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Radar satellites measure ice cover displacements induced by moving vehicles

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ABSTRACT

Vehicles moving on floating ice modulate its surface depending on ice, bathymetric, and traffic variables. Under certain conditions, they may cause ice cover breakthroughs that jeopardize productivity, property, and life. The initiation of ice cover failure by traffic is commonly referred to as the moving vehicle problem. Scientific progress towards mitigating this problem has been limited. Subject-matter experts have argued that this is due, in part, to the absence of convenient and accurate means to measure ice cover modulations. Here we demonstrate a previously unknown capacity of radar earth observation satellites to measure the modulation of ice cover by moving vehicles with an unparalleled breadth of view, superior spatial detail and millimeter-scale vertical accuracy. This capacity derives from satellite radar technology that is experimental at present and differential interferometric radar data processing techniques. Ice modulations measured by means of conventional devices are typically described as 'deflections'; we purposely refer to the radar satellite measurements as 'displacements' to signify a difference in the measurement method and result. Our findings indicate opportunities for ice road and radar earth observation stakeholders, may spark renewed interest in and progress towards mitigating the moving vehicle problem, and thus help improve the efficiency and safety of ice road transportation.

1. Introduction

Ice cover provides an effective and economical base for seasonal roads, facilitating valuable land transport links to isolated cold region sites (e.g. Gold, 1971; Masterson, 2009). Roads routed over ice are often complemented by portages, temporary roads that traverse adjacent lands, the combination is named a winter road. Vehicles driving on floating ice, as opposed to bottom-fast ice, modulate its surface and may induce breakthroughs. The initiation of ice cover failure by traffic is commonly referred to as the moving vehicle or moving load problem. Minimizing the failure risk is an important facet of winter road management because breakthroughs jeopardize productivity, property, and life. Here we will demonstrate that radar satellite technology can measure the effects of moving vehicles on ice cover. Current knowledge about these effects results from experimental and theoretical studies relating to lake and sea ice. Readers interested in the particulars are referred to an excellent review by Squire et al. (1996). Certain aspects of the interaction between ice and traffic are discussed in this paper to facilitate the interpretation of our results and help demonstrate the relevance of the study. Some basics of radar earth observation – in the context of ice cover – are reviewed for the benefit of readers unfamiliar with the technology or the application field.

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2. Moving vehicles on floating ice

The response of floating ice to moving vehicles is commonly categorized by means of the theoretical 'critical speed' concept and largely depends on a combination of ice thickness, ice strength, water depth, and vehicle speed (e.g. Nevel, 1970; Eyre, 1977). Vehicles travelling at subcritical speeds are known to move along surrounded by a localized symmetric ice deformation, called a deflection bowl. This bowl reaches its maximum depth and minimum width and causes the greatest strain when the vehicle's velocity attains the critical speed. The effects of vehicles that move at super-critical speeds extend beyond the ice cover to the underlying water and result in the formation of ice and water waves that propagate at the vehicle's velocity. At speeds just above critical, waves are excited both in front and behind the vehicle. The trailing waves have been observed to disappear when the velocity reaches a level well above the critical speed (Squire et al., 1985, 1988; Takizawa, 1985). Vehicles travelling at velocities equal to and greater than the critical speed present the highest risk to the structural integrity of ice roads.

Subject-matter experts have argued that scientific progress towards mitigating the moving vehicle problem has been sub-optimal because experimental work has not kept pace with theoretical work (Beltaos, 1980; Squire et al., 1988; Kerr, 1996). This research imbalance was explained, in part, from the absence of convenient and accurate means to measure ice cover modulations and persists today (Beltaos, 1980; Squire et al., 1985, 1988). A review of recent literature shows that, with one exception (Lanteigne and Van Der Vinne, 2014), experimental

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studies were essentially halted in the early 1980s while theoretical studies have remained quite popular (e.g. Davys et al., 1985; Rayner et al., 1994; Schulkes et al., 1987; Duffy, 1991; Strathdee et al., 1991; Sodhi, 1995; Nugroho et al., 1999; Părău and Dias, 2002; Wang et al., 2004; Bonnefoy et al., 2009). The resulting field data shortage lowers the prospect of alleviating the problem through empirical analysis and hinders the verification of solutions arising from theoretical studies.

Field trials typically involve the deployment of at least one in situ device that provides a temporal measurement of ice cover modulation, recorded at a specific location in the vicinity of a test track (Eyre, 1977; Beltaos, 1980; Squire et al., 1985, 1988; Takizawa, 1985; Lanteigne and Van Der Vinne, 2014). The measurements obtained are described as 'deflections'. Limited information regarding spatial variability in the ice cover's response can be obtained from concurrent measurement at multiple points. In the interest of acquiring definite data, field experiments have focussed on solitary vehicles at deep water locations away from shorelines.

3. Radar earth observation basics

Radar is an acronym for RAdio Detection And Ranging. The basic operating principle of radar systems is as follows: a narrow beam of electromagnetic (EM) waves is transmitted, irradiated objects reflect the incident waves in many directions, and waves reflected towards the system are received and recorded. In free-space, the approximate sensor to object or range distance follows from the EM signal's velocity, equal to the speed of light, and the delay in time between its transmission and reception. The signal recorded is referred to as the radar backscatter and expressed by means of a complex number that captures both its intensity and phase. The intensity is governed by structural and dielectric properties of the object observed while the phase complements the measured time delay, providing more precise information about the range distance. Radar systems used for the purpose of earth observation (EO) operate with waves that are about 1 cm to 1 m in length and exploit the forward motion of the platform to create a continuous image from successive measurements. Most EO radars incorporate advanced signal recording and processing technology that yields spatially consistent, high resolution images and are referred to as Synthetic Aperture Radar (SAR) systems. More details regarding the operating principles of radar EO systems can be found in literature (e.g. Henderson and Lewis, 1998).

