

# Spatiotemporal Analysis of Glacier Movement on Muztagh Peak Based on Hybrid Cloud Remote Sensing

Litao Xu\*

School of Surveying & Land Information Engineering, Henan Polytechnic University, Jiaozuo, China

\*Corresponding Author: Litao Xu(xulitao2002@home.hpu.edu.cn)

## ABSTRACT

Global warming is accelerating glacier dynamics in High Mountain Asia, which underscores the importance of high-precision monitoring for regional water security. This study investigates the surface velocity of the Muztagh Ata glacier group through a joint observation framework. We utilize the ASF-HyP3 cloud platform for efficient SAR preprocessing via the ISCE2 processor and MintPy for time-series InSAR inversion. By incorporating ERA5 meteorological data for tropospheric correction and performing geometric decomposition on multi-orbit Sentinel-1 data, we identify a radial flow pattern with peak horizontal velocities of approximately  $-2.0$  m/year.

## KEYWORDS

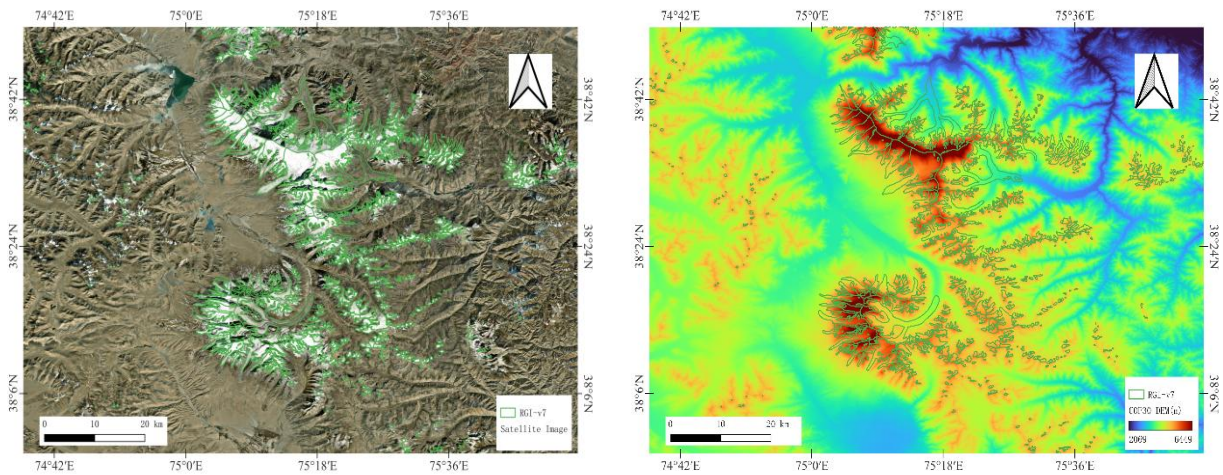
Muztagh Ata Peak; Glacier Flow Velocity; SBAS-InSAR; Multi-Orbit Decomposition.

## 1. INTRODUCTION

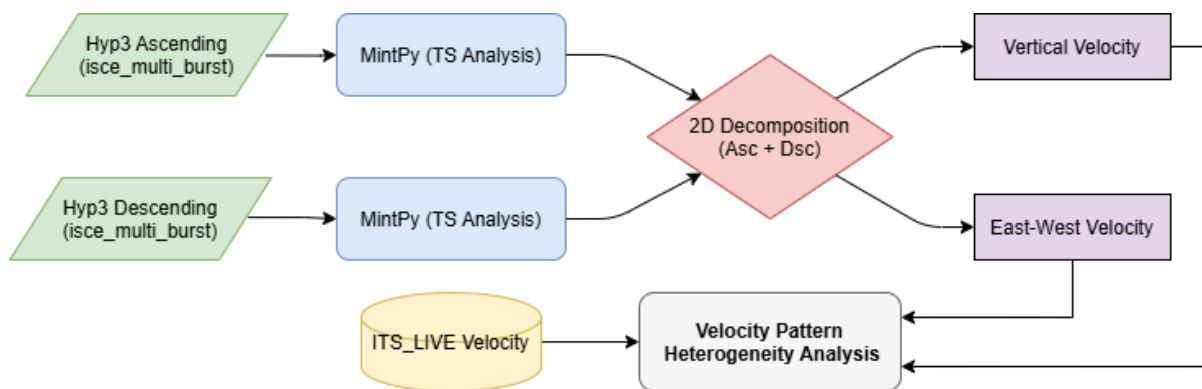
High Mountain Asia, often referred to as the Third Pole, contains vast glacier reserves that are vital for ensuring regional water security. In the context of global warming, the precise monitoring of glacier surface velocity as a key parameter reflecting glaciological processes has become increasingly urgent. Conventional monitoring methods such as interferometric synthetic aperture radar and feature tracking exhibit certain limitations, as the former is typically restricted to one-dimensional line-of-sight deformation and is susceptible to atmospheric interference, while the latter often suffers from low signal-to-noise ratios or data gaps in slow-moving accumulation zones. To address these constraints, this study examines the Muztagh Ata glacier group to explore a joint observation scheme that integrates time-series analysis and geometric decomposition. The research leverages the cloud computing advantages of the ASF-HyP3 platform for large-scale data processing, which significantly improves the batch processing efficiency of Sentinel-1 imagery and reduces local computational requirements, thereby supporting the construction of extensive interferometric networks. By utilizing open-source tools for small baseline subset time-series inversion to mitigate atmospheric phase impacts and reconstructing glacier flow fields through ascending and descending geometric relationships, this work further incorporates ITS\_LIVE products for complementary validation. This work aims to reveal the spatiotemporal heterogeneity of glacier velocity in the Muztagh Ata region and seeks to provide modest reference data for regional glaciological dynamics research.

