Potentials and Limits of Comprehensive 2D Glacier Motion Estimation using Satellite SAR Data

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Abstract: In this paper, the potentials and limits of comprehensive 2D motion estimation of glaciers are discussed and illustrated by the example of the Taku glacier, which is the biggest glacier in the Juneau Icefield, Alaska. The motion maps are extracted by the feature tracking technique based on geo-coded high resolution TerraSAR-X images. The estimation results show that successfully deriving comprehensive 2D glacier motions filed using feature tracking by SAR images acquired from only one imaging geometry is hard to achieve, and in areas with a steep slope in the topography the 2D estimations are intrinsically accompanied with significant errors regarding the real magnitude of the velocity.

Zusammenfassung: Diese Arbeit befasst sich mit den Möglichkeiten als auch den Beschränkungen einer umfassenden 2D-Geschwindigkeitsschaätzung für Gletscher und zeigt dies am Beispiel des Taku-Gletscher, der größte im Juneau Eisgebiet (Alaska). Die Geschwindigkeitsschätzung erfolgt mittels Merkmalsverfolgung basierend auf den geokodierten TerraSAR-X Daten. Die Ergebnisse zeigen, dass eine robuste Schätzung unter Verwendung von Daten eines einzigen Blickwinkels nur bedingt funktioniert. Es geht vor allem in Gebieten mit einer steilen Topographie mit großen Fehlern in der Größe der Geschwindigkeit einher.

1 Introduction

1.1 Glacier Velocity

The velocity of a glacier is not constant over the whole area and cross-section. Instead it exhibits a higher velocity on the surface and with some distance from the boundary. The glacier motion rate serves as a control parameter determining the mass balance of ice sheets and furthermore helps for the understanding of the local and global climate change. Especially SAR data have provided invaluable tools for monitoring glacier velocities.

The conventional in situ observations of glacier motion are costly and limited at the spatial coverage compared with remote-sensing data, although they can be of high accuracy. Spaceborne remote-sensing data acquired from different sensors can help in those cases. Satellite optical imagery, providing visible features (e.g., crevasses, debris) for the motion tracking procedure, have been applied extensively for many glaciers with different characteristics (SCAMBOS ET AL., 1992; KÄÄB, 2002; BERTHIER ET AL., 2005). However, the optical sensors are passive and rely on illumination by the sun, resulting in a strong dependence on weather phenomena which will disturb the scene backscattering characteristics in the sequential images. Active sensors like SAR have the ability to obtain timely data with a spatial resolution compatible with the topographic variation (HØGDA ET AL., 2010).

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1.2 Velocity Estimation Techniques by SAR

Recently, glacier surface velocity estimation using SAR data has become more and more popular due to its unique advantages. Based on SAR images, there are many methods available for estimating glacier motions. The ones mainly used can be divided into two groups: D-InSAR and offset-tracking.

1.2.1 Differential SAR Interferometry

A complex SAR image includes both the amplitude and phase of the backscattered signals. The phase information is proportional to the range from sensor to ground objects along the line of sight and depends also on the radar center frequency. Generally, after an interferometric image pair is precisely aligned pixel by pixel, an map of phase changes (i.e. a differential interferogram) can be generated by adding sequentially registered SAR images. Then, the glacier motion patterns between the acquisitions with the same frequency and over the same area can be derived. SAR interferometry, which is able to achieve a precision in the order of a fraction of radar frequency, is the most accurate technique compared to other SAR techniques (JOUGHIN ET AL., 1998; STROZZI ET AL., 2002; LUCKMAN ET AL., 2007; TROUVE ET AL., 2007).

1.2.2 Offset Tracking

The other frequently used techniques complementary to SAR interferometry can be called offset tracking or ‘correlation like’ methods. All these method are using various matching algorithms (e.g., normalized cross-correlation) and are based on different features, like isolated point targets, distributed targets, textures described by wavelets or other higher order statistics, as well as phase information.

