ADVANCEMENTS IN SYNTHETIC APERTURE RADAR (SAR) TECHNIQUES FOR GLACIER VELOCITY MEASUREMENT

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(Received 26th Aug 2024; accepted 23rd Dec 2024)

Abstract. Monitoring glacier velocity constantly is vital because it provides information on how glacier flow dynamics respond to climate change. Glacier velocity also significantly influences the determination of glacier mass balance and ice thickness. Differential SAR Interferometry (DInSAR) uses SAR images to measure very small surface motions with good resolution over large swaths. This article reviews advancements in SAR techniques for glacier velocity estimation. Various DInSAR approaches, from the conventional to the advanced ones, have been discussed. The three-pass and four-pass DInSAR methods require more SAR images but reduce the Digital Elevation Model (DEM) induced error as compared to the two-pass method. Advanced DInSAR approaches such as Persistent Scatterer Interferometry (PSI), Small Baseline Subset (SBAS), Multiple Aperture Interferometry (MAI) allow to examine the temporal evolution of glacier deformations. Offset tracking methods with their capability of determining both the slant range and azimuth components of glacier motion have also been discussed. The DInSAR approach is more suitable for slow-moving glaciers while Offset tracking excels in fast-moving glaciers. Both methods complement each other and one can obtain the best result by integrating both techniques.
Keywords: *remote sensing, Differential SAR Interferometry (DInSAR), offset tracking methods, environmental protection, climate change, glacier monitoring*

Introduction

Evolutional study of glaciers, as an important component of the cryosphere, is quite significant, considering the fast-changing global climatic conditions. The monitoring of glaciers holds profound significance due to their role as sensitive indicators of environmental changes and their substantial impact on societal systems. Glaciers are critical in regulating Earth’s water budget, serving as vital freshwater reservoirs for millions of people downstream (Nepal and Shrestha, 2015). Their dynamics are intrinsically linked to pressing global concerns, such as sea level rise, which is largely driven by the accelerated melting of mountain glaciers (Zemp et al., 2019). Additionally, the interplay between glacier dynamics and climate change exacerbates glacial hazards, such as floods and landslides, threatening infrastructure and agricultural systems (Gardelle et al., 2011; Benn et al., 2012).

The cryospheric system regulates the water budget of the earth. The hydrology of rivers that emerge from glaciers can be significantly impacted due to enhanced melting and can lead to significant flood dangers (Nepal and Shrestha, 2015). Despite making up only 4% of the cryosphere, alpine glaciers are crucial for understanding global sea level rise, predicting future water availability (Bolch et al., 2012), and assessing glacial hazards (Quincey et al., 2009; Gardelle et al., 2011; Benn et al., 2012). More than 25% of the rise

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

in sea level worldwide is caused by the shrinkage of these delicate mountain glaciers (Zemp et al., 2019), highlighting their importance in shaping coastal vulnerability. Higher glacial temperatures have also been connected to surface melting, which has sped up the ice-movement process (Miles et al., 2018). Glacier velocity is a significant factor in determining ice dynamics, ice thickness, and mass balance. It also gives information on how glacier flow dynamics respond to climate change, making it crucial to closely monitor glacier velocity (Ke et al., 2013; Nela et al., 2018; Nela et al., 2022).

Real-time monitoring of glacier velocity, therefore, is essential for understanding glacier flow dynamics, assessing ice mass balance, and predicting future water availability (Nela et al., 2018; Nela et al., 2022). These insights are indispensable for crafting sustainable environmental policies and mitigating risks to human populations.

Real-time and extensive monitoring of glaciers, however, is difficult due to their location in remote and difficult environments. Satellite remote sensing technology has overcome these challenges by enabling rapid and thorough monitoring of glacier changes through its properties of fast data acquisition, wide imaging range, rich information, and short revisit cycles (Goldstein et al., 1989; Joughin et al., 1998; Strozzi et al., 2002; Usman and Furuya, 2018; Guo et al., 2020). Synthetic Aperture Radar (SAR) (Wang et al., 2019; Guo et al., 2020), optical sensors (Copland et al., 2009), and unmanned aerial vehicles (Immerzeel et al., 2014) are only a few of the sophisticated remote sensing technologies that have become more and more common in glacier monitoring. Poor temporal resolution, cloud cover, and weather affect optical remote sensing observations. These constraints are overcome by microwave remote sensors. In the electromagnetic spectrum, microwave radiation has a frequency range of 300 to 0.3 GHz, or 1mm to 1m. The comparatively small particle size of clouds, fog, aerosol, and other gaseous molecules in comparison to the microwave wavelength causes less interference with the emitted microwave radiation. As a result, the atmosphere is almost transparent in microwave portions of the electromagnetic spectrum, and less energy is scattered as a result of scattering interactions. Due to these benefits, microwave sensors are the best options for detecting the signal from objects on Earth's surface in all-weather circumstances (Tanniru and Ramsankaran, 2023).

Both passive (radiometer) and active (radar) microwave technologies are available. Passive microwave remote sensing collects thermal (non-coherent) radiation emitted by the surface. So, they provide information on temperature, surface layer characteristics, and the presence of liquid water. The spatial resolution of these satellites is typically 20 to 30 km. Their applicability in glacier remote sensing is constrained by this factor (Pellikka and Rees, 2009). Synthetic Aperture Radar (SAR) has been designed to obtain high spatial resolution. Using an advanced signal-processing method, a large synthetic aperture (synthetic antenna length) is produced, enabling a fine resolution. NASA's SEASAT satellite, launched in 1978, was the first spaceborne SAR system. After that, a number of SAR sensors, including Sentinel-1A/B, Radarsat, Envisat, ESA ERS-1/2, Radarsat-1/2, ALOS PALSAR-1/2, TerraSAR, and Cosmo-SkyMed, have been extensively used to estimate the surface motion (velocity) of ice sheets and glaciers (Goldstein et al., 1989; Joughin et al., 1996a; Strozzi et al., 2002; Kumar et al., 2008). Interferometric SAR (InSAR) has been developed over the past few years into a potent technique for numerous glacier applications (Pellikka and Rees, 2009).

Among the various methods for glacier monitoring, Synthetic Aperture Radar (SAR) techniques offer distinct advantages. Unlike optical remote sensing, SAR can penetrate cloud cover and operate in all weather conditions, ensuring reliable data collection even

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

in challenging environments (Pellikka and Rees, 2009; Tanniru and Ramsankaran, 2023). Its high spatial resolution and ability to detect minute surface movements across vast areas make it a superior tool for glacier velocity measurement (Joughin et al., 1998; Pellikka and Rees, 2009). Furthermore, SAR techniques, such as Differential SAR Interferometry (DInSAR) and Offset Tracking, enable precise estimation of both slow and fast-moving glaciers (Goldstein et al., 1989; Strozzi et al., 2002; Nela et al., 2022). These advantages set the stage for an in-depth exploration of the advancements in SAR methodologies for glacier monitoring, as detailed in the following sections.