## 2. STUDY REGION

Muztagh Ata is situated at the boundary between Akto and Taxkorgan counties in Xinjiang, within the structural intersection of the West Kunlun Mountains and the East Pamir Plateau. The main peak reaches an elevation of 7546 meters, and the mountain generally exhibits a characteristic dome-shaped morphology. Because of spatial differences in slope, the western aspect is relatively gentle and facilitates snow accumulation as well as glacier formation, while the northern and eastern aspects are significantly steeper. Under the influence of its inland location and high-altitude effects, the regional climate is cold and arid, which maintains the thermal environment required for the sustained development of modern glaciers. There are 128 modern glaciers distributed across this region with a total area of approximately 377.21 square kilometers and an average equilibrium line altitude near 5200 meters. Among these glaciers, the Qili and Kemakule glaciers are most representative regarding their scale and dynamic activity, with their ice tongues typically extending to an altitude of 4300 meters. Furthermore, the summit is covered by an ice layer with a thickness of roughly 100 to 200 meters, and this micro-ice cap structure acts as a significant contributor to regional runoff and serves as a natural record of paleoclimate data.



**Figure 1** Research Location Map



**Figure 2** Technical flowchart

## 3. DATA AND METHODS

The research implements a cloud-to-local hybrid framework designed to optimize large-scale processing. Sentinel-1 Single Look Complex (SLC) stacks are processed on the ASF-HyP3 platform using the ISCE2 processor. This stage automates the generation of interferograms, including precise co-registration, multi-looking (5x1 ratio), and topographic phase removal using the Copernicus GLO-

30 DEM. The resulting interferometric stacks are ingested into MintPy. A small baseline network is constructed ,30-day temporal,300m spatial baseline thresholds, to mitigate decorrelation. nterferograms with an average coherence below 0.1 were excluded to ensure the robustness of the inversion.The weighted least squares (WLS) method is then applied to the unwrapped phases to reconstruct the raw Line-of-Sight (LOS) displacement history.This study aims to obtain a high-precision glacier surface velocity field in the Muztagh Ata region through a technical workflow comprising SBAS-InSAR[1] time-series processing of Sentinel-1 data, ascending and descending 2D velocity field decomposition, and accuracy validation based on ITS\_LIVE[2] products. Given the complex terrain and temporal decorrelation induced by snow cover on Muztagh Ata, the small baseline subset technique was employed for interferometric processing. Data preprocessing was performed using the HyP3 cloud platform provided by the Alaska Satellite Facility, while subsequent time-series analysis was implemented with the open-source MintPy toolkit[1]. The ISCE2 processor on the ASF-HyP3 platform was utilized for batch processing of both Sentinel-1 ascending and descending data. To suppress speckle noise and enhanceG interferogram coherence, a multi-look ratio of 5x1 in the range and azimuth directions was set, resulting in a ground resolution of approximately 20 m by 20 m. The preprocessed interferogram stacks were imported into MintPy for time-series analysis where an interferometric network was constructed by setting a time baseline threshold of 30 days and a spatial perpendicular baseline threshold of 300 m[3]. I. The weighted least squares method was applied to estimate the raw phase series during the inversion process. To mitigate significant tropospheric delays in the alpine environment, we utilized the PyAPS module driven by ERA5 reanalysis data[4]. ERA5 was selected for its superior spatiotemporal resolution, which allows for the precise modeling of stratified atmospheric components over the complex topography of Muztagh Ata, ensuring the physical reliability of the resulting velocity fields.. This module estimates and removes tropospheric atmospheric phase delay components based on an integration delay model. High-frequency noise was further removed through spatiotemporal filtering, and stable bedrock areas without glacier cover were selected as reference points to solve for the average annual line-of-sight velocity fields of the ascending and descending datasets. To verify the reliability of the results, NASA ITS\_LIVE annual velocity products were incorporated as independent validation data. These products, generated via feature tracking, exhibit strong capabilities for capturing rapid glacier flow and remain unaffected by interferometric decorrelation.

