ARTICLE IN PRESS
RSE-09622; No of Pages 11

Remote Sensing of Environment xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Rapid large-area mapping of ice flow using Landsat 8

Mark Fahnestock [a],*, Ted Scambos [b],*, Twila Moon [b,c], Alex Gardner [d], Terry Haran [b], Marin Klinger [b]

[a] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
[b] National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder, Boulder, CO 80303, USA
[c] Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA
[d] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 4 November 2015
Accepted 14 November 2015
Available online xxxx

Keywords:
Landsat
Ice flow
Greenland
Antarctica
Remote sensing
Glaciers

ABSTRACT

We report on the maturation of optical satellite-image-based ice velocity mapping over the ice sheets and large glacierized areas, enabled by the high radiometric resolution and internal geometric accuracy of Landsat 8's Operational Land Imager (OLI). Detailed large-area single-season mosaics and time-series maps of ice flow were created using data spanning June 2013 to June 2015. The 12-bit radiometric quantization and 15-m pixel scale resolution of OLI band 8 enable displacement tracking of subtle snow-drift patterns on ice sheet surfaces at ~1 m precision. Ice sheet and snowfield snow-drift features persist for typically 16 to 64 days, and up to 432 days, depending primarily on snow accumulation rates. This results in spatially continuous mapping of ice flow, extending the mapping capability beyond crevassed areas. Our method uses image chip cross-correlation and sub-pixel peak-fitting in matching Landsat path/row pairs. High-pass filtering is applied to the imagery to enhance local surface texture. The current high image acquisition rates of Landsat 8 (725 scenes per day globally) reduces the impact of high cloudiness in polar and mountain terrain and allows rapid compilation of large areas, or dense temporal coverage of seasonal ice flow variations. The results rival the coverage and accuracy of interferometric Synthetic Aperture Radar (InSAR) mapping.

1. Background

Feature tracking, in its early application for ice flow determination, was applied to oblique time-lapse photographs or repeat aerial photography, and involved manual identification of the same features in two images, displaced over the image pair interval by ice flow (e.g. Harrison, Echelmeyer, Cosgrove, & Raymond, 1992; Krimmel, 1987; Whillans & Bindschadler, 1988). Feature tracking expanded ice flow measurement beyond repeated geodetic surveys of markers on the ice, and allowed intermediate measurements during long intervals between field seasons. Efforts to follow displacement of features in satellite images started with similar techniques (e.g. Lindstrom & Tyler, 1984; Lucchitta & Ferguson, 1986), but tools were soon developed that exploited the digital nature of the imagery.

The advent of moderate-resolution imaging of the earth surface from space by Landsat led to the development of satellite-image-based tracking of ice sheet flow over twenty-five years ago. A major early advance was the development of computerized correlation algorithms and digital enhancement of the images (Bindschadler & Scambos, 1991; Emery, Fowler, Hawkins, & Preller, 1991; Scambos, Dutkiewicz, Wilson, & Bindschadler, 1992). The first significant areas mapped using computational methods were the broad ice streams flowing into the Ross Ice Shelf and regions of the Larsen Ice Shelf, both in Antarctica, where large crevasses could be followed in ~30 m resolution Thematic Mapper imagery from Landsat 4 and 5 (Bindschadler, Fahnestock, Skvarca, & Scambos, 1994; Bindschadler, Vornberger, Blankenship, Scambos, & Jacobel, 1996; Scambos, Echelmeyer, Fahnestock, & Bindschadler, 1994). Similar techniques were later applied to map surface displacements of smaller mountain glacier systems (e.g. Berthier et al., 2005; Kääb, 2002). Computer-based tracking of the long curvilinear crevasses common in these areas substantially increased knowledge of ice flow patterns compared to field-based techniques. Subsequently, imaging radars allowed wide-area ice flow mapping based on satellite-borne synthetic aperture radar (SAR) coverage, using both speckle tracking (similar to feature tracking in visible-band images) and interferometric determination of ice displacement (InSAR; Frolich & Doake, 1998). Radar coverage did not suffer from cloud obscuration of the surface, and had a strong textural response over both crevassed and uncrevassed areas due to unique speckle or phase-based signatures in the radar energy reflection from ice sheet surface and sub-surface structures. This again revolutionized our knowledge of large ice sheet flow patterns, leading to the first comprehensive ice flow maps at the ice sheet scale (e.g., Jezek, 2008; Joughin, Smith, Howat, Scambos, & Moon, 2010; Rignot, Mouginot, & Scheuchl, 2011).