- **Intensity tracking** (or cross-correlation optimization) method, based on normalized cross-correlation (NCC), can estimate the relative displacements in 2 dimensions: the range and azimuth directions. (STROZZI ET AL., 2002; DE LANGE ET AL., 2007; FLORICIOIU ET AL., 2008; FALLOURD ET AL., 2011; SCHUBERT ET AL., 2013).
- **Speckle tracking**, a variant of intensity tracking, depends on the fact that the speckle patterns appears in sequential coherent observations by SAR sensors which can be correlated between the aligned blocks (GRAY ET AL., 2001; JOUGHIN ET AL., 2010).
- **Coherence tracking**, a phase based measurement like D-InSAR, also known as the fringe visibility algorithm or coherence optimization procedure, selects small data patches from a pair of single-look complex products and constructs a series of small interferograms with changing displacements for which the coherence is estimated (STROZZI ET AL., 2002).

1.3 2D Glacier Motion Map

SAR interferometry has greatly contributed to glaciology by offering the ability to map ice flow in many applications with the most accurate precision (JOUGHIN ET AL., 1998; STROZZI ET AL., 2002; LUCKMAN ET AL., 2007; TROUVE ET AL., 2007). Nevertheless, two main limitations of D-InSAR remain: 1) the temporal decorrelation of the signal over the ice surface between the sequential acquisitions and 2) the restriction to only one-directional measurements (i.e. along line of the sight). This obstructs the more extensive application of this technique. The temporal decorrelation problem normally affects all the phase based tracking method including the coherence tracking method. InSAR technique can be used to derive 2/3D motion maps with the help of complementary data, like DEMs or SAR data from both ascending and descending tracks (JOUGHIN ET AL., 1998; TROUVE ET AL., 2007), but this introduces the need for additional data. In contrast, the offset tracking methods have the ability to obtain the two horizontal components of the glacier motions based on just one image pair.

Recently, the feature tracking method has been extensively applied to obtain 2D motion maps of glaciers successfully in glaciers located around the globe with different characteristics due to its advantages making it suitable for a large time span between image acquisitions and even for fast flowing glaciers. In the following section, the limitations and potentials of comprehensive 2D motion estimation of glaciers by SAR feature tracking will be discussed.

2 Data Set and Method

2.1 Study Area and Data Preprocessing

The Juneau Icefield is a low-latitude glacier system of small scale located in southeast Alaska, with the Taku glacier, the outlet glacier, having the biggest content in this area. In this paper, the scenes of Juneau Icefield imaged by high resolution TerraSAR-X in summer, 2009, are applied for experiments. All the experimental works in this paper are based on 2 TerraSAR-X repeat cycle scenes acquired in stripmap mode from a descending track (see Table 1). An additional optical Landsat-7 dataset imaged almost at the same time as the SAR data is used in order to provide visible ground truth information.

Imaging Mode	Acquisition Start Time	Incidence Angle Min	Incidence Angle Max	Pass Direction
stripmap mode	2009-06-30T15:27:06	26,95	30,57	descending
stripmap mode	2009-08-02T15:27:08	26,94	30,57	descending

Table 1. TerraSAR-X data delineation used for experiment.

Firstly, the TerraSAR-X Single Look Slant Range Complex (SSC) data with 3m ground resolution are orthorectified and geocoded using precise available DEM data. Hence, pixels in the geocoded data have a size spacing of 1.5m in both azimuth and range direction. Finally, sub-scenes covering almost the whole Taku Glacier are cut from the geocoded SAR data. These two sequential sub-scenes are coregistered using the geometric annotation information available in the metadata (see Figure 1).

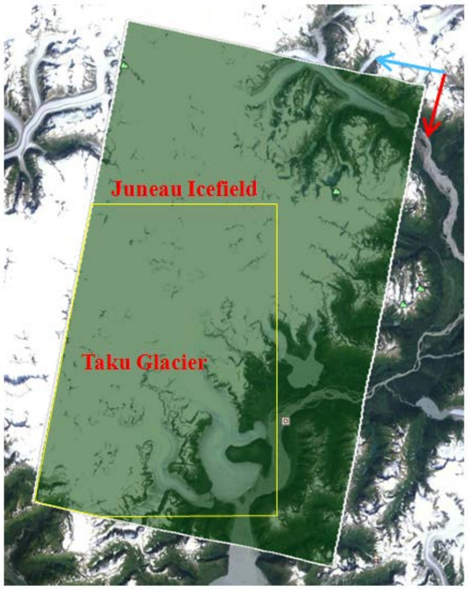

Fig.1. Ground coverage of geo-coded SAR images plotted on an optical image of the scene. Red arrow: azimuth direction; Blue arrow: Range direction. Yellow box: area used for experiment. (Underlying optical image ©2014 Google Earth).

