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Review

LiDAR remote sensing of the cryosphere: Present applications and future prospects

Anshuman Bhardwaj [a,b,*], Lydia Sam [b,c], Akanksha Bhardwaj [d], F. Javier Martín-Torres [a,e]

[a] Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Kiruna, Sweden
[b] Department of Environmental Science, Sharda University, Greater Noida, India
[c] Defence Terrain Research Laboratory, New Delhi, India
[d] Banaras Hindu University, Varanasi, India
[e] Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Armilla, Granada, Spain

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ABSTRACT

The cryosphere consists of frozen water and includes lakes/rivers/sea ice, glaciers, ice caps/sheets, snow cover, and permafrost. Because highly reflective snow and ice are the main components of the cryosphere, it plays an important role in the global energy balance. Thus, any qualitative or quantitative change in the physical properties and extents of the cryosphere affects global air circulation, ocean and air temperatures, sea level, and ocean current patterns. Due to the hardships involved in collecting ground control points and field data for high alpine glaciers or vast polar ice sheets, several researchers are currently using remote sensing. Satellites provide an effective space-borne platform for remotely sensing frozen areas at the global and regional scales. However, satellite remote sensing has several constraints, such as limited spatial and temporal resolutions and expensive data acquisition. Therefore, aerial and terrestrial remote sensing platforms and sensors are needed to cover temporal and spatial gaps for comprehensive cryospheric research. Light Detection and Ranging (LiDAR) antennas form a group of active remote sensors that can easily be deployed on all three platforms, i.e., satellite, aerial, and terrestrial. The generation of elevation data for glacial and snow-covered terrain from photogrammetry requires high contrast amongst various reflective surfaces (ice, snow, firn, and slush). Conventional passive optical remote sensors do not provide the necessary accuracy, especially due to the unavailability of reliable ground control points. However, active LiDAR sensors can fill this research gap and provide high-resolution and accurate Digital Elevation Models (DEMs). Due to the obvious advantages of LiDAR over conventional passive remote sensors, the number of LiDAR-based cryospheric studies has increased in recent years. In this review, we highlight studies that have utilised LiDAR sensors for the cryospheric research of various features, such as snow cover, polar ice sheets and their atmospheres, alpine glaciers, and permafrost. Because this technology shows immense promise for applications in future cryospheric research, we also emphasise the prospects of utilising LiDAR sensors. In this paper, a large compilation of relevant references is presented to allow readers to explore particular topics of interest.

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* Corresponding author at: Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Kiruna, Sweden.

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1. Introduction

The word "cryosphere" is derived from the Greek word "kryos", meaning "cold", and refers to the frozen water on Earth's surface in the form of glaciers, ice caps/sheets, lake/river/sea ice, snow cover, and frozen ground (i.e., permafrost) (Harris & Murton, 2005). Thus, the cryosphere is the frozen portion of the hydrosphere and lithosphere. Because of the reflective characteristics of ice and snow and their physical interactions with the atmosphere, the cryosphere plays an important role in the global energy balance and in global biogeochemical cycles, making it an essential part of the global climate system. Any qualitative or quantitative shifts in the physical properties and extents of the cryosphere affect global air circulation, ocean and air temperatures, ocean current patterns, and, ultimately, sea level. These effects indicate that the cryosphere should be continuously monitored at the global and regional scales. Various scientific groups are currently monitoring the global cryosphere at different spatial and temporal scales. The features that are currently being studied to enhance our knowledge of the changing cryosphere include glaciers (e.g., Bhardwaj, Joshi, Snehmani, Sam, et al., 2014, 2015; 2015a; 2015c; 2015d; Debella-Gilo & Kaab, 2011; Immerzeel et al., 2014; Kargel et al., 2005; Sam, Bhardwaj, Singh, & Kumar, 2015; Snehmani, Bhardwaj, & Pandit, 2014), ice sheets (e.g., Chen, Wilson, & Tapley, 2006; Huybrechts, 1990; Huybrechts & Oerlemans, 1988), snow cover (e.g., Dozier, 1989; Hall, Riggs, & Salomonson, 1995; Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002; Snehmani et al., 2015), sea ice (e.g., Aagaard & Carmack, 1989; Comiso, Cavalieri, Parkinson, & Gloersen, 1997, Tilling, Ridout, Shepherd, & Wingham, 2015), and frozen ground (e.g., Koren et al., 1999; Zhao et al., 2004). These studies use field-based and remote sensing-based methods to estimate the dynamics of the cryosphere. However, perennial, field-based cryospheric monitoring is limited by several factors, such as hostile climate, poor approachability, and inadequate labour and funding. Thus, remote sensing is a practical alternative for meeting the growing demands of cryospheric research.

