Analysis of Railway Subgrade Settlement Deformation in Permafrost Regions Based on Satellite Interferometry

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Abstract: SAR differential interferometry is an innovative space-based measurement technology for ground deformation. Under inclement Qinghai-Tibet plateau environment, monitoring and analysis of railway subgrade deformation using satellite interferometry in plateau permafrost region has very important engineering significance for stability evaluation and safety management. In the paper, a brief description of the principle and processing procedure of SAR differential interferometry was given, and the influencing parameters and error analysis were discussed. Then satellite interferometry was applied to measure subgrade deformation in the Beiluhe test site along the Qinghai-Tibet railway with gathered satellite interferometric SAR images. Based on the satellite-interferometry-derived data, the deformation characteristics of six points in different permafrost subgrades (the sliced rock embankment, the crushed rock embankment and railway bridge) along the Qinghai-Tibet railway were analyzed and compared. The analysis results show that settlement is the main behavior of railway subgrade deformation and the deformation amount of railway bridge is less than the sliced or the crushed rock embankment along the Qinghai-Tibet railway in permafrost regions. All these results are in good agreement with the ground measurements and other relevant studies.

Keywords: Railway subgrade, Settlement, SAR differential interferometry, Deformation monitoring, Leveling.

1. Introduction

Using conventional field surveying methods, such as leveling, settlement meter, inclinometer, or constructing time-serial GPS observation stations, acquiring the deformation information usually means labor-intensive, time-consuming and high-cost work. Especially under inclement plateau environment, ground measurement is not an easy work. The seasonally freezing bulge and thawing subsidence are the main hazards for engineering construction in permafrost regions [1]. Therefore, seeking for new surveying technologies with the advantages of high accuracy, high efficiency, high reliability and low cost, becomes an important research issue in permafrost region of Qinghai-Tibet plateau [2]. It has very important engineering significance for railway infrastructure long-term deformation monitoring [3].

In recent years, various non-contact monitoring and analysis systems for ground deformation have developed rapidly. Most of them are ground-based devices and cannot cover a large range of the ground deformation field. Synthetic Aperture Radar (SAR) differential interferometry (D-InSAR) is an innovative space-based measurement technology for surface deformation developing rapidly during recent...
years in photogrammetry and remote sensing field [4, 5]. R. Gens et al reported that SAR differential interferometry can be applied to investigation of deformation fields caused by earthquakes, volcanoes and active faults, surface subsidence, and terrain surveying [5-7]. It has the capability to detect subtle changes in the earth’s surfaces over periods of days to years with a scale (global), accuracy (millimeters), reliability (day or night, all weather), and no requirements for ground stations. In particular, the surveying results by InSAR can cover a large area of the ground deformation field in succession. In addition, the settlement information of point, line and surface can be measured and analyzed using this method. Because of its unique capability, which no other technique can provide high-resolution maps of deformation field, these pioneering studies have generated enormous interest in the science and technology community because they point to an entirely new way to study surface deformation of the earth [7-15].

For example, satellite interferometry can offer a useful contribution to the analysis and the study of an area of interest during the planning phase. The identification of unstable areas and the reconstruction of their historical displacement provide a synoptic view of local dynamics, useful for site and route planning. For linear structures, such as roads and railways, satellite data minimize survey time and cost, compared to other monitoring techniques. As to deformation monitoring for railway subgrade settlement, Satellite D-InSAR technology can improve efficiency and work condition for roadbed deformation monitoring with low cost and no or little field surveying work. Until now, some scholars in China have tried to do some preliminary researches [8-11].

In this paper, a brief description of SAR differential interferometry technique was presented, and the processing procedure, influencing parameters and error analysis related to topography were discussed. Then a case study, which persistent scatterers (PS) interferometry was applied to detect subgrade deformation over permafrost regions of Qinghai-Tibet Plateau in the Beiluhe test site along the Qinghai-Tibet railway with gathered ENVISAT-ASAR images, was introduced. The satellite-interferometry-derived experimental results were analyzed.