This article presents a comprehensive review of the advancements in different SAR techniques for glacier velocity estimation. To begin with, Section 2 summarises the theoretical foundations for using DInSAR for surface displacement measurement. Section 3 highlights the different types of DInSAR techniques, starting from conventional to advanced ones that have been employed for velocity measurement. Section 4 discusses the Offset tracking method and its different types. Section 5 presents a discussion highlighting the advantages and disadvantages of the different approaches. Finally, the review involves an overall summary and conclusions presented in Section 6.

Background of Differential Synthetic Aperture Radar Interferometry (DInSAR) Technique

Although the SAR interferometry theory has already been briefly discussed in a number of works, in this part, we summarize the key findings. Radar backscatter intensity and phase data are stored for each pixel on a SAR image. Intensity refers to the magnitude of the radar backscatter signal received from the target surface. It reflects the roughness and dielectric properties of the surface and is utilized in SAR intensity tracking methods for identifying offsets between images, even in areas of low coherence (Michel and Rignot, 1999; Strozzi et al., 2002). Coherence measures the degree of similarity between two SAR signals acquired from the same area at different times or viewing geometries. It indicates the quality of the interferometric data and is crucial for extracting meaningful displacement information, with values ranging from 0 (completely decorrelated) to 1 (perfectly correlated) (Derauw, 1999; Pellikka and Rees, 2009). The phases on a SAR image are affected by the radar wavelength and the distance of the radar round-trip between the SAR and various ground points. InSAR essentially produces an image of the phase difference (or interferometric phase) between the two coregistered SAR images by carefully aligning two SAR images pixel by pixel (Li et al., 2008).

Single-pass along-track interferometry, single-pass across-track interferometry, and repeat-pass interferometry are the three different InSAR principles. With two spatially distant antennas, the single-pass concepts illuminate the surface concurrently in time. They are primarily used to study ocean surface currents and digital elevation mapping (Pellikka and Rees, 2009). The repeat-pass technique involves interferometric phase comparison of SAR images gathered at different times and with different baselines and is therefore useful for studying phenomena related to surface changes. In glaciology, it is used to calculate glacier mass balance, predict glacier velocity, and monitor changes in glacial facies (Monti-Guarnieri et al., 1993).

Let us consider the repeat pass InSAR configuration as shown in *Figure 1*. In SAR interferometry, the baseline refers to the spatial separation between two satellite positions during acquisitions. This parameter, which can be horizontal (perpendicular baseline) or vertical (parallel baseline), directly influences the interferometric phase and the ability to

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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resolve elevation and deformation changes in the target area (Kwok and Fahnestock, 1996; Pellikka and Rees, 2009).

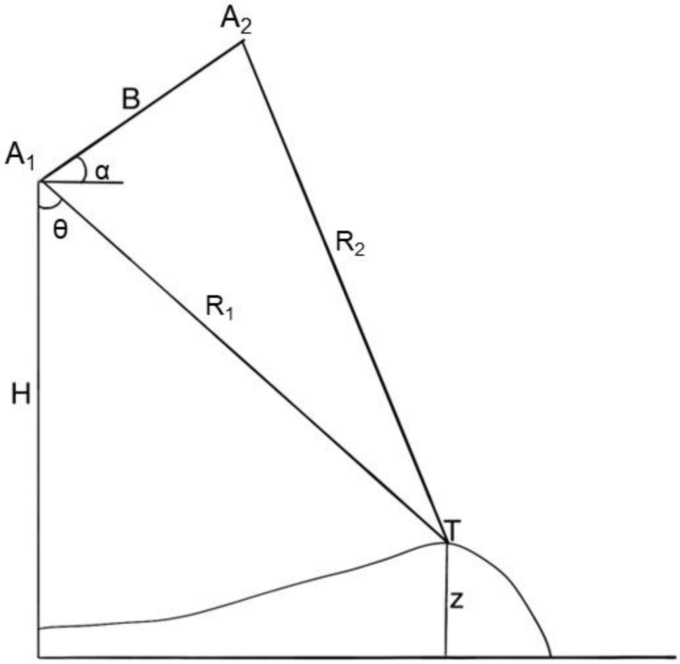

Figure 1. *Repeat-pass InSAR configuration*

Each radar antenna (A1 and A2) independently measures the time delay for the microwave pulse to reach the target (T) on the ground and return an echo to the antenna. A coherent radar is one in which the phase of each received echo is proportional to the time delay. Each SAR image received by the two radar antennas are complex signal represented as

$$u_1 = |u_1|e^{j\emptyset_1} \quad \text{(Eq.1)}$$

$$u_2 = |u_2|e^{j\emptyset_2} \quad \text{(Eq.2)}$$

where $|u_1|$, $|u_2|$ are the amplitudes and $\emptyset_1$, $\emptyset_2$ are the phases of the SAR signal.

$$\emptyset_1 = -\frac{4\pi}{\lambda}R_1 + \psi_1 \quad \text{(Eq.3)}$$

$$\phi_2 = -\frac{4\pi}{\lambda}R_2 + \psi_2 \quad \text{(Eq.4)}$$

where λ is the SAR wavelength, R_1 and R_2 are the slant range distances, and ψ_1 and ψ_2 are the scattering mechanism contributions to the observed phases. An interferogram is obtained by complex conjugate multiplication of the two coregistered SAR images (Pellikka and Rees, 2009) as given by *Equation 5*.

$$u_1u_2^* = |u_1||u_2|\exp[j(\emptyset_1 - \phi_2)] = |u_1||u_2|\exp(j\delta\phi) \quad \text{(Eq.5)}$$

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Usually, the scattering mechanism contributions is assumed to be the same between the acquisitions (Pellikka and Rees, 2009; Liu et al., 2016). Consequently, the path length difference alone determines the phase difference

$$\delta\phi = -\frac{4\pi}{\lambda}(R_1 - R_2) = -\frac{4\pi}{\lambda}\Delta R \qquad \text{(Eq.6)}$$

For displacement measurement of the ground target between the two acquisitions, the contribution in the interferometric phase due to displacement in the line of sight (LOS) direction can be written as

$$\phi_d \approx \frac{4\pi}{\lambda}\Delta R_d \qquad \text{(Eq.7)}$$

More elaborately, the InSAR phase is given by the total contributions due to flat Earth phase, topographic phase, displacement phase and noise (Liu et al. 2016).

$$\delta\phi_{total} = \phi_{flat\ earth} + \phi_{topo} + \phi_d + \phi_{noise} \qquad \text{(Eq.8)}$$

Here, the displacement phase ϕ_d is the signal part that DInSAR attempts to retrieve (Bombrun et al., 2009). The slant range R_1 for spaceborne interferometers is significantly greater than the baseline B. Because of this, the phase is more susceptible to displacement changes than to topographic changes (Pellikka and Rees, 2009). Moreover, the noise can be considered random (Liu et al., 2016) and after removing the flat earth phase, the *Equation 6* can be simplified as

$$\phi_{int} = \phi_{topo} + \phi_d \qquad \text{(Eq.9)}$$

This is the fundamental relationship for calculating the target displacement with the DInSAR method where the variable ΔR_d is to be obtained.

