MONITORING SNOW COVER IN REMOTE REGIONS USING RADAR INTERFEROMETRY: APPLICATION TO THE RADARSAT CONSTELLATION MISSION (RCM)

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ABSTRACT: Snow cover is highly variable in space and time, making its characterization particularly challenging in remote and complex environments. Synthetic Aperture Radar (SAR) offers promising capabilities for large-scale snow monitoring under all-weather and day-night conditions. This study investigates the potential of C-band Interferometric Synthetic Aperture Radar (InSAR) data from the RADARSAT Constellation Mission (RCM) to estimate snow depth and snow water equivalent (SWE). The approach is evaluated across two contrasting environments: the deep, maritime-influenced snowpack of Rogers Pass, British Columbia, and the Arctic and subarctic snow conditions of Nunavik, Quebec. Sequential RCM SLC acquisitions are processed to generate interferometric phase time series, which are calibrated using in situ snow observations to retrieve changes in SWE. The resulting estimates are compared with field measurements and outputs from the physically based SNOWPACK model to assess their accuracy and robustness. This research aims to evaluate the potential and limitations of RCM InSAR for characterizing the spatial and temporal variability of snow cover and to support the development of improved snow and geohazard monitoring approaches in remote regions.

KEYWORDS : Remote sensing, Snow, InSAR, RCM, Alpine

1. INTRODUCTION

In a context of rapid climate warming, snow cover is a key indicator of how the climate system and cryospheric processes works. Its variability directly affects the hydrological cycle, slope stability, permafrost dynamics, and the distribution of ecosystems (Tsai and al., 2019). That being said, remote sensing, particularly Synthetic Aperture Radar (SAR), is a crucial tool for snow mapping. Unlike optical sensors, which are limited by cloud cover and available light, SAR makes it possible to acquire data continuously, regardless of weather conditions or time of day, making it a particularly well-suited technology for monitoring snow cover (Tsai and al., 2019).

The RADARSAT Constellation Mission (RCM) represents a major advancement in this respect, thanks to its ability to provide high-resolution radar data with frequent site revisit times. These features open the door to new methods of spatial snow modeling (Raney and al., 2021). Despite these advances, retrieving snow properties from SAR observations remains challenging, and no existing method can yet provide accurate estimates of snow depth and snow water equivalent (SWE) over large and complex areas.

This gap is especially concerning for remote northern regions of Canada, such as Nunavik, Quebec, where infrastructure needs are increasing in a context of housing shortages and ground instability. In these regions, the lack of ground-based validation data, combined with geographic isolation, limits the development of operational tools for monitoring snow conditions and associated geohazards.

Given these challenges, the overall objective of this research is to investigate the potential of RCM C-band Interferometric Synthetic Aperture Radar (InSAR) for estimating snow depth and SWE across contrasting snow and climate conditions. The study focuses on Rogers Pass, British Columbia, and Nunavik, Quebec. A retrieval approach based on radar interferometric techniques will be developed and evaluated using field measurements and outputs from the SNOWPACK model. This comparison will be used to assess the consistency, accuracy, and robustness of the InSAR-derived estimates and, more broadly, to identify the potential and limitations of RCM imagery for snow monitoring and snow-related geohazard assessment.

2. STUDY AREA

The study focuses on two regions with contrasting climatic conditions: Rogers Pass in Glacier National Park, British Columbia, and Nunavik in northern Quebec.

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2.1 Roges Pass

The first study site is located at Rogers Pass, in Glacier National Park (GNP), British Columbia, Canada (Figure 1). GNP lies in the Selkirk Mountains, a mountain range extending across Canada and the United States.

The study area is characterized by complex mountainous terrain, with elevations ranging from 840 m above sea level in the valley bottom to 3,284 m at the highest peaks. It is situated in a climatic transition zone with a strong maritime influence (Haegeli and McClung, 2007). The area experiences an average of 155 days of snowfall per year and receives approximately 10 m of snow annually at treeline. This combination of complex terrain and substantial snowfall results in significant avalanche activity. Approximately 2,000 avalanches are recorded each year near the Trans-Canada Highway, of which an average of 20 affect the highway (Parks Canada, 2024).

Figure 1: Study area map of Glacier National Park (GNP), British Columbia.

2.2 Nunavik, QC

The second study area is located in Nunavik, the northernmost region of Quebec, Canada, covering more than 500,000 km² north of the 55th parallel. In 2021, the northern villages of Nunavik had a combined population of approximately 14,050 (Statistics Canada, 2023). This study focuses on four communities distributed along the coasts of Hudson Bay and Ungava Bay: Kangiqsualujjuaq, Kangiqsujuaq, Salluit, and Umiujaq (Figure 2).

