Remote Sensing of Environment 172 (2016) 190–204

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Velocity estimation of glaciers with physically-based spatial regularization — Experiments using satellite SAR intensity images

Oliver Maksymiuk [a,*], Christoph Mayer [b], Uwe Stilla [a]

[a] Photogrammetry and Remote Sensing, Technische Universität München, Munich, Germany
[b] Commision for Geodesy and Glaciology, Bavarian Academy of Sciences and Humanities, Germany

ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form 9 October 2015
Accepted 11 November 2015
Available online 21 November 2015

Keywords:
Glacier
Velocity estimation
Intensity tracking
SAR
Fluid dynamics
Physics
Navier-Stokes
Finite elements
Data assimilation
PDE constrained optimization
Spatial regularization
Segmentation
Delineation
Skeleton

ABSTRACT

Glaciers are an important climate indicator due to their sensitive dependence upon local and regional climate variables, which makes them worthwhile research subjects. A comprehensive description of the glaciers' interaction with the environment and their dynamical behavior requires complex physical models and the measurement of relevant parameters. In-situ data acquisitions are costly and often spatially sparse due to the large extent of glaciers; however, satellite-based sensors offer timely data with complete ground coverage, making them a good choice for continuous monitoring of glaciers. Synthetic aperture radar (SAR) allows a nearly weather-independent monitoring of glacier motion, which is beneficial for often cloudy regions like Alaska or Patagonia. This paper presents a new workflow for the automatic extraction of glacier surfaces from SAR intensity images and the determination of their velocities involving a fluid mechanics model. An initial motion estimation is obtained from intensity tracking on SAR image pairs and subsequently corrected by a physics-based spatial regularization. The surface velocity is approximated by the two-dimensional Navier–Stokes equation for incompressible fluids. The regularization is formulated as a data assimilation problem in which the final solution is a proper solution of the Navier–Stokes equation and simultaneously fitted to the observed velocity. This partial differential equation (PDE) constrained optimization is solved with adjoint models using finite element methods. The proposed method is evaluated on the Taku Glacier, AK, an outlet glacier of the Juneau Icefield. Our presented approach is independent from the type of sensor as long as initial velocity estimates can be obtained. The final results can be used as input to methods estimating ice volume and thickness.

1. Introduction

1.1. Glaciers as climate change indicators

Glaciers have a strong impact on the environment in mountain regions. They create their own local microclimate with spatio-temporal variations and are therefore an important component in the hydrological cycle. Furthermore they serve as water resource and their melt water affects the ecological system in the runoff area. But besides local effects they also have an impact on the global environment if the global warming leads to a rise of the sea level by glacial melt water. The melting process is therefore a very important climate indicator which has attracted much attention recently. Thus it is evident that glaciers are in the focus of many research disciplines and that their retreatment is carefully monitored and analyzed (Barry, 2006). In order to predict consequences it is important to understand the behavior of glaciers and how environmental changes and glaciers influence each other. Glaciers require a complex physical model based on fluid mechanics to describe the dynamics of the motion mathematically, but unfortunately this is not sufficient for a comprehensive analysis, because the strong interaction with the environment cannot be neglected. There are many examples where the interaction is of great importance, e.g. knowledge of the local climate is required to accurately analyze the mass balance in the accumulation and ablation zones or that the temperature as environmental parameter affects the material properties and thus also changes the dynamics of the glacier. Various research disciplines investigate mostly the glacier flow and mass changes. These properties are not independent from each other. The ice flow from the accumulation area to the ablation area is related to the mass balance and the corresponding geometry changes. Surface velocities can be used as input to numerical models that reconstruct or deduce other glacial parameters. In the simplest case the assumption of surface parallel flow allows only for the estimation of two-dimensional flows. Satellite based remote sensing has the potential for rapid and long term glacier observation avoiding problems arising from in situ measurement campaigns. Automatic products as presented in Paul et al. (2013) can contribute to the continuous monitoring of glaciers. This is important since the World Glacier Inventory (WGMS, and National Snow and Ice Data Center,