The traditional DInSAR approach was first developed by Gabriel et al. (1989). DInSAR uses SAR images to measure very small surface motions with good resolution over large swath. Goldstein et al. (1989) made the first demonstration of the potential use of DInSAR for measuring glacier velocity on the Rutford Ice Stream, Antarctica. This study underscored its potential for mapping velocity fields in Polar Regions.

With further advancement of the SAR sensor, glacier velocities in the Polar regions such as Greenland, Alaska, Antarctica as well as the mountain glaciers in mid-latitudes have been widely obtained using this technique (Kwok, et al., 1996; Mohr et al., 1998; Joughin et al., 2004; Cheng et al., 2007; Joughin et al., 2008; Li et al., 2008; Copland et al., 2009; Nela et al., 2018; Sharma et al., 2023).

Different Types of DInSAR Technique

Equation 7 has highlighted that we have to isolate the displacement-related phase from the topographic phase term to obtain the displacement of the target. This differential interferometric processing can be achieved using various techniques which are discussed below.

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Two-pass DInSAR

The two-pass DInSAR technique is the simplest one among the DInSAR approaches and requires two SAR images of the same area acquired at different times. Additionally, an external Digital Elevation Model (DEM) is needed to remove the topographic phase from the interferogram. The steps involved are:

1. Coregistration: Aligning the two SAR images so that each pixel corresponds to the same ground location.
2. Interferogram Generation: An interferogram is computed as the phase difference between the two coregistered images, which contains contributions from surface displacement, topography, and noise.
3. Topographic Phase Removal: An appropriate DEM is used to simulate and subtract the topographic phase from the intereferogram, isolating the displacement-related phase (Cheng et al., 2007; Zhou et al., 2009; Zhou et al., 2011; Kumar et al., 2011; Wang et al., 2013; Bhattacharya and Mukherjee, 2017).
4. Phase Unwrapping: Generally, the interferometric phase is wrapped i.e., it is measured on the confined interval $[-\pi, \pi]$. So an operation known as phase unwrapping must be performed on the measured phase so as to relate it to any geophysical phenomena. Thus, phase unwrapping or the process of adding the correct multiple of 2π to each pixel of the interferogram is necessary and the wrapped phase is converted into a continuous displacement map.
5. Velocity Estimation: The glacier velocity map is obtained by dividing the displacement by the time span between the two image acquisitions.

The above steps are presented in *Figure 2*. The phase unwrapping step is still one of the most challenging aspects of InSAR (Pellikka and Rees, 2009; Zhang et al., 2020). Many different phase unwrapping algorithms exist. Some well-known ones as discussed by Bamler and Hartl (1998); Chen and Zebker (2001); and Hanssen (2001) may be mentioned (Pellikka and Rees, 2009). Also, the two-pass method is limited by the accuracy of the external DEM and is sensitive to DEM-induced errors (Cheng et al., 2007; Pellikka and Rees, 2009).

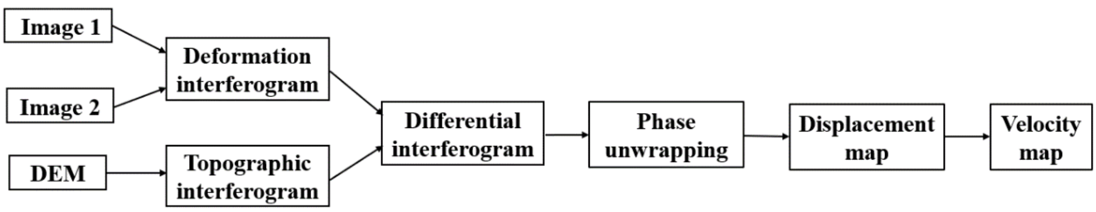

Figure 2. *Flowchart for Two-pass DInSAR method*

Cheng et al. (2007); Zhou et al. (2011); Goldstein et al. (1989); Li et al. (2008); and Zhang et al. (2020) have used this technique to measure glacier motion. Nela et al. (2018) applied two-pass DInSAR to study the movement of Chhota Shigri glacier in Himachal Pradesh, using ALOS-2 L-band data. This approach highlighted its effectiveness in slow-moving glaciers.

The main benefits of this method are its simplicity to implement, as well as suitable for slow-moving glaciers and areas with available DEMs. The limitations are it uses an external DEM to remove the topographic phase from the interferogram.

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So, it relies heavily on the accuracy of external DEMs (Cheng et al. (2007)) and is prone to DEM-induced errors (Pellikka and Rees, 2009), especially in regions with complex topography or poor DEM quality.

Three-pass DInSAR

The three-pass DInSAR method uses three SAR images to reduce the dependency on an external DEM. The steps involved are:

1. Interferogram Formation: Two interferograms are generated from the three images, with one common master image (Cheng et al., 2007; Bhattacharya and Mukherjee, 2017).
2. Differential Interferogram: Subtract the phase of one interferogram from the other to eliminate topographic contributions, assuming that surface displacement between the first and third acquisitions is comparable (Winebrenner et al., 1996; Wegmüller et al., 1998).
3. Phase unwrapping: The displacement-related phase is isolated and unwrapped to produce a displacement map.

The above steps are presented in *Figure 3*. Image 2 is the common master image, subscripted as 2 in equations 10 and 11. The viability of three-pass DInSAR was first examined by Joughin et al. (1996a); Kwok and Fahnestock (1996); and Wegmüller et al. (1998). The phase from two different interferograms produced from the three SAR acquisitions is given as (Kwok and Fahnestock, 1996),

$$\emptyset_{int\ 12} = \frac{4\pi}{\lambda} B_{12} \sin(\theta - \alpha_{12}) + \frac{4\pi}{\lambda} \Delta R_{d12} \quad \text{(Eq.10)}$$

$$\emptyset_{int\ 23} = \frac{4\pi}{\lambda} B_{23}\, sin(\theta - \alpha_{23}) + \frac{4\pi}{\lambda} \Delta R_{d23} \quad \text{(Eq.11)}$$

Three-pass DINSAR was employed by Cheng et al. (2007) to estimate the ice flow of Grove Mountain in East Antarctica. The method is also described comprehensively by Wang et al. (2013). This method was utilized by Nela et al. (2022) to map the LOS velocity of the glaciers in Svalbard. They compared the outcomes of the three-pass DInSAR method with the 2-pass method using Sentinel-1A/1B data. According to their study, it is possible to estimate glacier velocities reliably with an average atmospheric uncertainty of 0.24 cm/day over the study region using three-pass method. The study emphasizes the value of considering DEM-induced errors into account and recommends using the three-pass DInSAR method as a viable substitute for operational glacier velocity estimation.