2.2 2D Glacier Motion Estimation by Feature Tracking

The traditional feature tracking technique, with the NCC as the similarity function, described in detail in (STROZZI ET AL., 2002; DE LANGE ET AL., 2007; FANG ET AL., 2013), was applied here to derive a two-dimensional velocity field, and this method has been proved to be precise enough for the application of glacier surface motion vectors analysis. Generally, the ideal situation, using NCC for glacier velocity tracking, would be finding a match for every pixel independently. But this is not practically possible and applicable considering the computing efficiency and the definiteness of unique in the template windows. In this case, aiming to derive more reasonable estimations, we calculate the correlation field in the Fourier domain (even faster than in space domain) for each template pair having 87.5% overlap area with the neighboring patches.

3 Results and Discussion

The 2D comprehensive velocity vectors of the Taku Glacier with the corresponding signal-to-noise ratio (SNR) image are illustrated in Fig.2. The SNR is employed as a confidence measure expressing the comparison of the modeled correlation peak, by a regression fit, relative to the average value of the remaining original correlation field.

As can be seen in Fig. 2 the conventional feature tracking method fails to derive the motions in the firn area (the noise areas in the glacier motions map in Fig.2) associated with low SNR values mainly due to the snow cover which can be demonstrated by the related Landsat-7 optical imagery. Nevertheless, these noise-like values affiliated to the firn area can be a feature for classification from the surroundings. It is also found that stationary objects like mountains are reliably estimated with almost zero values (e.g., the dark blue colored area in upper middle of the motions map in fig.2), affected by registration error between the sequential SAR images, except for areas where they are also covered by snow.

Generally, the velocity estimation result can be improved under the benefit of using multiple aspects for the velocity estimation to complement data in areas where one aspect is affected by radar shadowing, which has already been demonstrated in (FANG ET AL., 2013).