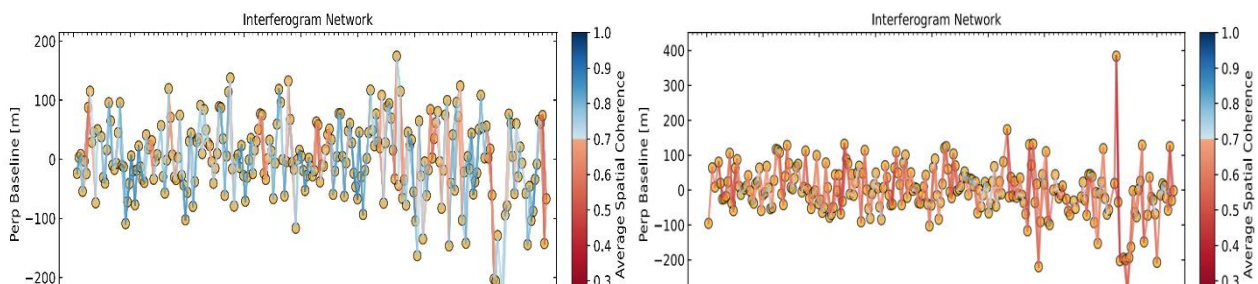


Figure 3 Sentinel-1 Network Connection Diagram

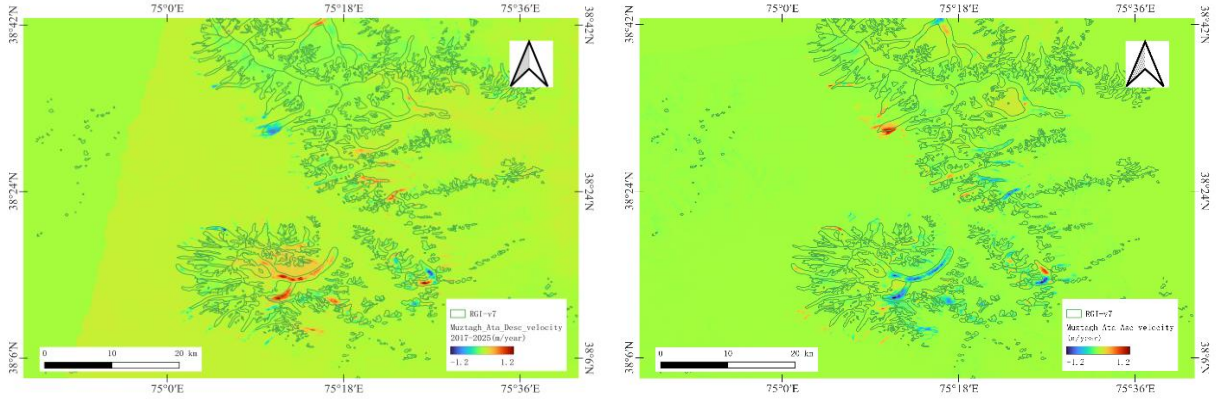
Figure 4 Sentinel-1 Network Connection Diagram