---

* Corresponding authors.
E-mail addresses: mark.fahnestock@mac.com (M. Fahnestock), teds@nsidc.org (T. Scambos).

http://dx.doi.org/10.1016/j.rse.2015.11.023

Please cite this article as: Fahnestock, M., et al., Rapid large-area mapping of ice flow using Landsat 8, *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.11.023

In these early applications, a limitation common to Landsat and other visible-band satellite image data sets with limited radiometric resolution over bright targets was that feature tracking required high-contrast surface features (crevassed areas), leading to patchy ice velocity retrievals. Image acquisitions were infrequent (typically 0 to 4 acquisitions per year for a scene center in the 1990s) and cloudiness in the polar regions further reduced usable coverage. Poor image geolocation and internal geometric distortion often meant extensive pre-processing to co-register image pairs prior to ice flow data extraction. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat 7, both launched in 1999, improved most aspects of ice flow mapping from visible-band satellite data, with better spatial resolution (10 and 15 m, respectively), improved acquisition rate, and better geolocation and image geometry. This has been widely applied to individual glaciers or small glacierized regions (e.g., Berthier, Arnaud, Baratoux, Vincent, & Rémy, 2004). However, large-scale ice sheet velocity mapping was still impractical because of low acquisition rates and because the dynamic range of the sensors, once distributed across dark (e.g. ocean) and highly reflective (snow and ice) targets, contained limited radiometric information over ice.

Improvements in radiometric resolution, geolocation accuracy, and image acquisition rates for Landsat 8, launched in 2013, allow us to overcome these limitations and provide velocity mapping on an ice-sheet-wide scale, or over an entire glacierized region, on a frequent basis. Landsat 8 has maintained a high acquisition rate, currently capturing ~725 images per day over the 16-day orbit repeat cycle, leading to excellent image coverage (Fig. 1). With 12-bit radiometric quantization, compared to the 8 bits per channel in earlier instruments, Landsat 8 can track subtle contrast variations over bright targets, such as sastrugi (snow dunes at ~five meter scale). This capability was first demonstrated with the Advanced Land Imager (ALI) on EO-1, a precursor to the Landsat 8 Operational Land Imager (OLI) (Bindschadler, 2003). OLI panchromatic band imagery has nearly an order of magnitude better signal to noise ratio than Landsat 7 ETM+, and much less saturation for bright targets (Morfitt et al., 2015). This, combined with ~half-pixel geolocation accuracy and high spatiotemporal data acquisition rates, enables ice velocity measurements having a quality and quantity not previously achievable with visible-band satellite imagery. Furthermore, the software presented here (*P*ython image *Corr*elation or PyCorr) and ongoing improvements in accessibility and geolocation of the USGS Landsat 7 archive (www.earthexplorer.usgs.gov) are facilitating improved, though not ice-sheet-wide, ice velocity mapping using Landsat 7.

2. Methods

2.1. Large area mapping via automated surface feature tracking

To map ice flow, small image subscenes, or ‘chips’, containing features from one image, are compared to a range of possible matching locations in a second image, with the best match determined by generating a normalized cross-correlation surface composed of the cross-correlations of the chips at each integer pixel offset in that range. Mathematical interpolation of the primary peak in this surface allows determination of feature offset at the sub-pixel level. The earliest available software that incorporated this process with a view toward tracking of surface feature movement, and made it available outside of large image processing packages, was IMCORR (nsidc.org/data/velmap/imcorr.html; Fahnestock, Scambos, & Bindschadler, 1992). A number of later implementations of this technique have been developed, beginning with Whillans and Tseng (1995). Several recent approaches are compared in Heid and Kääb (2012); differences between implementations involve approaches to image resampling, filtering and peak fitting, strategies for identifying incorrect offsets (“bad matches”) (e.g. Ahn & Howat, 2011), simultaneous estimation of strain and rotation as well as displacement (eg. Debella-Gilo &

