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Glacier-surface velocities in alpine terrain from optical satellite imagery—Accuracy improvement and quality assessment

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ABSTRACT

The worldwide retreat of mountain glaciers has important consequences for the water, food, and power supply of large and densely populated areas in South and Central Asia. Successful mitigation of the hydrological impacts on societies as well as assessing glacier-related hazards require large-scale monitoring of glacier dynamics. However, detailed glaciological data from the Asian highlands are lacking, due to its size and difficult accessibility. We have applied a novel technique for precise orthorectification, co-registration, and sub-pixel correlation of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery to derive surface velocities of Himalayan glaciers. Our approach allows for the correction of offsets due to attitude effects and sensor distortions, as well as elevation errors if a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) was used for orthorectification. After post-processing, the error on the displacements is on the order of 2–4 m per correlation. Translated into annual velocities, this error is reduced (increased) when the correlated images are more (less) than a year apart. Through application of a filtering procedure and several quality tests, the consistency of the results is validated to provide confidence in the remotely sensed velocity measurements, despite the lack of ground control. This novel approach allows fast, easy, and economically viable acquisition of detailed glaciological data in areas of difficult access and provides a means for large-scale monitoring of glaciers in high mountainous terrain.

1. Introduction

The global warming of climate has continued to cause the retreat of glaciers in many mountainous regions, and even the most optimistic scenarios for future temperature change involve pronounced glacier retreat over many decades to come (e.g., Oerlemans, 1994; IPCC, 2007a). This has important consequences for the global hydrological cycle, particularly in climatic threshold areas characterized by water stress. For example, the water, food, and power supply of densely populated regions in South and Central Asia are to a large degree dependent on snow and glacier melt water (Karim & Veizer, 2002; Winiger et al., 2005; IPCC, 2007b). Successful mitigation of the climate-related hydrological changes and their impacts on society therefore poses a pressing challenge, which calls for large-scale monitoring of glaciers and a better understanding of their dynamics (e.g., Haeberli et al., 2000, 2007; Kargel et al., 2005). Due to the large extent and difficult accessibility of high mountainous terrain, especially in Asian orogens, remote-sensing techniques provide an efficient way to collect data in disparate regions. For example, satellite images have been used to track changes in glacier geometry (e.g., Paul et al., 2002; Khalsa et al., 2004; Aizen et al., 2007); analyze and monitor supraglacial lakes (Wessels et al., 2002); determine the equilibrium line altitude (Rabatel et al., 2005), and estimate annual mass balances of glaciers (Berthier et al., 2007). Remote-sensing tools can also be efficiently used to determine the ice velocity of a glacier, which is a particularly crucial variable because it determines ice discharge (e.g., Scambos et al., 1992; Goldstein et al., 1993; Joughin et al., 2004, Rignot & Kanagaratnam, 2006).

Although glacier-surface velocities can be measured directly on the glacier with high accuracy at arbitrary spatial and temporal resolutions (e.g., Hubbard & Glasser, 2005), observations over long periods involve frequent revisits of the survey points, which can only be located on the accessible parts of a glacier. Therefore, field measurements commonly result in very sparse spatial coverage. In contrast, remote sensing-based measurements provide the opportunity to achieve large and possibly complete spatial coverage, even in very remote areas. Currently, three methods are commonly employed to derive glacier-surface velocities: interferometry of synthetic aperture radar (SAR) imagery, SAR tracking techniques, and cross correlation of optical satellite images.

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Velocity measurements by interferometry of SAR imagery (InSAR) may achieve high accuracies, but require that coherence between the images is not lost due to modification of the glacier surface by, e.g., melting or snowfall (Strozzi et al., 2002; Trouvé et al., 2007). This requirement, together with limitations regarding the resolvable displacement gradients, result in InSAR-derived velocity measurements that are typically constrained to time spans of 1, 3 or 6 days (e.g., Massonet & Feigl, 1998; Joughin et al., 1996). Thus, the obtained velocity data may be representative only for the observation period and an extrapolation to annual velocities is difficult.

Offset tracking in SAR imagery (Michel & Rignot, 1999; Joughin, 2002; Strozzi et al., 2002) is similar to cross correlation of optical satellite imagery (Lucchita & Ferguson, 1986; Bindschadler & Scambos, 1991). The basic approach is to track features from one scene to another and to calculate their velocity given the temporal separation and the measured displacement. In the case of SAR images, this can be done using either the intensity or coherence of the complex radar images (Strozzi et al., 2002). Compared to InSAR, tracking techniques using SAR images are more useful for measuring flow velocities over longer periods. However, a general drawback of SAR imagery in steep mountainous terrain is the high incidence angle of the sensor, which may inhibit visibility of the target glacier, and require very accurate DEMs to correctly orthorectify the measurements (Trouvé et al., 2007).

Using optical satellite imagery, the detail and accuracy of the measurements is largely limited by the ground resolution of the sensor, and by the ability to precisely co-register images acquired at different dates. The latter task is usually the most difficult and has led to inaccuracies on the order of 1 pixel, i.e., 15 m if ASTER imagery were used (Kääb, 2005; Stearns & Hamilton, 2005). Further errors may arise from changes in the satellite attitude during scanning of the images (Van Puymbroeck et al., 2000), and from an inaccurate DEM during orthorectification using a rigorous model (e.g., Toutin, 2004). A principle drawback of optical imagery is the dependency on cloud-free conditions.