To extract glacier motion information precisely from Sentinel-1 interferometric pairs, the total observed phase of a pixel in interferogram is decomposed into a linear superposition of physical components.  $\phi_{def}$  represents the line-of-sight deformation phase of the primary research target,  $\phi_{topo}$  accounts for the residual topographic phase resulting from the precision limitations of the external digital elevation model, and  $\phi_{atm}$  denotes the atmospheric delay phase influenced by water vapor and pressure,  $\phi_{orb}$  refers to systematic phase shifts caused by errors in satellite orbital parameters, while  $\phi_{noise}$  encompasses random noise phase arising from spatiotemporal decorrelation and system thermal noise. The effective isolation and modeling of these distinct components through the MintPy time-

series inversion algorithm provides a fundamental basis for obtaining high-precision glacier velocity fields[5].

$$\Phi_{x,y}^k = \varphi_{\text{top},x,y}^k + \varphi_{\text{def},x,y}^k + \varphi_{\text{orb},x,y}^k + \varphi_{\text{atm},x,y}^k + \varphi_{\text{noi},x,y}^k \quad (1)$$

## 4. RESULT

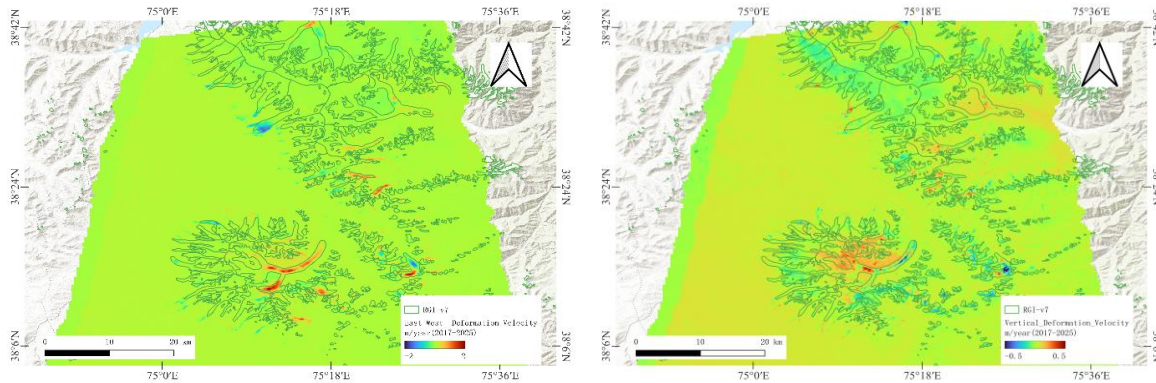


**Figure 5** LOS Deformaton Velocity (2017-2025)

$$\begin{pmatrix} -\cos\theta^{asc} & \sin\theta^{asc} \cos\alpha^{asc} \\ -\cos\theta^{desc} & \sin\theta^{desc} \cos\alpha^{desc} \end{pmatrix} \begin{pmatrix} d_v \\ d_e \end{pmatrix} = \begin{pmatrix} d_{\text{los}}^{asc} \\ d_{\text{los}}^{desc} \end{pmatrix} \quad (2)$$

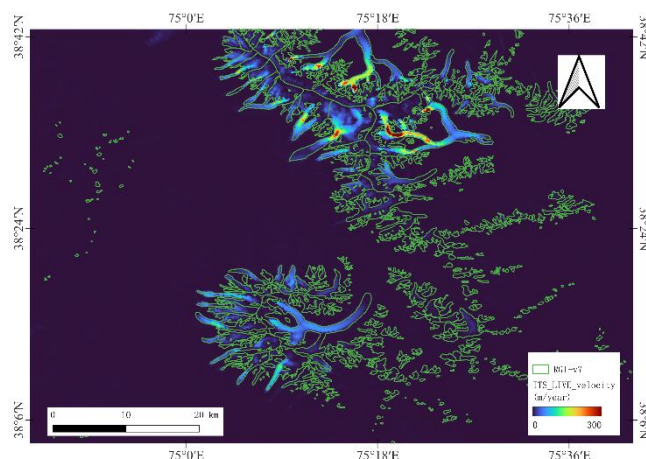
To reconstruct the 2D velocity field, the study utilizes the geometric relationship between ascending and descending orbits.  $\theta$  is Radar incidence angle.  $\alpha$  is Satellite azimuth angle.  $d_v$  and  $d_e$ : Vertical and East-West velocity components, respectively. By solving this matrix for each pixel, the one-dimensional LOS deformation is successfully decomposed into actual horizontal and vertical glacier movement. By utilizing the ASF-HyP3 platform for processing and MintPy for time-series inversion, the average annual line-of-sight deformation rate fields for the Muztagh Ata region from 2017 to 2025 were obtained for both ascending and descending orbits. The ascending mode results indicate that deformation signals are closely concentrated within the glacier boundaries defined by RGI-v7[6], while stable bedrock areas exhibit rates approaching 10 mm/yr, which appears to support the effectiveness of the applied atmospheric corrections and orbital error suppression. Spatial analysis of the western ice tongues of the main peak reveals prominent negative deformation rates representing movement away from the satellite, with maximum absolute values exceeding 1.0 m per year. This characteristic likely arises because the ascending Sentinel-1 satellite observes toward the east-southeast, creating an obtuse angle with the westward glacier flow on the western slopes. Corresponding descending observations over the same period exhibit a notable spatial symmetry and sign reversal compared to the ascending data. In the western slope areas, the descending rates are significantly positive, indicating motion toward the satellite, with peak velocities between 0.8 and 1.2 m per year concentrated along the middle and lower flowlines. This sign inversion between orbits stems from the descending satellite observing toward the west-southwest, where westward ice motion points toward the sensor. Such observations suggest that glacier movement in this region is primarily characterized by east-west horizontal displacement, as the line-of-sight rates are strongly modulated by the imaging geometry. Furthermore, slight negative deformation in both orbits at high-altitude accumulation zones potentially reflects vertical surface settlement or downslope flow components. The clear velocity gradients from the glacier margins to the main flowlines illustrate the internal shear deformation characteristics. These complementary ascending and descending datasets provide the