Nunavik extends across both subarctic and Arctic climate zones and is characterized by severe winter conditions. Extreme weather events include winds exceeding 150 km/h and substantial snowfall over short periods (Filion *et al.,* 2025). These conditions are evolving under climate change, with increasing snowfall and rain-on-snow events in northern regions, including Nunavik, potentially creating conditions more conducive to avalanche release (Hachem and Bleau, 2020). At the same time, Nunavik communities are experiencing rapid population growth, exceeding 6.5% between 2016 and 2021, resulting in an increasing need for new infrastructure (Statistics Canada, 2023).

Figure 2: Study Site Locations in Nunavik, Qc.

3. DATA

The primary data consists of Single Look Complex (SLC) radar images acquired by the RADARSAT Constellation Mission (RCM). RCM consist in 3 satellites that operate in a sun-synchronous orbit at an altitude of approximately 600 km, allowing repeated observations of the same area at approximately the same local time. For Rogers Pass and Nunavik, the dataset covers the 2025–2026 winter seasons, with spatial resolutions of 5 m or 30 m. The temporal resolution ranges from 4 to 8 days depending on the study area (eoPortal, 2024).

A Digital Elevation Model (DEM) is also required for the co-registration and processing of radar images. In addition, outputs from SNOWPACK simulations conducted at the GRIMP laboratory for the study areas will be used to support the analysis and validation of the RCM-derived results.

Finally, snowpack characterization data are collected during field campaigns at the study sites. For this study, the main variables of interest are snow depth, snow density, and snow water equivalent (SWE). These measurements provide ground-based observations for comparison with the RCM-derived estimates and SNOWPACK simulations.

4. METHODOLOGY

The methodology is organized into three main steps: interferometric processing, phase calibration, and conversion to SWE, and validation and comparison. The approach is based on analyzing changes in the phase of the radar signal to retrieve apparent surface displacement, which, in this case, is related to changes in snowpack conditions.

As shown in figure 3, the first step combines SLC images with a Digital Elevation Model (DEM) to georeference and co-register the radar acquisitions. This step is essential because the workflow relies on sequential pairing, in which each radar acquisition is compared with the subsequent image. The images are first ingested and co-registered to generate a consistent stack. The stack is then processed to remove geometric contributions, including the flat-earth and topographic components, followed by orbital refinement to reduce residual errors (Zhou et al., 2025). Filtering and coherence estimation are then applied to identify and remove low-coherence interferograms. Pairs associated with wet-snow events or unsuitable temperature conditions are excluded based on external meteorological data. Finally, phase unwrapping is performed (PCI Geomatics Enterprises, 2025). This workflow produces an interferometric phase time series representing apparent surface changes associated with the evlution of the snowpack.

