1. ABSTRACT

Due to its high spatial resolution, TerraSAR-X imagery offers new possibilities to observe and monitor the Earth and provide information about small scale landscape features. Such small-scale targets are the so-called lithalsas – typical permafrost features in the discontinuous permafrost zone forming mounds between 5 and 10 m in height and up to several 100 m² in size. Those lithalsas are experiencing seasonal heaving and subsiding dynamics caused by freezing and thawing processes and hence are also reflecting the annual course of temperature in a certain area.

Transitions in these natural landscape processes have been observed for several years: Many lithalsas shrink, collapse or eventually disappear at a growing rate. Phenomena of diminishing permafrost are accompanied by many consequences in the sub-Arctic ecosystem and are also adversely affecting people’s health and tradition in the predisposed areas. As they can be traced back to climatic changes, an intensification of the described processes is expected in the future.

Given this fact, more knowledge about the annual behavior of the lithalsas as well as their probable reactions to different climatic conditions is urgently required. Only when a profound understanding of these processes has been achieved, adaptation strategies can be developed to avoid further severe impacts for local (Arctic and sub-Arctic) communities. As the regions of concern are mainly remote, hard to access and hence difficult to observe, the research subject in itself is a major logistical problem. This issue is even more pronounced by the heterogeneity of permafrost in spatial distribution and depth. Previous common ways and methods to record permafrost dynamics were mainly ground-based observations or in some cases aerial photography, usually covering a very limited area and only applicable in very low temporal resolution.

Our study expands the possibilities of permafrost monitoring by using differential interferometric products from the TerraSAR-X data and hence contributes to the required gain of knowledge. The investigation conducted in Umiujaq, Northern Quebec, shows to which extent these differential interferograms can be used to monitor the inter- and intra-annual dynamics of the frozen mounds. For this purpose, TerraSAR-X scenes were acquired in 2009 and 2010, with more to be added in 2011. Concurrently, three lithalsas are surveyed by high-precision d-GPS during specifically designed field campaigns to validate the results of the remote sensing image analysis. Thus, the first methodological research question is to prove that the results from the interferogram analysis correspond to the findings in field surveys. The geodetic measurements show significant topographic deformation over the year and are thus confirming the hypothesis of the annual dynamics of the lithalsas. First attempts to use differential interferometric products delivered satisfying results and it is expected that the ongoing research will confirm, enhance and quantify these initial findings.

2. MOTIVATION AND IDEA

The recently observed increasing ground temperatures in the sub-Arctic and Arctic regions of the Northern Hemisphere and the accompanied thawing of the permafrost entails an abundance of problems for the affected communities and environment. Among the most severe are the changes to the northern ecosystems, by ways of alterations of vegetation cover, expanding marsh- and wetlands, or the decline of slope compaction and thus an increased risk of landslide. Damage and increased remedial work and maintenance are expected for roads, runways, residences and community buildings in the growing villages of the North. These expected consequences give reason to spatially monitor permafrost dynamics. Differential interferograms, generated from TerraSAR-X imagery are tested for their applicability to observe the mentioned alterations. Lithalsas, typical landform features of the discontinuous permafrost zone, served as study objects. As these mounds have a frozen core (?), they are expected to show elevation variations between the winter and the summertime due to freezing and thawing processes which might be detectable by means of differential interferometry.
3. TEST SITE

The test site of the study is about 60 km² in size and situated near the Inuit village of Umiujaq (56°33’ N, 76°33’ W), at the eastern shore of the Hudson Bay in Nunavik in northern Quebec, Canada (Fig. 1). It is located at the transition zone between the sub-Arctic and the Arctic where high climate change sensitivity and severe effects are expected, which makes the region suitable for a climate change impact study. This location at the borderline between the two climate zones is mainly characterized by two very important features for this investigation: the northern timber line and the occurrence of discontinuous permafrost. Hence, the region lies in a transition zone between different macro chores, and consequently, changing climatic conditions will be easily observed through alterations in vegetation and permafrost, accompanied by any kind of land surface deformation. A further aspect concerning the selection for the test site is the existing records from long-term research in the area [1].