necessary basis for reconstructing the two-dimensional velocity fields through geometric decomposition.



**Figure 6** Vertical and East-West Deformation Velocity (2017-2025)

Through the geometric resolution of Sentinel-1 ascending and descending data from 2017 to 2025, this study successfully isolated the east-west horizontal velocity  $U_{east}$  and vertical velocity  $U_{vert}$  of the Muztagh Ata region. The decomposition results clearly reveal the dynamic characteristics and mass balance status of glacier movement in this area. East-west movement is identified as the primary component of glacier deformation on Muztagh Ata, exhibiting a pronounced radial movement pattern where large glaciers on the western slopes, such as the Qili and Kemakule glaciers, demonstrate strong negative signals representing overall westward flow. Horizontal velocities in the main flowlines of these glaciers are significant, with peaks reaching -1.5 to -2.0 meters per year, reflecting vigorous dynamic activity driven by both topographic slope and ice mass scale. In contrast, glaciers on the eastern slopes are smaller and exhibit weaker positive signals representing eastward flow, with velocities generally below 0.5 meters per year. The velocity gradient from the glacier margins to the central flowlines shows a typical transition from slow to fast, consistent with the motion of viscous fluids under gravitational forcing. Vertical deformation velocity reflects surface displacement, integrating glacier dynamical uplift or subsidence with surface mass ablation or accumulation. In the middle and lower sections of major ice tongues within the ablation zones, coherent negative deformation signals were observed with rates between -0.3 and -0.5 meters per year, primarily attributed to surface thinning driven by regional warming alongside mass export from horizontal movement. In higher-altitude accumulation zones near the main ridges, vertical deformation signals remain faint or exhibit scattered positive values, potentially reflecting surface elevation gains from snow accumulation or dynamical thickening offsetting ablation. Spatial heterogeneity in vertical deformation is more pronounced in crevasse zones and slope transitions, indicating the influence of local complex terrain on mass transport.



**Figure 7** ITS\_LIVE Annual Glacier Flow Velocity

The movement patterns of Muztagh Ata glaciers show significant synergy where the fastest horizontal flow on the western ice tongues often corresponds to obvious vertical subsidence, suggesting a mode of dynamical mass deficit where the supply cannot compensate for losses caused by intense ablation and downstream transport. Precision validation in non-glaciated bedrock areas shows that both east-west and vertical deformation rates are closely distributed around 10 millimeters per year. This further confirms that the ASF-HyP3 and MintPy processing workflow, particularly the tropospheric delay correction via PyAPS, effectively eliminated topographically related atmospheric and systematic orbital errors, ensuring the physical reliability of the two-dimensional decomposition results. Considering the differences in spatial resolution and observational principles between the two methods, the observed level of consistency validates the effectiveness of the ascending-descending decomposition algorithm employed in this study.