2. SAR Differential Interferometry

Radar sensors mounted on satellites transmit microwave signals toward a target area, some of which are reflected back to the satellite. These 'back scattered' signals are read and stored by the satellite sensor to form radar images of the target area. Like all radar systems, the aim is to measure the sensor-to-target distance. In the particular case, since synthetic aperture radar (SAR) satellites regularly retrace over the same orbit, allowing a time-lapse sequence of temporally spaced images acquired for the same area, the basic idea is to compare successive satellite images, measuring the variation of the sensor-ground point distance, with the objective of measuring ground displacement. This approach is called synthetic aperture radar interferometry (InSAR). InSAR is a non-intrusive, non-destructive technology that measures relative displacement over time, with high accuracy. InSAR has significantly evolved in the last 20 years. The two most widespread InSAR techniques are Differential Interferometry (D-InSAR) and Persistent Scatterer Interferometry (PSI).

The interferometric data can be acquired by two antennae on the same platform, or by one antenna on repeating its orbit. Because all space-borne SARs in operation are single-band and single-antenna systems, many published literatures related to the technique have been using repeat-pass interferometric data. If ignoring certain factors influencing the quality of SAR interferometric data, such as atmospheric difference at the two times of imaging, internal clock drift, weather conditions, system noise et al., the interferometer geometry and range difference attribute to three factors: 1) A spherical earth with no topography, 2) topography, and 3) surface deformation. If phase gradients resulted from 1) and 2) on interferogram are subtracted, then the information of residual phase gradients can be used to monitoring dynamic change of earth surface. According to the different methods of removing topographic effects, basically we can classify the technique into two categories: 1) differential interferometry based on DEM (digital elevation model) simulated interferogram; and 2) differential interferometry based on unprimed SAR interferogram, but as to principles related to the two methods, there is no evident difference.

2.1. Differential Interferometry Geometry and Equations

Consider the condition of no existence of surface deformation during SAR imaging period, the general geometry of SAR interferometry is illustrated in Fig. 1. Two radar antennas A1 and A2 simultaneously viewing the same surface and separated by a baseline with length B and angle α with respect to horizon. A1 is located at height h above some reference surface. The distance between A1 and the point on the ground being imaged is the range \( \rho \), while \( \rho + \delta \rho \) is the distance between A2 and the same point. \( \lambda \) is the wavelength of the radar and \( \delta \rho \) is the range difference between the reference and repeat passes of the satellite, the phase difference \( \phi \) between the signals received from the same surface element at the two antenna positions is

\[
\phi = \frac{4\pi}{\lambda} \delta \rho ,
\]

(1)
According to the law of cosine, we have equation (2)

\[(\rho + \delta \rho)^2 = \rho^2 + B^2 - 2\rho B \sin(\theta - \alpha),\] (2)

where \(\theta\) is the look angle of the imaging radar. For space-borne geometries, we can make the parallel-ray approximation and rearrange the above equation by ignoring the second term \((\delta \rho)^2\), thus we obtain

\[\delta \rho = B \sin(\theta - \alpha) + \frac{B^2}{2\rho},\] (3)

Because of \(\rho \gg B\), we neglect the term of \(\frac{B^2}{2\rho}\) for the sake of simplicity, thus we have equation (4)

\[\delta \rho = B \sin(\theta - \alpha) = B_{||},\] (4)

where \(B_{||}\) is the component of baseline parallel to the look direction.

Combining with equation (4), we can rearrange equation (1) as

\[\phi = \frac{4\pi}{\lambda} B_{||},\] (5)

From equation (5), we know that the measured quantity of phase difference \(\phi\) is directly proportional to \(B_{||}\) and wave numbers \((2\pi/\lambda)\), with constant of proportionality 2.

The mixed phase term of surface displacement and topography will cause confusion in the interpretation. However, if the data from the initial unprimed interferogram are properly scaled with a proportional factor \(\frac{B'_{||}}{B_{||}}\) and subtracted from the primed interferogram, we can get a solution dependent only on \(\Delta \rho\) as equation (9)

\[\phi' = \frac{4\pi}{\lambda} (B'_{||} + \Delta \rho),\] (8)

Since the quantity on the left is determined entirely by the phases of the interferograms and the orbit geometries, the line-of-sight component of the displacement \(\Delta \rho\) is measurable for each point in the scene.

For operational use, commonly the baseline parameters of primed interferogram are used to simulate the unprimed interferogram derived from only topography effect, which then is subtracted from primed interferogram. The resulted differential interferogram contains only the information related to surface deformation.

