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Disaster debris estimation using high-resolution polarimetric stereo-SAR

Christian N. Koyama [a,*], Hideomi Gokon [b], Masaru Jimbo [c], Shunichi Koshimura [c], Motoyuki Sato [a]

[a] Tohoku University, Center for Northeast Asian Studies (CNEAS), 41 Kawauchi, 980-8576 Sendai, Japan
[b] The University of Tokyo, International Center for Urban Safety Engineering (ICUS), Institute of Industrial Science, 4-6-1 Komaba, 153-8505 Tokyo, Japan
[c] Tohoku University, International Research Institute of Disaster Science (IRIDeS), 468-1 Aoba, 980-0845 Sendai, Japan

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ABSTRACT

This paper addresses the problem of debris estimation which is one of the most important initial challenges in the wake of a disaster like the Great East Japan Earthquake and Tsunami. Reasonable estimates of the debris have to be made available to decision makers as quickly as possible. Current approaches to obtain this information are far from being optimal as they usually rely on manual interpretation of optical imagery. We have developed a novel approach for the estimation of tsunami debris pile heights and volumes for improved emergency response. The method is based on a stereo-synthetic aperture radar (stereo-SAR) approach for very high-resolution polarimetric SAR. An advanced gradient-based optical-flow estimation technique is applied for optimal image coregistration of the low-coherence non-interferometric data resulting from the illumination from opposite directions and in different polarizations. By applying model based decomposition of the coherency matrix, only the odd bounce scattering contributions are used to optimize echo time computation. The method exclusively considers the relative height differences from the top of the piles to their base to achieve a very fine resolution in height estimation. To define the base, a reference point on non-debris-covered ground surface is located adjacent to the debris pile targets by exploiting the polarimetric scattering information. The proposed technique is validated using in situ data of real tsunami debris taken on a temporary debris management site in the tsunami affected area near Sendai city, Japan. The estimated height error is smaller than 0.6 m RMSE. The good quality of derived pile heights allows for a voxel-based estimation of debris volumes with a RMSE of 1099 m^3. Advantages of the proposed method are fast computation time, and robust height and volume estimation of debris piles without the need for pre-event data or auxiliary information like DEM, topographic maps or GCPs.

1. Introduction

Geophysical disasters like earthquakes, tsunamis, floods, landslides, etc., result in disaster debris. The removal and management of debris generated in such events is a major challenge in the immediate aftermath as well as the longer-term recovery efforts. The debris generated by tsunamis is often more complicated to handle and causes more problems than other types of disaster debris. This is due to a number of factors: (i) Unlike an earthquake, a tsunami usually moves a substantial amount of debris from its origin location and deposits it chaotically across the inundated area. (ii) The tsunami wave thereby mixes up materials from everything in its path, causing various kinds of debris to be combined into piles. (iii) Vast quantities of debris are usually carried back into the sea by the returning waves with the heavy materials being deposited in the coastal area and the lighter ones floating out to the sea where they can remain for month or years causing a number of hazards to marine environment, shipping and fishing industry. (iv) The tsunami waves can also transport large volumes of marine sediments inland. Depending on the quality of sediments and where they have been deposited, they usually have to be handled as disaster debris as well. As this study will deal with the estimation of debris volumes deposited on the affected land surface, special attention has to be paid to factors (i), (ii) and (iv).

The challenges caused by tsunami debris are urgent. Apart from the inspection for victims, the most urgent task is the removal of debris from roads in order to allow rescue workers gain access to the affected areas. This makes the localization and estimation of debris volumes one of the most important initial challenges in the wake of a disaster. In order to scope the damage and coordinate

* Corresponding author.
E-mail addresses: christian.koyama@cneas.tohoku.ac.jp, christian.koyama@outlook.com (C.N. Koyama).

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the response, it is prerequisite that reasonable estimates of the disaster debris in terms of amount and distribution are available to decision makers as quick as possible. Being logistically challenging, time consuming and potentially dangerous, debris estimates are rarely computed from ground based information but usually rely on satellite or aerial photographs (Hansen et al., 2007). However, optical sensors either space- or airborne cannot operate during night or clouded conditions. Furthermore, the interpretation of a debris strewn landscape from 2D photographs alone cannot provide detailed information about the volume of deposited piles and thus the computation requires considerable experience and expert knowledge to yield somewhat reliable estimates. A faster and more powerful method for debris volume estimation could considerably improve the disaster mitigation in the direct aftermath of such a large scale disaster. As the overall debris management is a multi-billion dollar operation, more accurate estimations of the debris volume would also help to significantly reduce the economic impacts.

This motivates us to develop a method for improved debris volume estimation from multi-angular fully polarimetric Synthetic Aperture Radar (PolSAR) data in this paper. Due to the active illumination and cloud penetration of a SAR, the proposed approach has the advantage to provide debris estimates at night or other atmospheric conditions under which optical sensors cannot operate. Moreover the use of polarimetric SAR stereographic height estimation allows obtaining detailed information about the 3D structure of the debris providing much richer *a priori* information to decision makers planning the initial rescue and clean up measures as well as the following long-term waste management operations. We use the March 11 2011 Great East Japan Tsunami as case study for the development and validation of the novel approach.

