



Article

Research on Monitoring the Speed of Glacier Terminus Movement Based on the Time-Series Interferometry of a Ground-Based Radar System

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Abstract: The Tibetan Plateau (TP) is the largest glacier reserve outside the Antarctic and Arctic regions. Climate warming has affected the reserve of freshwater resources and led to frequent glacier disasters. However, due to its extreme environment of hypoxia and low pressure, it is extremely difficult to obtain data. Compared with other traditional monitoring methods such as markers and satellite remote sensing technology, Ground-Based (GB) radar systems have the advantages of convenient carrying and installation, sub-second level sampling, and sub-millimeter measurement accuracy. They can be used as an effective way to study the short-term rapid movement changes in glaciers. Based on a self-built GB radar system, monitoring experiments were conducted on two glacier termini on the TP. The movement speed of the Rongbuk glacier terminus on Mount Qomolangma was obtained through time-series interferometric measurement as 4.10 cm/day. When the altitude was about 5200 m, the glacier movement speed was 7.74 cm/day, indicating the spatial differences with altitude changes. And in another region, the movement speed of the Yangbulake glacier terminus on Mount Muztag Ata was 198.96 cm/day, indicating significant changes in glacier movement. The cross-validation of Sentinel-1 data during the same period proved the effectiveness of GB radar system interferometry in measuring glacier movement speed and also provided field validation data for remote sensing inversion.

Keywords: GB radar; time-series interferometry; TP; movement at glacier terminus; signal process



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1. Introduction

The continual rise of global temperatures has led to large-scale melting and a reduction in glaciers and snow cover. At the same time, seasonal changes directly lead to soil erosion in the middle and lower reaches, causing frequent disasters such as large-scale glacier mudslides and avalanches, seriously threatening the security of persons and property as well as national engineering construction [1,2]. Due to its high terrain, TP is the region with the most glaciers distributed in mid-low latitudes, accounting for 11.8% of the world's glacier area [3], and is known as the third pole of the Earth. It is controlled by alternating westerly and monsoon winds, which not only affect the climate pattern of the plateau, but also affect modern glaciers, lakes, and ecosystems on the plateau. It is one of the most sensitive regions to global climate change [4–7]. The research on glaciers on the TP started relatively late, and the extremely harsh environment of the plateau is mostly uninhabited, making observation and data collection extremely difficult. Therefore, it is of

great significance to carry out monitoring and research on glaciers. The TP location and glacier study areas are shown in Figure 1.

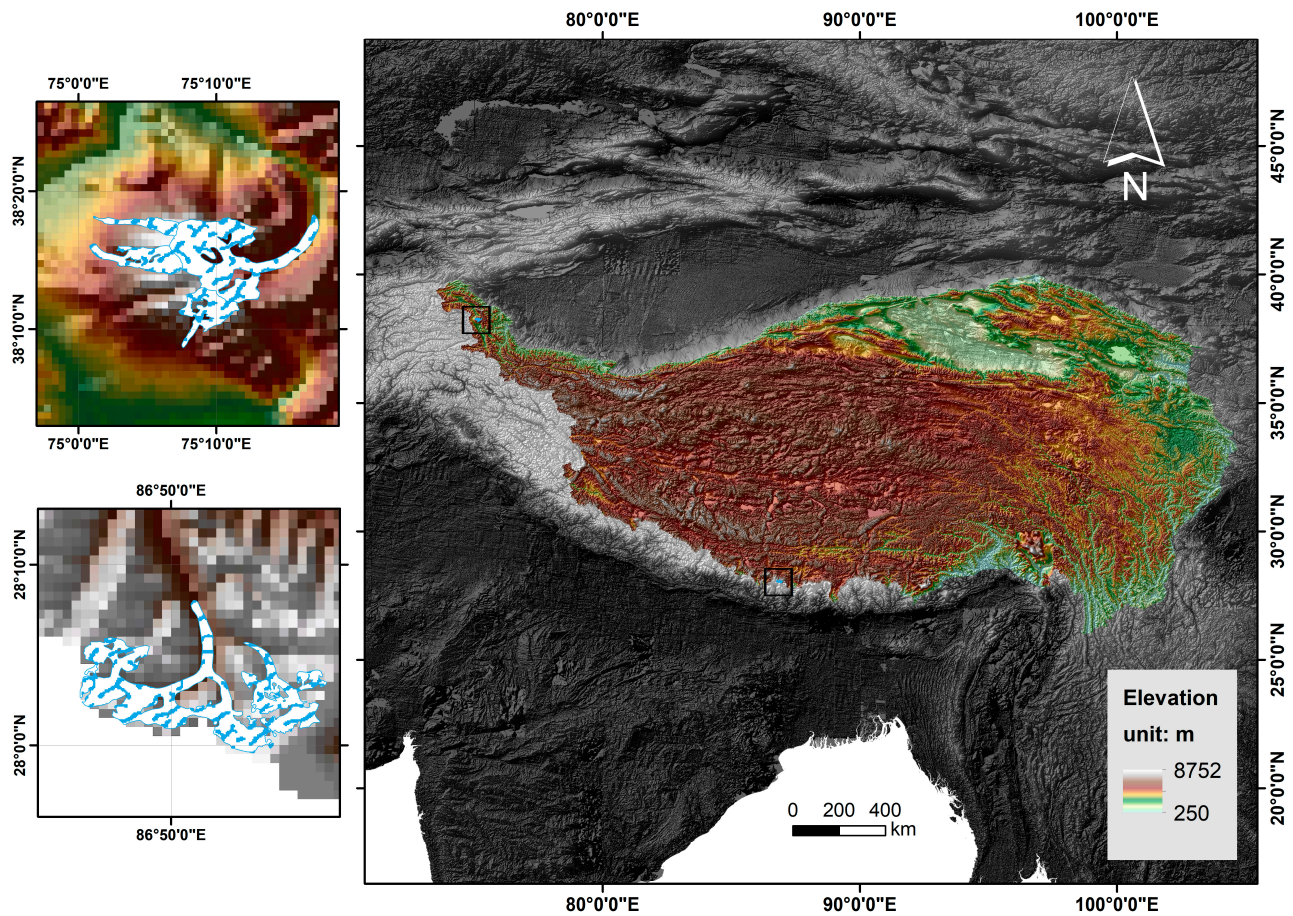


Figure 1. Locations of the TP and glacier study areas measured (the boundary of TP was from <https://data.tpdc.ac.cn/zh-hans/data/0c84a954-435d-45f4-bf42-d561f7c7da2a>, accessed on 29 August 2024).

Glacier deformation can indicate the characteristics of glacier movement, and glacier movement speed can quantitatively characterize glacier deformation. The stake is a traditional field measurement method, for example, Yanhui Chen et al. used the stake to measure the obvious reduction in the surface mass balance of both the Large and Small Anglong Glaciers from 2014 to 2016 [8]. The development of the Global Positioning System (GPS) has provided a new method for field measurement. For example, Yuande Yang et al. found that when the ice surface velocity was less than 5 m/a, the insensitivity of InSAR to low ice surface velocities resulted in differences from GPS, confirming the importance of ground truth high-resolution ice surface velocity estimation based on GPS field work in constraining ice sheet dynamics [9]. Jianmin Zhou et al. showed that the glacier flow distribution displays strong spatial variations depending on elevation, which are related to the complexity of the terrain and the convergence and uptaking effect of ice in steep slope areas with opposite flow directions [10]. However, due to the extreme climate of hypoxia and low pressure in the TP, manual installation and station deployment are extremely difficult, and measurement and maintenance costs greatly increase, making it impossible to achieve long-term and large-scale monitoring of glacier movement speed. The emergence of satellite remote sensing technology enables the retrieval of the relationship between glaciers and climate change at the annual, seasonal, and monthly scales through massive datasets. However, due to the abundant water vapor on the TP [11] and the year-round cloud cover over the sky, optical satellite data acquisition is limited, and cloud removal

algorithms (Lee K Y et al. resulted in faithful cloud-free images with almost no artifacts in training a hierarchical cloud removal network by devising a reliable cloudy image synthesis model, which considers the background surface color, misalignment of channel images, and blur in clouds [12]. Mattar C et al. reduced the overall cloud coverage of the northern region of Chile (Pulido river basin) from 26.56% to 7.69% based on Moderate Resolution Imaging Spectroradiometer (MODIS) Snow Cover daily products, achieving an overall accuracy of 86.66% in snow mapping [13]. Singh M K et al. used the MODIS daily Snow Cover Product (SCP) to remove clouds for the upper Bhagirathi basin in the western Himalayas, with an average overall accuracy of approximately 95% [14]) inevitably introduce errors. Microwave remote sensing provides a new method for monitoring glacier movement speed in the TP with its advantages including the following traits: all day, all weather, unaffected by clouds and rain, certain penetration ability, and deformation measurement accuracy reaching sub-millimeter level. However, the resolution of data obtained from radar satellite remote sensing is low, susceptible to interference from mixed pixels, and the revisiting period is long, making it difficult to meet the real-time monitoring requirements for glacier movement speed.