It is important to assess the relative sensitivity of the phase measurement to topography and displacement since the topography itself may be
poorly known. From the imaging geometry in Fig. 1, we can get the height $z$ of the point $z(y)$ as equation (10)

$$z = h - \rho \cos \theta,$$  \hspace{1cm} (10)

where $h$ is the flying height. For the relative sensitivity of the phase with respect to $\theta$, by differentiating equation (10), we can get

$$dz = \rho \sin \theta d\theta.$$  \hspace{1cm} (11)

Because of the irrelevance between $\Delta \rho$ and $B_0$ and recalling equation (4), by differentiating equation (8) with respect to $\theta$ and displacement $\Delta \rho$, we can get equation (12) and equation (13)

$$d\phi' = \frac{4\pi}{\lambda} B' \cos(\theta - \alpha')d\theta,$$  \hspace{1cm} (12)

$$\frac{d\phi'}{d\Delta \rho} = \frac{4\pi}{\lambda},$$  \hspace{1cm} (13)

Combining equation (11) with (12), we have

$$\frac{d\phi'}{dz} = \frac{4\pi B' \cos(\theta - \alpha')}{\rho \sin \theta}.$$  \hspace{1cm} (14)

Since baseline length (a few hundred meters) is much less than $\rho$ (a few hundred kilometers for a spacecraft system), it is evident from equations (13) and (14) that $\frac{d\phi'}{dz}$ is much smaller than $\frac{d\phi'}{d\Delta \rho}$. Thus, the measured phase is much less sensitive to topography (equation (14)) compared to displacement (equation (13)). When the accuracy of measuring topography using SAR interferometry reaches the level of meter, the accuracy for measuring deformation displacement can reach the level of centimeters or millimeters. Comparing the two results numerically for the case of ERS-1/2, 1 m of topography gives a phase signature of 4.3 degree (actually less than the real noise limit about 20 degree, implying that ERS-1/2 is not sensitive to topography at this level). However, for the same pass pair, a 1-m surface displacement yields a phase signature of 12,800 degree, or nearly 3000 times greater sensitivity. Since we seek to measure 1-cm surface changes, this implies that we require topographic data accurate to about 3000×1cm, or ±30 m.

2.2 Analysis of Errors

The rationale of differential SAR interferometry is to measure the relationship between the propagated delay of radar wave and the phase gradient. Theoretically, any factors influencing the propagated delay of radar wave will contribute to the phase gradient on the resultant interferogram. These parameters include surface deformation (generated from earthquake, volcano, subsidence et al.), topography, atmosphere, backscattering variation of objects, and non-parallel orbits et al. If only to measure the displacement of surface deformation, it is necessary to remove all other effects influencing the phase gradient. But in practical, only topography effects is considered, thus the artifacts derived from other factors, such as atmospheric effect, surface characteristics variation et al. remain on the differential interferogram, resulting in errors to the measurement.

On the other hand, some residual topographic effects certainly remain on the differential interferogram no matter whether DEM or unprimed interferogram be used to remove the effects of topography. The smaller the baseline length is, the less sensitivity to topography the interferogrametry technique is, then the less the residual topography effects are on the differential interferogram. In general, height error as a function of phase error for topographic analysis is given by equation (15)

$$\delta = \frac{\hbar_2\pi}{2\pi} \cdot \delta_\theta = \frac{\lambda \Delta \rho}{4\pi B} \cdot \frac{\sin \theta}{\cos(\theta - \alpha)} \cdot \delta_\phi,$$  \hspace{1cm} (15)

where $\hbar_2\pi$ is the ambiguous height, $\sigma_\theta$ is the phase error in the interferogram, and $\delta_\phi$ is the resultant height error, other symbol is similar to previous equations.

According to equation (15), we can use ambiguous height to evaluate the residual topographic effects. For example, while using USGS DEM to remove topographic effects, the vertical accuracy of DEM is 30 m and the ambiguous height of interferogram is 220 m, then we know the fringe numbers of differential interferogram generated from errors of DEM are 30/220 at most. If the wavelength of radar system is 5.6 cm, the measuring error derived from DEM error is $\frac{28\times30}{220} = \frac{840}{220}$, approximately equal to 4 mm.

Utilizing DEM to remove topography effect, only the effects of surface deformation and DEM errors remain on the differential interferogram, the area of needing to unwrap is relatively less. But the residual topographic effects, that is, the errors of DEM can easily be delivered to differential interferogram. Zebker discusses the limitation of this method and he proposed to use another interferogram (unprimed interferogram) for removing the topographic effects. But the method is relatively complex except that the residual topographic effect is less than the former and has higher accuracy and automation.