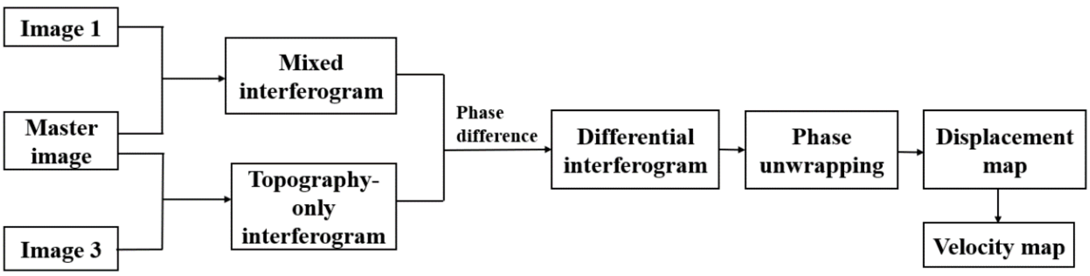

Figure 3. *Flowchart for Three-pass DInSAR method*

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The advantage of this method is that an external DEM is not necessary to construct the topography-only interferogram as the phase difference from one of the interferograms is directly related to the topography of the terrain features (Bhattacharya and Mukherjee, 2017).

The main benefits are it reduces dependence on external DEMs; better suited for regions without accurate DEMs or moderate glacier movement (Kwok and Fahnestock, 1996; Nela et al., 2022). The limitations are it assumes consistent displacement between acquisitions; sensitive to atmospheric and temporal decorrelation, which can degrade results in fast-changing environments (Cheng et al., 2007; Pellikka and Rees, 2009).

Four-pass DInSAR

The four-pass DInSAR method requires four SAR images and explicitly separates topographic and displacement contributions by forming two independent interferometric pairs. The steps involved are:

1. Topo Pair: Two SAR images acquired with longer perpendicular baseline are selected to create an interferogram dominated by topographic information. The topo pair synthesizes the DEM of the region.
2. Defo Pair: Another pair of images acquired with shorter perpendicular baseline are selected to generate an interferogram containing both topographic and displacement information.
3. Topographic Phase Removal: The DEM-derived phase is subtracted from the defo pair to isolate displacement-related information.
4. Phase unwrapping and velocity estimation: The phase is unwrapped and the displacement and velocity maps are calculated.

Figure 4 represents the processing steps required in four-pass DInSAR. The differential processing of the topo and defo pairs or the removal of the topographic phase from the total phase then produces the displacement map of the study area (Hanssen, 2001; Cheng et al., 2007).

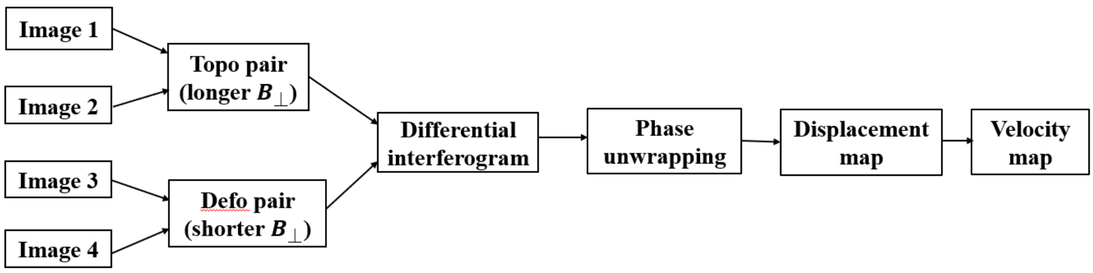

Figure 4. *Flowchart for Four-pass DInSAR method*

Using a small spatial baseline DInSAR pair is the easiest method to mitigate the effects of DEM inaccuracies for repeat pass interferometry (Joughin et al., 1996; Mohr et al., 1998; Shugar et al., 2010). But, small spatial baselines suitable for interferometric processing do not always exist (Liu et al., 2016). A baseline-combination method to minimize DEM-induced errors in ice-motion estimates was proposed by Zhou et al. (2013). However, the majority of mountain glacier areas do not frequently have access to high-accuracy DEMs. Additionally, coregistering the DEM and SAR images is a crucial yet difficult task (Cheng et al., 2007; Liu et al., 2016).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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The intricate ice flow of Grove Mountain, which is located on the eastern slope of the Lambert Glacier-Amery Ice Shelf System (LAS), was obtained by Cheng et al. (2007) using four-pass DInSAR processing. The absolute DEM for the region was created using a tandem ERS-1/2 image pair. A JERS-1 INSAR pair with 44-days temporal baseline was used to create an interferogram containing both the topographic and ice-flow information. The JERS-1 interferogram's topographic phase was then eliminated using the DEM generated earlier from tandem ERS pair. Finally, a differential interferogram that only included the ice displacement data was created.

The main benefits of this method are it explicitly separates topographic and displacement components; effective for regions with significant topographic complexity or variable glacier speeds. Its limitations include requirement of more data and is computationally intensive; careful coregistration of multiple datasets. Modified versions of this method address the challenge of glacier movement during the acquisition of topo pairs (Liu et al., 2016).

Modified Four-pass DInSAR

This technique to determine glacier velocity without utilizing a DEM was suggested by Liu et al. (2016). In order to create topographic DInSAR pairs, the traditional three- or four-pass approaches make the assumption that there is no glacier movement between the dates of image acquisition. According to this method, the displacement term should also be considered in the topo-pair because glaciers are constantly moving. Contrary to the traditional two- or four-pass techniques, modified four-pass DInSAR also decreases the coregistration error between the SAR image and external DEM. Consequently, the usual challenge for DInSAR applications in mountainous terrain is diminished.

Advanced DInSAR Techniques

Persistent Scatterer Interferometry (PSI)

Ferretti et al. (2001) developed the PSI technique. This method identifies and exploits permanent or persistent scatterers (PSs), which are stable natural reflectors exhibiting good coherence over long time intervals. These PSs can be used for accurate elevation and velocity measurements. The authors conducted experiments in Ancona, Italy, using 34 ERS SAR images with long temporal and geometrical baselines. They successfully identified PSs and estimated DEM errors, LOS velocities, and linear atmospheric phase screen contributions.