The GB radar system can achieve real-time and dynamic monitoring of the glacier termini due to its sampling time reaching the sub-second level. Combining the theory of interference with GB radar signal processing, micro deformation can be inverted based on the phase difference between the two measurement results. Linhsia Noferini et al. used the C-band GB Synthetic Aperture Radar (GBSAR) system to monitor the deformation of the Belvedere Glacier and established a Digital Elevation Model (DEM) [15]. Jialun Cai et al. combined drone aerial photography data with GBSAR data to establish an accurate GBSAR geographic coding model based on a solution space search. They monitored the old observation platform landslide on the Hailuoguo Glacier, achieving sub-pixel level geocoding accuracy and spatiotemporal analysis [16]. Harcourt et al. demonstrated the unique ability of 94 GHz millimeter wave radar to obtain high-resolution measurements of glacier surfaces under reduced visibility conditions by combining with three-dimensional point clouds [17–19]. Moreover, GB radar system monitoring is also of great significance for research on iceberg collapse [20–22], glacial lake outburst floods (GLOFs) [23,24], and daily melting and refreezing cycles [25].

This article first introduces the basic situation of Mount Qomolangma and its surrounding Rongbuk Glacier, as well as Mount Muztag Ata and its surrounding Yangbulake Glacier. Then, the composition and parameters of the independently built GB system are introduced, and the principle of radar time-series interferometry is derived. Subsequently, the monitoring results of the radar system on the glacier termini in two study areas in June 2023 are presented. At the same time, a comparative analysis was carried out in conjunction with the corresponding Sentinel-1 satellite radar data, which verified the effectiveness and progressiveness of time-series interferometry of the GB radar system in monitoring the speed of glacier terminal movement. It has practical engineering significance and can serve as an auxiliary means of monitoring, providing on-site validation data for satellite remote sensing inversion. It has guiding significance for hydrological changes in the watersheds, glacier surging analysis, and disaster prevention.

2. Materials and Methods

2.1. Study Area

This survey selected the Rongbuk Glacier termini of Mount Qomolangma (also known as Mount Everest) and the Yangbulake Glacier termini of Mount Muztag Ata. Mount Qomolangma is located in the middle section of the Himalayan Mountains in the southern part of the TP, with a total glacier area of 1600 km² [26]. The Rongbuk Glacier is the largest subcontinental glacier on the northern slope of Mount Qomolangma, with a length of approximately 18 km and an average thickness of 120 m, a maximum thickness exceeding 300 m, and a glacier coverage of 68% [26]. From 1974 to 2008, the total area of the Rongbuk Glacier decreased by 10.4%, from 144 km² to 129 km² [27]. The region has strong solar

radiation, low latitude, and varying rates of ice melting. At the Rongbuk Glacier termini, there are natural glacier phenomena such as glacial erosion lakes, cirques, and angular peaks [28]. When the median height of the Rongbuk Glacier is 5498.1 m, the movement speed of the ablation zone is 4.2 cm/day, and the movement speed of the debris zone is 3.7 cm/day from June to September 2006 [29]. The debris has a significant effect on slowing down glacier movement speed and has an important impact on the mass balance gradient of the debris-covered glacier, the development of ice cliffs, ponds, and drainage systems, and the downstream runoff process. Figure 2 shows the topographic map of Rongbuk Glacier and aerial photographs taken by an Unmanned Aerial Vehicle (UAV) at the Rongbuk Glacier termini. The red arrow in the image indicates the direction of glacier movement.

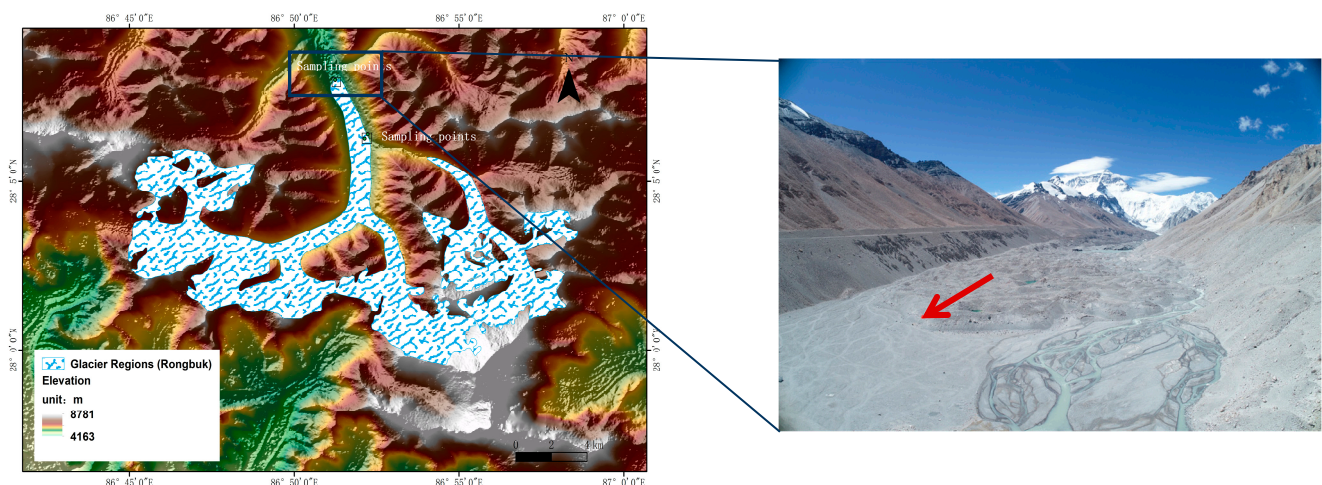


Figure 2. Topography and Sampling Area Map of Rongbuk Glacier.

Mount Muztag Ata is located on the eastern edge of the Pamir Plateau in the western part of the TP, with a peak elevation of about 7509 m. This area is a polar continental glacier area. From 2014 to 2021, the speed variation range of the Muztag Glacier was 68.63 m/a to 330.91 m/a, with an average movement speed of 218.49 m/a [30]. In 2021, the average glacier flow rate in the region was $0.531 \text{ m/d} \pm 0.007 \text{ m/d}$ [31]. This region is characterized by some of the most dynamic glaciers and a high frequency of natural disasters. Influenced by westerly circulation patterns and orographic barriers, annual precipitation exhibits a gradual decline from west to east. According to the statistics, the average annual precipitation at the snow line of Mount Muztag Ata Glacier ranges from 450 mm to 600 mm. A large number and scale of glaciers have developed around it and on both sides of the mountain ridge, distributed radially to provide replenishment for runoff. After leaving the valley, they supply Kalakuri Lake. After leaving the lake, they enter the Gaizi River through the Kangxiwa River and finally flow into the Tarim Basin [32,33]. The Yangbulake Glacier is located on the west side of Mount Muztag Ata, flowing due west. It is developed in a faulted trough valley, with the upper limit of the glacier reaching the top of Mount Muztag Ata. It covers an area of 8.91 km^2 with a length of 9.4 km. The ice tongue is 6.2 km long, with an average width of 0.7 km [34]. It has alternating rows of ice towers and ice trough valleys and is a non-debris-covered glacier. Due to the lower extension of the ice tongue, the melting of the ice tongue area is very strong, making it an active glacier. The ice-covered river channels formed by glacier meltwater and distributed along glacier flow lines have deeper incisions, generally 2 m–3 m lower than the debris valleys at the bottom of the ice tower, and some deeper. Figure 3 shows the topographic map of Yangbulake Glacier, etc., and aerial photographs taken by a UAV at the Yangbulake Glacier termini. The red arrow in the image indicates the direction of glacier movement.