2.3. Persistent Scatterer Interferometry

DInSAR, the first generation InSAR technology, analyses ground deformation that occurs in the time
spanning two image acquisitions. This technique is based on the comparison of a couple of radar images and is limited by the inability to remove errors introduced by atmospheric effects and is only able to measure total displacement and average displacement rates; it cannot distinguish between linear and nonlinear movement.

The Persistent Scatterer (PS) technique has been developed in the late 1990s by A. Ferretti, F. Rocca, and C. Prati of the Technical University of Milan (POLIMI) to overcome the major limitations of repeat pass SAR interferometry; temporal and geometrical decorrelation, and variations in atmospheric conditions [6-7, 12-14]. The main characteristics of this multi-image processing method are that it utilizes a single master stack of differential interferograms, and that only time–coherent pixels, i.e., "Persistent or Permanent Scatterers," are considered. Furthermore, this technique distinguishes itself from other common interferometric processing methods by the fact that all acquired images can be used, including those with large baselines. This is the case since pixels with point like scattering do not suffer from geometrical decorrelation as targets with a distributed scattering mechanism do, and such pixels thus remain coherent in all interferograms. The details of the PS technique are based on [12]. A patent, held by POLIMI, protects the PS technique and the term "Permanent Scatterer technique" is trademarked. A commercial POLIMI spin-off company was founded that exploits the patent and performs ongoing research (Tele-Rilevamento Europa, TRE, treuropa.com).

The PS interferometry is based on the analysis of the interferometric phase of individual long time-coherent scatterers in a stack of tens of differential interferograms with one master image. To date, the PS methods have successfully been used for monitoring subsidence in urban area. The key processing steps of the reference PS technique are the following [7]: 1) Computation of the interferograms. 2) Computation of the differential interferograms using a digital elevation model (DEM). 3) Preliminary estimation – at a coarse grid – of the presumably most coherent pixels. These pixels are referred to as Permanent Scatterer Candidates (PSCs). 4) Refinement of step 3). In the PS technique the long wavelength part of the atmospheric signal is estimated at the coarse grid of PSCs. After interpolation of these estimates, the differential interferograms are corrected, and additional PSs are computed [7, 12].

### 2.4. Data Processing

The interferometric processing can start with focused complex SAR data, sometimes referred to as Single-Look Complex (SLC) data, which may be available as a product from the agency exploiting the satellite. Nevertheless, raw ( unfocused) SAR data are often preferred over SLC data, since they are usually cheaper, can be delivered faster, and exclude the possibility of different focusing strategies at the various processing facilities. From a technical point of view, radar systems are sensitive to range variations in the Line of Sight (LOS) direction. Therefore, measurement provided by any SAR system refers to the projection of the real displacement along the satellite Line of Sight (LOS). An outline of data processing procedure of differential SAR interferometry is illustrated in Fig. 2. Fig. 3 shows the data processing procedure for Persistent Scatterer Interferometry.

#### Fig. 2. Data processing procedure for differential radar interferometry.

#### Fig. 3. Data processing procedure for persistent scatterer interferometry.

### 3. Case Study

The environmental conditions of Qinghai-Tibet plateau permafrost region are extremely beneficial to application of SAR differential interferometry: 1) natural landscape of plateau surface is monotonous, no trees, shrubs and vegetation cover. The rock and soil surface is basically bare. For the lack of perennial vegetation, there exists a single color background. This is not only very favorable for the interpretation of a variety of surface environmental features in remote sensing images, but more
importantly, the radar backscatter characteristics data for SAR interferometry can guarantee highly correlated or basically unchanged during the observation. 2) The permafrost exists mostly large, consecutively, and mostly in micro-open flat terrain. This helps to reduce the terrain effects in differential interferometry. 3) The sparsely populated region is high-altitude, low pressure and cold. The transport facilities, life-oxygen, and living supplies are very difficult. This allows for spatial differential interferometry measurement results little affected by human activities. 4) The continuous surface coverage capability of SAR interferometry is ideal for monitoring large areas of permafrost zone. The permafrost surface deformation information of the overall space distribution can be acquired. Relative to the current ground-based measurements, which set a large number of discrete points or monitoring sections, spaceborne D-InSAR measurement technique application have irreplaceable advantages in obtaining spatially continuous surface displacement field. The use of satellite imagery for InSAR is convenient in that one can monitor almost any region, or as many regions in the world as desired with equal ease. 5) Ground field measurement method not only requires a lot of manpower, material and financial resources, and labor-intensive and inefficient. Spatial differential interferometry method does not require the establishment of ground-based observatories, while greatly improving observing conditions and efficiency, reducing costs. Technically, it has huge potential economic benefits.