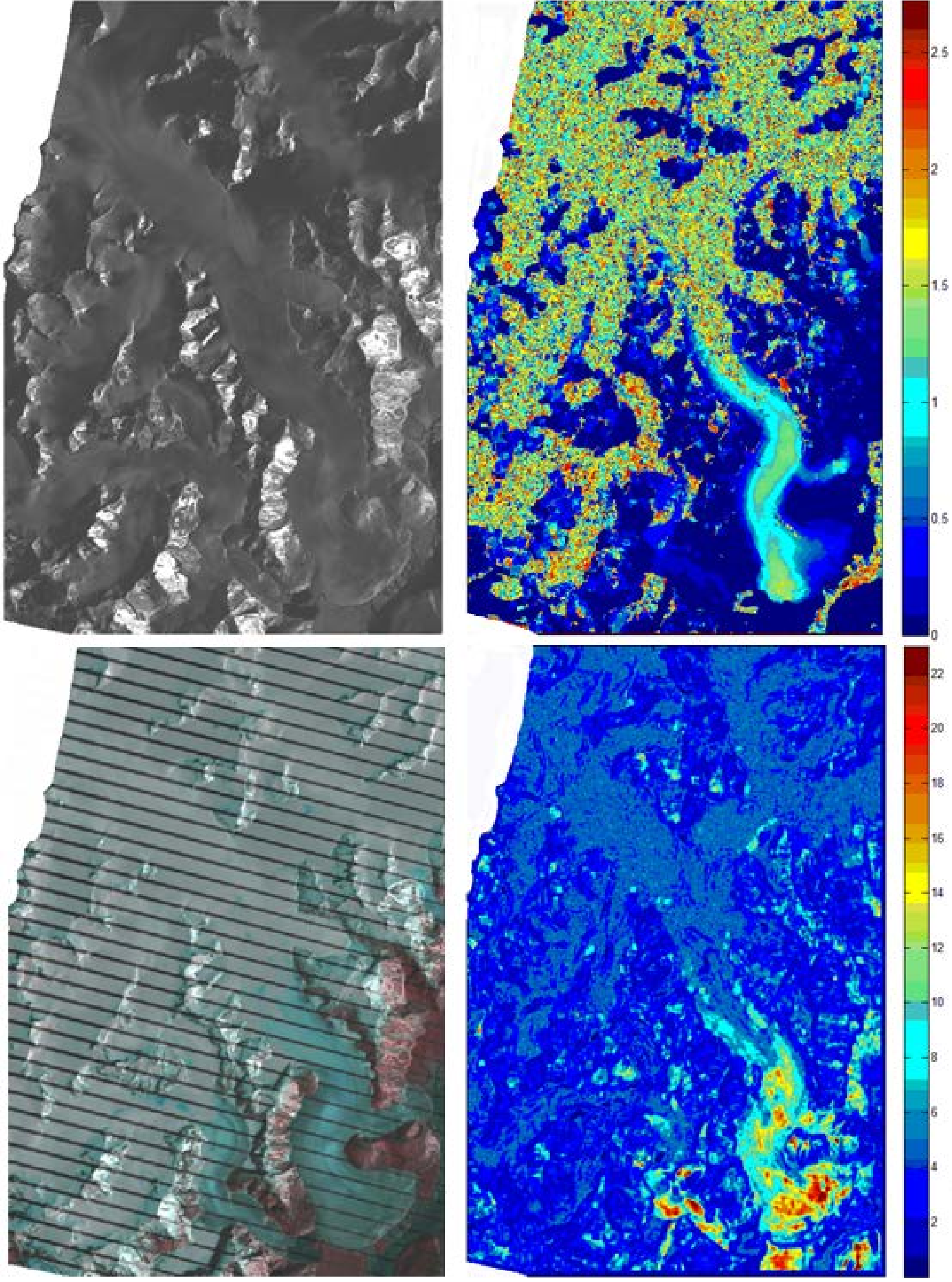

Fig.2. Upper left: the SAR amplitude image; Upper right: 2D motion map; Lower left: Landsat-7 data with the same coverage and acquisition time as the ground truth; Lower right: Corresponding SNR image.

Additionally, for this 2D velocity estimation which does not take the flow based surface topography into account, one of the major limitations is the obvious fact that not all three dimensions of the velocity can be measured directly. In areas with a steep slope in the topography this results in a significant error regarding the real magnitude of the velocity. Several glacier patches with different slopes are randomly chosen to examine this topographical affect on real velocity values and with positive outcomes (see Table 2). In this case, based on the flow direction derived by feature tracking applied on the orthorectified SAR images and the DEM data, we translate the Euclidean displacement between the sequential blocks into 3D parallel to the surface slope. It is found that the steeper slope results in bigger difference compare with 3D values.

2D Velocity (m/d)	3D Velocity (m/d)	Slope Degree	Relative Difference
1.0611	1.0611	0.05	0
1.3373	1.3383	2.16	0.07%
0.0771	0.0773	3.35	0.17%
0.3988	0.3997	3.85	0.23%
0.5261	0.5278	4.62	0.32%
0.6508	0.6557	6.97	0.74%
0.9760	0.9913	10.09	1.56%
0.7489	0.7813	16.57	4.24%

Table 2. 2D and 3D glacier velocity differences related to surface topography.

Furthermore another limitation of the feature tracking method has been demonstrated which arises in the velocity estimation especially at the boundary line between glacier and the surroundings (e.g., mountain, water). In Fig. 3, two templates including glacier and the other classes are shown and used to carry out the cross-correlation process. Finally, the velocity vector of center pixels located in rock and water areas, respectively, which are supposed to have zero magnitude, are wrongly assigned by 0.36m/d and 0.98m/d separately.