## 5. DISCUSSION

The integration of the ASF-HyP3 cloud platform and MintPy time-series analysis significantly enhanced the efficiency and precision of glacier velocity monitoring in high-mountain regions. Automated processing of extensive Sentinel-1 interferometric pairs via the HyP3 platform markedly reduced the time required for data preparation. Furthermore, the small baseline subset algorithm in MintPy effectively suppressed turbulent atmospheric delays and residual topographic phases through redundant observations in both spatial and temporal dimensions. By performing geometric decomposition on ascending and descending datasets, this study successfully converted one-dimensional line-of-sight deformation into actual horizontal and vertical glacier velocity components. This joint approach proved particularly effective in the gentle western slopes of Muztagh Ata, capturing subtle deformation signals as low as several centimeters per year and addressing the difficulties of traditional differential interferometry in quantitatively inverting complex flow fields. Comparison between the interferometric results and ITS\_LIVE feature tracking products revealed a significant complementarity between the two techniques across different glacier zones. In accumulation zones above 5200 meters, where optical and radar imagery often lack distinct texture due to perennial snow cover, ITS\_LIVE data frequently exhibit low signal-to-noise ratios or significant data gaps. In contrast, the phase sensitivity of interferometry maintained high coherence in these slow-moving and uniform areas, filling critical monitoring gaps at high altitudes. Conversely, in fast-moving ice tongues or terminus regions near 4300 meters, intense surface deformation often led to interferometric decorrelation or phase unwrapping errors, whereas feature tracking effectively captured large-magnitude displacements[7]. Consequently, combining the strengths of both methods facilitates the construction of a complete glacier velocity field spanning from accumulation to ablation zones. The monitoring results highlight pronounced spatiotemporal heterogeneity in the flow of Muztagh Ata glaciers. Taking the Qili Glacier on the western slope as an example, the velocity exhibits clear vertical zonation where flow is slow and uniform in the accumulation zone, accelerates in the middle section due to increased slope, and decelerates again at the terminus because of ablation and topographic obstructions. Although the ascending-descending decomposition eliminated most geometric distortions, radar layover and shadow effects remain significant error sources in the extremely steep terrain of the northern and eastern slopes, leading to localized data loss. Future research could incorporate high-resolution TerraSAR-X data or integrate pixel-offset tracking techniques to improve monitoring capabilities in rapidly deforming regions while maintaining high precision.

## 6. CONCLUSION

This study addresses the issues of insufficient spatiotemporal coverage and limited accuracy in monitoring glacier velocity across High Mountain Asia by establishing a joint inversion framework based on the ASF-HyP3 cloud platform and MintPy time-series analysis tools for the Muztagh Ata

region in the West Kunlun Mountains. Through systematic processing and geometric decomposition of Sentinel-1 ascending and descending data, several primary conclusions were reached. First, the feasibility of the efficient joint resolution scheme was verified, as the ASF-HyP3 platform significantly simplified the preprocessing of massive radar data while the small baseline subset algorithm in MintPy effectively removed atmospheric phase delays, making high-precision and long-term surface deformation monitoring possible in complex alpine environments. The joint ascending-descending decomposition further overcame the geometric distortions inherent in single line-of-sight observations and reconstructed the two-dimensional and three-dimensional velocity vector fields of the glacier surface. Second, the research revealed refined spatiotemporal characteristics of glacier flow on Muztagh Ata, demonstrating significant spatial heterogeneity where flow in the gentle accumulation zones of the western slopes remains relatively stable and slow while velocity changes in the ice tongue areas are more active. Interferometric synthetic aperture radar technology, with its high sensitivity to subtle deformations, captured low-speed motion signals that are difficult for traditional feature-tracking techniques to identify, resulting in a more detailed map of glacier movement. Third, the complementarity mechanism of multi-source remote sensing was clarified, confirming that interferometry possesses irreplaceable advantages in high-altitude snow-covered accumulation zones lacking texture features, effectively filling the data gaps left by feature-tracking products such as ITS\_LIVE. The combination of these methods achieved seamless monitoring across the entire glacier basin from the source accumulation zone to the terminal ablation zone, providing a complete data chain for understanding glacier mass balance and dynamical processes. In summary, the joint monitoring scheme proposed in this study provides a new perspective and data support for glacier research in the Muztagh Ata region and offers a replicable, high-precision technical paradigm for glacier disaster warning and water resource management in the West Kunlun Mountains and the broader High Mountain Asia region. Future work will incorporate higher-resolution radar data and field observations to deepen the quantitative analysis of driving mechanisms for seasonal and interannual glacier variations.

## ACKNOWLEDGEMENTS

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