![Figure 1 Location of the test site Umiujaq, Northern Quebec](image)

4. METHODS AND RESULTS

4.1 Differential Interferometry

Radar interferometry is a method that provides three-dimensional information about objects at the land surface by means of the phase content of the complex radar signal. In order to obtain a good signal to noise ratio at sufficient spatial resolution, a coherent synthetic aperture radar (SAR) is required which uses the movement of the sensor to simulate a much larger antenna than its actual size. Differential interferometry (D-InSAR) is a technique which allows the estimation of relative deformations of the land surface in the order of several centimeters, depending on the sensor’s resolution. It is always based on at least two images provided by repeat-pass or multi-pass interferometry. Herein, the temporal baseline, the time gap between two acquisitions, must be long enough to ensure alterations of the target of interest [2; 3]. The time shift can also bring about numerous uncertainties for the subsequent analysis, since in most cases not only the object’s elevation, but also several other factors influence the radar signal change. These include atmospheric conditions, changes in the vegetation cover, and the so called spatial baseline. The latter is one of the most crucial factors in radar interferometry and defined as the separation in meters between two antenna positions realized by two ideally parallel satellite orbits [4; 5]. These influencing factors can all have negative impacts on the coherence, i.e. the statistical relation between the multitemporal scenes, with high values indicating...
good correspondence and thus little change. To obtain adequate coherence values (>0.5) for D-InSAR applications a precise co-registration of the images is essential. Furthermore, by means of orbital parameters, the flat earth and reference phase can be calculated and subtracted from the interferogram [6; 7]. To eradicate the impact of the spatial baseline, the topographic phase contribution has to be removed. In doing so, all system-inherent error sources are eliminated.

Radar interferometry emerged after the Second World War. The first scientific article was published in 1969 [8] and in 1989 Gabriel et al. [9] used D-InSAR techniques for the first time to monitor the swelling of water absorbing clays in California. In the following decades D-InSAR was mainly applied for the detection of large-scale deformations. Brisco et al. [10] also tried to use SAR interferometry for permafrost mapping. But except for a joint U.S.-German-Italian project which implemented SIR-C/X-SAR instruments in 1994 [11] for only two acquisitions, all approaches to use D-InSAR methods were based on data delivered by either C- or L-band sensors. Only since 2007 is X-Band data of the Italian system COSMO-SkyMed as well as the radar sensor on board the German TerraSAR-X available.

Based on this new availability of high-resolution radar data and the huge amount of unexplored possibilities for earth observation, images of the TerraSAR-X satellite were used for this study to explore D-InSAR methods in order to monitor topographical movements related to permafrost.

For the first attempt, the seasonal topographical alterations between winter and summer were surveyed during field visits in 2009 and 2010. The TerraSAR-X imagery from the same time period with multiple acquisition parameters (ascending/descending, polarizations (VV, HH, VH)) were also analyzed and phase-interferograms from multi-temporal image pairs were computed. Besides the Norwegian PERMASAR project at the University Centre in Svalbard [12], this is the first time that satellite data acquired by the X-Band is used in order to detect topographical movements of permafrost landforms.

4.2 Data
The database for this study consists of information collected during 6 field campaigns in 2009 and 2010 and a database of contemporary TerraSAR-X imagery.

For the field data 6 geodetic surveys on selected permafrost mounds were conducted in April and August 2009 and in March, May, August and October 2010. Based on earlier studies in the area [13; 14], three lithalsas close to the village of Umiujaq, turned out to be the most suitable investigation landforms. According to Calmels et al. [15] lithalsas are permafrost mounds with no insulating peat cover, which are typical for discontinuous permafrost regions [16; 17;18]. The three lithalsas are all about 40 m in diameter and between 5-10 m in height. They differ in their vegetation cover as well as in their state of life cycle.