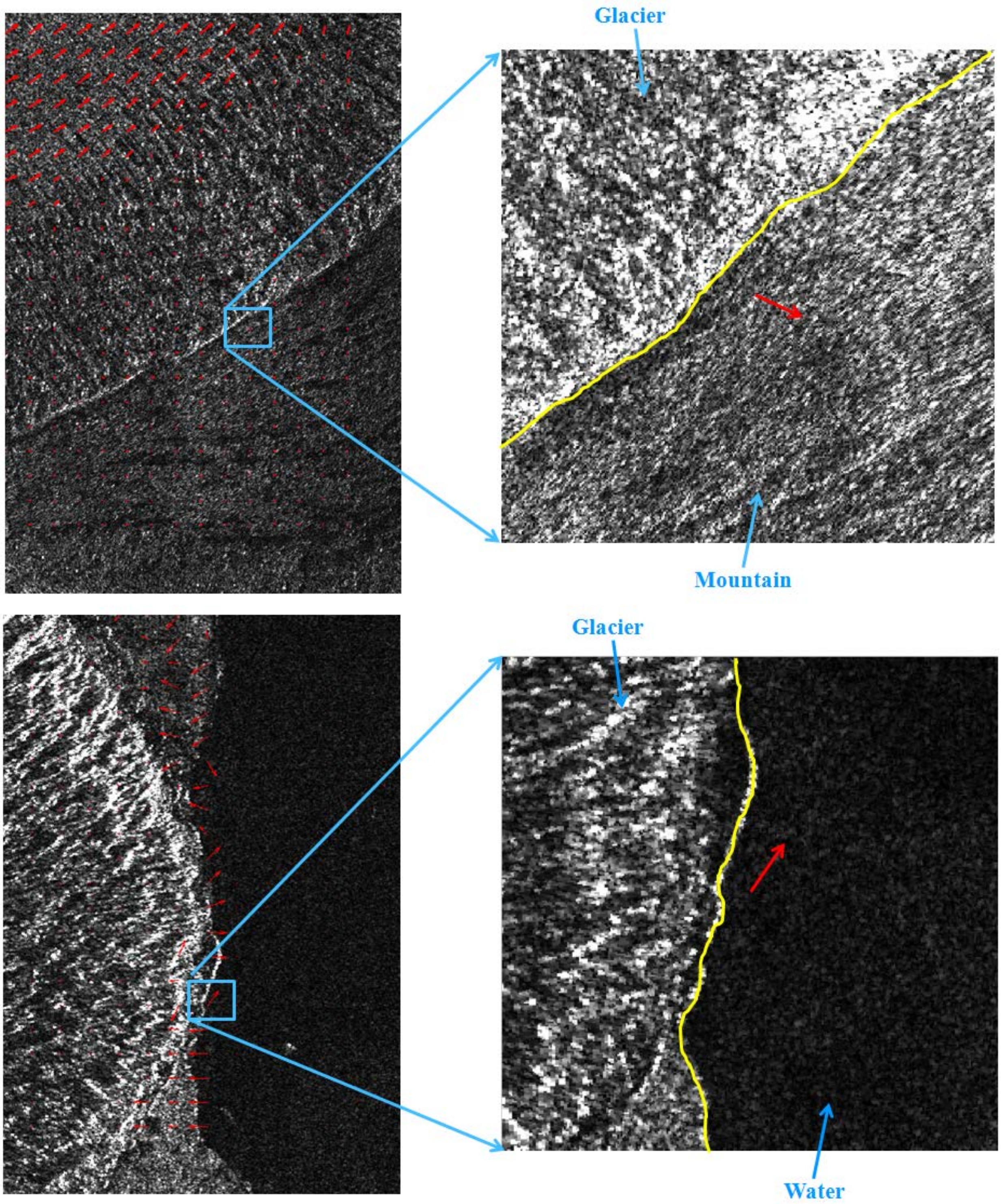

Fig.3. Two examples show the limitation of NCC in glacier boundary areas. Yellow line: boundary line between glacier and other classes derived manually; Red arrows: the velocity vector of center pixel of the example template window (blue box).