In summary, velocity measurements by InSAR are most appropriate for analyzing very short time scales, i.e., days, or where extrapolation to longer time scales is justified, e.g., in ice sheet studies (Joughin et al., 2002). Feature tracking, using SAR or optical imagery is more appropriate for analyses over longer periods. Although limited by cloud cover during image acquisition, cross correlation of optical imagery provides a quick and efficient way of measuring glacier-surface velocities. Importantly, a huge and global archive of optical images from glaciers already exists and new images are continuously acquired. In order to achieve the measurement accuracy required to infer, e.g., annual velocity variations, the co-registration requires high accuracy and errors due to attitude effects or inaccurate DEMs need to be minimized.

Here, we evaluate the potential and the limits of a new application for orthorectification, co-registration and correlation of optical imagery, COSI-Corr (Co-registration of Optically Sensed Images and Correlation; Leprince et al., 2007), to measure glacier-surface velocities in mountainous terrain. We provide guidelines to improve the accuracy of the measurements and to assess their quality without available ground-truth data. This includes correction of offsets in the displacement maps due to attitude effects and due to elevation errors in the DEM. The methodological principles are applicable to a wide variety of optical satellite imagery and are demonstrated here using ASTER images.

We have studied the glaciers in two Himalayan regions: Khumbu in Nepal and Garhwal in India, where the glacier shrinking is observed. First, we demonstrate the methodological principles, including quality assessment, on the relatively slow Khumbu glacier at Mount Everest. Second, we investigate and model displacement errors induced by systematic elevation errors in the SRTM-based DEM, at the Gangotri glacier group in Garhwal. In a further step, the recent velocity history of Gangotri glacier, situated in the headwaters of the Ganges, is analyzed to demonstrate the capabilities and the limits of the method to monitor glacier dynamics

2. Methods and data

Table 1 presents the imagery analyzed in this study, along with details on the acquisition parameters. Although we generally avoided

Table 1
List of the ASTER scenes used in this study

Region	Granule ID	Date [yyyy-mm-dd]	Sun azimuth [degree]	Sun angle [degree]	Incidence angle [degree]	Orientation [degree]	Cloud cover[a] [%]
Khumbu (*case study 1*)	ASTL1A 0009280513510312080	2000-09-28	155.78	57.51	−2.870	9.26	63
	ASTL1A 0010140513270106251	2000-10-14	161.76	52.29	0.022	9.26	70
	ASTL1A 0112200502290201111	2001-12-20	160.96	36.18	0.025	9.26	43
	ASTL1A 0210040500380210261	2002-10-04	152.76	54.87	−2.829	9.26	49
	ASTL1A 0211210500340212070	2002-11-21	162.48	40.26	−0.041	9.26	36
	ASTL1A 0301080500160303170	2003-01-08	157.48	36.44	−0.030	9.26	48
	ASTL1A 0310230459290311050	2003-10-23	158.65	48.60	0.019	9.26	25
	ASTL1A 0410090458390410220	2004-10-09	154.41	52.87	0.022	9.26	72
	ASTL1A 0410250458240411040	2004-10-25	158.11	47.51	−2.873	9.26	77
	ASTL1A 0411100458190411210	2004-11-10	160.38	42.70	−1.480	9.26	55
	ASTL1A 0511130458410511190	2005-11-13	161.12	41.93	0.022	9.26	47
	ASTL1A 0511290458400512020*	2005-11-29	161.18	38.58	−0.019	9.26	45
	ASTL1A 0512060504390512090	2005-12-06	162.41	37.35	8.588	9.31	76
	ASTL1A 0512150458320512180	2005-12-15	160.27	36.29	0.016	9.26	43
	ASTL1A 0602010458090602040	2006-02-01	151.87	39.99	−2.876	9.26	40
	ASTL1A 0701190459340701220	2007-01-19	154.56	37.74	−2.867	9.26	67
Garhwal (*case study 2*)	ASTL1A 0109090542130109210	2001-09-09	149.10	60.91	5.699	9.56	52
	ASTL1A 0310100529250310220	2003-10-10	156.13	49.64	−5.727	9.56	44
	ASTL1A 0310100529340310220	2003-10-10	155.70	50.21	−5.727	9.51	13
	ASTL1A 0407240529140408100	2004-07-24	116.65	68.37	−8.586	9.56	40
	ASTL1A 0508190534580508220	2005-08-19	133.17	65.31	5.729	9.56	87
	ASTL1A 0510150528360510180	2005-10-15	157.07	47.74	−8.583	9.56	69
	ASTL1A 0609230535100609260	2006-09-23	151.63	55.82	2.878	9.56	52
	ASTL1A 0610090534580610120*	2006-10-09	158.14	50.61	5.729	9.56	62
	ASTL1A 0611100535050611130	2006-11-10	163.20	40.39	2.873	9.56	57

All given data were extracted from the metadata of the images. The orientation measures the angle between the along-track direction and North in a clockwise direction. The images that were used as the master images in the co-registration procedure are marked with an asterisk (*).

[a] The listed cloud cover is taken from the images metadata and usually overestimates the true cloud cover.