The main purpose of the measurements was the exact record of the lithalsas dimensions, with a special focus on their elevation. For the geodetic survey, the high precision differential global positioning instrument (D-GPS) ProMark 3D with L1 GPS the antenna type NAP100 (Magellan) was utilized. Afterwards, the post-processing software GNSS Solution v3.10.07, also provided by Magellan, was used to analyze the records. For the measurements of this study, a record time of 60 s for each point was chosen and due to the fact that no obstacles interrupting the signal were present, the accuracy ranges were between 1 to 5 mm.

For the interferometric processing, images delivered by the TerraSAR-X satellite were used. Acquisitions from 26 dates in 2009 and 2010 spread over the entire year were available. After an initial check of the most convenient acquisition modes for the purpose of this study, only ascending path (fig. 2) and VV polarization was used for this investigation.
4.3 Analysis and Outcomes

The interferometric processing was done by means of the GAMMA SAR and Interferometry Software developed by the Swiss Gamma Remote Sensing AG. For the generation of the interferogram and the calculation of the differential interferogram and the resulting displacement map, programs of the modules ISP and DIFF&GEO were used [19].

The first step was the calculation of an interferogram by combining two single look complex (SLC) images. Therefore the two images had to be co-registered at a sub-pixel accuracy. This process consists of the estimation of the offset in range and azimuth between the two images and the resampling of the so-called slave image which should afterwards match perfectly with the master image.

In this case, two scenes from summer 2009 were selected to form the interferometric pair. Similar weather conditions as well as a short time interval, in order to keep the atmospheric phase noise as well as the displacement phase as little as possible, were the main factors for the selection of the images acquired at the 14th and 25th of August 2009. The co-registration delivered excellent results with a final model fit of 0.0609 in range and 0.0916 in azimuth direction. This equals to an accuracy of 1/16 pixel or 1/11 pixel respectively, results which do easily accomplish the required 0.2 pixels [19]. After the co-registration and the resampling, the offset was refined by estimating the residual offsets, which afterwards were added to the initial offset model.

At this stage the interferogram usually shows almost parallel fringes caused by the curvature of the earth. To remove this so-called flat earth effect that can be expressed by

\[
\phi_{\text{flat\_earth}} = \frac{-4\pi}{\lambda} R
\]  

(\lambda = \text{wavelength}; R = \text{radar to target distance}), a flattening has to be performed. The embedded operation in the GAMMA Software generates for it a phase trend by means of a spherical earth and baseline model, which is afterwards subtract from the earlier calculated interferogram [19]. Fig. 3 shows the flattened interferogram of the discussed image pair with the correlation image in the background. It is clearly visible that the almost linear phase trends, appearing in the unflattened interferogram are completely erased and only fringes related to topography and eventual displacement (as well as noise and atmosphere) are left.
At this point the phase of the interferogram is only given Modulo $2\pi$ and a further operation, the phase unwrapping, is required to finally retrieve a topographic height. There are several approaches existing for this transformation, for this study the minimum cost flow (MCF) algorithm and a triangular irregular network (TIN) was implemented [20], as this approach is known to work the best for images containing low coherence pixels.

Before starting the phase unwrapping process, the two images were up-scaled by dividing them by the factor 4. This was necessary due to the huge size of the image: To avoid allocation memory failures the phase unwrapping would only have been possible by means of dividing the images into overlapping patches. Unfortunately the outcomes showed serious errors at the overlapping areas and following the up-scaling method was chosen. After this up-scaling, areas with low coherences were identified and a validity mask was generated to exclude these pixels from the unwrapping step. Surprisingly, although a coherence threshold of 0.3 was used, the validity mask only represents water and a few other pixels to be excluded from the process. Finally after successfully finishing the phase unwrapping, the image was re-downscaled to its original size.

For computing the differential interferogram the 2-pass differential interferometry was applied which is based on an interferometric image pair and a height map. For the interferometric image pair a scene from April 2009 (14.04) and the one from August (14.08) were used. The only Digital Elevation Model (DEM) at hand for this region was the DEM from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 90 m. As this is much too coarse to fit the high-resolution radar images, the previously generated interferogram and some selected ground control points should serve to generate the required height map in radar geometry. Unfortunately, caused by a lack of data, there were no ‘real’ ground control points existing. As it was still desired to progress, a file containing ‘fake’ control points, all assumed to have zero elevation, was created. Using this file and the interferogram the, height map was prepared.