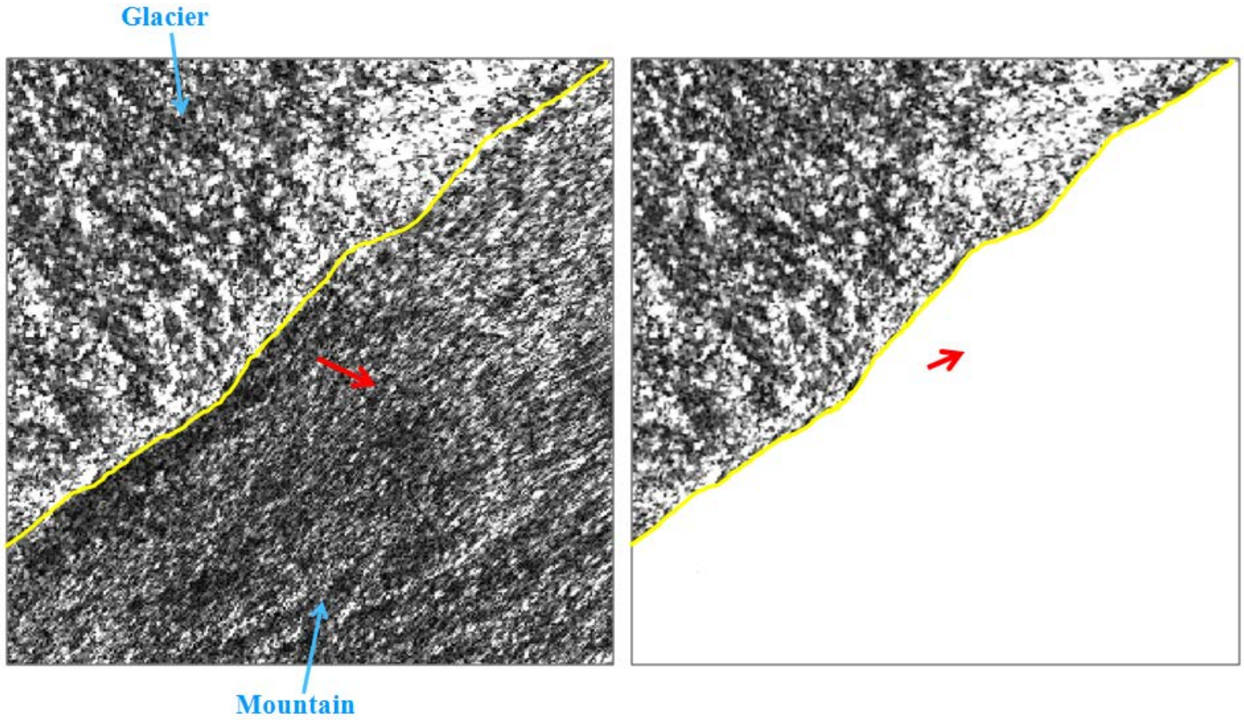

Fig.4. Example shows the limitation of fixed window for NCC estimation. Left: original template. Right: masked window after removing non-moving surroundings manually. Yellow line: boundary line. Red arrows: the velocity vector of center pixel derived by NCC matching.

Additionally, when a template window is dominated by other information than that of the glacier, the similarity match will be influenced disturbing the final motion estimation result. In order to prove this, a template window, as used before in Fig. 3, including glacier and even more mountain pixels is selected for velocity estimation. The NCC estimation is first applied on the original window including mountain information (left part of Fig. 4). Then, the mountain pixels are manually masked out and the only glacier information left in this block is used to find the best similarity match (right part of Fig. 4). Finally, the magnitudes of the velocity estimated in the original sized window and masked block are 0.36m/d and 0.01m/d, separately, with significant differences both in magnitude and direction. It is obvious that without disturbing information from other non-moving surroundings glacier velocity estimation using the NCC method will be much more precise and reasonable.

4 Conclusion and Recommendation

It can be concluded that successfully deriving comprehensive 2D glacier motions fields using feature tracking by SAR images acquired from only one imaging geometry is hard to achieve, as this method relies on the glacier surface features (e.g., crevasses or drainage patterns) which are obstructed by snow cover, especially in winter time. This maybe can be solved by coherence tracking as the snow covered area shows a coherence relatively higher than the surrounding curriculum, which can be demonstrated in future research. In order to reduce the error difference between the 2D velocity estimations and real 3D surface motion values (especially in aeras with high-relief topography), a DEM can be used for this purpose without the assumption that the glacier flows towards the maximum averaged downhill slope. Additionally, a multiscale template for cross-correlation becomes even more important in dealing with the challenge faced when the template window includes glacier ice and other stationary-like surroundings (e.g., mountain, water) at the glacier boundary areas. In sum, combined use of the SAR glacier motion estimation techniques is recommended especially in case of extracting comprehensive glacier dynamics.

5 References

BERTHIER, E.; VADON, H.; BARATOUX, D.; ARNAUD, Y.; VINCENT, C.; FEIGL, K. L.; F., R. & B., L., 2005: Surface motion of mountain glaciers derived from satellite optical imagery. Remote Sensing of Environment, vol. 95, pp. 14-28.