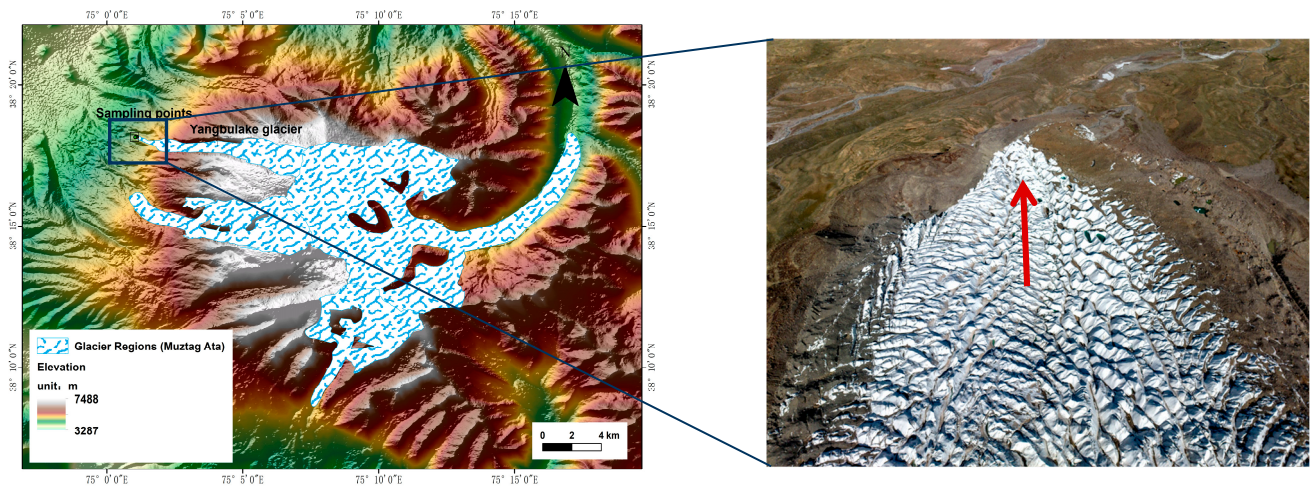


Figure 3. Topography and Sampling Area Map of Yangbulake Glacier, etc.

2.2. Monitoring of Glacier Termini Movement Speed from GB Radar

2.2.1. GB Radar System and Parameters

In Radio Frequency (RF) engineering, Vector Network Analyzer (VNA) is designed as an instrument for efficiently and accurately performing circuit or network analysis. The range of circuits that can be tested with VNA is extremely wide, from simple microwave devices such as filters, amplifiers, and mixers, to integrated microwave equipment. A Stepped Frequency Continuous Wave (SFCW) signal is an important form of signal composed of a series of continuous waves with linearly increasing carrier frequencies. The processing of single-frequency sub-signals by the receiver reduces its requirement for instantaneous bandwidth, making the synthesis of large bandwidth signals more convenient. By combining VNA with antennas and control computers, a radar system that emits SFCW signals can be formed.

Based on the above considerations, an independent radar experimental system was built, which mainly consists of three parts: a standard gain horn antenna, VNA, and Programmable Computer (PC). The physical diagram of the system is shown in Figure 4, and the parameters are shown in Table 1.



Figure 4. Physical diagram of the GB radar system.

Table 1. Main parameters of the GB radar system.

Parameters	Value	Parameters	Value
Start frequency	16 GHz	Pulse repeated frequency (PRF)	20 Hz
Bandwidth	300 MHz	Number N ¹	201
Intermediate Frequency (IF) bandwidth	30 kHz	Number M ²	50
Output power	0 dBm		

¹ Number of the frequency step. ² Number of transmitted pulses.

Compared to the C band and Ka band, the Ku band has less spectral resource interference and lower atmospheric attenuation [35]. The dynamic range of the Ku frequency band can reach 100 dB, which is much larger than the difference in radar cross sections between strong and weak scattering targets. It has a better micro deformation measurement effect for weak scattering targets. This system uses a Ku band standard gain horn antenna with a gain of 20 dB, model XB-HA62-20S, produced by Beijing Xibao Electronic Technology Co., Ltd, Beijing, China. When the frequency is 16 GHz, the measured beam width is about 16°, and the measured gain is about 16 dB, which can meet the measurement requirements. The antenna adopts a dual antenna structure with separate transmission and reception, which can simultaneously transmit and receive signals, improving the isolation between the receiving and transmitting links, while avoiding excessive coupling signals and reducing the dynamic range of the receiver [36].

The VNA used in this system is a dual port Ceyear3656D produced by Ceyear Technologies Co., Ltd, Qingdao, China. It can quickly and accurately measure the amplitude, phase, and other characteristics of the Scatter (S) parameter of the tested object and has wide applications in military [37–39], civilian [40,41], and other fields. The VNA supports programmable programming interfaces such as General Purpose Information Bus (GPIB) and Local Area Network (LAN). These interfaces, combined with I/O libraries and the C++ programming language, can enable remote control of VNA. The radar system built in this article is interconnected with a PC through an LAN interface. The PC uses the Virtual Instrument Software Architecture (VISA) library to transmit Standard Commands Programmable Instrumentation (SCPI) commands to VNA to define the system's test parameters. The main parameters of VNA are shown in Table 2.

Table 2. Main parameters of Ceyear3656D.

Parameters	Value	Parameters	Value
Frequency range	300 kHz~20 GHz	Frequency resolution	1 Hz
Measurement points	1~160,001	Effective directivity	36 dB (Ku)
Measurement domain	Time domain, Frequency domain	Sweep frequency method	Stepped frequency
Impedance	50 Ω	IF bandwidth	1 Hz~5 MHz

The PC is used for system error correction and display of measurement data and also provides a user interface and remote control interface through software compilation. The PC mainly completes two functions: system control and data processing. In order to achieve remote control of VNA by the computer, the VISA library is pre-installed in the PC, providing a standard Input/Output (I/O) function library for instrument programming. SCPI defines standardized instrument program control messages, respons messages, status report structures, and data formats. Based on the Qt Creator 4.8.2 (software) programming environment, combining SCPI programmable commands, I/O library functions, and C++ programming language can remotely control VNA to achieve signal transmission and reception. Finally, the data stored in the VNA are transmitted to the computer through an Ethernet interface. The software control interface is shown in Figure 5. This section is used

for system error correction and the display of measurement data and also provides a user interface and remote control interface.