With respect to a single master image, a number of single-look differential interferograms are produced in this technique (Bhattacharya and Mukherjee, 2017). The master image is selected in a way that reduces the expected decorrelation of the produced interferograms. In natural terrain like the Himalayas, which is also home to many mountain glaciers, it is still exceedingly difficult to recognize PS. It takes a lot of data - more than 30 images - to effectively utilize the PSI technique. Moreover, it can be challenging to assess the effectiveness of PSs approach without knowing the deformation in advance (Bhattacharya and Mukherjee, 2017). On the other hand, the invention of this technique was a big step forward toward a high-accuracy observation of slow-moving surfaces over long time spans, as it enables the identification, isolation, and estimation of millimeter surface deformation processes from space (Zhou et al., 2009).

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Small Baseline Subset (SBAS) DInSAR

SBAS DInSAR was first proposed by Berardino et al. (2002). In this technique, differential interferograms from multiple SAR data pairs having small values of spatial (perpendicular) and temporal baselines are combined. Du et al. (2020) used this technique to study the average rate of glacier deformation on Karlik Mountain, China. In their study, the spatial baseline threshold was set as 2% of the maximum spatial baseline value in units of metre, and temporal baseline threshold as 50% of the maximum temporal baseline value in days. This technique effectively reduced noise and decorrelation while capturing glacier dynamics.

Moreover, SBAS DInSAR can obtain continuous, large-scale, and high-precision deformation information, which plays an important role in the evaluation of changes in glacier morphology (Wang et al., 2009). This technique utilized many master–slave pairs with small perpendicular baselines and short-time intervals, while the PS only applied a single master to generate the result (Bahti et al., 2023).

Time-series deformation analysis using SBAS provided insights into seasonal glacier movements and helped in evaluating climate change impacts on glaciers in the Eastern Tien Shan, China (Wang et al., 2009).

Multi-Aperture Interferometry (MAI)

InSAR measurements are sensitive to two-dimensional motion along the line of sight (LOS) of the satellite sensors, and do not capture the north/south (along-track) velocity component, which is essential for a complete 3-D estimation of glacier deformation (Kumar et al., 2023). Bechor and Zebker (2006) presented a new method for measuring along-track displacements using InSAR. MAI approach exploits the interferometric phase to estimate the surface displacement along the azimuth direction (Yan et al., 2016). Bechor and Zebker’s method was based on split-beam InSAR processing, which creates forward- and backward-looking interferograms. The phase difference between these inteferograms provides the along-track displacement component. The proposed method also provides a more efficient and accurate measurement of the along-track deformation component compared to pixel amplitude correlation. It offers improved precision with significantly reduced computation time.

Kumar et al. (2023) combined across-track observations from ascending and descending passes with the along-track movement derived from Multi-Aperture InSAR (MAI). This new approach called Ascending, Descending InSAR and Multi-Aperture InSAR (ADIMAI) was used to estimate the full three-dimensional (3-D) velocity of the Siachen glacier. The study found that the use of MAI improved the velocity estimation compared to the conventional approach. The research paper highlights the potential of the ADIMAI technique for precise glacier surface velocity estimation, particularly in the Himalayas.

SAR Offset Tracking Technique

In Offset tracking two SAR images are precisely coregistered to obtain the interferogram. Finding the cross-correlation peak (CCP) allows one to calculate an offset.

Generally, cross-correlation is used as a similarity measure in signal processing. It can be calculated in the spatial domain or frequency domain. The values of the normalized cross-correlation (NCC) range between -1 to +1 and the maximum height of the CCP is called the NCC coefficient. This maximum CCP's location provides a rough estimation

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of the offset between the two image templates. Higher confidence in the offset measurement is characterized by higher CCP and higher signal-to-noise ratio (SNR) (Leinss et al., 2022).

SAR Intensity Tracking

This technique is based on cross-correlation optimization between SAR intensity image patches (Gray et al., 1998; Rott et al., 1998; Michel and Rignot, 1999). It is also called incoherent intensity tracking as it tracks image features containing uncorrelated speckles (Leinss et al., 2022). Speckle is a granular noise pattern inherent in SAR images, resulting from the coherent summation of radar signal reflections from multiple scatterers within a single resolution cell. While it reduces image interpretability, speckle patterns can also be tracked to measure glacier motion when features are preserved (Gray et al., 1998; Leinss et al., 2022). To adequately average out the incoherent speckle noise in the cross-correlation, more larger templates are required for intensity tracking. Typical template size ranges from 64×64 and 256×256 pixels (Strozzi et al., 2002; Li et al., 2008). Using a DEM, the topography-induced offsets that only occur in the range direction can be eliminated (Kumar et al., 2011).

The main benefit of intensity monitoring is that it may be applied even when there is no coherence. When dealing with extremely large and incoherent displacements brought on by swiftly moving ice or by lengthy acquisition times between the two SAR images, it complements other approaches (Strozzi et al., 2002; Fan et al., 2019). Large surging glaciers can be studied using intensity tracking (Strozzi et al., 2002). Success of offset tracking approaches depend on whether the features in the study area are preserved for a long duration. Himalayan debris covered glaciers preserve features due to cold environment and allow the intensity tracking to be used for movement estimation. Extremely large image patch sizes, reduced spatial resolution, and limited accuracy in comparison to InSAR are some of the drawbacks of intensity tracking.

Kumar et al. (2011) applied SAR intensity tracking approach for surface motion estimation of Gangotri and Chaturangi glaciers in Uttarakhand. They used TerraSAR-X data. Sharma et al. (2023) also used this approach to estimate the glacier velocity of 15 transboundary glaciers in Eastern Himalaya. Zhou et al. (2011) also used intensity tracking to study the ice flow velocity of calving glaciers of the Polar Record glacier, East Antarctica, and concluded that this method is effective for fast-flowing glaciers.

SAR Coherence Tracking

This approach to offset estimation, also known as the fringe visibility algorithm or coherence optimisation procedure, was put forth by Derauw (1999). This technique yields satisfactory result when the phase and speckle pattern of the SAR image pair are correlated. It can complement DInSAR to obtain displacement in the azimuth direction. Relatively, small size correlation windows e.g. 8×8 SLC pixels are sufficient (Strozzi et al., 2002). A demerit of this method is that phase gradients within the template can decrease the CCP (Joughin, 2002).

Coherence tracking is suitable in cases where there are disconnected areas of high coherence and for very large displacements. Also, coherence over the glacier surface is affected by meteorological and flow conditions and generally reduces with increasing temporal baseline between the SAR image pairs (Strozzi et al., 2002). However, the accuracy and resolution of coherence tracking are poorer than those of DInSAR. The computational efficiency is also a limiting factor. Strozzi et al. (2002) discussed both intensity tracking and

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DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

coherence tracking techniques to study the surge of Monacobreen, a tidewater glacier in Northern Svalbard between 1992 and 1996. Additionally, Zhou et al. (2011) studied the calving of the East Antarctic Polar Record glacier using coherence tracking.