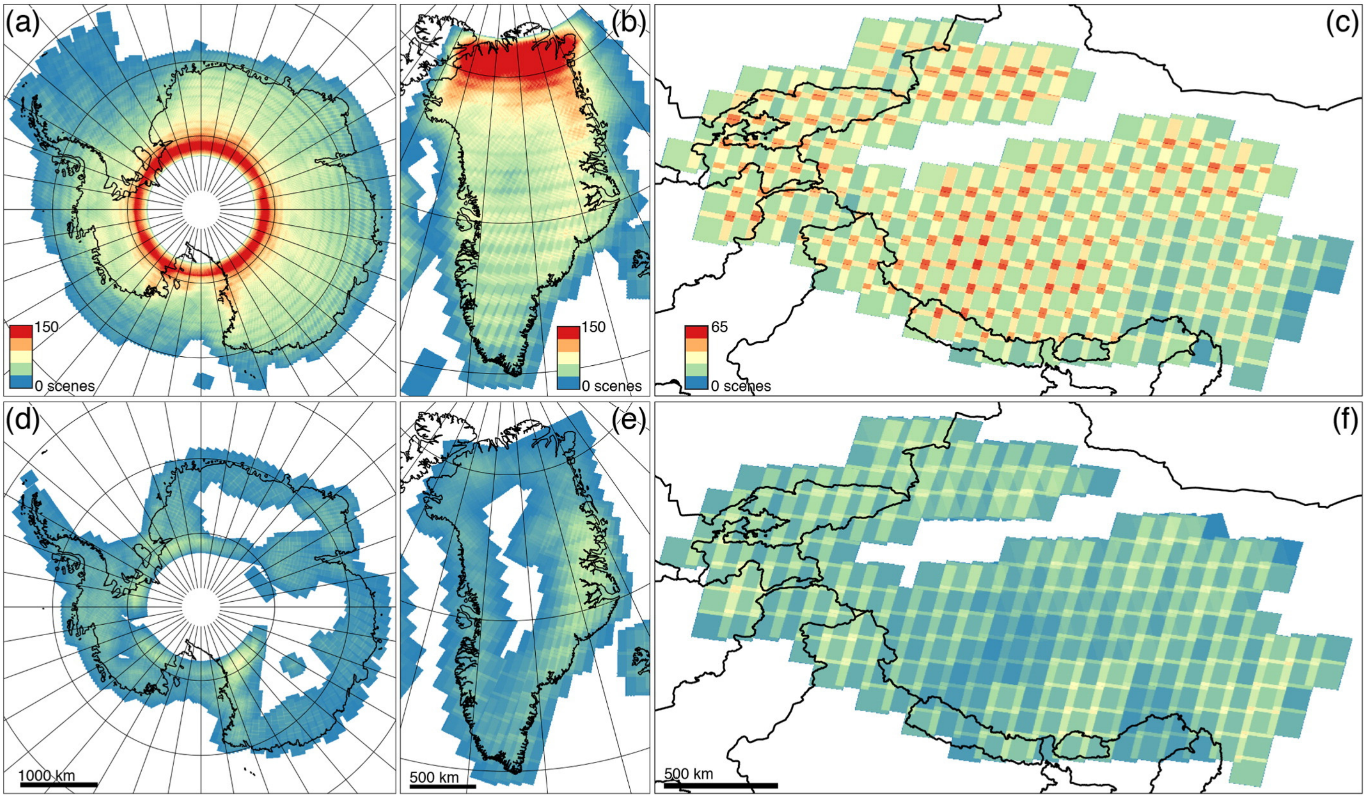

Fig. 1. Maps of Landsat 8 image coverage in a) Antarctica (1 Oct. 2014–31 Mar. 2015); b) Greenland (1 Mar.–31 Oct. 2014); and c) central Asia (1 Mar.–31 Oct. 2014); and Landsat 7 image coverage in d) Antarctica (1 Oct. 2012–31 Mar. 2013), e) Greenland (1 Mar.–31 Oct. 2012), and f) central Asia (1 Mar.–31 Oct. 2012). Images included have a 5° sun elevation cutoff and ≤50% cloud cover.

Please cite this article as: Fahnestock, M., et al., Rapid large-area mapping of ice flow using Landsat 8, *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.11.023