.002