* Corresponding author at: Technische Universität München (TUM), Arcisstr. 21, 80333 Munich, Germany.
E-mail address: oliver.maksymiuk@tum.de (O. Maksymiuk).

http://dx.doi.org/10.1016/j.rse.2015.11.007
0034-4257/

1999, updated 2012) lists more than 130,000 glaciers which are continuously monitored thanks to satellite sensors. An automatic processing is therefore a prerequisite to their analysis in large scale and the motivation for our efforts since glaciers are very important subjects of interest in climate change research.

1.2. Glacier classification and delineation

In order to automate the process of glacier velocity mapping and modeling a classification of glacier areas and their delineation is required. Unfortunately most approaches published in the domain of surface velocity estimation do not investigate the glacier extraction and delineation. However, our automatic processing chain for glacier velocity mapping require glaciers to be treated as separate entities distinguishable from the environment. This is also necessary for an automatic construction of glacier inventories. The Global Land Ice Measurements from Space (GLIMS, and National Snow and Ice Data Center, 2005, updated 2012) is an international endeavor for the acquisition of satellite data from glaciers and their analysis in terms of extent and change. The changes are further analyzed for causes and implications on the environment. The first attempt to perform automatic glacier classification was presented in 1992 where Bischof, Schneider, and Pinz (1992) accomplished the task on multispectral data from Landsat with artificial neural networks. In 2007 Hendriks and Pellikka (2007) showed a semi-automatic approach for glacier delineation on MSS-Landsat data using multiple indices computed from different bands. An overview of the contribution of multispectral imaging on glacier and ice detection can be found in Kargel et al. (2005). A different methodology was presented 2001 by Bishop, Bonk, Kamp, and Shroder (2001). They used a two-fold hierarchical model of different attributes like elevation, slope and curvature to detect debris-covered glaciers. Approaches capable of detecting debris covered glaciers based on Landsat data and DEMs are presented in Paul, Huggel, and Kääb (2004) and Bolch, Menounos, and Wheate (2010). Paul, Kääb, Maisch, Kellenberger, and Haeberli (2002) presented in 2002 an approach to detect clean ice based on data from Landsat Thematic Mapper together with an external DEM and GIS data. Taschner and Ranzi (2002) investigated the comparison of Landsat-TM and ASTER data for monitoring of debris covered glaciers and Racoviteanu, Williams, and Barry (2008) reviewed the advances of glacier monitoring using ASTER data.

Although the classification of glacier areas is mostly done using multispectral data there are some approaches utilizing SAR data. In 2010 Atwood, Meyer, and Arendt (2010) presented a method to use the coherence of a L-band SAR sensor to perform glacier delineation. Later Fang, Maksymiuk, Schmitt, and Stilla (2013a) showed another method based on SAR intensity images of X-band radar with the result that a pixelwise classification is feasible.