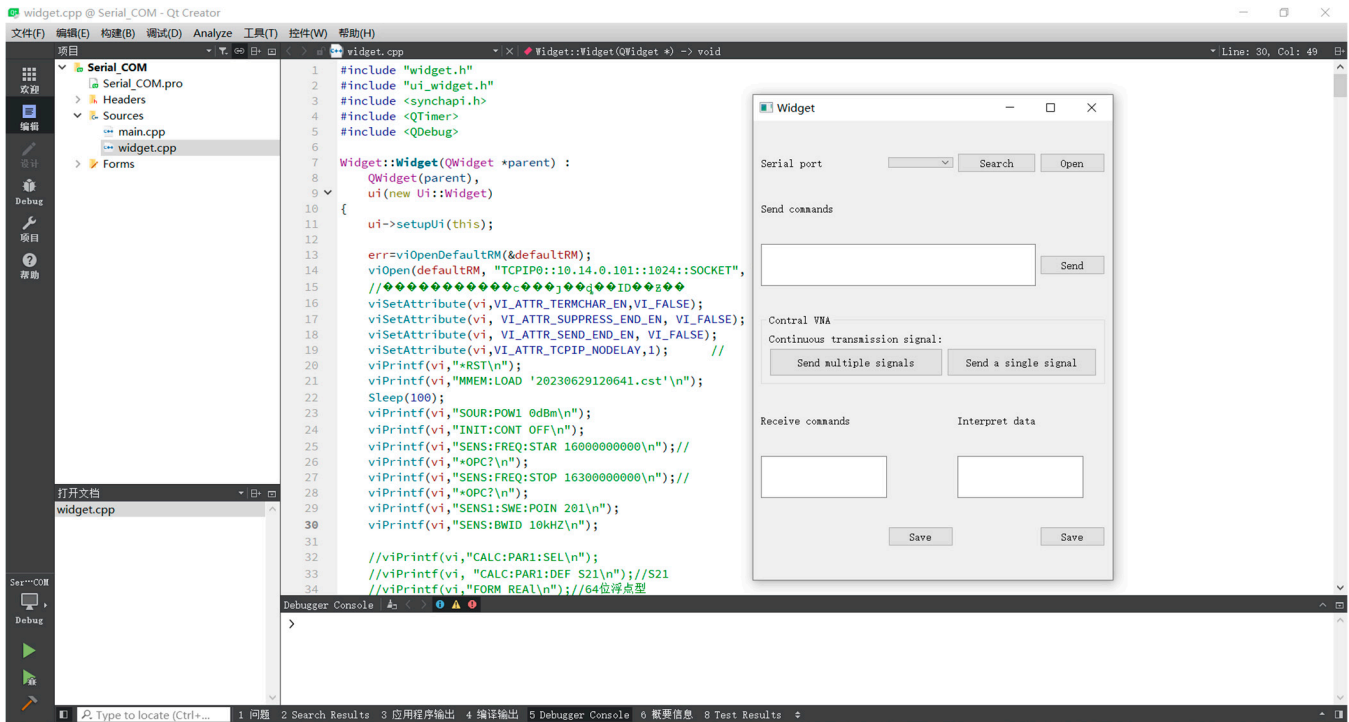


Figure 5. User interface for system control.

The characteristic of a radar system is that it can control VNA to continuously transmit signals at the fastest possible speed to capture the fast one-dimensional micro deformation of targets, which has significant practical application value for targets such as bridges and buildings. Additionally, the controller can operate away from the experimental site to avoid many dangers. This system integrates instrument control, datastore, data-processing, and other operations into the computer terminal, facilitating straightforward operation and management.

2.2.2. Principle of Radar Time-Series Interferometry Measurement

1. Signal model

The concept of SFCW was first proposed in 1972 for detecting buried objects. However, extensive research on SFCW radar sensors only began in the early 1990s [42]. The pulse width of the single frequency sub signal of SFCW is τ , the speed of light is c , the starting frequency of the carrier frequency is f_0 , the center frequency is f_c , the frequency step is Δf , and the number of frequency steps is N . The frequency of the SFCW signal is shown in Figure 6.

B is the bandwidth of the transmitted signal, as follows:

$$B = N \cdot \Delta f \quad (1)$$

δ_r is the resolution of the system, as follows:

$$\delta_r = \frac{0.886 \cdot c}{2B} \quad (2)$$

The signal time is t , n is an integer from 0 to $N - 1$, and the transmitted signal $S_t(t)$ can be expressed as

$$S_t(t) = \exp[2\pi(f_0 + n \cdot \Delta f)t] \quad (3)$$

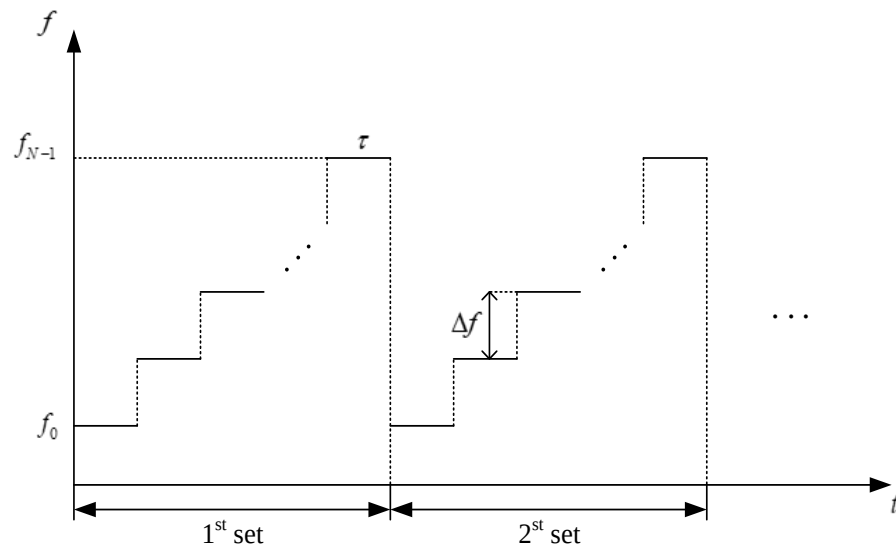


Figure 6. Schematic diagram of SFCW signal frequency.

The echo signal $S_r(f)$ generated by radar illumination from a target at a distance of R from the antenna is

$$S_r(f) = \exp[2\pi(f_0 + n \cdot \Delta f)(t - 2R/c)] \quad (4)$$

After quadrature demod, the normalized baseband signal $S_{IF}(f)$ is

$$S_{IF}(f) = \exp(-j4\pi f_0 R/c) \cdot \exp(-j4\pi n \Delta f \cdot R/c) \quad (5)$$

In the above equation, the first term is a constant, and the second term can be regarded as a frequency domain discrete signal with a linear change in frequency. Directly performing Inverse Fast Fourier Transform (IFFT) on the signal can complete distance compression and obtain a high-resolution one-dimensional range profile of the target [43], as follows:

$$H(l) = \frac{1}{N} \exp\left(\frac{-j4\pi f_0 R}{c}\right) \cdot \exp\left[\frac{j(N-1)\pi}{N} \left(l - \frac{2NR\Delta f}{c}\right)\right] \cdot \frac{\sin[\pi(l - 2NR\Delta f/c)]}{\sin[\pi/N(l - 2NR\Delta f/c)]} \quad (6)$$

By taking the modulus of Equation (6), the following is obtained:

$$|H(l)| = \left| \frac{\sin[\pi(l - 2NR\Delta f/c)]}{N \sin[\pi/N(l - 2NR\Delta f/c)]} \right| \quad (7)$$

The distance sampling of the target is l , at which point the amplitude of the signal is a sinc function, and the peak position l_0 is the following:

$$l_0 = 2NR \cdot \Delta f / c \quad (8)$$

The above equation indicates the correspondence between the peak position of the sampling point and the distance to the target. After distance compression, the position of the target to be measured is determined through the sampling point. If the scattering intensity of the target is high, it appears as a large amplitude sinc pulse in the time domain.

Assuming that the distance between a target and the radar is 100 m, and the bandwidth of the transmitted signal is 300 MHz, simulate the raw data of the target and implement distance compression through IFFT. After interpolation, the signal amplitude is displayed in logarithmic form, and the simulation results of the one-dimensional distance profile are as follows Figure 7.