SAR Speckle Tracking

In this method, the radar amplitude or intensity is used to obtain the NCC coefficient. Gray et al. (1998) demonstrated that radar speckle can be tracked in slant-range and azimuth direction by using cross-correlation, and derived glacier velocity maps. When the speckle patterns are at least partially retained between two images, speckle tracking is successful (Leinss et al., 2022). Correlated high-frequency noise can be inferred from the extremely sharp and narrow peak that appears in the cross-correlation function of correlated speckle patterns. A slightly sharper peak can be obtained as compared to coherence tracking (Leinss et al., 2022). Corti et al. (2023) used high-resolution SAR speckle tracking to assess spatially discontinuous glacier motion and its impact on the glacier dynamics of Thompson Glacier in Arctic Canada. The findings demonstrate that spatial smoothing, a method frequently used to reduce errors, hides the discontinuities in the results of the speckle tracking. A SAR simulator is used to examine the best intensity rescaling as a pre-conditioning step to enhance speckle tracking performance.

Tracing SAR speckle from image to image has been shown by multiple authors to be an effective method of measuring velocity in fast-moving areas, even in the absence of visible features. However, a demerit of this approach is that the velocity estimates have lower resolution and poorer accuracy than direct phase measurements. On the other hand, it works effectively in situations where there are no data suitable for conventional interferometry (Joughin, 2002).

Integrated Method

Joughin (2002) demonstrated the combined use of interferometric and speckle-tracking data to construct algorithms for estimating velocity for Lambert, Mellor, Fisher, and other glaciers feeding the Amery Ice Shelf, using the RADARSAT data. They explain the application of speckle tracking as an alternative that can measure velocity in regions of high velocity when traditional interferometry is ineffective. When compared to actual phase measurements, they do admit that the estimates derived from this method are less accurate and have lower resolution.

Yan et al. (2016) proposed an integrated approach combining DInSAR, MAI, and pixel tracking (PT) and obtained the ice motion patterns of Chongce glacier, West Kunlun Mountains, China. DInSAR was applied to process the ALOS PALSAR images. To eliminate the topographic phase influence, SRTM DEM data was employed. Using the interferometric phase, the MAI technique estimates the displacement of the surface along the azimuth direction. The motion pattern of the glacier was derived in 2-D coordinates when paired with the DInSAR method. For determining ice motion using SAR intensity data, PT is considered to be the best substitute. The PT method, in contrast to SAR interferometric methods, may overcome low coherence brought on by a broad spatial or temporal baseline. It can also simultaneously show the displacement in both the along-track and across-track directions. It has been demonstrated that the PT approach can measure ice motion across the whole glacier surface, particularly in areas where there have been significant movements between SAR acquisitions. Therefore, it might be the best method to identify rapid ice migration in mountainous areas. The integrated method

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DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

is beneficial in locations with both low and high ice velocities. *Figure 5* presents the different SAR techniques used for glacier velocity measurement.

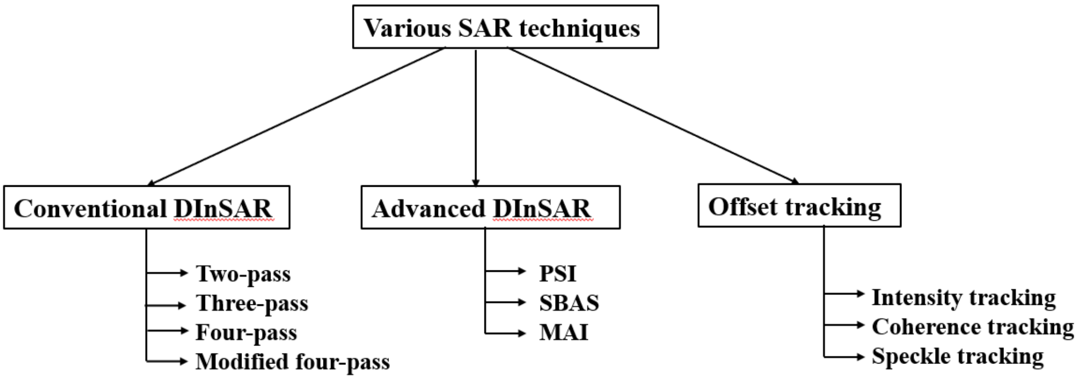

Figure 5. *Various SAR techniques used for glacier velocity measurement*

Results

DInSAR requires that the difference in the two-way slant range distances between consecutive pixels be less than half of the radar wavelength in order to view interferometric fringes unambiguously (Catani et al., 2005). Using SAR interferometry to generate velocity maps is a computationally demanding process. To generate SAR images for vast regions, hundreds of gigabytes of data must be processed. These images are then combined to create interferograms, which are then filtered for noise removal to make the final velocity product (Joughin, 2002). Although the offset tracking technique (Strozzi et al., 2002) employs amplitude/intensity to identify the pixel change in range and azimuth, its precision is low (i.e., in the order of one-tenth of the pixel spacing) (Nela et al., 2019). DInSAR techniques provide displacement or ice velocity maps with high spatial resolution and precise accuracy (mm-cm level) (Zebker and Goldstein, 1986; Gabriel et al., 1989; Joughin et al., 2010; Zhou et al., 2011; Rignot et al., 2011). The 2-pass DInSAR method is well known for accurately estimating glacier movement (Mohajerani et al., 2021), however it needs an external DEM to eliminate the topographic phase information. Longer lags between DInSAR acquisitions and availability of suitable DEM/topographic data may lead to greater velocity estimation uncertainty (Nela and Singh, 2020). The three-pass DInSAR requires three SAR images and the four-pass requires four datasets. Both methods reduce DEM-induced error as compared to the two-pass method (Singh et al., 2011), although the four-pass method may produce more atmospheric-induced error than the three-pass DinSAR method (Nela et al., 2022).

Additionally, DInSAR has been widely utilized to identify single deformation events. These applications could be considered successful because of the short temporal baseline between the two acquisitions that were employed to reduce decorrelation. But many applications need estimating slow rates of deformation. Processing data sets with a significant time lag between acquisitions might be necessary for this. The observed interferometric phase, however, becomes more ambiguous as the temporal gap between the two SAR images widens due to a decline in their correlation. Advanced DInSAR approaches allow to examine the temporal evolution of deformations (Bhattacharya and Mukherjee, 2017). The temporal evolution of the target deformation can be derived from several SAR images using InSAR time series methods, such as SBAS, PSI, and MAI, and the decorrelation effects can be minimized by merging multiple SAR observations.

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DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

The data requirements and challenges encountered in mountainous glacial environments for each SAR technique are as follows.

DInSAR

SAR data with high (1–30 meters) spatial resolution is needed to resolve glacier dynamics at a detailed scale. SAR images acquired with short temporal baselines (days to weeks) is required to minimize decorrelation. Minimum of two SAR images for the two-pass method; three for three-pass and four images for four-pass DInSAR methods are required for the study area.

