ISPRS Journal of Photogrammetry and Remote Sensing 138 (2018) 164–175

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Towards breaking the spatial resolution barriers: An optical flow and super-resolution approach for sea ice motion estimation

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ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 25 January 2018
Accepted 25 January 2018

Keywords:
Arctic sea ice
Drift estimation
Maximum cross-correlation
Motion tracking
Optical flow
Super-resolution

ABSTRACT

Estimation of sea ice motion at fine scales is important for a number of regional and local level applications, including modeling of sea ice distribution, ocean-atmosphere and climate dynamics, as well as safe navigation and sea operations. In this study, we propose an optical flow and super-resolution approach to accurately estimate motion from remote sensing images at a higher spatial resolution than the original data. First, an external example learning-based super-resolution method is applied on the original images to generate higher resolution versions. Then, an optical flow approach is applied on the higher resolution images, identifying sparse correspondences and interpolating them to extract a dense motion vector field with continuous values and subpixel accuracies. Our proposed approach is successfully evaluated on passive microwave, optical, and Synthetic Aperture Radar data, proving appropriate for multi-sensor applications and different spatial resolutions. The approach estimates motion with similar or higher accuracy than the original data, while increasing the spatial resolution of up to eight times. In addition, the adopted optical flow component outperforms a state-of-the-art pattern matching method. Overall, the proposed approach results in accurate motion vectors with unprecedented spatial resolutions of up to 1.5 km for passive microwave data covering the entire Arctic and 20 m for radar data, and proves promising for numerous scientific and operational applications.

1. Introduction

Sea ice motion is a critical factor in climate models and local-level human activities in the polar regions. It significantly affects the thickness distribution of sea ice, causing leads—open water areas—or ridging in cases of divergent or convergent motion, respectively. These dynamic processes co-act with thermodynamic ocean-atmosphere processes and affect the ice mass balance and thickness which determine the survival or summer melting of sea ice in a region (Haas, 2017). Convergent motion creates thicker ice and enhances sea ice survival, whereas divergent motion promotes energy and moisture fluxes (Meier, 2017; Gettelman and Rood, 2016). In fact, sea ice motion has been a major factor in the loss of multi-year ice in the Arctic through its advection out of the region (Meier, 2017; Smedsrud et al., 2011). Given these facts, it is an important component for the calculation, initialization, fine-tuning, or validation of climate models that quantify exchanges of energy and mass between the ocean and the atmosphere and predict polar ice pack conditions (Kræmer et al., 2015; De Silva et al., 2015; Berg et al., 2013; Kimura et al., 2013; Meier et al., 2000). Besides, sea ice motion can significantly affect, or even endanger, human activities on a local level, including ship navigation, fisheries, and oil/gas drilling. Considering the increasing trends on average sea ice drift speed during the last decades (Spreen et al., 2011; Rampal et al., 2009), accurately monitoring sea ice motion at a fine scale is of great importance.

Data from a variety of satellite sensors have been employed to estimate sea ice motion. They include (i) passive microwave sensors, e.g., Special Sensor Microwave Imager (SSM/I), Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), Advanced Microwave Scanning Radiometer 2 (AMSR2) (Tschudi et al., 2016b; Girard-Ardhuin and Ezraty, 2012; Lavergne et al., 2010); (ii) microwave scatterometers, such as QuikSCAT (Girard-Ardhuin and Ezraty, 2012; Haarpaintner, 2006); (iii) Synthetic Aperture Radars (SAR), e.g., ENVISAT Advanced SAR (ASAR), RADARSAT-2, European Remote Sensing 1

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https://doi.org/10.1016/j.isprsjprs.2018.01.020
0924-2716/

(ERS-1) SAR (Karvonen, 2012; Komarov and Barber, 2014; Berg and Eriksson, 2014); and (iv) optical, such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS) (Ninnis et al., 1986; Emery et al., 1991; Tschudi et al., 2016b; Petrou and Tian, 2017). Although passive microwave and scatterometer sensor data can provide daily coverage of the entire Arctic, their typical spatial resolution of around 5–25 km makes monitoring of small leads and ridges difficult and is prohibitively coarse for any fine-scale applications, such as ship navigation. The resolution of optical data used in sea ice monitoring studies can be one order of magnitude higher, between 250 m and 1.1 km. Even in the case of SAR data which have higher resolution of several tens to hundreds of meters, tasks such as estimating motion at a scale of a ship size still remains challenging.

Sea ice motion between two time instances is typically represented through a motion vector field. Each motion vector quantifies the displacement, or velocity, of a sea ice parcel in a pixel or patch in the image from the first to the second time instance. This makes the spatial resolution of sea ice motion described as a two-parameter problem: the first parameter is the *density* of the vector field, i.e., the number of vectors originating from a unit area; the second is the *minimum detectable motion*, i.e., the minimum possible non-zero motion that a vector can describe. Both parameters are restricted by the inherent spatial resolution of the satellite images used. Several sea ice motion estimation approaches have attempted, implicitly or explicitly, to improve one or the other parameter, but rarely both. In addition, most proposed approaches have been evaluated in solely one, or sometimes two, types of sensor data, mainly of similar spatial resolution and nature.