The severity of the tsunami attack on the Pacific coast of Northeastern Japan was unprecedented in both height and reach. In principle Japan's entire east coast was impacted by the tsunami. However, the by far most heavily affected areas were in the three prefectures closest to the epicenter, Miyagi, Fukushima and Iwate (Fig. 1). Despite Japan being considered as one of the best disaster-prepared countries in the world, the tsunami caused the loss of nearly 20,000 people and damaged hundreds of thousand houses and other buildings. The National Police Agency has confirmed 15,891 deaths and 2584 people missing and a total of 129,225 buildings and/or houses completely destroyed or washed away. Due to the vastness of destruction, the tsunami created extensive volumes of debris making the debris management operation the largest and most expensive of its kind in the world (Ranghieri and Ishiwatari, 2014). Anything standing in the way was instantly turned into disaster debris and swept away often by several hundred meters or more (Tanikawa et al., 2014). Large amounts of sediments, up to 20% of the total estimated debris in some areas, were deposited on the land (Goto et al., 2014). In the most extreme case of Ishinomaki city, the tsunami generated an estimated 6.16 Mt of debris – equivalent to more than 100 years of waste production under normal circumstances (UNEP, 2012). Fig. 1 provides a map of debris volumes for the most affected cities in Tohoku as estimated by the Sendai municipal government (Sendai City Environmental Bureau, 2012). The Tohoku (literally "East North") region consists of the six prefectures in the north of Japan's largest island, Honshu.

Based on post-event airborne SAR imaging campaigns in the area, we develop a method for robust and fast estimation of heights and volumes of debris piles. State-of-the-art high-resolution fully polarimetric X-band SAR data of the Japanese *P*olarimetric *i*nterferometric *S*ynthetic *A*perture *R*adar 2 (Pi-SAR2) operated by the National Institute of Communication and Information Technology (NICT) (Satake et al., 2013; Yamaguchi et al., 2014) is used which

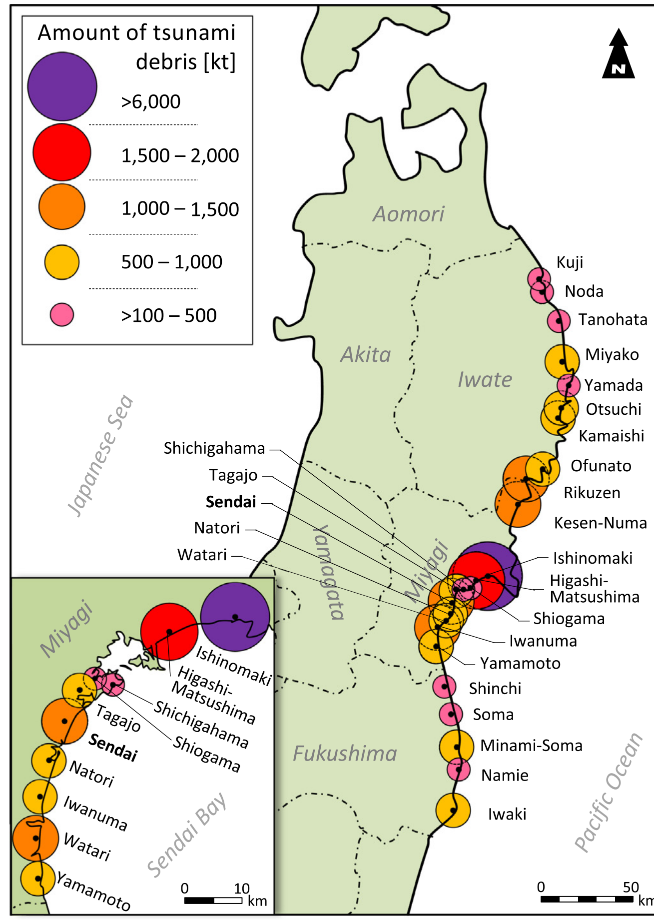

Fig. 1. Map of the Tohoku region in Northeastern Japan showing the amounts of tsunami debris in the most affected cities along the Pacific coast.

were acquired in square-flight path campaigns (Fig. 2) over the Sendai area (Koyama et al., 2014; Koyama and Sato, 2014).

Numerous studies dealing with investigation and mitigation of the earthquake and tsunami impacts using SAR and PolSAR data have been published since the event. Chen and Sato (2013), Satake et al. (2012) and Watanabe et al. (2012) demonstrated detection and analysis of coarse scale damaged areas based on polarimetric target decomposition techniques. Yulianto et al. (2015) proposed semiautomic unsupervised change-detection to map flooded areas using multi-temporal single polarization ALOS/PALSAR data. However, as these approaches are all based on change detection techniques using pre- and post-event SAR data they cannot be applied in cases in which (suitable) pre-event data is not available. Kobayashi et al. (2012a) and Sato et al. (2012) studied the Pi-SAR2 data taken immediately in the aftermath of the event, on March 12 and 18, 2011, demonstrating the potential to detect flooded areas and damaged urban areas by fully polarimetric data without the need for pre-event data. Sato et al. (2007) presented a hybrid scheme based on scattered power decomposition and scattering feature extraction to classify buildings damaged after an earthquake. Aoki et al. (2013) and Arii et al. (2014) developed a novel approach to track floating debris on the sea surface based on ship detection methods which allows obtaining information about the amounts of debris as well as about their vector velocities. Even though no pre-event data is used, the method is not a tool for immediate disaster response as it requires a multitude of SAR imagery and relies on time series analysis. Principally, a method that only requires limited post-event SAR