Some challenges of DInSAR method are that temporal and geometric decorrelation limits effectiveness, especially in fast-moving glaciers. It also requires accurate external DEMs to remove topographic phase as errors in DEMs can propagate into results, particularly in rugged terrains. Limited SAR coverage or infrequent revisits can hinder applicability in remote glaciers.

PSI

High spatial resolution SAR data is required. The method needs a consistent time series of SAR images over a long period viz. months to years. And, at least 30 SAR images are needed for reliable results. Some of the challenges of PSI method are that it demands a large number of images, which may not be available for remote or less-monitored regions. Effectiveness decreases in areas with sparse stable scatterers, such as debris-covered or highly dynamic glacier surfaces. Thus, it is highly environment sensitive.

SBAS

Moderate to high spatial resolution SAR data is needed. It needs multiple SAR acquisitions with small temporal and spatial baselines to reduce decorrelation effects. Typically, 10–20 SAR images are required, though more can improve accuracy. This method is limited by SAR availability in regions with low revisit frequency.

MAI

High spatial resolution data is needed as it resolves along-track motion in addition to LOS displacement. Moreover, SAR images from ascending and descending passes is required for complete 3D motion analysis. Minimum of two images per pass is needed.

Some challenges include the need for data from diverse viewing angles, which may not always align with the glacier orientation. Processing for combining datasets is very computationally intensive.

Offset Tracking Methods

SAR data of moderate (30–100 meters) spatial resolution is required and is suitable for wide-area glacier motion analysis. It is effective with longer temporal baselines (months to years), accommodating large displacements. Minimum of two SAR images are essential though results improve with additional pairs.

Some challenges of this method include lower resolution compared to interferometric methods, with higher sensitivity to noise. Also, it works well with fast-moving glaciers but is not suited to small-scale deformations.

A brief summary of all the SAR techniques is presented in *Table 1*.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

Table 1. *SAR based techniques for glacier velocity calculation*

Processing technique	Satellite data	SAR band used	Study area	References
Two-pass DInSAR	ALOS-2	L	Chhota Shigri glacier, India	(Nela et al., 2018)
	ERS-1/2, Envisat	C	Polar Record glacier, Antarctica	(Zhou et al., 2011)
	ERS-1/2	C	Nabesna Glacier, Alaska	(Li et al., 2008)
	ERS-1	C	Rutford Ice Stream, Antarctica	(Goldstein et al., 1989)
	Sentinel-1A/1B	C	Eidembreen and Kongsbreen glaciers, Svalbard archipelago	(Nela et al., 2022)
Three-pass DInSAR	JERS-1, ERS-1/2	L, C	Grove Mountain, Antarctica	(Cheng et al., 2007)
	Sentinel-1A/1B	C	Eidembreen and Kongsbreen glaciers, Svalbard archipelago	(Nela et al., 2022)
Four-pass DInSAR	JERS-1, ERS-1/2	L, C	Grove Mountain, Antarctica	(Cheng et al., 2007)
Modified four-pass SBAS InSAR	ALOS	L	Dongkemadi glacier, China	(Liu et al., 2016)
	Sentinel-1A	C	Glaciers of Karlik Mountain, China	(Du et al., 2020)
MAI	ERS-1/2	C	Siachen Glacier, India	(Kumar et al., 2023)
Intensity tracking	COSMO-Skymed	X	Yiga Glacier, Tibet, China	(Wang et al., 2019)
	ERS	C	Monacobreen Glacier, Northern Svalbard	(Strozzi et al., 2002)
Coherence tracking	ERS	C	Monacobreen Glacier, Northern Svalbard	(Strozzi et al., 2002)
Speckle tracking	RADARSAT-2	C	Thompson Glacier, Arctic Canada	(Corti et al., 2023)
Integrated approach	RADARSAT	C	Lambert, Mellor, Fisher glaciers, Antarctica	(Joughin, 2002)
	ALOS PALSAR	L	Chongce Glacier, China	(Yan et al., 2016)

Discussion

Glaciers constitute an important cryospheric component regulating the water budget of the earth. Understanding global sea level rise, glacial lake outburst floods, predicting future water availability are a few of the many applications of studying glacial systems. Glacier velocity is a significant factor in determining ice dynamics, ice thickness, mass balance, glacier recession rate. It also gives information on how glacier flow dynamics respond to climate change, making it crucial to closely monitor glacier velocity. Satellite remote sensing technology has enabled rapid and thorough monitoring of glacier velocity. Synthetic Aperture Radar (SAR), which is an active microwave remote sensing technique provides high-resolution data, besides overcoming the constraints due to cloud-affected data provided by using optical sensors. The article presented a comprehensive review of the advancements in different SAR techniques used for glacier velocity estimation. The theoretical foundations of Differential SAR Interferometry (DInSAR) technique, as well as its various types namely, the two-pass, three-pass, four-pass, modified four-pass, persistent scatterer interferometry, small baseline subset, multi-aperture interferometry that have been employed for velocity measurement were discussed in detail. Also, the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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Offset tracking techniques viz. intensity tracking, coherence tracking, speckle tracking were discussed. Finally, the advantages and disadvantages of the different approaches were highlighted.

Each technique offers unique strengths and limitations, depending on the glacier's movement rate and environmental conditions. DInSAR, which relies on measuring phase differences excels in high-precision measurements of glacier motion, particularly for slow-moving glaciers. Its ability to detect minute deformations makes it a preferred tool for studying ice dynamics and mass balance in stable regions. DInSAR loses effectiveness in fast-moving glaciers due to decorrelation caused by rapid changes between image acquisitions. This can result in incomplete or erroneous velocity maps for high-displacement regions. On the other hand, Offset tracking, which detects pixel shifts is well-suited for monitoring fast-moving glaciers and large displacements, where DInSAR coherence may fail. Though slightly less precise than DInSAR, it provides reliable results in areas with significant motion or decorrelation. Its limitations are lower spatial resolution and sensitivity to noise compared to interferometric techniques. However, it compensates by maintaining accuracy in dynamic regions.

Traditional DInSAR is highly sensitive to decorrelation caused by temporal and geometric factors. It also requires external Digital Elevation Models (DEMs) to eliminate topographic influences, which can introduce inaccuracies due to DEM errors. Offset tracking provides lower spatial resolution and precision compared to DInSAR. It is also less effective in detecting small-scale movements.

PSI is less affected by temporal and geometric decorrelation as it focuses on stable scatterers. SBAS minimizes decorrelation effects by using interferograms with small temporal and spatial baselines. It is highly effective for continuous and large-scale deformation monitoring over time, making it ideal for detecting subtle glacier dynamics. MAI was combined with ascending and descending InSAR data to obtain full 3D velocity fields in the Siachen Glacier, Himalayas. This application demonstrated its ability to complement traditional DInSAR by resolving along-track motion.