In this study we propose an approach that attempts to accurately estimate sea ice motion, by both increasing the density of the calculated motion field and reducing the minimum detectable motion. An example-based super-resolution technique is explored to increase the inherent resolution of the employed satellite images. Then, an optical flow-based approach is applied to estimate motion in a dense per-pixel field, providing vectors that describe continuous subpixel displacements. In addition, to demonstrate its robustness and transferability in local and regional level studies, the method is extensively evaluated on passive microwave, optical, and SAR data of different spatial resolutions. To our best knowledge, it is the first sea ice motion methodology applied in satellite data of such high diversity in sensor types and spatial resolutions. In addition, it produces the highest resolution motion vector fields ever generated from each sensor type, reaching up to around 1.5 km for passive and 20 m for SAR data.

This paper is organized as follows. Previous work related to sea ice motion and super-resolution is presented in Section 2. Section 3 details the data employed in this study and Section 4 describes the proposed methodology. Experimental results and discussions on the outcomes are presented in Sections 5 and 6, respectively. Main conclusions are drawn in Section 7.

2. Related work

The vast majority of sea ice motion estimation studies have been based on pattern matching—or *template* matching—approaches. Given a template on an image, i.e., an image patch, these approaches search for the candidate template in a second image, captured later in time, with the most similar pattern to the first one. Based on the relative distance and orientation of the two templates, the motion of the patch—and of the underlying sea ice parcel—during the time interval between the two images can be estimated. The motion has been expressed either as displacement or as mean velocity, by dividing the displacement with the time interval.

Normalized cross-correlation (NCC) has been a pattern similarity measure widely employed to be maximized by several studies with satellite data (Ninnis et al., 1986; Emery et al., 1991; Kwok et al., 1998; Meier et al., 2000; Meier and Dai, 2006; Haarpaintner, 2006; Lavergne et al., 2010; Girard-Ardhuin and Ezraty, 2012; Tschudi et al., 2010, 2016b), and airborne data (Hagen et al., 2014). For a template A centered in position $p = (x, y)$ in one image and a template B centered in position $p + \boldsymbol{u} = (x + u_x, y + u_y)$ in a second image, NCC is calculated as $NCC(\boldsymbol{u}) = cov(A, B)/[\sigma(A)\sigma(B)]$ (Gao and Lythe, 1996), where $cov(A, B)$ stands for the covariance between A and B, $\sigma(A)$ and $\sigma(B)$ for the standard deviations of the pixel values of A and B, respectively, and $\boldsymbol{u} = (u_x, u_y)$ for the motion vector. More recent approaches employed Phase Correlation (PC) as a pattern similarity measure alternative to (Karvonen, 2012; Berg and Eriksson, 2014) or in combination with NCC (Thomas et al., 2008, 2011; Hollands and Dierking, 2011; Komarov and Barber, 2014), to counterbalance the inherent shortcoming of NCC in rotational motion. For templates A and B, PC is calculated in the Fourier domain as their normalized cross-power spectrum and transformed back to the spatial domain as $PC = \mathscr{F}^{-1}(F_A^* F_B / |F_A^* F_B|)$ (Berg and Eriksson, 2014; Karvonen, 2012), where F_A^* represents the conjugate Fourier transform of A, F_B is the Fourier transform of B, and $\mathscr{F}^{-1}$ is the inverse Fourier transform operator. PC is expressed as a matrix in the spatial domain, with the relative motion of the templates estimated from the location corresponding to the maximum value of the PC matrix. In their conceptual form, both NCC and PC approaches are able to express displacements at least equal, or larger, than one pixel of the image. Thus, the estimated motion in each of the two Euclidean axes is quantized to the pixel resolution.

A number of studies attempted to provide subpixel motion estimation through modifications of the original pattern matching approaches. Linear oversampling by a factor of four has been applied in the vector field in order to approximate displacements four times smaller than the original maximum cross-correlation algorithm (Tschudi et al., 2016b; Meier and Dai, 2006; Meier and Maslanik, 2003; Meier et al., 2000). Oversampling on the image data by a factor of six was applied by Kwok et al. (1998) to provide subpixel motion estimation, followed by a biquadratic surface fitting in the correlation value domain. Lavergne et al. (2010) expressed the search for a matching template as a continuous maximization problem, with subpixel motions being estimated using bilinear interpolation. Despite the attempts to decrease the motion quantization error, none of the studies explicitly attempted to increase the density of the motion vector field.

Optical flow has been an alternative approach to pattern matching for sea ice motion estimation. The approach is mainly based on the *brightness constancy* assumption that the intensity of a pixel remains the same during its motion between two images (Fleet and Weiss, 2006). The relative displacement of each pixel between the images is calculated, thus, optical flow approaches result in a dense motion vector field. They usually involve a variational minimization process which results in motion vectors estimated in the continuous domain. Although some early studies on sea ice motion estimation employed optical flow (Sun, 1996; Leppäranta et al., 1998; Gutiérrez and Long, 2003), pattern matching remained the most popular choice. In a recent study, an optical flow method applied to MODIS imagery outperformed a state-of-the-art pattern matching approach in both accuracy and processing speed (Petrou and Tian, 2017). Despite the fact that optical flow approaches provide dense motion vector fields, none has attempted to improve this density beyond the boundaries imposed by the image resolution.

Example-based image super-resolution has been popular in recent studies. Different from other approaches where the prior