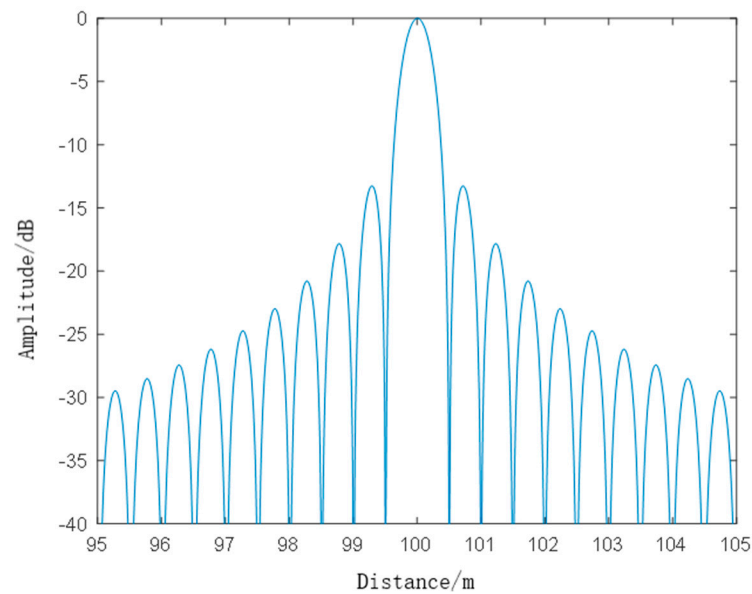


Figure 7. One-dimensional range profile of SFCW radar.

After IFFT, the signal exhibits a sinc function at 100 m with a 3 dB width of 0.448 m, which is consistent with the theoretical value shown in Equation (2). The SFCW signal processing technology has been verified through simulation.

2. Time-series interferometry measurement

After signal processing, the phase containing deformation information can be extracted. Interference refers to obtaining surface change information from the phase of two radar images obtained in the same region at a relatively close time, specifically through phase subtraction or complex conjugate multiplication.

When observing the target in practice, the radar will emit signals to the target at a certain PRF. Set η as the sampling time; therefore, the original radar echo signal is a set of two-dimensional time-series signals, as shown in Table 3.

Table 3. Two-dimensional raw signal matrix.

Pulse No.	f				
	f_1	f_2	...	f_N	
1	S_{11}	S_{12}	...	S_{1N}	
2	S_{21}	S_{22}	...	S_{2N}	
3	S_{31}	S_{32}	...	S_{3N}	
...	...	...	...	...	
M	S_{M1}	S_{M2}	...	S_{MN}	

The horizontal axis represents the frequency sampling and the vertical axis represents signal sampling, forming a two-dimensional signal matrix. The expression is as follows:

$$S_{IF}(f) = \exp(-j4\pi f_0 R(\eta)/c) \cdot \exp(-j4\pi n \Delta f \cdot R(\eta)/c) \quad (9)$$

The difference from Equation (6) is that the instantaneous slant distance becomes a function of η . After compression in the distance direction, the following is obtained:

$$H(l, \eta) = \frac{1}{N} \exp\left(\frac{-j4\pi f_c R(\eta)}{c}\right) \cdot \exp\left[\frac{j(N-1)\pi}{N} \left(l - \frac{2NR(\eta)\Delta f}{c}\right)\right] \cdot \frac{\sin[\pi(l - 2NR(\eta)\Delta f/c)]}{\sin[\pi/N(l - 2NR(\eta)\Delta f/c)]} \quad (10)$$

At present, the horizontal axis is transformed from the frequency domain to the time domain, representing time or distance. Extracting the phase from a certain distance gate in the above equation yields the following:

$$\phi(\eta) = \frac{-4\pi f_c R(\eta)}{c} + \frac{(N-1)\pi}{N} \left(1 - \frac{2NR(\eta)\Delta f}{c} \right) \quad (11)$$

If it is within a distance gate, the phase will not be entangled, that is, there will be no phase jump. If it is greater than a distance gate, phase unwrapping is required to obtain the phase truth. The phase extracted from the first sampled signal is defined as the initial phase ϕ_0 , which interferes with $\phi(\eta)$ to obtain the following:

$$\Delta\phi(\eta) = \phi(\eta) - \phi_0 \quad (12)$$

The position change in the target can be obtained based on the phase difference between two target echoes, as follows:

$$\Delta R(\eta) = -\frac{c \cdot \Delta\phi(\eta)}{4\pi f_c} \quad (13)$$

Take the phase of the timing echo signal of the distance gate from the target to be tested and subtract it from the initial phase. By inverting with Equation (13) and accumulating multiple times, the temporal micro deformation of the target can be obtained. The motion speed of the target can be calculated based on the deformation and acquisition time.

3. Linear least squares fitting

Assuming that the variable changes uniformly over time, in an ideal situation, the cumulative phase is linearly related to time. However, due to factors such as clutter noise and the internal structure of ground targets in signal reception, the two are approximately linear. Therefore, better measurement results can be achieved by linearly fitting the deformation results. Define y_t as the cumulative linear fitting phase at time t , and the relationship between the two is as follows:

$$y_t = at + b \quad (14)$$

Among them, a and b are constants, and the solution satisfies the minimum sum of squared errors [44], as follows:

$$I = \sum_{t=0} (y_t - \phi_t)^2 = \min \quad (15)$$

The goodness of fit refers to the degree to which the regression curve fits the observed values, and the determination coefficient (R^2) can measure the goodness of fit. The maximum value of R^2 is 1, and the closer the value is to 1, the better the fit of the regression curve to the observed values. Calculate the mean as $\bar{y}$ and the fitted data as $\hat{y}$. The calculation is as follows:

$$R^2 = 1 - \frac{\sum_{t=1}^n (y_t - \hat{y}_t)^2}{\sum_{t=1}^n (y_t - \bar{y})^2} \quad (16)$$

2.3. Monitoring of Glacier Termini Movement Speed from Sentinel-1

The C-band Sentinel-1 satellite radar data released by the European Space Agency (ESA) have high quality, with a revisit period of 12 days and multiple imaging modes. Among them, Interferometric Wide (IW) is the main acquisition mode on land, with a resolution of $5 \text{ m} \times 20 \text{ m}$. It is selected from the website of the Alaska Satellite Facility (ASF) of the National Aeronautics and Space Administration (NASA), covering the measurement area and time, including SAR images of two ascending orbits and two descending orbits

(<https://search.asf.alaska.edu/> accessed on 15 August 2023). The parameters are shown in Table 4.

Table 4. Main parameters of Sentinel-1 SAR images.

Image File Name		Time		Perpen- dicular	Polari- zation	Flight Direction	Study Area
Master Image	Slave Image	Master Image	SLAVE IMAGE				
S1A_IW_SLC_1SDV_20230605T001132_20230605T001159_048843_05DFB2_846E	S1A_IW_SLC_1SDV_20230617T001133_20230617T001200_049018_05E508_EB5D	5 June 2023	17 June 2023	64 m	VV	Descending	Rongbuk Glacier
S1A_IW_SLC_1SDV_20230622T125817_20230622T125844_049099_05E777_6E14	S1A_IW_SLC_1SDV_20230704T125818_20230704T125845_049274_05ECD4_38F1	22 June 2023	4 July 2023	−64 m	VV	Ascending	Yangbulake Glacier

In addition to providing rich data sources, the website has also developed HyP3 automation services for SAR image processing [45], which can be accessed directly through the website and includes three products: Radiometric Terrain Correction (RTC), Interferometric Synthetic Aperture Radar (InSAR), and Autonomous Repeat Image Feature Tracking (AutoRIFT). The AutoRIFT feature tracking algorithm can directly generate velocity maps from observed motion [46]. The coherence coefficient can be derived from the ancillary results of InSAR for further analysis.

2.4. Glacier Boundary Data

The Glacier Area Mapping for Discharge from the Asian Mountains glacier inventory was updated in 2018 (Abbreviated as GGI-18) using temporal coverage data from 1990 to 2010 and manual digitization and covers 134,770 glaciers in the high Asian region, encompassing an area of $100,693 \pm 11,790 \text{ km}^2$, as extracted from Landsat 5 and Landsat 7 satellite remote sensing imagery. Research has shown that GGI-18 products have the best effect on most glaciers in China [47,48]. Therefore, this study uses GGI-18 to extract glacier boundaries for mapping.