While traditional DInSAR and offset tracking are well-suited for specific scenarios, slow and fast-moving glaciers, respectively, advanced methods like PSI and SBAS provide significant improvements in reliability and accuracy by addressing decorrelation and noise-related limitations. PSI excels in high-precision monitoring of slow deformations, whereas SBAS offers a robust approach for long-term and large-scale glacier monitoring. PSI overcomes the limitations of the conventional InSAR approach due to temporal and geometrical decorrelation, as well as atmospheric inhomogeneities. The appropriate combination of multiple SAR data pairs in SBAS helps in reducing errors caused by spatial and temporal incoherence and reduces the impact of noise (Onn and Zebker, 2006). It also limits the geometric decoherence due to long baselines (Du et al., 2020). One demerit of this technique is that the resolution of the image is reduced (Ansar et al., 2022).

Obtaining reliable Digital Elevation Models (DEMs) in remote glacial areas is a challenge due to their inaccessibility, dynamic topography, and extreme environmental conditions. Some solutions to this issue are:

Utilization of Automated Algorithms viz. AI-based techniques can improve DEM accuracy by correcting artifacts and filling gaps.

Engaging the research community or local knowledge can improve data reliability.

Temporal Analysis may be conducted by repeating DEMs from different times to understand changes and validate data consistency.

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DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

Utilization of UAVs and Drones equipped with cameras or Light Detection and Ranging (LiDAR) for localized high-resolution DEMs.

The challenges of obtaining reliable Digital Elevation Models (DEMs) in remote glacial areas significantly impact both the accuracy and feasibility of Synthetic Aperture Radar (SAR) methods. DInSAR rely on DEMs to remove the topographic phase from interferograms. If the DEM has errors or insufficient resolution, it can introduce inaccuracies into displacement estimates, leading to erroneous glacier velocity measurements. Inaccurate DEMs can cause baseline errors, which affect the phase unwrapping process in DInSAR. This is particularly critical in steep, rugged terrains where even small elevation errors can lead to large phase errors.

Three-pass or four-pass DInSAR attempt to mitigate DEM-related issues by generating internal topographic models from SAR data. However, these methods require additional acquisitions, increasing data and computational demands, which might not be feasible in data-scarce regions. Techniques like Modified Four-Pass DInSAR were specifically developed to reduce reliance on external DEMs by accounting for glacier displacement during topographic pair processing. While effective, these methods still have limitations, such as sensitivity to coregistration errors and noise.

Reliable DEMs in remote glacial areas are vital for understanding climate change impacts, glacier dynamics, and hydrology. Leveraging advancements in remote sensing and combining multiple data sources can significantly improve their quality and accessibility.

In the near future, we can look forward to leverage the potential glacial applications of the NASA–ISRO Synthetic Aperture Radar (NISAR) mission. NISAR will provide high-resolution, frequent, and systematic observations of ice sheets, glaciers, and sea ice, enabling better monitoring of changes. Current SAR missions often lack the precision or coverage to study rapidly moving or thinning glaciers effectively. NISAR promise higher-resolution DEMs, which can improve the accuracy of SAR methods in remote glacial regions and reduce reliance on external models. PSI and SBAS mitigate DEM dependency by using time-series SAR data, making them better suited for regions where reliable DEMs are unavailable.

By utilizing both L-band and S-band radar, NISAR can penetrate clouds and darkness, overcoming the visibility challenges in regions like the Himalayas and polar areas. This ensures continuous data collection regardless of weather or lighting conditions, essential for regions often obscured by clouds.

In high-altitude regions like the Himalayas, NISAR will help quantify glacial water storage and its variations, aiding in risk assessment for glacial lake outburst floods and water resource planning for downstream populations.

Conclusion

In this article, we have reviewed the current state of the art in different SAR methods used for estimating glacier motion. In order to extract useful information utilizing SAR techniques, it is important to match, select, and have access to the appropriate data set. The three-pass and four-pass DInSAR methods require more SAR images but reduce the DEM-induced error as compared to the two-pass method. The temporal evolution of the glaciers can be derived using advanced techniques, such as SBAS, PSI, and MAI. Offset tracking methods such as Intensity tracking, Coherence tracking, and Speckle tracking, based on finding the CCP of the precisely coregistered SAR images were also discussed.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_29652986

The key differences between advanced DInSAR techniques and Offset tracking methods are that DInSAR techniques often require coherent data and external DEMs, while offset tracking can operate with less stringent requirements. Also, PSI and SBAS excel in long-term monitoring, while offset tracking is suited for capturing rapid or large displacements. Offset tracking estimates both the slant range and azimuth motion components of glaciers while DInSAR approach measures only the LOS velocity component. When used in slow-moving glaciers, the DInSAR approach excels, whereas offset tracking is better appropriate in fast-moving glaciers. An integration of both the methods will produce accurate glacier motion information in study areas containing both slow and fast-moving regions.

The lack of reliable DEMs limits the precision and scope of traditional SAR methods in remote glacial areas. However, advancements in SAR methodologies and the development of new satellite missions are addressing these challenges, making SAR more robust for glaciological applications.

The utility of SAR techniques in glaciology has been demonstrated in critical regions such as the Himalayas and Polar Regions, providing insights into glacier dynamics, mass balance, and hazards. These case studies illustrate the versatility of SAR techniques in monitoring glacier dynamics across diverse environments. Advanced methods like PSI and SBAS excel in long-term monitoring, while offset tracking addresses challenges in fast-moving and decorrelated regions. Their application in regions like the Himalayas and Polar Regions highlights their critical role in understanding climate change impacts and managing associated risks.

There are a lot of potential and expectations to fully utilize the DInSAR and offset tracking outcomes in studying various cryospheric regions of the Earth, including the Himalayas. NISAR equipped with its dual frequency SAR system (the L-band and S-band) will add on to the existing stock of SAR sensor systems and enable the study of snow and glaciers at much-improved scales. NISAR's advancements in radar technology and its systematic observation strategy will significantly enhance our ability to study and predict changes in the cryosphere. These data are vital for addressing challenges related to climate change, sea-level rise, and water resource management in glacier-fed regions.

While DInSAR is unmatched in precision for slow-moving glaciers, its performance diminishes in high-displacement scenarios. Offset tracking, though less precise, effectively fills this gap by maintaining accuracy in regions with rapid ice motion. Advanced techniques like PSI and SBAS extend the applicability of SAR by addressing decorrelation and enhancing long-term monitoring, making them invaluable for understanding glacier dynamics under varying conditions.

By integrating these techniques, researchers can optimize glacier monitoring strategies across diverse environments, improving our ability to track and respond to climate-induced changes.

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DOI: http://dx.doi.org/10.15666/aeer/2302_29652986