DE LANGE, R.; LUCKMAN, A. & MURRAY, T. ,2007: Improvement of satellite radar feature tracking for ice velocity derivation by spatial frequency filtering. IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 7, pp. 2309-2318.

FLORICIOIU, D.; EINEDER, M.; ROTT, H. & NAGLER, T., 2008: Velocities of major outlet glaciers of the Patagonia Icefield observed by TerraSAR-X. IEEE International Geoscience and Remote Sensing Symposium (IGARSS).

FANG, L.; MAKSYMIUK, O.; SCHMITT, M. & STILLA, U., 2013: Improvement of motion estimation of the Taku glacier using spaceborne SAR images. In: Seyfert H (Eds.) Proceedings of 33. Wissenschaftlich-Technische Jahrestagung der DGPF, 22, pp. 62-70.

FALLOURD, R.; HARANT, O.; TROUVE, E.; NICOLAS, J.; GAY, M.; WALPERSDORF, A.; MUGNIER, J.; SERAFINI, J.; ROSU, D.; BOMBRUN, L.; VASILE, G.; COTTE, N.; VERNIER, F.; TUPIN, F.; MOREAU, L. & BOLON, P., 2011: Monitoring temperate glacier displacement by multi temporal TerraSAR-X images and continuous GPS measurements. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol.4, pp.372-386.

GRAY, A.; SHORT, N.; K.E., M. & JEZEK, K., 2001: Velocities and flux of the Filchner ice shelf and its tributaries determined from speckle tracking interferometry. Canadian Journal of Remote Sensing, vol. 27, pp.193-206.

HØGDA, K. A.; STORVOLD, R. & LAUKNES, T. R., 2010: SAR imaging of glaciers. In: P. Pellikka, and W. G. Rees (Eds). Remote Sensing of Glaciers. Taylor & Francis Group, London: 153.

JOUGHIN, I.; KWOK, R. & FAHNESTOCK, M., 1998: Interferometric estimation of three-dimensional ice-flow using ascending and descending passes. IEEE Transactions on Geoscience and Remote Sensing, vol. 36, pp. 25-37.

JOUGHIN, I.; SMITH, B. & ABDALATI, W., 2010: Glaciological advances made with interferometric synthetic aperture radar. Journal of Glaciology, vol. 56, pp.1026-1042.

KÄÄB, A. 2002: Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: examples using digital aerial imagery and ASTER data. ISPRS Journal of Photogrammetry and Remote Sensing, vol. 57, pp. 39-52.

LUCKMAN, A.; QUINCEY, D. & BEVAN, S., 2007: The potential of satellite radar interferometry and feature tracking for monitoring flow rates of Himalayan glaciers. Remote Sensing of Environment, vol. 111, pp, 172-181.

SCAMBOS, T. A.; DUTKIEWICZ, M. J.; WILSON, J. C. & BINDSCHADLER, R. A., 1992: Application of image cross-correlation to the measurement of glacier velocity using satellite image data. Remote Sens. Environ., vol. 42, no. 3, pp. 177–186.

STROZZI, T.; LUCKMAN, A.; MURRAY, T.; WEGMÜLLER, U. & WERNER, C. L., 2002: Glacier motion estimation using SAR offset-tracking procedures. IEEE Transactions on Geoscience and Remote Sensing, vol. 40, no. 11, pp. 2384-2391.

SCHUBERT, A.; FAES, A.; KÄÄB, A. & MEIER, E., 2013: Glacier surface velocity estimation using repeat TerraSAR-X images wavelet- vs. correlation-based image matching ISPRS Journal of Photogrammetry and Remote Sensing, vol. 82, pp.49-62.

TROUVE, E.; VASILE, G.; GAY, M.; BOMBRUN, L.; GRUSSENMEYER, P.; LANDES, T.; NICOLAS, J.; BOLON, P.; PETILLOT, I.; JULEA, A.; VALET, L.; CHANUSSOT, J. & KOEHL, M., 2007: Combining Airborne Photographs and Spaceborne SAR Data to Monitor Temperate Glaciers: Potentials and Limits. IEEE Transactions on Geoscience and Remote Sensing, vol. 45, pp.905-924.