3. Results

AutoRIFT extracts glacier motion velocity map data from Sentinel-1 satellite in two regions, while InSAR extracts coherence coefficient map data from two regions. For the measured data of the ground-based radar system, the phase temporal variation results were obtained by imaging the sampled point signals and performing time-series interferometry processing based on MATLAB R2020b and then fitted, as shown in Figure 8.

The glacier movement velocity data at the sampling point at the glacier termini can be extracted from the Sentinel-1 satellite radar remote sensing data velocity map. The phase accumulation of the sampling points measured by GB radar interferometry is calculated using Equation (13), and the average of multiple measurements is taken to obtain the results of the glacier termini movement velocity in the direction of the radar line of sight, as shown in Table 5.

Table 5. The results of velocity at the glaciers termini.

Glacier	Type	Sampling Points			Motion Speed by GB Radar (cm/day)	Motion Speed by Sentinel-1 (cm/day)
		Longitude (°E)	Latitude (°N)	Elevation (m)		
Rongbuk Glacier	Debris-covered	86.8689	28.1042	5197.5100	7.74	11
		86.8540	28.1333	5130.7875	4.10	3
Yangbulake Glacier	Non debris-covered	75.0173	38.3020	4187.1825	198.96	14

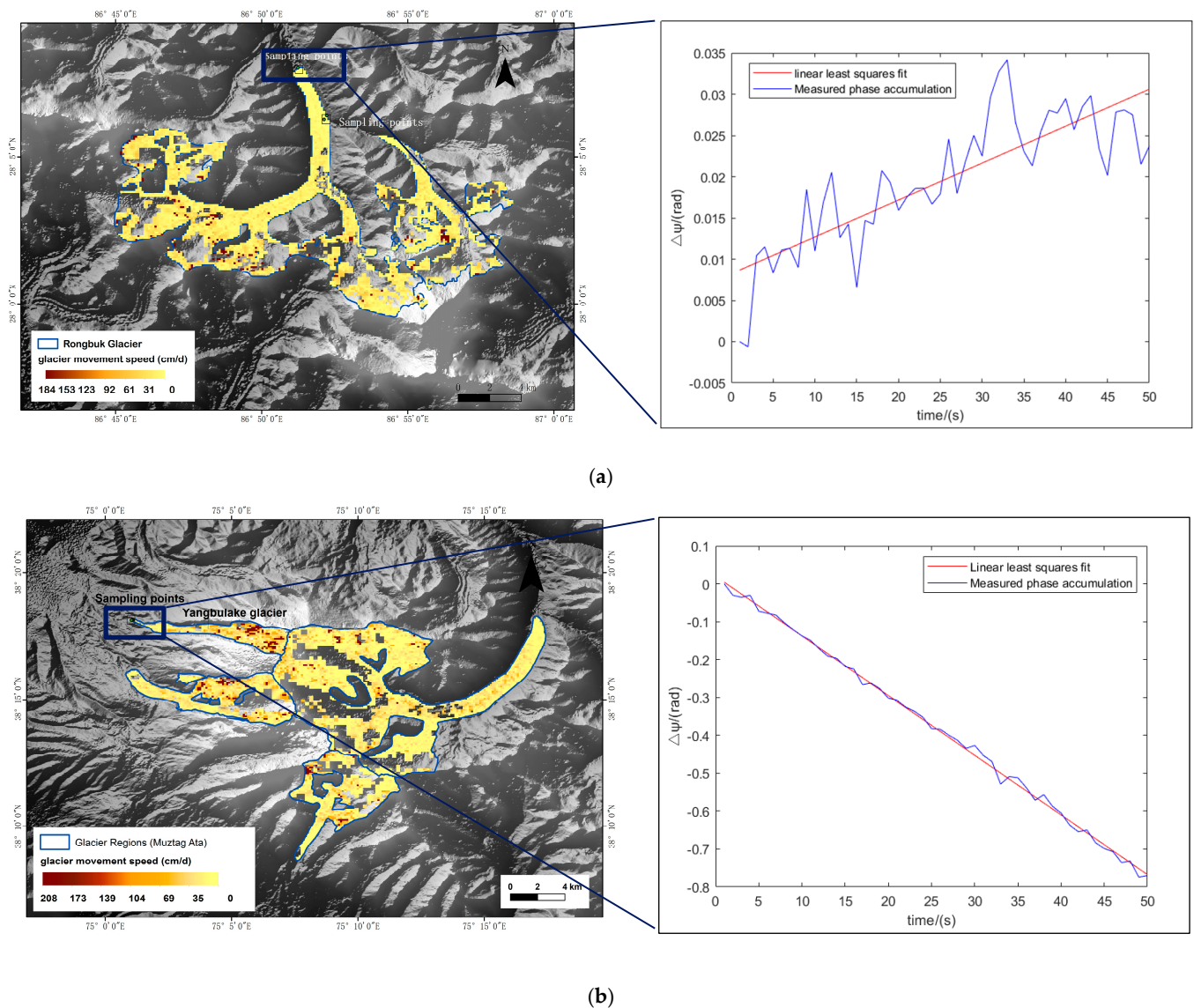


Figure 8. The glacier movement speed map extracted by Sentinel-1 and the phase accumulation results of the sampling points at the glaciers termini measured by GB radar time-series interferometry: (a) Description of glacier movement speed map of Rongbuk Glacier and phase accumulation of sampling points of Rongbuk Glacier termini; (b) Description of glacier movement speed map of Yangbulake Glacier, etc., and phase accumulation of sampling points of Yangbulake Glacier termini.

According to the Sentinel-1 remote sensing data on the left side of Figure 8a,b, both regions exhibit spatial distribution characteristics of faster glacier movement in the upstream accumulation areas than in the downstream melting areas and faster glacier movement in the central areas than in the edge areas. The terminal speed of the Rongbuk Glacier covered by debris is lower than that of the Yangbulake Glacier, which is a non-debris-covered glacier. The maximum central speed of Rongbuk Glacier is 184 cm/day, which is also lower than the maximum central speed of Yangbulake Glacier, which is 208 cm/day. This is because during the sliding process, the friction between the ice and the mountains on both sides slows down the speed. The high values of glacier movement speed are concentrated in the upstream development center of the glacier, and the debris covering the surface of the glacier has a heat blocking effect, which slows down the melting of downstream areas of the glacier [49,50]. The movement speed of Rongbuk Glacier shows spatial differences at different elevations and increases with elevation. According to the statistical results in Table 5, at an elevation of 5197.5100 m, the glacier movement speed by GB radar interfer-

ometry measurement is 7.74 cm/day, while the result obtained by Sentinel-1 is 11 cm/day; at an elevation of 5130.7875 m, the glacier movement speed by GB radar interferometry measurement is 4.10 cm/day, while the result obtained by Sentinel-1 is 3 cm/day. The two results are generally consistent, indicating the feasibility of GB radar interferometry for measuring glacier movement speed. Further analysis shows that the accuracy of ground-based radar interferometry measurement reaches the sub-millimeter level, and the distance resolution can be calculated as 0.5 m based on the speed of light and bandwidth. However, the accuracy of satellite remote sensing data is centimeter level, and the spatial resolution is meter level, indicating that GB radar has better monitoring performance.

For the phase accumulation map and fitting analysis of the sampling points at the glacier termini by GB radar interferometry measurement on the right side of Figure 8a,b, the determination coefficient (R^2) of the fitting results at the Rongbuk Glacier termini is 0.68 and the determination coefficient (R^2) of the fitting results at the Yangbulake Glacier termini is 0.99. The closer the coefficient is to 1, the better the fitting effect. The measured results in the monitoring of the termini of the Yangbulake Glacier are highly consistent with the fitting results, but there are significant differences in the analysis of Sentinel-1 data results. The GB radar measurement result is 198.96 cm/day, while the Sentinel-1 measurement result is 11 cm/day. Due to the melting season of glaciers during field measurements and the fact that the Yangbulake Glacier is a non debris-covered glacier, its movement speed is very fast. However, the revisit period of the Sentinel-1 radar satellite is relatively long, and the two interfered images differ by 12 days. In addition, the terrain in the study area is complex, and natural phenomena such as snowfall, melting, wind blown snow, avalanches, and cracks can cause changes in the scattering characteristics of the target. Therefore, the misalignment of the two SAR images often leads to some “hollow values” or speed mutation points in the speed map [51]. When the glacier moves too fast and exceeds the monitoring range of offset tracking technology, it is also difficult to monitor the glacier movement. On the other hand, GB radar uses second level sampling, with a total signal acquisition time of less than 1 min, which can obtain information on glacier movement changes better. This also indicates that GB radar interferometry measurement has better monitoring effects when the glacier movement speed is fast.