For the permafrost region of Qinghai-Tibet Plateau, the radar phase can be affected by changes in the reflectivity of the ground, by changes in the viewing perspective, and by changes in the atmosphere of plateau geographical environment. So, an improved PS processing scheme is necessitated. The experimental research used a dataset composed of 22 images (Acquisition Date: April 3, 2003 ~ May 17, 2007) produced by ENVISAT/ASAR systems in Beiluhe test site of Qinghai-Tibet Railway. With an improved PS processing chain, Chou Xie et al. (2010) had analyzed temporal and spatial performance of phase caused by different components and derived deformation sequence in the Beiluhe area [10].

Most of the deformations that occurred in the Beiluhe area were subsidence. Deformation sequence of PSs on the Qinghai-Tibet railway are compared to the surrounding PSs, and the comparison shows that there is a great difference between the deformation sequences of the two kinds of PSs. Due to the impact of environmental ecological destruction from railway engineering, the PSs on Qinghai-Tibet railway have relatively larger deformations than the surrounding PSs. The study showed that PS interferometry can effectively acquire long-time deformation sequence through analyzing the ground scatterers with relative stable phase and are in accordance with the results obtained by conventional in-situ ground leveling.

In order to further evaluate the deformation details of Qinghai-Tibet railway permafrost embankment, six PS points were extracted from the deformation sequence derived from PS-InSAR processing. Fig. 4 and Fig. 5 showed the deformation curves of the six PSs from April 3, 2003 to May 17, 2007. Fig. 4(a), Fig. 4(b), Fig. 4(c) showed the deformation curves of three PSs located on the sliced or the crushed rock embankment along Qinghai-Tibet railway. Fig. 5(a), Fig. 5(b), Fig. 5(c) showed the deformation curves of three PSs located on the Beiluhe railway bridge.

![Fig. 4. Deformation curves of three PSs located on the sliced or the crushed rock embankment.](image)

Based on the settlement curve comparison from the PS-InSAR measurement analysis, we concluded that settlement is the main behavior of railway
subgrade deformation and the deformation amount of railway bridge is less than the sliced or the crushed rock embankment along the Qinghai-Tibet railway in permafrost regions. For example, the overall settlement was about 60 mm for the sliced rock embankment point located on the sliced embankment of DK1136 (Fig. 4(a)). However, during the same period the overall settlement was about 20mm for the point located on the Beiluhe railway bridge (Fig. 5(a)).

Regular monitoring of post-construction ground movement allows engineers to identify displacement (subsidence or uplift) that could indicate structural weaknesses, or threaten infrastructure. Moreover, satellite monitoring produces quantitative and qualitative deformation maps of surrounding embankment instabilities that often precede slope failure, providing a network-wide monitoring tool for assessing areas at elevated risk of landslides.

4. Conclusions

In recent years, space borne repeat-pass InSAR has received much attention for its ability to generate deformation maps with unprecedented accuracy (centimeter or millimeter level). SAR interferometry is unique and hardly comparable to any conventional technique of deformation measurement. Although it is becoming more accepted, the technique has to date been used in a limited number of operational applications. The unique, continuous subsidence information of point, profile and surface derived from this method can help discover new knowledge for roadbed deformation, provide new scientific data for roadbed stability evaluation, and open a new pathway to deeply study subgrade engineering deformation. In the experiment of subgrade deformation monitoring along the Qinghai-Tibet railway in permafrost regions using D-InSAR, it is found that settlement is the main behavior of subgrade deformation and the deformation amount of railway bridge is less than the sliced or the crushed rock embankment. Due to the gathered InSAR data limitation, our experiment can’t derive more details of railway subgrade deformation over the permafrost region as expected. Future work will gather more InSAR data in the test area and produce a clearer description of deformation over the permafrost region. Meanwhile, more deformation data measured by other method, such as levelling and GPS, will be gathered to further analyze the result from PS and improve the accuracy of deformation measured by PS.

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