Space-borne sensors allow us to monitor the physical changes in the cryosphere at different spatial and temporal scales. However, the spatial resolutions achieved through satellite remote sensing are still evolving with proportionally high costs. The revisit times of most space-borne sensors are also predetermined and difficult to adjust based on user requirements, prompting the need for a multi-sensor approach that further enhances the costs and complexities of data handling. To monitor Polar Regions, where light conditions are constantly compromised for nearly half of each year, it is not practical to rely only on the passive optical capabilities of the space-borne sensors. Although space-borne active microwave sensors are cloud-penetrating and free of illumination limitations, they are generally error-prone due to the increased layover and shadow effects caused by oblique viewing Synthetic Aperture Radar (SAR) sensors and rugged snowy alpine terrain (Bhardwaj et al., 2015). In addition, SAR sensors can penetrate snow to varying depths, and are therefore not preferable for accurately modelling the digital elevation of snow-covered terrain. Due to these limitations, space-borne remote sensing platforms require aerial and terrestrial remote sensing platforms and sensors to cover the temporal and spatial gaps of cryospheric data. One type of active remote sensor, Light Detection and Ranging (LiDAR) sensors, actively dissipate LASER (Light Amplification by Stimulated Emission of Radiation) pulses to locate the positions of targets and have been deployed on all three platforms, i.e., satellite, aerial, and terrestrial. Cryospheric elevation data generated using conventional optical photogrammetry requires high contrast amongst various reflective surfaces (ice, snow, firn, slush) in addition to reliable ground control points, which are often very sparse in the cryosphere. Active LiDAR sensors can overcome such issues and provide very high resolution and accurate Digital Elevation Models (DEMs). LiDAR sensors are also being employed to profile the atmosphere above the Polar Regions to understand surface-atmosphere interactions. LiDAR sensors are gaining popularity amongst researchers due to their advantages over conventional passive remote sensors. A detailed comparison of conventional photogrammetry and LASER scanning is presented by Baltsavias (1999a, 1999b, 1999c).

During an extensive literature survey, we found several quality review articles, which highlighted the development and capabilities of LiDAR technology and the physical principles behind it (e.g., Bradbury et al., 2005; Deems, Painter, & Finnegan, 2013; Hyyppa et al., 2008; Jaboyedoff, Oppikofer, et al., 2012b; Lim, Treitz, Wulder, St-Onge, & Flood, 2003; Mallet & Bretar, 2009; Wang, 2013; Wulder et al., 2012; Yan, Shaker, & El-Ashmawy, 2015). However, we observed two clear research gaps: (1) the lack of a review exclusively devoted to the applications of LiDAR in the cryosphere, and (2) the coverage of airborne LiDAR platforms but not terrestrial and space-borne platforms. These observations helped us frame the following objectives of this review paper:

- To present a systematic survey of studies using LiDAR sensors for cryospheric monitoring
- To include all three platforms (space, air and land) of LiDAR monitoring in the review
- To suggest the future scope and utilisation potential of LiDAR in cryospheric research.

In this review, we focus on the applications of LiDAR systems for studying various cryosphere components. We have avoided extensive discussions of the hardware, engineering and commercial aspects of this technology to focus mainly on the objectives of this review. Interested readers can find information regarding the basic physical and mathematical relations and formulas governing airborne laser scanning, existing systems, firms, and other resources in the articles by Baltsavias (1999a, 1999b). We begin by presenting a brief history of the evolution of LiDAR systems without repeating the basic physical principles behind the technology (discussed in detail by Mallet and Bretar (2009)). In the following sections, we discuss several pioneering studies that used LiDAR for cryospheric monitoring. We examine the achievements of these studies and their scope of improvement, if any. Finally, we present an elaborate and conclusive section that highlights the importance of LiDAR remote sensing of the cryosphere and its possible future contributions. This section outlines the major highlights of the review while acknowledging the efforts of the pioneer researchers and guiding interested readers to pursue this exciting area of research. A relevant compilation of the references is presented to help readers explore this topic. The data shown in this paper and the discussion focus only on significant studies that have been published as complete research articles in peer-reviewed journals or as peer-reviewed conference proceedings. Although we have not included abstracts of scientific meetings in this review, interested readers can find and interact with the concerned researchers to explore more about their abstracts. For example, Thomas H. Painter's group at the Jet Propulsion Laboratory (JPL) has extensively used LiDAR for contemporary spring snow pack assessments in California and has shared results in the American Geophysical Union (AGU) fall meetings. We have discussed their peer-reviewed papers in this review (e.g., Cline et al., 2009; Deems & Painter, 2006; Deems et al., 2013; Liu et al., 2008) and many of their unpublished but relevant and interesting