In order to better analyze the satellite radar remote sensing results, coherence coefficient maps of Sentinel-1 InSAR data were extracted and statistically analyzed. The results are shown in Figure 9 and Table 6.

Table 6. The results of the coherence coefficient.

Study Area	Min	Max	Mean	StdDev	<0.4 (%)
Rongbuk Glacier	0.0006	0.9859	0.2694	0.1677	83.6998
Yangbulake Glacier, etc.	0.0007	0.9718	0.2622	0.1541	84.2363

Overall, from the coherence coefficient maps on the left side of Figure 9a,b, the coherence coefficients in the two regions are mostly low. From the statistical maps on the right side of Figure 9a,b, it can be seen that the coherence coefficient values of most pixels are less than 0.4. When the pixel value is about 0.2, the count of pixels is at the peak level, indicating that the number of pixels is the highest when the coherence coefficient is 0.2. According to the statistical results in Table 6, the average coherence coefficient of Rongbuk Glacier is 0.2694, and the coherence coefficient of Yangbulake Glacier and its surrounding glaciers is 0.2622. The average coherence coefficients of both regions are around 0.26. The proportion of pixels with a coherence coefficient less than 0.4 in the two regions is 83.6998% and 84.2363%, respectively. This means that only about 15% of the pixels in the two regions have a coherence coefficient greater than 0.4. The coherence coefficient of satellite radar remote sensing data in the two glacier areas is relatively low, and the glacier movement speed results inverted by this method need to be studied. The maximum values of the two regions are 0.9859 and 0.9718, both approaching 1. From the map, it can be seen that the

region with the highest coherence coefficient of the Rongbuk Glacier is located at glacier termini. This is because the glacier at glacier termini moves slowly and maintains a certain coherence during a revisit period, making satellite inversion results more reliable. For the Yangbulake Glacier, the coherence coefficient of the sampling location at the glacier termini is about 0.2, indicating low coherence. This suggests that the inversion results at this location are distorted and have poor credibility. This is consistent with the Sentinel-1 radar data and GB radar interferometry measurement results analyzed earlier at the termini of the Rongbuk Glacier, while there is a significant difference at the termini of the Yangbulake Glacier.

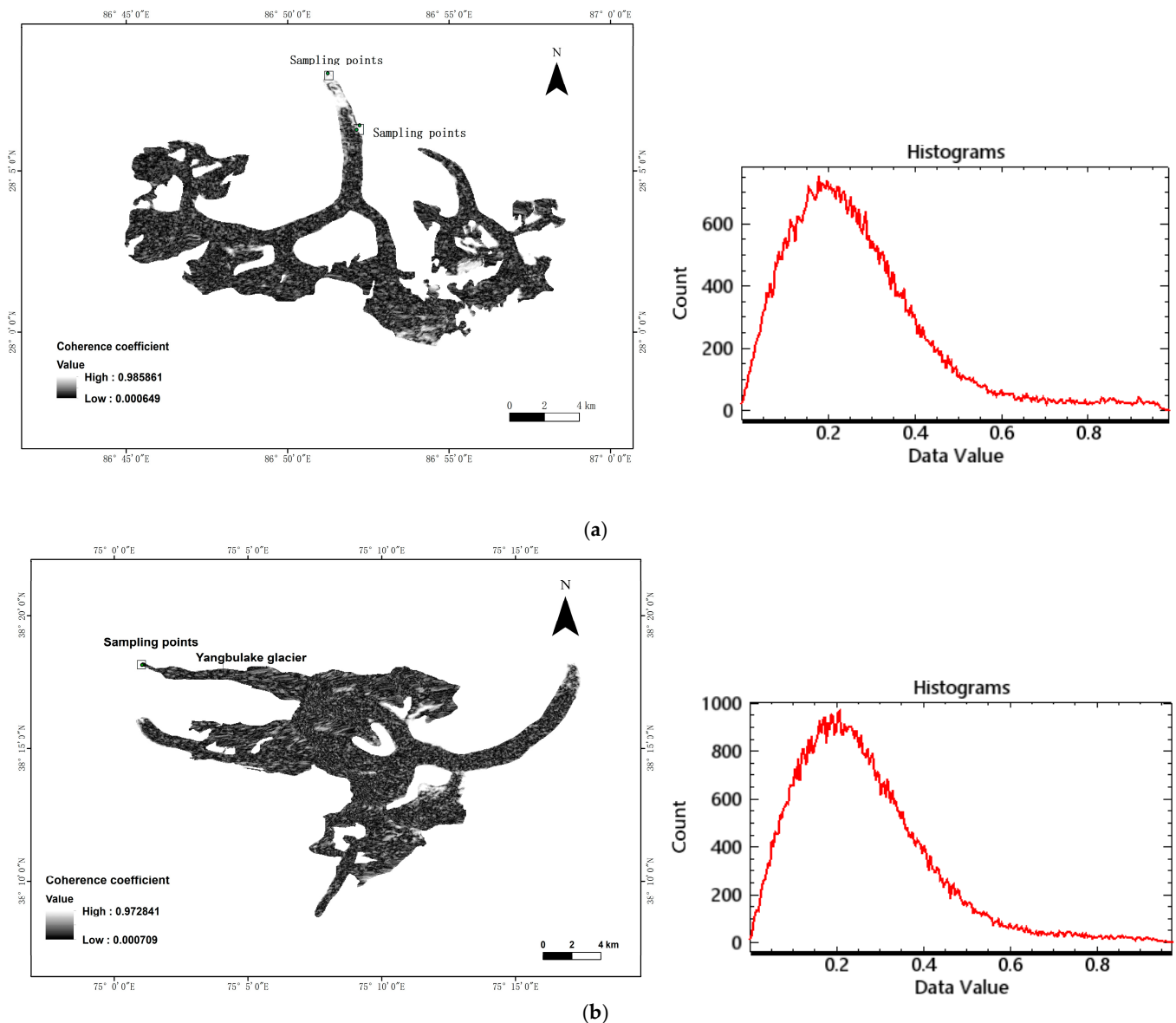


Figure 9. InSAR coherence coefficient maps and statistical results. (a) Coherence coefficient map and statistical results of Rongbuk Glacier; (b) Coherence coefficient map and statistical results of Yangbulake Glacier, etc.

From this perspective, the large-scale inversion of Sentinel-1 radar satellite remote sensing and GB radar interferometry measurement provide consistent and reliable monitoring results for the slow-moving Rongbuk Glacier termini covered by debris. However, the termini of the Yangbulake Glacier is less affected by debris, and the glacier is exposed during the melting season. Glacier movement speed is faster, and Sentinel-1 radar satellite

remote sensing results are distorted due to longer revisit periods and lower coherence, which is significantly different from GB radar interferometry measurement results. This indicates that GB radar systems can quickly extract glacier movement speed through interferometric measurements, with a short monitoring time, high accuracy, and more reliable results. This indicates the advantages and potential of GB radar system interferometry measurement in the study of glacier dynamics and real-time monitoring.