1.3. Velocity estimation methods

Many approaches to surface velocity estimation from remote sensing data were published in recent decades. Starting in the year 1983 Della Ventura, Rampini, Rabagliati, and Barbero (1983) and later in 1986 Lucchitta and Ferguson (1986) presented velocity estimation based on optical satellite images. These interactive methods were later automated by image cross-correlation methods (Scambos, Dutkiewicz, Wilson, & Bindschadler, 1992). The principle of cross correlation with subpixel accuracy for image matching techniques is still widely used for deriving surface velocities (Heid & Kääb, 2012; Redpath, Sirguey, Fitzsimons, & Kääb, 2013). These methods were adapted to SAR data (Fahnestock, Bindschadler, Kwok, & Jezek, 1993) which, nowadays, offer very high spatial resolution (3 m in case of TerraSAR-X). Since the data acquisition is independent of weather and sun illumination SAR sensors became a very popular sensor in glacier monitoring. Recently several alternatives to cross correlation technique were investigated. Deledalle et al. (2010) presented a texture tracking approach adapted to the multiplicative nature of the speckle noise in SAR data. Most recently Schubert, Faes, Kääb, and Meier (2013) assessed wavelet- and correlation based methods on TerraSAR-X images. In general, amplitude-based speckle tracking has proven to be robust requiring only a fair amount of coherence and is therefore frequently used in glacier monitoring (Floricioiu, Eineder, Rott, Yague-Martinez, & Nagler, 2009; Strozzi, Luckman, Murray, Wegmüller, & Werner, 2002). Speckle tracking is not restricted to amplitude data but can also be applied to complex data from SAR sensors. The utilization of the phase in SAR interferometry leads to a large gain in accuracy. Nowadays the sensitivity of phase measurements is very high, allowing the measure of displacements within a fraction of the wavelength. The performance of these methods is analyzed in Bamler and Eineder (2005). However, this high sensitivity comes with an increase in temporal decorrelation and the necessity of phase unwrapping which can be challenging in areas with complex terrain. Overall, SAR interferometry is an important technique for the remote sensing of glaciers (Joughin, Smith, & Abdalati, 2010; Mohr, Reeh, & Madsen, 1998). Most methods have the restriction that they assume a surface parallel flow. The approach presented in Nagler et al. (2012) computes three-dimensional velocities from TerraSAR-X data using ascending and descending tracks. In Mohr et al. (1998) SAR interferometry and external DEMs were used to obtain three-dimensional velocities. Nevertheless, the results of the methods are pixelwise and based on the image data only, not considering the neighborhood conditions resulting from the physical properties of glaciers. Our approach extends these methods by incorporating a fluid mechanical model to obtain a spatially continuous, two-dimensional velocity field.

1.4. Glacier physics

It was already stated that glacier analysis is based on a very complex dynamical model (Jiskoot, 2011; Nye, 1952) with a manifold interaction with the environment (Zwinger, Greve, Gagliardini, Shiraiwa, & Mikko, 2007). One of the first comprehensive works on glacier dynamics was presented in 1952 by Nye (1952)). In 1959 he also published a method to determine the strain rate at the glacier surface (Nye, 1959). At a first glance it might appear that glaciers are mainly steady but there are events like surges in which the advance of glaciers increases dramatically with velocities that are many times higher than in the normal state. Understanding the causes for these events is important. The mass-balance is one important measure of glaciers and its interrelation to the local climate is investigated in Lenaerts, van den Broeke, van den Berg, van Meijgaard, and Kuipers Munneke (2012). Tidewater glaciers and numerical models of their dynamics are investigated in Vieli, Funk, and Blatter (2001). They developed a time-dependent numerical flow model which includes the full equations of stress and velocity. The tidewater dynamics are also investigated in Truffer, Motyka, Hekkers, Howat, and King (2009) on the terminus of the Taku glacier in Alaska. The findings of the glacier dynamics on Greenland outlet glaciers presented in Nick, Vieli, M., H.I, and Joughin (2009) show that large-scale changes start at the terminus and propagate upstream and are not necessarily related to the warming trend in Greenland. But glaciers cannot be treated as isolated objects since the local climate has a strong impact on the glacier and vice versa. Calmanti, Motta, Turco, and Provenzale (2007) presented an empirical study on the glacier snout fluctuation and the climate variability. The process of melting and its relation to the local atmosphere is investigated in Hock (2005). It includes a review on all relevant processes at the boundary layer of surface and atmosphere. The ice velocity and its relationship to the local climate variations is subject of the research presented by Quincey et al. (2009). Zwinger et al. (2007) presented a full Stokes-flow with a thermo-mechanical model. While general physical modeling of glaciers has been developed in recent years which facilitates the understanding and prediction of certain behavior, little attention has been paid to integrate this model knowledge into the image data analysis.