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High resolution (400 m) motion characterization of sea ice using ERS-1 SAR imagery

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Abstract

Using Synthetic Aperture Radar (SAR) images from ERS-1, we render high resolution motion fields of sea ice using a multi-resolution processing system. The results are provided at a 400 m resolution, which is an order of magnitude greater than the standard SAR motion products (5–10 km). An error propagation experiment shows a standard deviation of 1.3% day^{-1} for the noise in invariant shear resulting from position uncertainties and processing techniques. We use this noise level to determine a significant lower threshold when identifying shear zone discontinuities. As example, a 24-day sequence of images is processed using this system to examine the development and evolution of a shear zone. This evolution is in response to the topographic steering caused by ocean circulation and wind forcing along a continental shelf break. In addition, we adapt the Line Integral Convolution (LIC) to depict flow patterns present in the motion field. Collectively, these motion products provide valuable descriptions of the non-rigid dynamics taking place within the sea ice. Our goal is to complement the existing RADARSAT Geophysical Processing System (RGPS) motion products and aid in the validation and further development of the most progressive "lead-resolving" sea ice models currently available. This form of sea ice visualization is important for understanding air–ice–sea momentum transfer processes that transcend through small-scale to large-scale fracture events with application to ship navigation.

Keywords: Sea ice; ERS-1 SAR; Buoys; Motion estimation; Discontinuity identification; Line integral convolution; Computer vision

1. Introduction

At spatial scales of 1–100 km and temporal scales of hours to days, sea ice is seen as a collection of ice floes and composite plates undergoing differential motion subject to both local and non-local forcing. These scales are equivalent to the oceanographic mesoscale (depending on the Rossby internal deformation radius — Pedlosky 1987) and, like its oceanographic and atmospheric mesoscale counterparts, is rich in complex processes.

We are interested in observing the non-rigid motion of sea ice at this scale, in particular, the observed differential motion of features called leads, families of slip lines, cracks, and ridges. Within the sea ice community, the literature describes observations of "linear kinematic features" (LKFs) (Kwok 2001; Moritz and Stern 2001) and "piece-wise rigid motion" (Moritz and Stern 2001). Within other scientific and engineering fields such features might be called "damage zones" or "dislocations".

There are a number of modeling studies of sea ice including those which support the hypothesis that sea

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ice has no characteristic scale (i.e., it is scale invariant — Hopkins and Thorndike 2006). So to clarify, we are identifying this as a scale of observation (as opposed to a scale of physics) and emphasize the fact that this range (1–100 km and hours to days) of sea ice dynamics has not been studied in detail. It is an observation range which is larger than the floe–floe interactions which can be seen and analyzed using point measurements (i.e., at the human scale of observation), and also at the lower limit of what has been studied through continuum mechanics ice models since the time of Hibler (1979).

In this paper, we explore the characteristics of discontinuous regions of sea ice within the observational range clarified above. For simplicity, we defer to a few fundamental mathematical definitions regarding composition such that leads, slip lines, cracks, and ridges are called "discontinuities". The development of a discontinuity in a field of sea ice is a shock (from shock theory) and our visualization system is being built with the intention of resolving, quantifying, and characterizing dynamic processes in a shock-based discontinuous non-rigid material. In this way, we examine a field of sea ice that looks like a piece-wise continuous material made up of a collection of aggregated floes. Our main premise is that sea ice motion is subject to the basic principles of continuum mechanics with limitations in continuity due to shock events in close proximity to discontinuities.

The above definitions place the motion of sea ice under a larger field of study known as non-rigid motion analysis (Kambhamettu et al., 1994a,b, 2003). The interdisciplinary field of non-rigid motion involves the understanding of three basic types of materials, namely, continuous, piece-wise continuous, and discrete particle motion. Depending on the type of studies conducted through the years on sea ice, each of these descriptions has been applied. At the large (basin) scale, sea ice is traditionally regarded as a non-rigid continuum and at the small scale, it is regarded as a collection of discrete particles/floes. While great progress has been made in understanding sea ice from these two traditional perspectives, the study of sea ice as a piece-wise continuous material has been studied far less. This is because discontinuities of sea ice are very narrow features which extend thousands of kilometers with scale-invariant sea ice properties in terms of floes size distribution.

The analysis of sea ice as a piece-wise continuous material is one which researchers have only recently been able to observationally explore thanks to the availability of high-spatial resolution, all-weather remote sensing platforms (e.g. ERS-1 and RADARSATSAR) from agencies such as the European Space Agency (ESA) and Canadian Space Agency (CSA). United States (US) investigators have access to these data thanks to data exchange agreements between these agencies and the US National Aeronautic and Space Adminstration (NASA). Prototype technology needed to render kinematic information from these images is two decades old (Fily and Rothrock 1987; Kwok et al., 1990; Emery et al., 1991; Kwok et al., 1998b; Liu and Cavalieri 1998; Drinkwater 1998a,b; Li et al., 1998) with public domain software still not easily accessible. Hence, visualization and characterization of features within this observational range are still in relatively early stages of development.

From an operational and human perspective, sea ice features such as leads, slip lines, cracks, and ridges are either a useful conduit or great impediment when navigating in polar waters or maintaining offshore structures. Thus, mobility at the human scale is greatly affected by changes in discontinuities of the sea ice pack. These discontinuities are also fundamental regulators of heat, mass, and momentum transfer at the air-sea interface of one of the world's most sensitive climatic regions (Geiger and Drinkwater 2005). Hence, there is also a relevant need to analyze, quantify, visualize and understand the distribution, orientation, size, and duration of both continuous and discontinuous motion regimes.

Numerical sea ice models are at a stage of development where their spatial and temporal resolution and underlying physics have evolved far enough to simulate the discontinuities described above, in particular, models by Hibler (2001), Aksenov and Hibler (2001), Zhang and Hibler (1997), Hopkins (2001), Hopkins (1996), Hunke (2001), Pritchard (2001), Heil and Hibler (2002) and others. While a few example data sets including the RADARSAT Geophysical Processing System (RGPS) data set over the western Arctic (Kwok et al., 1998a) currently exist, there are still an enormous number of research topics that can be explored both in the visualization and understanding of the physics of these data.

Making use of 12 ERS-1 SAR images coincident with a buoy from the 1992 Ice Station Weddell (ISW) experiment, we explore the application of a multi-resolution image processing method to quantitatively describe, and eventually numerically test, the discontinuous non-rigid motion of sea ice. The paper proceeds as follows. A short overview of the data selected from ISW is provided. Next, in the methodology section, we review our processing method for rendering a discontinuous non-rigid motion field. An example application of this method is provided next followed by some recent developments for visualizing the motion field at high resolution (400 m) over a large region (100 km). Finally, we summarize our findings.