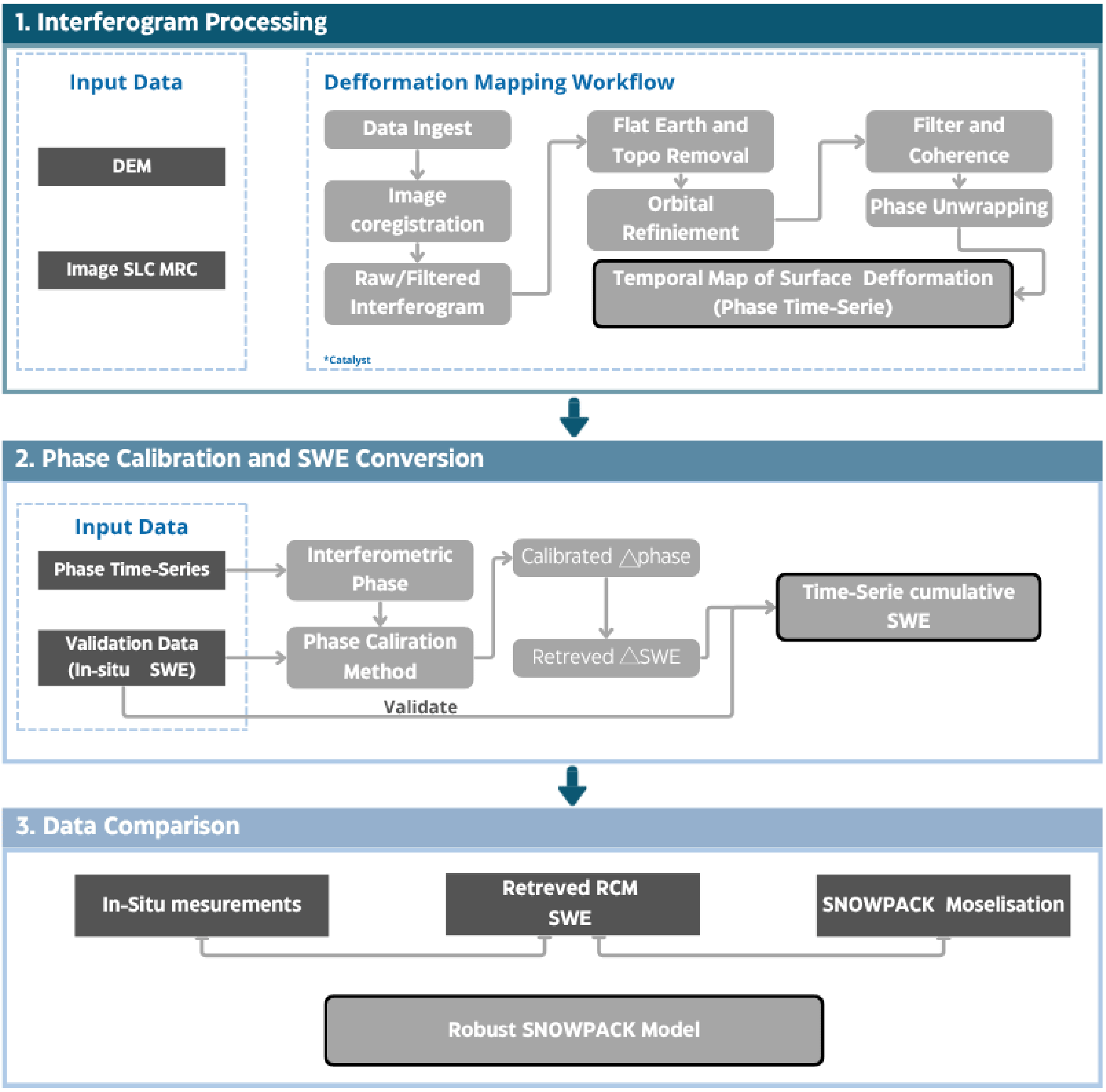

Figure 3 : Methodological scheme for RCM Data Processing

The resulting phase time series forms the basis of the second step, which focuses on phase calibration and conversion to snow water equivalent (SWE). The interferometric phase measurements are combined with in situ observations providing absolute SWE values, allowing the relationship between phase variations and snow accumulation to be calibrated (Zhou et al., 2025). The theoretical relationship between interferometric phase changes (Δφ) and changes in SWE (ΔSWE) is described by Leinss et al. (2015). By approximating the permittivity term as a function of snow density and applying a Taylor expansion under assumptions of low snow density and small incidence angles, the authors derive an approximately linear relationship between Δφ and ΔSWE, expressed as follows:

$$\Delta\emptyset = zk_i \cdot \frac{\propto}{2}(1.59 + \theta^{\frac{5}{2}}) \cdot \Delta SWE$$

where Δφ represents the interferometric phase change, ΔSWE the change in snow water equivalent, k_i the wavenumber defined as $k_i = 2\pi/\lambda$, where λ is the radar central wavelength, and θ the incidence angle at the air–snow interface. The parameter α, which is close to 1 for typical incidence angles below 50°, is used to optimize the approximation. Applying this calibrated relationship provides corrected phase values and SWE variations consistent with field observations. These variations are then integrated over time to produce a cumulative SWE time series representing the seasonal evolution of the snowpack. The RCM-derived SWE estimates are subsequently validated against in situ measurements to assess the accuracy and robustness of the retrieval approach.

The third step focuses on the comparison and validation of the RCM-derived snow estimates. The retrieved snow depth and SWE are compared with both in situ measurements and outputs from the physically based SNOWPACK model. This comparative analysis will be used to assess the agreement between the three sources of information and to evaluate the accuracy and robustness of the RCM-derived estimates. Ultimately, this step will help identify the potential and limitations of RCM InSAR for characterizing the spatial and temporal variability of snowpack conditions across the study areas.

5. EXPECTED RESULTS

The expected results include the production of time series of snow accumulation maps, spatial distribution maps of snow depth, and potentially, assessments of suitable areas for infrastructure development in selected Nunavik communities. Ultimately, these data could also be integrated into physically based models such as SNOWPACK as an additional reliable source of information for snowpack modeling. Finally, this work will help assess the performance, potential, and limitations of radar remote sensing for monitoring snowpack conditions in complex and remote environments.

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