4. Discussion

Previous research has thoroughly investigated the contextual significance, development trends, and practical applications of GBSAR studies for glacier monitoring. A comprehensive one-dimensional detection experiment was conducted to measure the movement speed of the glacier terminus using GB radar. Through comparative analysis with Sentinel-1 satellite radar data, the viability and superiority of GB radar in deformation monitoring applications were substantiated. It is important to note that the precision of glacier movement speed measurement is intricately linked to various factors including the characteristics of the glacier, the surrounding environment, the measurement properties of the radar system, and data processing methodologies. These findings underscore the complex interplay between these elements in achieving accurate and reliable results in glaciological research. The analysis is as follows:

4.1. Heterogeneity of Glaciers

The deformation rate of glaciers is intricately linked to external pressure. The accumulation of mass due to precipitation and wind-blown snow in the upstream regions, coupled with the melting and disintegration of ice in the downstream regions, leads to continuous fluctuations in ice thickness, which serves as the fundamental driver for glacier movement. In regions where glaciers are thickest, glacier movement speeds tend to be higher [52]. Danni Huang et al. showed that changes in glacier movement speed are moderately positively correlated with glacier area size (linear correlation of 0.648) and glacier length (linear correlation of 0.675) and weakly correlated with surface slope [53]. Although surface slope does not exert a direct influence on glacier movement speed, a positive correlation between glacier movement speed and surface slope for large and medium size glaciers exists ($>5 \text{ km}^2$), thereby increasing the uncertainty of glacier movement speed inversion results [54].

4.2. Environment

There are many meteorological factors that affect glacier movement, among which precipitation and temperature have the greatest impact. In June 2023, the average high temperature in Shigatse, where the Rongbuk Glacier on Mount Everest is located, was 21°C , the average low temperature was 8°C , the extreme high temperature was 25°C , and the precipitation was 25 mm~50 mm. The average high temperature and low temperature in Taxkorgan, where Mount Muztag Ata is located, are 25°C and 6°C , respectively. The extremely high temperature is 34°C , and the precipitation ranges from 10 mm to 25 mm [55]. The temperature difference between day and night in the two regions is relatively large, with temperatures about 1°C higher than usual. The precipitation is about 50 mm less than usual, with less rainfall. They affect the conversion efficiency of glacier melting and accumulation, which in turn affect the replenishment and storage of glaciers. The influence of westerly winds and southwest monsoons has intensified the surface melting of glaciers in the southern and western regions of Mount Muztag Ata, leading to increased precipitation. Consequently, the movement speed of the Yangbulake Glacier is relatively rapid [56].

4.3. Debris

Glacier melting will expose a portion of the inner debris on the surface of the glacier, forming a glacial moraine that covers the glacier. Impurities such as ice and rock debris that directly fall on the surface of the glacier can also form debris. The debris area is mostly located at the termini of large ice tongues and the thicker and larger area downstream

of the glacier. The thickness of the debris generally decreases with increasing altitude and will affect the melting rate of glaciers. If the debris is too thin, it will accelerate the melting of ice. If the debris is too thick, it is not conducive to the downward transfer of heat. Therefore, as the thickness of the debris increases, the melting rate of glaciers first increases and then decreases. With the warming of the climate, there is a severe trend of terrain fragmentation [57]. These have a significant impact on glacier melting, thereby affecting the movement of glaciers.

4.4. Atmosphere

The signal emitted by radar is electromagnetic waves. During the propagation process in atmospheric media, uneven media can cause disturbances to the propagation path, causing changes in the direction and path of signal propagation and generating an atmospheric additional phase. This phase is affected by atmospheric parameters such as temperature, humidity, and atmospheric pressure. If there is a significant change in atmospheric parameters during the two measurements, it will have a significant impact on the inversion of the true deformation value, thereby affecting the measurement results of glacier movement speed. The atmospheric parameters in the Sichuan Tibet region change rapidly, and the runoff after glacier meltwater in the experimental environment is relatively large, which has a certain degree of interference with data collection. The normal methods include atmospheric parameter correction [58,59] and Permanent Scatter (PS) technology [60,61]. Atmospheric parameter correction requires measuring the dry temperature, wet temperature, air pressure, and absolute temperature of the atmosphere to establish an atmospheric refraction model and solve the atmospheric refractive index. However, obtaining parameters on the TP is very difficult. It is not easy to determine whether there is a stable atmospheric region around it, and isolated coherent regions cannot achieve atmospheric phase estimation, which is also a key aspect that needs to be focused on in the processing of micro deformation measurement results.

4.5. Radar Line of Sight (RLOS)

Both spaceborne radar and GB radar observation methods are limited by the feature of the RLOS observation, and displacement perpendicular to the line of sight cannot be measured. The movement direction of glaciers is actually three-dimensional. In addition to movement in the line of sight direction, glaciers also move in the vertical direction. In the following research, combining multi-source data analysis of glacier vertical movement is considered to achieve a three-dimensional measurement of glacier movement speed through vector synthesis.

4.6. Ku Band

Although the Ku band has better measurement performance compared to the C band and Ka band, it is very sensitive to small deformations in the natural environment. The decrease in coherence can lead to image distortion, but coherence and temporary decorrelation will increase with the increase in the system operating wavelength. It can be considered to select a suitable band based on the measurement results of different bands, and then adjust the parameters of the GB radar system for micro deformation measurement to optimize the measurement performance as much as possible.

4.7. Fitting Model

The speed of glacier movement over time is not an entirely perfect linear correlation relation. With the influence of temperature or the surrounding environment, the changes in different time periods are also not the same. Radar satellite remote sensing data represent the average change in glacier movement during a revisit period, while GB radar data reflect the average change during the collection period. However, the study of the changing pattern of glacier terminal movement still requires long-term and multiple observations to determine the fitting model and obtain better monitoring results.

5. Conclusions

This article is based on a GB radar system and conducts research on monitoring the movement speed of glacier termini through interferometry measurements. The system emits SFCW system signals through VNA and operates in the Ku band. After MATLAB signal processing, it can quickly extract the movement speed information of glacier termini. The velocity map extracted from Sentinel-1 satellite remote sensing data and the coherence coefficient results extracted from InSAR during the same period are summarized as follows:

Based on an independently built GB radar system, the glacier termini movement speed was extracted from two typical areas, Rongbuk Glacier on Mount Qomolangma and Yangbulake Glacier on Mount Muztag Ata, with a sampling time of seconds. The measurement accuracy reached a sub-millimeter level, and the feasibility of the system's interferometric measurement for glacier movement velocity monitoring within a certain range was verified.

For debris-covered glaciers like Rongbuk Glacier, the debris at the termini is the thickest, so the glacier movement is slow in this position. Based on satellite remote sensing inversion methods, large-scale and long-term glacier movement monitoring can be achieved, but there is a lack of field validation data. In this field experiment, the glacier movement speed measured by GB radar system interferometry and satellite remote sensing inversion showed spatial differences with elevation. As the altitude increased, the movement speed increased. The consistency between the two methods was high, which was consistent with the actual glacier movement trend in the area. This proved the accuracy of the glacier movement speed results by the GB radar system interferometry measurement and also assisted in verifying the accuracy of satellite remote sensing data inversion.

For fast-moving non-debris-covered glaciers like Yangbulake Glacier, glacier surging can easily cause glacier disasters. However, Sentinel-1 and other satellites have a long revisit period, and glacier movement is significant, leading to serious inconsistency in satellite remote sensing data inversion results and making it difficult to meet the short-term and rapid monitoring of glacier movement. GB radar system interferometry can quickly extract glacier movement information, and the fitting of experimental interferometry results is good. This proves that GB radar system interferometry can be an effective supplementary method for monitoring glacier movement changes, making up for the shortcomings of satellite remote sensing inversion.

Overall, the GB radar system is easy to carry and install, with a wide range of glacier movement changes that can be monitored in the direction of the radar line of sight, ranging from a few millimeters to several hundred millimeters per day, and monitoring accuracy at the sub-millimeter level. Due to its sub-second sampling time, it can efficiently extract glacier movement information in real-time, and the monitoring process is highly automated, enabling dynamic monitoring of glaciers and providing good data support for analysis and research on hydrological changes, glacier surges, and ice collapse disasters. It has practical engineering significance and provides guidance for related research on the TP region.

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