SAR satellites are useful for collecting up-to-date information about ice roads because they can image extensive remote areas independent of weather and daylight conditions. Due to a relatively long wavelength, radar waves are able to penetrate dry, i.e. solidly frozen, freshwater ice cover and overlying dry snow. Consequently, radar images comprise ice cover information that is not visible to the human eye or in images acquired by optical EO satellites. Unlike freshwater ice, ice with high salt concentrations (e.g. first year sea ice) and water are impenetrable to radar waves. Travelling in media with different dielectric properties, for example, from free-space into ice or vice versa radar waves maintain their frequency but change their wavelength, speed and direction of propagation. Models developed by Mätzler and Wegmüller (1987) can be used to estimate these variables as well as the depth of penetration for radar waves passing through pure freshwater ice with internal temperatures equal to -5 °C and -15 °C. However, in reality, the ice cover's temperature is not constant but changes from 0 °C at the ice-water interface to some sub-zero value at the ice-air interface. The latter is governed by environmental conditions such as air temperature, solar irradiation, snow depth etc. (e.g. Leppäranta, 2015). Furthermore, common ice impurities like air bubbles and cracks can be expected to moderate the depth of penetration (e.g. Unterschultz et al., 2008; van der Sanden and Drouin, 2011).

The radar EO technique used in this study is differential SAR interferometry (DInSAR). DInSAR involves the joint analysis of two SAR data sets to obtain measurements of earth surface displacement. Eligible data must be acquired from virtually identical positions in space by a single SAR sensor or by two SAR sensors with identical or equivalent operating characteristics. The time interval between successive acquisition opportunities is dictated by the repeat period of the satellite(s) and is typically on the order of days to weeks. DInSAR processing involves the superposition of the two SAR data sets, in complex number format, to create an interferogram. Each pixel in this interferogram contains information regarding the similarity between the successive radar measurements and their phase difference. The degree of similarity or coherence ranges from 0 to 1 and signifies the quality of the phase difference measurement. Low and high coherence values denote spurious and meaningful phase difference measurements, respectively. A pre-existing Digital Elevation Model (DEM) is required to model and subtract the contribution of topography in the phase differences. The topographically corrected phase differences reveal the temporal change in height of the observed earth surface to a fraction of the deployed radar wavelength. Short acquisition time delays improve the accuracy of displacements measured for natural surfaces such as ice by limiting coherence loss due to temporal change in structural and/or dielectric properties. More in depth and yet not overly technical discussions of (differential) SAR interferometry principles can be found in Madsen and Zebker (1998), Rosen et al. (2000), Woodhouse (2006) and Moreira et al. (2013). Smith (2002), Joughin et al. (2011) and Xu et al. (2015) review the current array of (differential) SAR interferometry application fields.

Due to the penetrating capacity of radar waves, DInSAR can be expected to detect the displacement of solidly frozen freshwater ice cover at depth rather than at the surface. Provided the ice cover, at a certain geographic location, is displaced evenly over its vertical extent, the depth at which the radar waves reflect is irrelevant. The use of DInSAR to measure the displacement of ice cover *at one specific point* is illustrated in Fig. 1. Reflection of the incident radar waves is assumed to centre at the ice – water interface. T1 and T2 associate with the height of the ice cover at the time of the first and second SAR acquisition. The free-space and in-ice direction of propagation of the radar waves is marked by the incidence angle (θ_{inc}) and refraction angle (θ_{ref}), respectively. Fig. 1 shows an offset in the location of the physical reflection centre and the detected reflection centre. This offset results from the incapacity of SAR sensors to detect the, earlier mentioned, changes that radar waves undergo when passing through ice cover. The detected reflection centre exists in the SAR data space only and coincides with the location of the DInSAR measurement. In essence, SAR sensors and DInSAR assume that the radar waves used are propagating through free-space. Regardless, DInSAR yields accurate measurements of vertical ice cover displacement ($D_{\mathrm{DInSARver}} = D_{\mathrm{icever}}$) provided the T1 and T2 radar signal reflect at virtually the same physical location. Under this condition, the distance travelled by each signal *in ice* is identical ($R_{\mathrm{ice\,T1}} = R_{\mathrm{ice\,T2}}$) and therefore does not contribute to the phase difference and displacement measurement. Good satellite orbit control and short time delays enhance the likelihood of achieving consistent interaction between successive radar signals and ice cover. As illustrated in Fig. 1, DInSAR measures displacement along the direction of propagation of the radar signals ($D_{\mathrm{DInSARdop}}$). The corresponding vertical displacement ($D_{\mathrm{DInSARver}}$) is calculated by means of the incidence angle.

Fig. 2 builds on Fig. 1 by depicting the use of DInSAR to measure vehicle induced height changes along an ice cover transect. In addition, Fig. 2 portrays how DInSAR observations relate to 'deflections', that is, measurements from conventional in situ devices. The SAR data acquisition time interval is assumed to be 10 s and matches the repeat period of the satellites that acquired the data used in our study (see Section 5). The successive SAR data sets comprise geolocated information regarding the height of the ice cover at a specific moment defined by the time of acquisition (T1 or T2). In a cross-sectional view such as presented in Fig. 2, the individual SAR observations can be conceptualized as