It has to be mentioned at this point, that it is important to keep in mind, that for all following steps only the ‘fake’ height map was used and hence the output cannot be used for any quantitative interpretations.

The first steps of the differential interferogram processing are basically the same than carried out for the interferogram: Also in the case of the differential interferogram the co-registration went very well, with a final model fit of 0.0647 in range and 0.3926 in azimuth direction. The baseline estimation calculated a parallel component of 26.22 m and a perpendicular component of 86.72 m. By means of the critical baseline estimation equation

$$Bn \leq \frac{B_{\lambda}}{2Lc\cos\theta}$$

with $Bn =$ the critical baseline, $R =$ the height of the satellite, $\lambda =$ wavelength of the sensor, $Lc =$ size of the resolution cell in slant range and $\Theta =$ the incidence angle [21], it was ensured that this values meet the preconditions of a successful processing. In our case that would be

$$Bn \leq \frac{514000\ m+0.031\ m}{2\times1.177\ m\times\cos\ 40.5^\circ} = 8.902\ km.$$
Hence the estimated baselines are much lower than the critical baseline.

Now, the actual generation of the differential interferogram starts. By dint of the earlier explained ‘fake’ height map, the reference SAR geometry and an interferometric baseline model, a so-called reference interferogram is simulated, whose phase only corresponds to the topographical phase [19]. The estimated topographical phase now has to be subtracted from either a complex interferogram or from the unwrapped phase. In this study the first method was applied, meaning that the simulated topographical phase was subtracted from the wrapped original interferogram that still contains the curved Earth phase trend. This way is considered to produce a more robust differential interferogram as phase unwrapping of the original interferogram is not required.

After the simulation of the reference interferogram and its subtraction from the wrapped original interferogram the final differential interferogram is achieved and the unwrapping of the differential interferogram can be done. In analogy to the computation of the interferogram, the unwrapped differential interferogram was also up-scaled to avoid the division of the image into tiles.

Fig. 4 shows the final differential unwrapped interferogram and the appearance of more or less parallel fringes make it obvious that there are still more components included that only the desired differential phase. It is very likely that these are residuals relating to the topographic or even system phase component. They could also be attributed to baseline-related effects and of course they have to be removed for the further processing and interpretation. As in this particular case it was only intended to see, if it would be generally possible to use this dataset, it was proceed without correction.

The discussed errors are consequently also still slightly reflected in the finally obtained displacement map, displayed in fig. 5. Although it can be seen that areas, expected to be stable – like the mountainous area north of the village - show less fringes than others. But as these outcomes are all based on the ‘fake’ height map no further interpretation shall and can be done at this point.

Figure 4 Final differential unwrapped interferogram from the image pair 15.04.2009 and 14.08.2009

Figure 5 Displacement map of the differential interferogram in radar geometry.
In this picture one fringe equals 1cm vertical displacement
5. CONCLUSION AND OUTLOOK

The study depicted the possibility to use TerraSAR-X images in order to generate differential interferograms. The problem of too low coherence values that often occurs in high latitudes with such high-resolution datasets seems to be nonexistent in this area, at least not by using an image pair with a time delay shorter than one year. This already allows detecting oscillating heights between the summer and winter season, and of course it is also possible to trace rapid changes due to solifluction, landslides or sudden sinking caused by permafrost thawing.

Although these are already important steps, there are many more tasks that need to be tackled, tried out and analyzed within the next time: It is obvious that a solution for the missing DEM has to be found. This could be the 3-pass interferometry, an approach that would only need two InSAR pairs but no DEM. If this method proves to deliver good results, more interferometric and differential interferometric pairs shall be calculated, compared and interpreted. Therefore also the field measurements will be taken into account and it shall be ascertained if similarities can be found between the displacement values measured with the remote sensed data and in the field data.

One very interesting issue will be the computation of inter-annual differential interferograms and to find out, if such a long time delay still results in adequate coherence values.

6. REFERENCES

